Reader

Module 6 – Data Handling Technologies

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Preface

These lecture notes contain the topics treated in the GIMLA module on Data Handling Techniques (Module 6). As with any textbook the text provided here cannot be complete. Therefore, the material published on blackboard and hands-out provided during lectures and practicals form an integral part of the material to be studied.

Mathias J.P.M. Lemmens, January 2008.

Chapter 1

Introduction

By Mathias Lemmens

Land is essential for our being on earth and as a result of its indispensability human beings maintain certain basic relationships with land. First of all the same piece of land is used for one or more purposes, such as car parking, shops, offices and housing, which functions might be positioned on top of each others. The use of land and its location determines its market value, important for establishing a well-functioning land market, which is considered by many as a prerequisite for economical development. (Real estate agents often state that the value of a piece of the earth is determined by the tripod: location, location and location.) Land value is also important for taxation purposes. Tax on real estate maybe dates back to the time that mankind switched from a nomadic life style to permanent settlement. In 1400 B.C. boundary surveys were already carried out in ancient Egypt for taxation purposes. The use of land is usually grounded on some formal or informal right on the land. Indeed, subjects may have rights on land. Here subjects may be an individual (man, woman), a group of individuals, an organization or a group of organizations. Different subjects may have different types of rights on the same piece of land. For example, one subject may own the land, another exploits the land based on rent, and a third one may have a right based on mortgage.

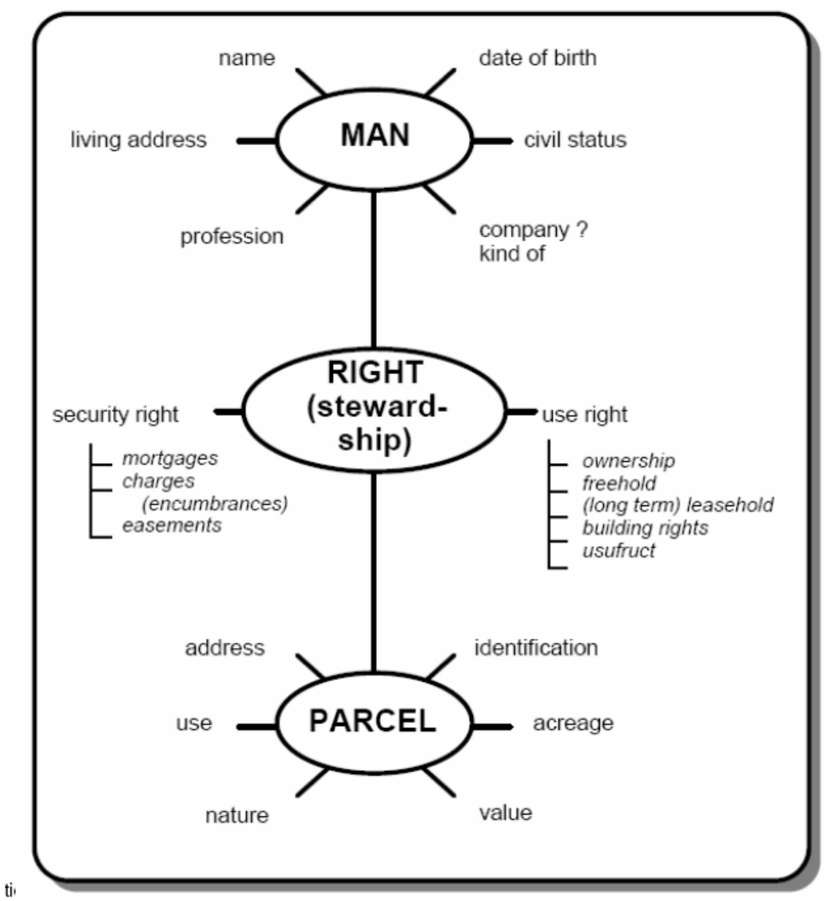


Figure 1, *Relationship between man and parcel. From: Henssen, 1995, Basic Principles of the main cadastral systems in the world. Note that what is indicated as subject in the text, is in this scheme named MAN.*

A key characteristic of rights on land is that they may be transferred from the one subject to another subject. The transfer of rights is usually associated with money and the price a subject is willing to pay for a certain right on the land will depend on its use and value. Since world population increases at breathtaking pace, but land (and also water) does not, land and water become scarce and their value increases accordingly. To avoid conflicts on rights on a piece of land it is essential that the rights, the subjects and the piece of land are clearly identified and registered orally or in writing. In small, tribal communities one may suffice with oral registration and recognition, but in today's complex society in which over 50% of the six billion inhabitants of this planet live more or less anonymously in urban settings, registration which does not depend on the memory of the tribe seniors becomes essential. An effective registration system makes transactions easier, since buyers of right can be relatively secure in their belief that they are dealing with sellers who are legal owners of the rights and have the legal right to sell.

Land Administration

The United Nations Economic Commission for Europe through its Working Party on Land Administration (WPLA) defines land administration as the processes of determining, recording and disseminating information about the ownership, value and use of land when implementing land-management policies.

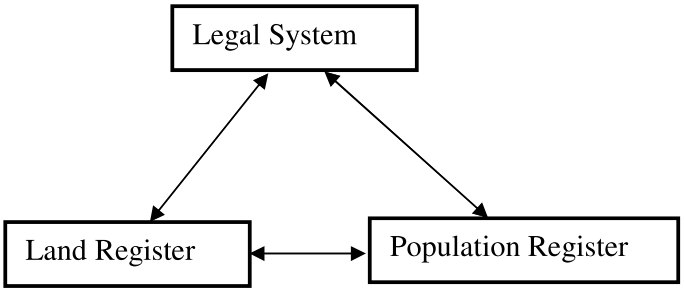
Land → Value

Land ←Rights→ Subject(s)

Land → Use

The value of land is primarily influenced by its possible use and that does not only depend on location and physical characteristics including elevation and soil type but also on the rights associated with the land. When government allows to erect houses on farm land, its value will immediately increase substantially although nothing changed with respect to its physical characteristics and location.

Figure 1 illustrates that a land administration system can not functioning properly, without well-functioning population registration and also not if an adequate legal system is lacking. Population registration and proper laws and legal protection facilities are prerequisites for the establishment of land administration systems. Since also organisations such as firms may have rights on land, Chambers of Commerce play also an important role in the land administration arena.



Parcel

The individual land parcel is the key element in most land administration systems; all cadastral plans and legal records are based on the individual land parcel. A parcel may be defined as a unit of land over which homogeneous tenure is established. Since the individual parcel is the key element it is important that the location of boundaries between parcels are determined with high quality. The creation and maintenance of a register of land parcels and rights on them requires that the boundaries of the parcels can be unambiguously located. A parcel boundary consists of a chain of at least three boundary lines; a boundary line connects two boundary corners whose locations need to be known in a local, national or regional geodetic reference system. Surveying of parcel boundaries is an essential prerequisite for land administration. Land surveyors are experts in designing, building and managing the spatial component land administration systems. They are experienced in creating, describing and defining land parcels and associated rights and restrictions.

Cadastral Surveying

Cadastral surveying and mapping is the corner stone of any Cadastral system. Cadastral surveying is that branch of surveying which is concerned with the survey and demarcation of land for the purpose of defining parcels of land for registration in a land registry. A boundary map should be helpful for the following purposes:

- parcel identification
- parcel indexing
- area determination of parcels
- boundary relocation
- parcel subdivision
- land management
- equitable valuation and property assessment
- land planning
- facilities management.

Many areas of the economy, public administration and private life depend on cadastral survey data. The ownership of real estate is recorded in the land register and is based on the cadastral survey. If an architectural office is planning the design or construction of a building, precise boundary information is required, and also the location of pipes, cables and many other features. The necessary data and information is available from the cadastral map itself or from a variety of sources such as utility asset maps, local authority plans and zoning plans.

All of this information is based on data from the cadastral survey; the terrain surface is measured accurately and reliably, thereby defining the location of property boundary points, the land cover type and the height of the ground. This public data is carefully gathered, scrupulously maintained and constantly kept up-to-date.

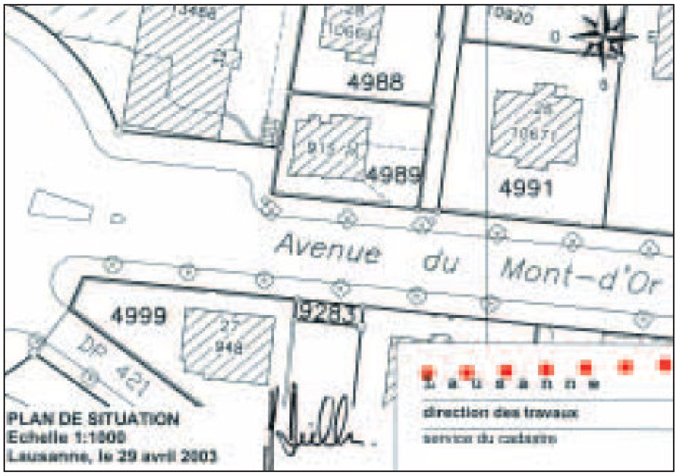
In Switzerland the cadastral survey data is used as a basic input in a wide range of activities:

Applications of cadastral survey data	Direct and derived products of the cadastral survey data
• Development planning • Tourism • Environmental protection • Fire and rescue services • Construction projects • Public administration • Traffic engineering • Agriculture • Marketing • and many others	• The cadastral map itself • The general map • Digital terrain models (DTMs) • City and district street maps • Zoning plans • Utility asset maps • Geographical information systems (GIS) • and many others

Cadastral surveying consists of the measurement of the position, form and content of a parcel of land, and the recording of this information on the cadastral map. These maps can be produced at a variety of scales ranging from 1: 500 to 1:10,000 and form an integral part of the land register. They also contain additional information such as the state of land ownership. Cadastral surveying and the land registry together constitute the cadastral system. The cadastral map is an official document and in many countries, such as Switzerland, the property boundaries recorded on it have the force of law. The registration of land ownership provides the basis for obtaining a mortgage on land or property. The Swiss land registration system, together with its accurate cadastral survey, is perceived as secure and reliable and it thus secures considerable assets: in 1999 the total of the issued mortgages was estimated to be over 550 billion Swiss francs.

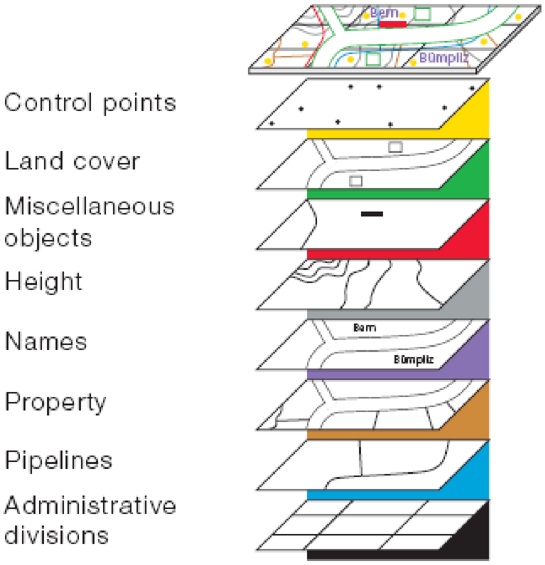
Use of cadastral survey data

In addition to providing secure tenure, cadastral survey data can be used for a variety of additional applications such as the generation of city and district street maps, zoning plans and utility asset maps. Street maps are used to find exact addresses, roads and streets or public places. City maps are also used for many other purposes such as the definition of school catchment areas or the design of new road layouts. Increasingly, city and district street maps can be found on the internet, showing for example the locations of branches of a particular company. Before a building construction project can be planned the builder must find out whether the site in question is actually within the approved building zone. This is where the zoning plan helps, as it identifies where the construction of buildings is permitted within the development planning framework, and thereby contributes to the protection of the landscape. If the construction plans adhere to the requirements of the zone then an application to build may be submitted. Anyone who wishes to lay pipes or cables also needs to know what lies underground. Where are the pipes and cables located? The utilities' versions of the cadastral maps will help because the locations of both underground and overhead and cables such as those for electricity, water, sewage, gas, telephone, TV, etc. are all clearly shown.



Example of a Cadastral map in Switzerland

Cadastral survey data might be available in conventional (on paper maps) and in digital (computerised) form. Digital geo-data is structured into a number of layers thematic layers, which can be freely combined with each other.



- Control points provide the reference to the coordinate system
- Land cover or land use indicating what is on ground such as buildings, roads, hydrology, and forest
- Miscellaneous objects (walls, wells, masts, bridges, etc.)
- Height (Digital Elevation Model)
- Names (place names, locality names)
- Property (land parcels)
- Pipelines, such as gas, water and oil)
- Administrative divisions / boundaries (province, municipal boundaries, building addresses, etc.)

The above geo-data can be linked and combined with additional spatially relevant data such as noise maps and zoning plans. In Switzerland a data description language, called INTERLIS, specifically developed for geographical information, facilitates the exchange of data between different computer systems. INTERLIS has been the official Swiss Standard since 1998 and is legally prescribed for data exchange within the cadastral survey. INTERLIS is also suitable for the exchange and documentation of geodata in other fields such as development planning and environmental protection.

By well organised notification and updating procedures through which the data is continuously revised for change on the ground, the cadastral survey is has to be kept up-to-date and reliable. When this is the case, the cadastral survey provides a consistent reference for all geo-information.

Data Capturing Techniques

There are various methods for the determination of coordinates of corner points of parcel boundaries. The oldest method makes use of direct measurements in the field. Today's typical measuring instrument is the "total station" or electronic theodolite, which measures angles and distances to provide the basis for calculating the coordinates of boundary points and house corners. In South Africa, for example, most cadastral surveys are done with using total stations and/or GPS. In most countries the methods that may be used in cadastral surveying are not rigidly prescribed, although it is a requirement that all work be adequately and carefully checked. All recognised methods, using modern accurate instruments, are acceptable.

Photogrammetry is another method used in cadastral surveying. The terrain is photographed either from the ground (terrestrial photogrammetry) or from the air (aerial photogrammetry) with fixed-wing aircraft or helicopters equipped with special cameras pointing vertically downwards take a series of photographs to form strips in which each successive image overlaps the last by 60 to 80%. Using a special stereoscopic plotting instrument the images are optically rectified and fused in pairs, to form a 3D model in which mountains tower up towards the observer and ravines appear to gape open. From this 3D model, contour lines can be plotted and other 3D objects can be measured and mapped.

The Global Positioning System (GPS) is best known as a navigation system for cars, aircraft and ships, but it is also very effective for cadastral surveying. GPS uses special satellites which orbit the earth, continuously emitting signals which can be picked up by GPS receivers. From these signals, distances and coordinates can be calculated so as to determine 3D position of the receiver. With specialised measurement and computational methods, coordinates can nowadays be rapidly determined to an accuracy of a few centimetres.

Levelling is a very precise method of determining height differences. The levelling instrument is set up between two vertical levelling staves; by reading the height on each staff the vertical difference can be calculated.

The manner in which rights to land are held (land tenure system) should include a method that property parcels can be found on the ground. Such methods might include permanently monumented or marked boundaries and / or keeping a record of the boundary in national agency. Physical identifiers of land parcel boundaries include:

- Natural objects: trees, rivers, rock outcrops, etc.

- Manmade objects (fences, hedges, common walls, wooden posts, iron, steel or concrete markers etc.

An abstract identifiers of a parcel can be the address, but that does not tell anything about the spatial extent of a parcel. Another way to find back a parcel in the terrain is to include an extensive boundary description in the transfer act. An example, from Iceland, is shown in the textbox below.

Boundary Description: Arnarbæli, Grímsnes
Corner monument: the ruin close to Heidrimakelda spring, south of Oddholtsmúla mound; from where there is a line of sight west to Hédinslækjabotnar hollow. From here the boundary follows Hédinslækur creek, and then Höskuldslækur creek to the Hvítá-river. To east of the above mentioned ruin close to Hedirimakelda spring the boundaries run south to verkelda spring, which runs from Galtatjörn pond…(Source: National Archives of Iceland, 1884).

Brief History

Ancient Egypt was probably the first region where man took steps to become a food producer rather than a food gatherer. Until man had taken his first step in advancing from a nomadic to a more settled existence, he had no need for land measurement, nor did he have a need to record his claim to ownership of individual pieces of land. It is highly probable therefore, that Egypt saw the first use of a cadastral system and of cadastral surveying. Evidence from the contents of tombs indicates that there was indeed a form of public land registration and that the land courts would entertain no claim if the land were not registered. There is also evidence that a simple but effective system of cadastral surveying was used to set out the boundaries of individual plots of arable land. Even more importantly, cadastral surveying was needed to recover the beacons and boundaries of these individual plots after they had been inundated during the annual flooding of the Nile. The corner beacons of the plots were set out or recovered by measuring from permanent markers above the flood line.

The system in Ancient Egypt shows the important characteristics of today's modern cadastral system, in that the properties were surveyed and that ownership was recorded in a public register. The importance of having the basic details of a property in an official register, where these could easily be consulted, was recognised from the beginning and this contrasts to the system used in some countries, until very recently, where information relating to land ownership was not registered in a public office but in the offices of private conveyancers. From there this information could be obtained only with considerable difficulty. In contrast to Egypt, in many countries where there was a settled population, there was also an abundance of natural and cultural (artificial) features which, conveniently leant themselves to be used as boundaries. These included permanently flowing streams, hedges and stone walls. There was no need therefore, for corner beacons and so it came about that two basic systems of boundary demarcation developed - that of using natural and man-made features as boundaries, called the general boundary system, and that of relying on beaconed corners.

Fixed and General Boundaries

A boundary can be an invisible line denoting the limit of ownership, or the boundary may be a physical feature (hedge, ditch, wall). A fixed boundary has been accurately surveyed or is a boundary for which a surveyor can accurately find or replace any corner monument from the recorded survey measurements. It can also be described as a corner point that becomes fixed in space by agreement and can not be changed without proper documentation (or in some cases judicial decision). In both cases the boundary location is fixed on the ground and overrides any written record. Another concept is that a boundary becomes "fixed" when agreement is reached between adjoining owners and a line of division is recorded as such in the register which will take precedence over what is on the ground. The location of the boundaries in this system has usually to be done by field surveys, in which the surveyor is physically present in the field, as the boundaries are usually difficult to identify or survey from aerial or satellite images. Field based methods are, in general, time consuming and costly.. However, the benefits are high positional accuracy and precision of boundary location, thereby reducing the potential for disputes.

A general boundary, also called approximate boundary, is not as well defined in space as a fixed one. It can be defined as: "a linear marking by fence, ditch, wall, river bank or other physical feature with a precise line of division between parcels left undetermined." The boundary lines shown on the map are therefore only indicative not definitive. This 'undetermined' nature is the basis of the English system and has often been the boundary system of choice for cadastres established in developing areas where time and financial constraints restrict the establishment of fixed boundaries. Generally boundaries, especially are a more realistic approach in rural areas where highly precise measurements can seem less relevant when surveyed in such large tracts of land. Furthermore, line features that identify general boundary positions are usually more beneficial to photogrammetric surveys for the simple reason of them being more highly visible form the air than single point features.

The precision with which a boundary has to be measured will depend on several factors including the accuracy required (often in relation to its value), land use, legal constraints and cost considerations.

Boundary Type	**Advantages**	**Disadvantages**
Fixed	Location is precisely determined Can be easily retraced in case of dispute	Requires costly surveying Danger of lost of boundary marks
General	Surveying is cheap As long as physical demarcated less chance of dispute	Linear feature may not (anymore) exist in the terrain Reduced level of confidence

Fixed versus general boundaries

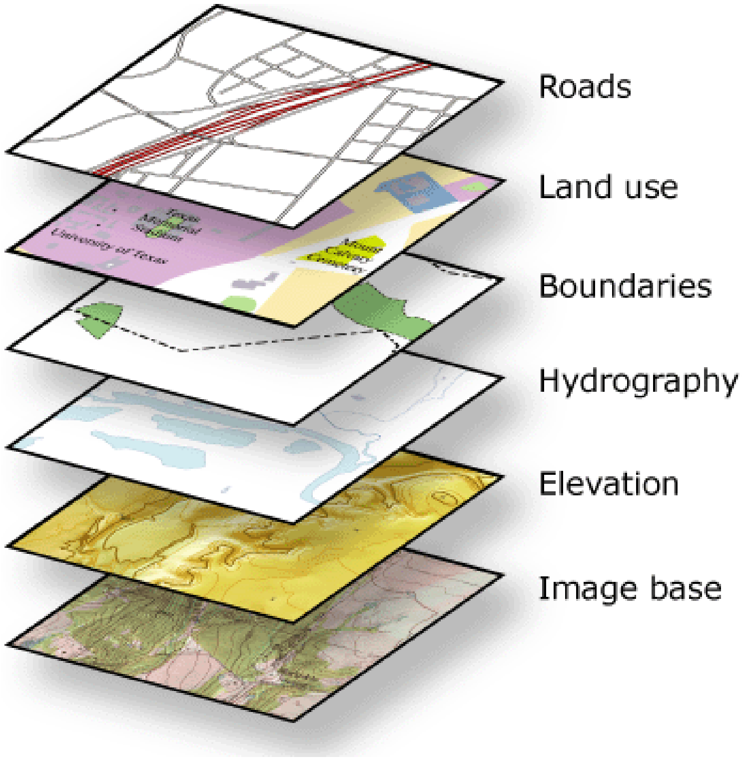
Although registration of title to land is primarily directed at protecting the interests of individual landowners, it is being seen increasingly as an instrument of national land policy, an aid in planning and in general a mechanism to support greater economic development. From a technical point of view the associated activities often consists of combining land administration information (property boundaries) with other types of information such as elevation data (digital elevation model (DEM), hydrography and roads.

In this framework it is important to consider that combining different geo-datasets with each other by means of address is only feasible when the amount of objects and the number of attributes assigned to each is fairly small. This is because the procedures involved require a lot of manual processing. However, today's datasets are often mammoth-sized. Furthermore, all geo-sciences have made mathematical their understanding of the spatial and temporal dynamics of processes of the parts of the real world they study. Today all real-world processes are modelled as systems of mathematical equations, some more complex than others; and these systems have been transmuted into algorithms. This allows calculations involving such cumbersome and tedious exertion for us humble human beings to be done by computers, fast and free of blunders. In addition, today's scientists are no longer happy simply proving spatial correlation through visual inspection alone. The great strength of geomatics is that it enables us to place earth-related object data, by locating features by coordinates in the same geodetic reference system. And for that it is necessary that property boundaries are registered by the coordinates of the characteristic points, which are often marked by corner markers in the terrain.

Boundary Surveys

The determination of the location of boundary lines is done by determination of the location of the corners. There are three major categories of boundary surveys:

- original surveys to establish new section corners in areas which are not yet surveyed that still exist in many parts of the world, not only in developing countries but also in for example Alaska.
- Retracement surveys to recover previously established boundary lines
- Subdivision surveys consist in establishing new smaller parcels of land within larger previously surveyed tracts.



Adjudication

With respect to the first category – original surveys – adjudication is important. In general terms, adjudication refers to determining a binding resolution in a dispute or claim by a neutral third party, which has the authority to make a judgment; often this will be one or more representatives of the court system. Within the field of land administration adjudication represents the process whereby the particular of all rights and liabilities over a parcel are ascertained. Adjudication and demarcation are both important elements to the development of cadastral systems, especially in those countries where one tries to establish new systems and they are generally the initial steps undertaken when developing a cadastral system to define boundaries and their corresponding legal aspects. Demarcation is concerned more with defining or indicating boundaries in the terrain. Adjudication and demarcation can be expensive, with surveying usually contributing highly to this overall cost. Ideally, a cadastral survey should be co-ordinated with the national control network and therefore is usually completed along the "whole to the part" principle, that is from a high order national control system to a lower order system in a given area.

An effective registration system makes transactions easier, since buyers of rights can be relatively secure in their belief that they are dealing with sellers who are legal owners of the rights and have the legal right to sell.

Property systems and land markets are not static and therefore there is an ongoing need for maintaining the database.

Digital Cadastre

Land surveying is the process of measurement and delineation of the natural and artificial features (including property boundaries) of the earth. The resulting documents include digital (softcopy) or paper (hardcopy) maps. In almost every country, a great body of public and private rights and privileges relating to the land has grown up, usually accompanied by an almost equally complex system of duties and responsibilities. An accurate large-scale map is the only sound basis for a record of such rights, privileges, duties and responsibilities. That is because a well-made map is an accurate scale model of the landscape in which features can be accurately identified. Compared to an aerial or satellite image, a map has the following advantages:

- distortions can be eliminated to a much greater degree
- through the use of conventional signs, contour lines and so on, the map can show all significant detail with greater simplicity and clarity
- non-visible information can be shown, also what is above or below the ground, and property boundaries which do not coincide with physical features in the terrain
- irrelevant detail can be omitted

Maps are the best means of obtaining, recording and analysing land information. Large-scale maps (hardcopy and softcopy) are the only sound basis for recording public, communal and individual rights on land. Since geo-information is increasingly stored in digital format the map component of land administration systems is getting stored in digital databases. Basically, one can arrive at a digital cadastre along three lines:

- Digitization or scanning of existing documents
- Surveying in the terrain using GPS, total stations or other surveying devices
- Extracting information from aerial and satellite images.

Whatever method seems to be appropriate in a given setting, acquisition of geo-data by any of the above three means is based on a number of sound land surveying principles. These are:

- *"Working from the whole to the part"* that is establishing a framework of control points at a nationwide level, which is next split into smaller networks with points closer together
- *Consistency*: once the higher order networks have been established, it is possible to work to less rigorous standards in the lower orders without affecting overall accuracy. There has been no point in working to higher standards since in connecting the later work to the earlier, the higher order work is held fixed and hence the new survey cannot be better than the higher order control

- *Economy:* since higher accuracy in general costs more money the surveyor should seek no higher accuracy than is necessary and sufficient for the task at hand
- *Redundancy:* measuring more data than strictly necessary enables to carry out independent checks on the data (built-in quality control), for example by measuring all three angles of a triangle even though the third angle measurement is redundant. The methodology to use and to cope with redundant data is based on least-squares adjustment.
- *Maintenance*: Since changes take place over time, mechanisms must be incorporated to ensure that the survey is kept up to date if it is to be of continuing use.

Digitising Maps

In developed countries, the most common current method of building the land ownership layer in a land administration system is by digitising boundaries from cadastral maps. Many of these were designed simply to show the relationship of various attributes one to another, rather than being compiled to an accurate coordinate base. Consequently, accuracy of position varies from place to place, and any mistakes in original map compilation are carried forward into digitised records and other spatial layers. There are many systems in use to improve the accuracy of this type of data, including ‘rubber sheeting’ or adjusting to control from GPS or photogrammetric sources. These systems improve positional accuracy near each control point but do nothing overall to correct inaccuracies in base data. To overcome this problem it would be necessary to have a control point at nearly every corner.

Digitizing Tablet

With manual digitizing the operator manually measures all the boundary points present in the hardcopy map using a pointer device and a digitizing tablet. It is also possible to trace lines in continuous track; the operator moves the pointer device over the line and at regular time intervals the position of the pointer device is stored. This method is particularly applied when digitizing contour lines on topographic maps. Manual digitizing has been widely used and the result is a digital map which is identical to the hardcopy map. Some features of manual digitising are:

- Need for experienced operator
- Time consuming; digitizing a complex contour map might take 100 man hours
- Degradation of accuracy; the accuracy can never be better than the accuracy of the original hardcopy map. The digitization process introduces degradation because the spatial accuracy level of the human hand is about 40 DPI (dots per inch) in the best case and will lower when the operator gets tired and bored after working on it for a period of time. Experiments show that the new map is heavily distorted as compared to the original map.

Manual digitizing is supported by most GIS packages with direct link to a digitizing tablet.

Heads-Up Digitizing

It is also possible to carry out manual digitizing on the computer screen using the scanned map as backdrop. The method requires that the map is scanned. Since the raster image may be scanned at high resolution, normally from 200 DPI to 1600 DPI, and the operator is enabled to zoom in the accuracy level is higher than for manual digitizing tablet. At the other hand the characteristics of the scanning device might introduce geometric distortions. Since these distortions can be often modelled by a relative simple geometric correction model, such as an affine transformation, the influence on the accuracy of these distortions may be significantly reduced. However, as with using a digitizing tablet, the accuracy level highly depends on the operator and is also time-consuming taking about same amount of time as the manual digitizing method.

Measuring Scales

Scale	Examples	Characteristics
Nominal	Citizenship (e.g. German, Dutchman, Greek, Italian)	Result from classification (e.g. remote sensing images). Classes differ but no ordering between them or other relationships
	Land Use data (e.g. classification of an area into forest, urban area, agricultural area and water bodies)	No computations can be carried out on the data. One may only examine if the value for certain object(s) equals the value of other object(s) or count the number of occurrences of each value, e.g. the number of males and the number of females in a certain population.
	Numbers in a lottery	Arbitrary labels can be assigned, e.g. 1, 2, 3, 4
	Gender (male, female)	If the number of classes is only two (present/absent) called: **binary scale**
Ordinal	Ranking of people on length	Classes are ordered in ascending or descending order, but the interval is not important
	Political parties ordered from left to right wing spectrum into e.g. 1 to 6	
	Preference scores, e.g. ratings of eating establishments where 10=good, 1=poor, but the difference between an establishment with a 10 ranking and an 8 ranking can't be quantified	Simple statistical values can be performed, e.g. median value and determination whether the value of an object is larger than the value of another object
	Ratings of popularity of songs	
Interval	Temperature	Arbitrary origin. Difference between two interval scale values is equal but there is no natural zero. 25 ^{0}C is 5 ^{0}C warmer than 20 ^{0}C, and that is the same temperature difference as between 8^{0}C and 3^{0}C. However the origin has been chosen arbitrarily (in this case the transition of water from liquid phase to solid). But it does not makes sense to say that 25 ^{0}C is 20% warmer than 20 ^{0}C.
	Coordinates in a geodetic reference system	
Ratio	Age of People	Natural origin (zero dollar is zero Euro regardless of exchange rate). When somebody is 22 years (s)he is twice as young as somebody of 44 and 10m is twice as long as 5m. This ratios hold true regardless whether measures in years or months, meters or yards, Celsius or Fahrenheit, dollars or euro and so on.
	Population density	
	Gravitational forces	
	Speed of wind	
	Length, distance	

Chapter 2
Pivotal Role of Cadastres
By Mathias Lemmens

2.1 Introduction
In many parts of the world both individuals and collectives possess ownership rights on land. How do others in the community know of individual or group rights to real estate? Ownership rights are usually registered in the National Cadastre, which comprises both Land Registry and Cadastre. Land Registry is the public register in which the documents effecting interests in land are kept. This concerns the official legal registration of properties such as land, buildings and apartments, of legal rights and of rightful claimants. Land Registration may be defined as 'the process of recording legally recognised interests (ownership and / or use) in land', whilst a cadastre is 'an official record of information about land parcels, including details of their bounds, tenure, use and value' (Laughlin & Nichols, 1989). Land Registration essentially provides owner and (potential) purchaser with legal security. It is also one of the three legs of the tripod supporting a properly functioning land market, consisting further of valuation and financial services. The Cadastre, being an entrance to Land Registry, contains the essential data from the input documents. Often, the information overlap between Land Registry and Cadastre is 70% or more. Rapid accessibility of data is a key characteristic of the Cadastre. The Cadastre today plays an important role in improving land tenure security, regulating the land markets and implementing urban and rural land use planning, development and maintenance. According to the FIG Statement on Cadastre, a cadastre 'may be established for fiscal purposes, such as valuation and equitable taxation, legal purposes (conveyancing), to assist in the management of land and land use, such as for planning and other administrative purposes, and enables sustainable development and environmental protection.' The purpose of a cadastre is to help secure land tenure, stimulate land markets and make better use of land and its resources (Figure 1).

2.2 Origin
Considered by many to be the mother of all cadastres, the French cadastre was instituted in 1807 by Napoleon Bonaparte. The essential idea behind the Napoleonic Cadastre was legal security, not primarily as protection against violation of rights by other citizens but as a dam against unpredictable government ("L'etat cést moi"). In the words of Napoleon: "The cadastre just by itself could have been regarded as the real beginning of the Empire, for it meant a secure guarantee of land ownership, providing for every citizen certainty of independence. Once the cadastre has been compiled […] every citizen can for himself control his own affairs, and need not fear arbitrariness of the authorities." Today, two centuries after the establishment of the French cadastre, many countries do not have a well functioning system of Land Registration and efforts continue to implement and improve it.

2.3 Trustworthiness
Land registration is a complex process consisting of many strongly interactive technical, legal and organisational systems parts and aspects (Zevenbergen, 2003). Linking of the parts of a system is much more important than striving for strengthening of one ore some whilst leaving others fragile: the weakest link determines the strength of the chain. Which parameter is most suited for expressing appropriateness and sound functioning? According to Zevenbergen, this is trustworthiness, meaning that the information present in Land Registers is of such high standard that people value it as the truth. In case of boundary conflicts the opponents accept

the situation as laid down in the Registers as decisive. However, trust is a seed which slowly grows and reaching maturity is long lasting: trust comes by foot and leaves on horseback.

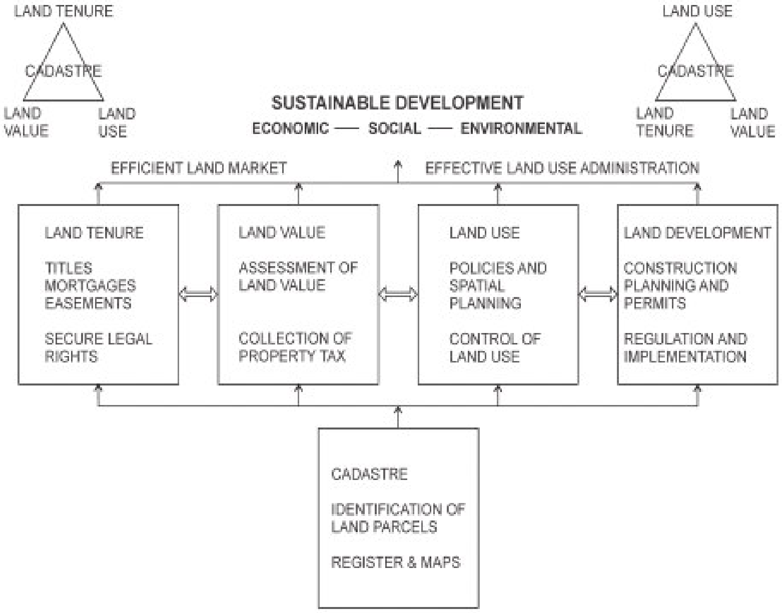


Figure 1, *Cadastres enable to establish efficient land markets and effective land use development. Together, these are necessary elements for effective land management on national and regional scale (from Enemark and Sevatdal, 1999; courtesy: Cashin, 2003).*

2.4 Without Title

Which consequences does have a Land Registration which is not properly functioning or which is virtually absent? In countries with properly functioning Land Registration – these are mainly western countries – one can take cadastral information concerning one's title-deed to a bank to convert the right to a debt. The benefits of this system are so taken for granted that one no longer reflects upon its mysterious consequences. This conversion possibility provides a plethora of investment prospects and gives people in the West the feeling of being rich because it enables us today to buy goods or begin an enterprise on the strength of future earnings and on ownership right. In contrast, people of so-called poor countries (80% of mankind) even when they own property – and many do – have often no access to this conversion process. The implication here is that they are not as poor as one might think. We simply mark them as poor because of the manner in which ownership is defined. When property comes into existence only once it is formally described, then poverty is nothing other than lack of registration. Once (s)he has a formal deed of entitlement an owner can extract capital from the house (s)he lives in. Its market value can be used for purposes which lie far beyond its physical function as a shelter against the cold, rain, and sun. Its existence in a virtual world enables the house to be capitalised upon whilst, in the meantime, it continues to be lived in. What happens in the event of a national standardised information system malfunctioning? By definition the people remain poor.

2.5 Failing Legal Status

Many people in what we call poor countries have no access to the process of storing their ownership in formal information systems. As a result, they have no registered deed of entitlement and thus no capital. According to de Soto (2000) the total value of the property held without title-deed in these countries is about US$10 trillion. However, these assets can not be transferred to the virtual world of capital because they are not officially registered. Consequently, the owners are not able to capitalise on such assets. So the governments of these countries have to beg for capital from ‘rich’ countries. And this whilst, quote of de Soto: ‘In the midst of their own poorest neighbourhoods and shanty towns, there are trillions of dollars, all ready to be put to use if only the mystery of how assets are transformed into capital can be unravelled”. The challenge facing developing countries is to create official information systems trusted by the people, whilst rights are, in addition, protected by a clear and effective set of laws. It is rare to find a developing country where information systems are completely absent. However, the presence of such a system may be a necessary but not sufficient condition. Such systems should also be efficiently managed and co-operate effectively. The reason that land ownership in developing countries often fails to attain legal status is that the path is often blocked by officialdom. When it takes 150 steps to formalise one’s ownership of a house, while this process may take fifteen years and cost an amount of money several times one’s yearly earnings, then one might prefer to remain in extrajudicial anonymity. So, the hurdles are many; cultures cannot be changed overnight and by fiat.

2.6 Sustainable Development and Tenure Systems

“De Soto's most insightful contribution was to raise the topic of the futility of waste of investment in property,” Dr Anna Tibaijuka, UN Under-Secretary-General and Executive Director, UN-Habitat said in GIM International November 2007. “We face, and this is almost an absurdity, the problem that valuable houses are never accepted by banks as security for loan because there is a threat that these houses will be demolished at any time and people do not have secure tenure, official registration of house ownership. So the banks are not willing to treat these houses as tradable goods and the owners have no possibility of turning them into commercial assets. De Soto made a very important, seminal contribution in popularising this awareness. And it is clear to us that to arrive at sustainable development and social equity it is necessary to establish proper tenure systems.”

2.7 3D Cadastres

In the meantime countries with smoothly running cadastres are faced with problems of literally another dimension. In countries like Germany, Israel, Japan and The Netherlands one is struggling with scarcity of land. To cope with that problem their governments are stimulating multiple use of space, that is simultaneously carrying out a great variety of activities within the same column of space. There are thousands of locations where different types of constructions are built on top of each other: underground railway line, parking garage, shopping mall, bank office, living quarters and many, many others. Usually, the exploiter of any one of these constructions will differ from another who exploits the area of space above or below.

How should we deal with vertical ownership rights? This is not a trivial question, because in most countries ownership right is unlimited in the vertical dimension; it ‘extends vertically from hell to heaven’. So, theoretically any land ownership covers a pyramid, or cone, the apex of which is situated at the centre of the earth and the base floor of which expands into infinity. In practice, the owner takes many restrictions for granted, such as over-fly rights, mineral rights and other law-induced restrictions. In addition, land ownership is unlimited in time; it lasts forever. Land ownership is, so to say, a millennium-old, sacred right. The description of the rights on objects with boundaries in the vertical space column is resolved by several legal instruments, including rights regarding servicing, condominium, building right and property in strata. The legislative detailing of these rights differs from country to country. The building of different types of construction on top of each other induces questions such as: -

- Should the concept of land ownership be modified so that the extension of boundaries is defined not only horizontally but also vertically?
- How should the obligations and rights of vertical neighbours be defined?
- Should a more consistent and secure description of the rights on superimposed constructions result in a modification of land ownership?
- Should the geometry of the vertical boundaries of rights be reflected in today's cadastres so as to better serve the management of our complex environment?

Although today some countries, such as Norway, Sweden, Queensland (Australia) and British Columbia (Canada) have properly addressed the legal issues involved in stratified ownership, these solutions are not complete in terms of 3D-cadastral registration since they are still not registered in their full three dimensional extensions (Stoter et al., 2004). The move from registering parcels as 2D objects to volumes is comprehensive as it requires redefinition of the cadastral concept. At the technical levels some of the issues are lrelated to storage, querying and visualisation of volume objects and how to make sure that they do not overlap.

Answers are not yet completely available. Because an alert government increasingly needs land information to manage the growing complexity of urbanized areas, the above issues require further research.

2.8 Boundary Surveying is South Africa

The remaining part of this Chapter presents, as an example of the pivotal role of Cadastres in society, boundary surveying in South Africa (http://csg.dla.gov.za/cadsurv.htm). In South Africa, where natural and cultural features are few and far between, the only practical method of demarcating property is that of using beaconed corner points joined, with few exceptions, by straight line boundaries.

2.8.1 Colonial Era

The first land surveyor came to the Cape in 1657, some five years after Jan van Riebeeck had established the first European settlement at the southern tip of Africa. The first cadastral survey was the survey of a piece of land on the banks of the Liesbeeck River, in order to transfer this land to a released servant of the Dutch East India Company. Apart from the river, which conveniently formed one boundary, poles were erected to demarcate the other boundaries, which were straight lines.

This and other early cadastral surveys were however graphical, which was suitable for Europe with its many permanent features, but not at all suitable for a newly settled country. As the farming areas spread out from Cape Town, the farms became larger and graphical surveys became even more unsatisfactory as a means of determining the position of corner beacons. However, graphical surveys were to persist for two centuries, until 1857, when the use of theodolites and the recording of numerical data on diagrams were made compulsory.

The British occupation of the Cape in 1806 had also brought about a tightening up of land registration procedures, and from 1813 no sale of land would be recognised unless that land had been properly surveyed and registered. The new office of the Surveyor-General was created in 1828 in order, amongst other duties, to register all grants of land. The examination of diagrams and the examination of surveyors themselves, were undertaken by the Surveyor-General from the 1830's. When Natal became a separate district of the Cape Colony in 1845, a

Surveyor-General was appointed there also and the Transvaal and Orange Free State followed suit in 1866 and 1876 respectively.

After Union in 1910, these four territories retained their individual legislation, controlling cadastral surveying until the commencement of the Land Survey Act 9 of 1927. The Land Survey Act of 1927 put cadastral surveying in South Africa in the position it is today; it is one of the best and most reliable systems of defining the boundaries of properties, and the positions of rights affecting those properties anywhere in the world. The individual land surveyor's field and office records were now examined and, after approval, were preserved in the Surveyor-General's office as evidence for any future boundary relocation. All surveys also had to be connected to the national control survey system, as this was extended across the country. That this Act was a well thought-out document, based on sound experience, is evident as it was used with only minor amendments to it for sixty years until it was replaced by a new, but substantially similar, Land Survey Act 8 of 1997.

2.8.2 National Control Survey System

South Africa is fully covered by the National Control Survey System which is of high accuracy and which is marked by a network of trigonometric stations and town survey marks. It is a legal requirement that all cadastral surveys are connected to this control network, ensuring that the position of every beacon and boundary is accurately known, and that property boundaries do not overlap, and that beacons that are lost or destroyed can be replaced with the minimum delay and expense. The great majority of non-cadastral surveys, such as those for road construction, are also based on this national control network with tremendous benefits for orderly and cost-effective development in South Africa. All cadastral and all other surveys that are referred to the National Control Survey System, are calculated in plane coordinates. The projection used is the Gauss Conform Projection (an adaptation of the Transverse Mercator projection), with central meridians at odd-numbered degrees of longitude and two-degree wide belts. The unit of measure of length is the International Metre. As from 1 January 1999, the South African National Control Survey System has been based on the World Geodetic System 1984 (WGS 84) ellipsoid, with the position of the Hartebeeshoek Radio Astronomy Telescope as the origin of the system.

2.8.3 Accuracy Classes

Although the methods that may be used in cadastral surveying are not rigidly prescribed, it is a requirement that all work be adequately and carefully checked. All recognised methods, using modern accurate instruments, are acceptable. Special requirements are however laid down when surveys are undertaken, using GPS or photogrammetric techniques. In South Africa most cadastral surveys are one using total stations and/or GPS.

The accuracies to which surveys must be carried out, are prescribed and categorized into three classes:

- Class A: Surveys for the determination of the positions of reference marks in urban surveys
- Class B: Surveys in urban and peri-urban areas and for mining titles in respect of precious stones and minerals
- Class C: Other surveys, including farm surveys and surveys for mining titles in respect of base minerals.

2.8.4 Beacons and Boundaries

South Africa is generally a large open country, with few natural or artificial features that are suitable for adoption as property boundaries. The boundaries of properties or land parcels are marked by permanent corner beacons joined, usually by imaginary straight lines, although the boundary lines between beacons may be curvilinear features in certain circumstances.
The types of beacon that may be used are prescribed by regulation, and new beacons must be iron pegs of specified dimensions. Well-constructed corner fence posts and corners of permanent buildings may also be adopted as beacons. Should rock or buildings prevent placing a beacon, a hole may be drilled to indicate the position.

Although the boundaries between beacons are usually straight lines, certain natural or artificial features that are permanent and clearly defined, may be adopted as curvilinear boundaries. The most common examples are the middle of a river and the top edge of a cliff. Artificial features which are liable to be moved, such as fences, roads and railway lines, may not be adopted as new cadastral boundaries.

2.8.5 Original and Division Surveys

When an unregistered piece of land is granted, an original survey is carried out and a diagram prepared by the land surveyor. Before being approved by the Surveyor-General, this diagram is made available for inspection by the public to give all interested parties an opportunity to satisfy themselves that the land to be granted does not conflict with their property. Only after any objections have been resolved, is the diagram approved and bound with the deed of grant, which can then be registered in the name of the new owner or grantee. Original grants do not often occur now in South Africa. Subsequent division and subdivisions do not require making diagrams available for public inspection before approval.

In undertaking a survey to subdivide an existing piece of land, the land surveyor has very specific responsibilities. He/she must:

- study all available information from previous surveys
- where possible find and determine the positions of the original beacons
- then determine the best agreement between the old and new surveys.

In the event of disagreement between the evidence on the ground and the data on the diagram, a 1924 High Court decision lays down that the lawful position of a property corner is that occupied by the original beacon itself and not the position according to the diagram. Such disagreement is only likely to occur when dealing with very old original surveys.

The permissible differences between old and new surveys are prescribed by regulation and, if these are exceeded, the land surveyor must obtain the agreement of all affected landowners to the position he has selected for the beacon or boundary. Once the relationship between old and new has been settled, the land surveyor proceeds to place the subdivisional beacons, so as to subdivide the land in accordance with the approval plan of subdivision. The subdivision can be a relatively simple matter, creating a small number of new properties, or it can be a highly complex township layout involving the "pegging out" of hundreds or even thousands of erven, public places and streets.

2.8.6 Restraints

There are many statutory restraints placed on landowners wishing to develop their land and, which the cadastral surveyor is bound to observe. Although this restricts an owner's right to deal with his/her land as he/she wishes, the State has imposed these restrictions in the interest of orderly planning and development, and for the benefit of the community as a whole. With few exceptions permission must be obtained before land can be subdivided. The list of laws and ordinances, which control the subdivision of land, is a long one and is subject to change. In many cases permission to subdivide must be obtained from more than one authority. The Surveyor-General must ensure that all applicable consents have been obtained before approving a subdivisional survey.

2.8.7 Surveyor-General

There are four Surveyor-General's offices in South Africa, each of which regulates cadastral surveys in the provinces for which it is responsible. Their principal functions are to:

- Examine and approve diagrams, general plans and sectional title plans prior to them being registered in a Deeds Registry
- Preserve and keep up-to-date all documents and records pertaining to cadastral surveys
- Prepare and keep up to date cadastral maps and plans, both in paper and digital form.
- Supply copies of documents kept in the office in hard copy or digital form. The office also provides advice and information pertaining to the cadastre to all who ask.

The fact that the Surveyor-General's office holds complete records of all cadastral surveys, ensures that there is virtually no possibility of properties overlapping and, once registered, little chance of conflicting claims to ownership.

2.8.8 Survey Documents

The diagram is the fundamental registerable document prepared by the land surveyor. The essential information shown on a diagram is:

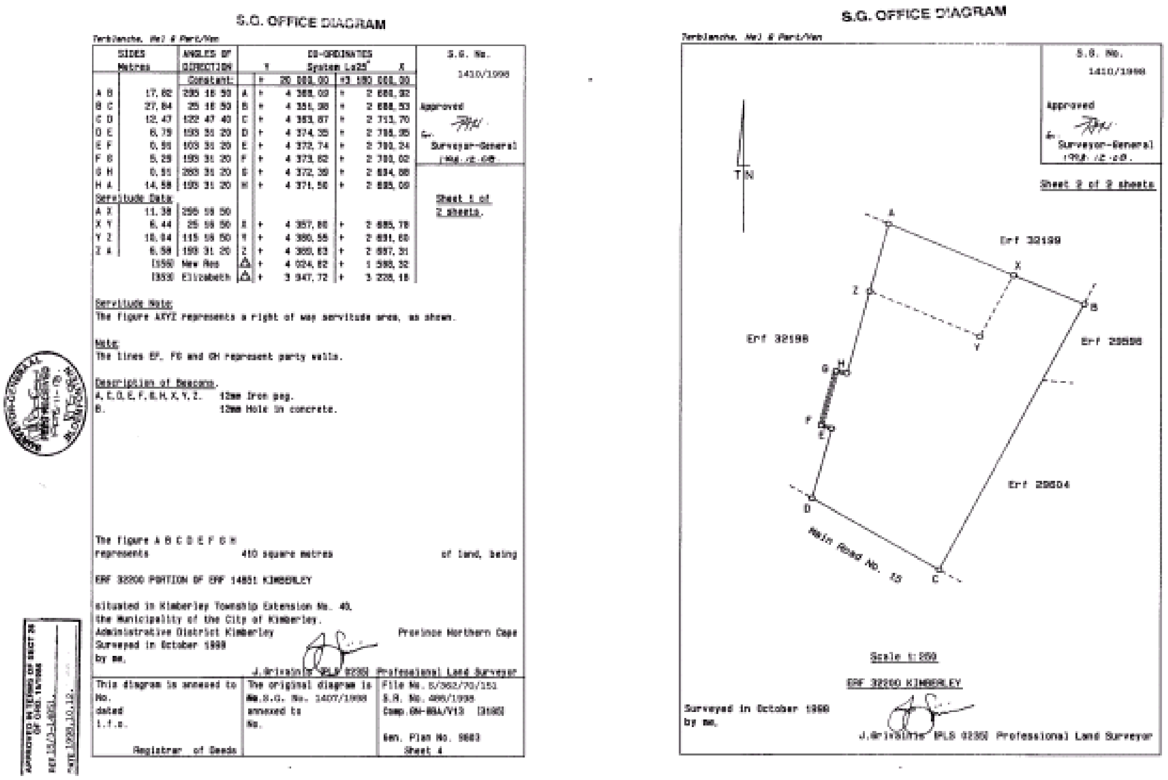
- The unique designation of the property.
- An illustration depicting the property
- The boundary description listing the corner beacons and the details of any curvilinear boundary
- Descriptions of the corner beacons
- Table listing the numerical data of the boundaries
- Area of the property.

The Surveyor-General gives each diagram a unique reference number. The most common type of diagram is a subdivisional diagram. This is framed for the purpose of cutting off a portion of a parent property. There are other types of diagram however, including:

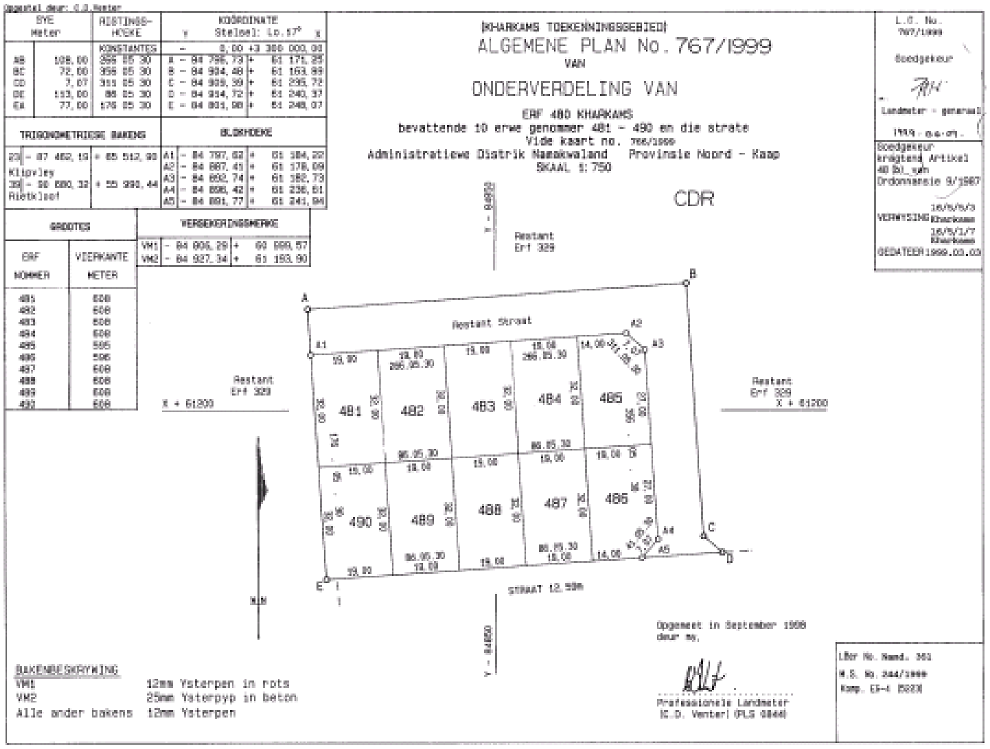
- Servitude diagrams for registering servitudes over an existing property
- Lease diagrams for registering long leases over portions of properties
- Consolidation diagrams when it is required to consolidate several individual properties into one, taking out certificates of consolidated title
- Mineral diagrams to register mineral rights separately from the land rights
- Mining title diagrams for registering the right to extract minerals from the land.

With the exception of mining title diagrams, which are registered with the Department of Minerals and Energy, these diagrams are registered together with their deeds in a deeds registry.

When parcels are subdivided into several pieces the land surveyor usually prepares a general plan instead of individual diagrams. This is a document showing the relative position of two or more pieces of land together with the same essential information in respect of each piece as is required on a diagram. It is also allocated a unique reference number by the Surveyor-General. It is compulsory to prepare a general plan for any subdivision into ten or more pieces of land and when required, in terms of any law, usually for township establishment or the amendment of an existing general plan. General plans may comprise many sheets and depict a very large number of erven (lots).



Example of a subdivisional diagram



Example of a small general plan

2.8.9 Survey Records

When submitting the diagrams and general plans framed from his/her survey, a land surveyor is obliged also to lodge the records of that survey with the Surveyor-General. These records are used to support the examination process and are then preserved in the Surveyor-General's office. Land surveyors later refer to these records when relocating or replacing lost beacons and when extending the earlier survey. The principal records kept by the Surveyor-General are:

- Field observations, which are the primary record of the survey
- List of co-ordinates of the beacons and reference stations,
- Working plan,
- Plan on which is shown the comparison between the original and the new survey data, and
- Land surveyor's report.

These records are now being captured in the document imaging system (DIS) for easier access and to facilitate the supply of information to land surveyors.

2.8.10 Future

At present the benefits of our sound cadastral survey and land registration system are not readily available to many of our traditional communities, particularly in remote rural areas. To address this need and to make security of property a reality in these communities, innovative alternative forms of cadastral survey and land tenure are being developed. These new systems will be affordable but secure, as modern survey techniques have enabled us to reduce the cost of survey without compromising accuracy or reliability. It is a fallacy that an accurate survey must be more expensive than a less accurate one.

The availability of cadastral information is essential for sound governance and planning. This information is readily available to all that are able to visit the relevant Surveyor-General Office or who have access to the Internet, which is not the case in many communities. Ways and means are being actively investigated whereby computers can be set up in even the remotest and most impoverished areas and linked to the Surveyor-General's data. The aim is to make information available to all.

At present the documents lodged by the land surveyor are paper documents, although they are generally drawn by computer using data held in a digital database. It is envisaged that in the future all documentation for examination will be submitted to the Surveyor-General electronically and that the movement of hardcopy documents will be kept to a minimum. The Deeds Registries are currently investigating proposals for electronic lodgement as well.
In keeping with international trends, the day is in sight when the present separation of cadastral maps and plans, and the land registers will be abolished, and the national cadastre will be managed as one digital entity.

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Chapter 3

Using GPS for Boundary Surveys

By Mathias Lemmens

Basically, satellite positioning is a trilateration problem. From the known position of three satellites and the measured distances between them and the receiver, the three-dimensional coordinates of receiver position can be calculated. The distances are determined by multiplying the travelling time of the radio signals by the speed of light. To ensure that the coordinates of the satellite positions are available at the receiver they are continuously transmitted by the signals themselves.

Satellite positioning thus means that from the positions of a subset of "visible" satellites and the range distances between the each satellite and the receiver the position of the receiver is de4termined. Visible here means that the satellites are above horizon.

Satellite point positioning is thus the process by which:
(1) given the position of satellites being tracked
(2) given the range distance from the receiver to the satellite being tracked
(3) position of the receiver is determined**.**

The range distance between receiver and satellite is determined by measuring the travel time of signals emitted by the satellite and measured by the receiver.
Since radio signals travel at a speed of approximately 300,000km per second (speed of light through vacuum), an inaccuracy in time measurement of 1 nanosecond (one billion part of a second or 10^{-9} second) induces a distance error of 30cm. With geodetic receivers we can achieve accuracy at the centimetre level.

Position and Time
The ground segment monitors and controls the position of GPS satellites. With a master station at Falcon Air Force Base, Colorado Springs, USA, and remote stations in Hawaii, Ascension Island, Diego Garcia and Kwajalein, the satellites are tracked and monitored for 92% of the time. For two daily windows lasting one-and-a-half hours, each satellite is out of contact with the ground stations. The main station acts as data processing centre for all information, including that collected at the remote stations. Orbit coordinates are continuously determined by triangulation. Comparing the time of the satellites' four atomic clocks with similar devices on the ground provides information on time errors. When a satellite drifts slightly out of orbit, repositioning is undertaken. The clocks may also be readjusted, but more usually information on time errors is attached to GPS signals as correction factors. The computed corrections, time readjustments and repositioning information are transmitted to the satellites via three uplink stations co-located with the downlink monitoring stations. In this way, all the GPS satellites are able to continuously attach corrections to the parameters they send out, which include ephemeris data, almanac data, satellite health information and clock correction data.

But how is a continual check to be kept on the positions of satellites? Their orbits are not completely deterministic but fluctuate due to celestial gravity forces. Since radio signals travel at a speed of approximately 300,000km per second, an inaccuracy in time measurement of 1 nanosecond (one billion part of a second or 10^{-9} second) induces a distance error of 30cm, whilst with geodetic receivers we can achieve accuracy at the centimetre level.

Distance and Difference

The travelling time of a radio signal may principally be determined as the difference between arrival time at the receiver and time of transmission by the GPS satellite. As already described, to achieve positional accuracy at centimetre level the time difference has to be determined at sub-nanosecond level. To attain such accuracy would require atomic clocks in both receiver and satellites. Atomic clocks are, however, rather too expensive for the everyday consumer. The solution found by clever engineers is simple and effective. Because they are few, only the satellites are equipped with costly atomic high-precision clocks having an annual drift of just 2 nanoseconds. The GPS receivers are equipped with relatively cheap, quartz clocks accurate up to 10 nanoseconds a day. This accuracy is sufficient to allow it to be assumed that time bias between the receiver clock and those onboard the satellites is the same for all satellites. So that just one time parameter is actually unknown: the time bias. This can be determined by measuring the travelling time of radio signals not to three but to four satellites. Discrepancies among the calculated coordinates of receiver position (which should, of course, be absent, it concerning just one location) provide sufficient information accurately to determine time bias. Every land surveyor knows that for purposes of reliability one should gather more measurement data than is actually needed to solve the unknowns. Therefore geodetic GPS receivers will require data from more than four satellites before release of coordinates giving receiver location.

Differential GPS

Positioning and navigation by satellites has now become part of everyday life for many citizens all over the globe, and a plethora of (commercial) services rely on the continuous well functioning of these systems. Operating a handheld, stand-alone GPS receiver in locations with favourable satellite availability, coordinates with an accuracy of approximately 3-5 meter in the horizontal (95%) can be achieved. Since, as a rule of thumb, the vertical accuracy is two times worse as the horizontal accuracy, the achievable accuracy for a stand-alone receiver is 6-10 meter in the vertical. Note that manufacturers, without saying quote accuracy in terms of 1 Root Mean Square Error (RMSE), that is 67% of data points collected will fall within this accuracy.

Typical sources of GPS Errors are:

- Atmospheric delay (Ionosphere and Troposphere). As the satellite signal passes through the atmosphere slows down the speed of travel of the radio wave
- Signal Multi-Path: The satellite signal can be reflected off of objects such as tall buildings, mountains and other large rock surfaces. This causes the signal to increase its travel time
- Errors in navigation messages: Receiver Clock Errors (the receiver clock in a is not an atomic clock as it is in the satellite and the built-in clock can generate small errors in timing) and Position of the satellite
- Low Number of Visible Satellites: The fewer satellites signals the receiver receives will result in a less accurate determination of location. Buildings, high terrain, trees etc. can block satellite signals
- Bad Satellite Geometry resulting from satellites being located either in a line or are closely grouped together.

To mitigate some of these errors, Differential GPS (DGPS) has been developed. DGPS basically involves two GPS receivers: one is a stationary (base or reference station) receiver and the other is roving and doing the actual position measurements of unknown points. By combining the known position of the base station with satellite measurements satellite signal errors can be calculated. This is done by measuring the ranges to each satellite using the received signals which are compared to the actual ranges calculated from its known location. These differential corrections for each tracked satellite are transmitted to the roving GPS receiver. Dependent on the quality of the satellite receivers and sophistication of the observational model, positional accuracies at the meter, sub-meter, decimetre, sub-decimetre, centimetre and finally sub-centimetre level can be achieved. The estimation of coordinates can be done in a post-processing procedure were observations from the reference receiver(s) and the rover are brought together to a single computer and processed after survey. Transmissions for real-time use can be over FM radio frequencies or cellular phone, by satellite or by beacon transmitters that are maintained. For retracement surveys to recover previously established boundary lines real-time measurements are a prerequisite, but due operational considerations it seems that real-time systems are more and more preferred also for other survey tasks.

Satellite Based Augmentation (SBAS) supports wide-area or regional augmentation through measurements taken at multiple ground stations. Correction messages are derived from these measurements and sent to one or more satellites for broadcast to the end-user to improve initial GPS measurements. The United States has in place its Wide-area Augmentation System (WAAS), the Russian Federation its Wide-area System of Differential Corrections and Monitoring (SDCM), the European Space Agency (ESA) operates the European Geostationary Navigation Overlay Service (EGNOS), the Ministry of Land, Infrastructure and Transport of Japan operates the Multi-functional Satellite Augmentation System (MSAS) while Japan is working on the Quasi-Zenith Satellite System (QZSS), which operates regionally and will ultimately consist of three satellites. Since the accuracy of its standalone mode is limited, this is actually regarded as an augmentation service for other GNSS systems. Furthermore, there are two commercial systems on air: StarFire navigation system, operated by John Deere and Starfix DGPS System, operated by Fugro. In addition, India is working on developing a system which will consist of seven satellites operating regionally up to 2,000km around its boundaries and providing an accuracy of better than 20m and a GNSS augmentation system.

Satellite based augmentation enables to improve accuracy of GPS positioning without the need to put a second receiver on a reference station. Instead the data collected at the multiple reference station is packaged together, analyzed, converted to a set of correction data by a master station and then uploaded to the geo-stationary satellite, which in turn transmits the data down to the local GPS receiver. The GPS receiver then figures out which data is applicable to its current location and then applies the appropriate corrections to the receiver. For boundary survey purposes it is usually necessary to determine positions in a national reference framework. Also for these types of application, services have been developed. As examples, recent articles on the Online Positioning User Service (OPUS), operating in the US, and the UK SmartNet are included in these lecture notes (see next pages).

Multipath

An electromagnetic or sound signal hitting a surface may interact with it one of three ways: the signal may be reflected, absorbed or transmitted. Having once been reflected a signal may be reflected a second, or even third time from another surface. In airborne Lidar multiple reflection results in the recording of faster pulse travel times that ultimately appear as a dip in the elevation model. Since these are usually individual events, they can be removed by spatial filtering. Similarly, in radar imagery multiple reflection causes objects to produce returns of greater signal strength than might be expected from the size of the object; this results in bright spots. Multipath effects may be also experienced when walking along a tower block, when balconies may reflect sharp sounds such as that of a car claxon, making a vehicle seem nearer by than it really is.

Source of Error

The precision of GPS positioning is also affected by reflections from nearby objects such as ground and water surfaces, buildings, vehicles or trees. Multipath results in the same satellite signal being received at least twice by the GPS receiver via different paths, distorting C/A and P-code modulations and carrier-phase measurements. Multipath may even be regarded as the main remaining source of error, since others can be removed by advanced processing methods such as differential and kinematic GPS. Particularly in urban areas that are characterised by multiple reflecting surfaces, multipath may significantly reduce precision. Hence it is of the utmost importance to detect and/or mitigate multipath error. In contrast, multipath effects are minor in a moving vehicle because a mobile GPS receiver results in solutions from indirect signals failing to converge; only direct signals produce stable solutions.

Multipath effects occur when GPS receiver picks up direct and indirect signals, the latter due to reflection from nearby objects.

Numerical or Physical

There are three basic approaches to dealing with multipath. The first, adopting the adagio 'prevention is better than cure', is to avoid measuring in environments where multipath might occur. The second is to physically protect the GPS antenna from indirect signals using a reverse umbrella, thus safeguarding the antenna from those "bad" coming from below. The third method is to separate the bad from the good using signal-processing techniques. The first option is obviously impractical and too much impedes operational application of GPS. But caution during field measurements may help. For example, tracking satellites only when they are more than 15 degrees above the horizon already limits multipath effects. It is also possible to filter bad from good signals by numerical techniques utilising redundancy. Reflected signals are always delayed in comparison with direct signals because of their longer paths of travel and this shows as time-dependent variations in measured range to the satellite, which can be detected. In this way a direct signal can be separated from indirect. However, when difference in path length between direct and indirect signal is less than a few metres the signal-processing technique proves ineffective. The remedy is then to entirely ignore the signal from the satellite concerned. This is often quite feasible, as GNSS receivers typically receive signals from eight to twelve satellites, while only four are needed for determination of the three positional coordinates and time bias. And crossing the fingers might help to avoid signals from all satellites being affected by multipath.

Choke-ring

But a more reliable method is to use a reverse umbrella, or "choke-ring". Such a physical device enables rejection of indirect signals hitting the bottom of the antenna, but the device does not stop signals reflected by a building hitting the antenna from above. However, since such indirect signals have a path length of ten metres, or even more, they may be mitigated by signal-processing techniques. So numerical and physical protection techniques are complementary: by numerical filtering distant indirect signals hitting the top of the antenna can be mitigated, while choke-rings prevent the antenna picking up signals, usually with a path length of a few metres, reflected from nearby ground.

Choke-ring antennae from Trimble and Topcon.

Time

Without atomic clocks, GPS would not be possible. Three main types of atomic clock can be distinguished depending on the element used: caesium, hydrogen or rubidium. The caesium-133 atom is most commonly used. Atomic clocks do not rely on atomic delay and they are not radioactive. The adjective 'atomic' refers to the characteristic oscillation frequencies of atoms. The measurement of vibrations is the principle of all atomic clocks. The major difference concerns, in addition to the element chosen, the way of detecting the change in energy level: caesium clocks separate atoms of different energy levels by magnetic field; hydrogen clocks maintain hydrogen atoms at the required energy level in a container of a special material so that the atoms do not lose their higher energy state too fast, and rubidium atomic clocks, which are the simplest and most compact, use a glass cell of rubidium gas that changes its absorption of light at the optical rubidium frequency when the microwave frequency is just right.

Master Clock

Atomic clocks keep time better than any other clock; they are even more steady than the Earth's rotation. The caesium atomic clock is the most accurate in the long term: better than 1 second per 1 million years. Hydrogen atomic clocks show a better accuracy in the short term (1 week): about 10 times the accuracy of caesium clocks. The hydrogen maser oscillator provides fractional frequency stability of about 1 part in 1016 for intervals of a few hours to a day. The maser's high frequency stability is ideally suited for a variety of space applications such as Very Long Baseline Interferometry (VLBI) from space, precision measurements of relativistic and gravitational effects and GPS. The hydrogen maser clock will therefore be Galileo's master clock (see article by Droz).

As a result of the extremely high accuracy of atomic clocks, the world's time-keeping system lost its astronomical basis in 1967. Then, the 13th General Conference on Weights and Measures derived the SI second from vibrations of the caesium atom, which is now internationally agreed as the interval taken to complete 9,192,631,770 oscillations of the caesium-133 atom, exposed to a suitable excitation.

The two GNSS systems currently available for civilian use are NAVSTAR (NAVigation Satellite Time and Ranging) and GLONASS (GLObal´naya NAvigatsionnaya Sputnikovaya Sistema: Global Navigational Satellite System). Development of NAVSTAR, owned by the US and managed by its Department of Defense, got underway in 1973. Nearly ten years later its continuation became a critical issue as US Congress expressed doubts about the usefulness of the system. However, the trouncing of a civilian Korean airplane (Flight 007) in 1983 over Russian ground changed minds and Congress decided to increase funding for NAVSTAR and allow its civilian use. Loss of the space shuttle Challenger in 1986 caused further disruption to system plans because these vehicles were designed to carry GPS satellites; delta rockets eventually replaced the shuttle as carrier.

GLONASS, presently owned by the Russian government and managed by the Russian Space Forces, was developed by the former USSR at the same time that the US was building GPS. Launch of the first GLONASS satellites took place on 12th October 1982. The constellation originally consisted of twelve satellites, but by decree of 7th March 1995 the Russian Government opened, GLONASS for free-of-charge civil use and the number of twelve satellites was increased to 24. This constellation was completed in 1997. Since then GLONASS has been designated a 'dual system', available to both civil and defence users. Civil users worldwide are able to make use of the Standard Precision (SP) signal mode, whilst the High Precision (HP) signal mode is reserved for government or military use.

Lack of economic impetus jeopardised continuation of the programme, and by the start of the new millennium Russia had to rely on US GPS signals. By April 2002 only eight satellites were in operation, far too few to act as a global navigation utility. Presidential and governmental decrees issued in 1999 and 2001 were necessary to reverse the downward spiral. An ensuing Federal Target Programme for the ten years 2002-2011 was to revive the system. Currently in orbit are twelve GLONASS satellites with expected lifetime of three years, and four GLONASS M satellites with an expected seven-year lifetime. By April 2006 the probability of receiving four or more satellites was 76%, whilst the positioning gap fell from 13.7 hours in 2001 to 2.6 hours in 2006. In December 2006, three more GLONASS M satellites have been put into orbit. The constellation will be further improved by the launch of GLONASS-K satellites. By 2008, these satellites of reduced weight and increased operational lifetime of ten to twelve years will have been added. According to the goals set by a

Presidential Directive of 18th January 2006, eighteen satellites should be in orbit by the end of 2007, giving the constellation a total of 24 satellites after two years.

The aim is to make GLONASS performance comparable by 2010 with GPS and Galileo. The main goal of the Russian policy is to bring GLONASS to the mass-market. This should be achieved by enabling developers of equipment and applications guaranteed access to the GLONASS civil signal structure by promoting within Russia the combined used of GPS/GLONASS receivers and maintaining GLONASS compatibility and interoperability with GPS and the future Galileo. GLONASS is gaining increasing international attention from partners and users in India, EU, the US and other nations. For example, in December 2004 the US and Russia agreed to shelve any idea of direct user fees for civil GLONASS and GPS services. India and Russia are willing to co-operate on GNSS infrastructure development.

GPS and GLONASS are very similar, but some differences are significant. Most noticeable is that GLONASS has neither the degradation of precision nor the cryptography of GPS.

> The first four Galileo validation satellites are unlikely to be launched before 2008, and possibly not until 2009. Four satellites do not make an operational system, although I expect that it should be possible to use these Galileo satellites in conjunction with the operational GPS and Glonass satellites at that time. Certainly we plan to be ready to generate augmentation data for the first Galileo satellites as soon as they are available. However, it is likely to be 2012 before the Galileo system itself is fully operational on a stand-alone basis.
> *Owen M. Goodman, Chief Operating Officer, Fugro N.V. , GIM International, vol. 20 (3), March 2006.*

Galileo

On the eve of 2006 Galileo became tangible reality. Launched from Balkonur, Kazakhstan, atop a Soyuz-Fregat vehicle, the first Galileo-In-Orbit Validation Element (Giove A) was rocketed beyond Earth’s atmosphere in the early morning of 28th December 2005. Galileo is a joint initiative of the European Commission (EC) and the European Space Agency (ESA) to build a Global Navigation Satellite System (GNSS). The system is interoperable with GPS and GLONASS and will operate under civilian control at all times, except in the direst emergency. Claimed to be more accurate than the US GPS system, the services foreseen are many, and include navigation and positioning applications in transport, telecommunications, fishery, agriculture and oil prospecting. In addition to Europe, several other countries are participating in the project, among which Israel and China.

Tripartite Mission

Weighing in at 600kg, Giove A has during its two-year mission to accomplish three tasks. Firstly, securing use of the signal frequencies allocated by the International Telecommunications Union. The second part of the mission will consist of determining radiation characteristics of the three Medium Earth Orbits at altitude 23,222km to be circulated by the projected constellation of thirty satellites (27 + three active spares). Finally, critical technologies contributing to the future operational constellation have to be examined and checked. These consist primarily of two signal-generation units and two rubidium atomic clocks with a stability of 10 nanoseconds per day.

Beidou

China now has five navigation-and-positioning satellites, the launch of the fifth Beidou satellite took place in April. The system provides regional coverage of China and surrounds. It is named Beidou after the group of seven stars (Septentrio is Latin for 'north') of the constellation Ursa Major, known in many cultures under different designations, in the UK 'The Plough', 'Big Dipper' in the US and 'Big Mother Bear' in Russia. Others see the constellation as resembling a wagon. The first Beidou satellite (1A) was launched on 30th October 2000 followed by 1B on 20th December 2000. Since 2001 China's army and others have thus had access to a domestic satellite positioning system.

Estimate and Dual

Positioning by two satellites? Has satellite positioning with the turn of the millennium become no longer a trilateration problem for which at least three satellites are needed? From the known position of three satellites and the measured distances between them and the receiver the three coordinates of the receiver can be calculated. A fourth satellite is definitely necessary to eliminate the time bias. These are the basic principles of satellite positioning that every high-school pupil should know, and that is how GPS works. So by what magic does China make do with just two satellites? It's not magic. Beidou derives an approximation of one of the three coordinates from a digital elevation model (DEM) and eliminates time bias by dual-way transmission. Today DEMs can be accurately generated from a multitude of techniques, including InSAR, Lidar and digital photogrammetry, and are abundantly available. Time bias can be eliminated if the signal is shuttled back and forth from satellite to receiver and receiver to satellite. The satellite clock measures travel time, eliminating, most advantageously, the need for extremely accurate atomic clocks.

Iterative Positioning

How does Beidou accomplish this? Just as with GPS, each of the Chinese satellites broadcasts signals continuously. Once the user terminal has picked up signals it responds by transmitting them back to the satellite, which in turn forwards the received signals to a central control station. Here the range between terminal and satellite are inferred from travel time; principally by multiplying travel time by speed of light and dividing the result by two. From the ranges to the two satellites and an initial estimate of the elevation coordinate, perhaps taking sea level, a rough estimate is calculated of user's latitude and longitude. This approximate position is then used to extract an enhanced elevation from an existing DEM, which can then be used to obtain improved estimates of latitude and longitude. In the next round, new time measurements are used, or the originals but now with the improved estimate of elevation. This iterative process ends with convergence, and the user receives his position within the Beijing 1954 Coordinate System, claimed accuracy of 100m and 20m when using calibration stations. Since the user terminal is not only a receiver but also communicates itself, network capacity limits to 150 the number of simultaneous users. But since the signals travel with the speed of light, over half a million users can be served per hour. Dual transmissions also mean a need for more space to accommodate devices, so Beidou terminals are bigger, heavier and more expensive than GPS receivers. China's army uses the two-way communication function to talk to units and monitor their position. However, two-way communication is strategically unfavourable: the enemy may also pick up processed signals and determine from them troop position and movement.

Regional Coverage

The third Beidou satellite (2A) was blasted into orbit two and a half years after launch of 1B, on 24th May 2003 to be precise. Nearly four years later, on 23rd February 2007, the fourth Beidou (3A) was put into orbit and operates as spare. The fifth Beidou, rocketed beyond earth's atmosphere on 12th April 2007, was not like the other four positioned in an approximately geostationary orbit 35,800km above earth's surface. Instead it is in an orbit of perigee 21,519km and Apogee 21,544 km. Beidou 1A is positioned north of Irian Jaya at longitude 140E, Beidou 1B south of Sri Lanka at 80E, and Beidou 2A rotates geo-synchronously with the western part of Borneo, Indonesia, at 110.5E. The advantage of geostationary satellites is ease of control. GPS is monitored by a master station at Falcon Air Force Base, Colorado Springs, USA, and remote stations in Hawaii, Ascension Island in the Southern Atlantic, Diego Garcia in the midst of the Indian Ocean and Kwajalein in the South-West Pacific. Six more National Geospatial Intelligence Agency monitoring stations were added in summer 2005. Beidou’s ground segment includes the central control station and orbit-tracking stations at Jamushi, Kashi and Zhanjiang. However, the price paid for a system comprising so few satellites and limited ground control is regional coverage.

Compass

Regional coverage would seem to constitute something of a disgrace in the eyes of China’s leaders, who want a doubling in Gross Domestic Product (GDP) this decade. They thus wish gradually to extend Beidou to become a real global satellite navigation system (GNSS), referred to as the Compass Navigation Satellite System. Ultimately scheduled for 2008, but definitely for 2010, the constellation will comprise five geostationary satellites and thirty medium-orbit satellites intended to provide positions with 10m accuracy, using, like GPS, the principle of trilateration.

PHOTOGRAMMETRIC IMAGE ACQUISITION AND IMAGE ANALYSIS OF OBLIQUE IMAGERY - A NEW CHALLENGE FOR THE DIGITAL AIRBORNE SYSTEM PFIFF

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ABSTRACT: Due to the intuitive perception of the oblique view to humans, recently oblique images come in the focus of photogrammetrists again. Also new flexible digital airborne camera systems allow for the easy collection of such imagery with a photogrammetric quality. In the article the application potential of oblique images, the digital airborne remote sensing system PFIFF, and two test flights with oblique and oblique stereo images are presented. The data processing, display and measurement within oblique images from different perspectives requires new software such as Multivision.

1. INTRODUCTION

1.1 Oblique images - a new data source for photogrammetry and GIS

In the past oblique images were generally taken for visualisation and interpretation purposes, rather than for metric applications. An exemption is the military sector were oblique images are a standard for reconnaissance purposes since a long time, e.g. WELZER, 1985. Thus oblique images were generally outside of the focus of photogrammetrists.

The use of standard vertical orthoimages as a topographic background in a GIS is nowadays very common, thus generating a strong demand for current photogrammetric airborne and high resolution satellite data. Planners, administrative users and the general public use the available orthoimages, e.g. in Google Earth and other similar services mainly for orientation and visual inspection of selected features. Yet vertical orthoimages may not be read easily by everyone. Due to the intuitive use of the oblique images, which is similar to the common human perspective, these images are very attractive to decision makers, as well as for the general public. To fully exploit the information from the oblique perspective, a minimum of four images from all sides have to be acquired and managed.

Standard GIS-packages do not support oblique images, due to their geometry with varying scales, therefore new viewers and software packages have to be developed to guide the users and provide them with the necessary functionality.

Oblique images are an indispensable tool for the following general uses, which will be subsequently described in more detail.

- Tax Assessment & Building Deviation
- Urban and infrastructural planning
- Management of military und security operations
- Critical infrastructural protection
- Cadastral capturing and management

Tax Assessment & Building Deviation

- Accurate measurement of areas, building facades and constructions of the capital assets
- Effective identification, measurement and documentation of deviations
- This results in an increase of the tax revenues for built estates

Urban and infrastructural planning

- Comparative measurements of buildings and structures
- In landscape architecture and urban planning it can be used to capture and evaluate real estates or for the build-up of pylons
- For the telecommunication planning it can be used to do line of sight calculations

Management of military und security operations

- Immediately availability of information about critical locations
- Accurate visualisation of these locations
- Identification of surrounding areas and infrastructure
- Measurement of accesses and openings
- Planning of access and exit routes

Critical infrastructural protection

- MultiVision is a valuable tool for the following facilities
  - Airports, ports, railroad stations, malls
  - Power authorities, military and police facilities
  - Government buildings, hospitals, prisons
  - Dense populated areas, tower blocks

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[*] Corresponding author

- factory premises and industrial areas

Cadastral capturing and management

- Accurate capturing and organisation of cadastral activities in rural areas
- Perfect for 3D cadastral projects

Additionally oblique images can be used to texture 3D-buildings and 3D-city models. These textured buildings can than be used as realistic objects in 3D visualisation projects.

The Microsoft Virtual Earth viewer (Microsoft, 2007) provides high resolution oblique images for many cities around the world, but only from one viewing perspective at a time. Viewer solutions from Pictrometry Inc. (Pictrometry, 2007) and Multivision Inc. (Multivision, 2007) allow for several perspectives of one object simultaneously. Additionally these specialized viewers provide additional features, such as the measurement of distances and the integration of addition GIS-data. In chapter 4 the functionality and the workflow of the MultiVision software will be presented in greater detail.

The system PFIFF, a digital airborne remote sensing system developed by the author, will be described in detail with special respect to demonstrate the photogrammetric potential of PFIFF. The focus of the paper will be the exploration of possibilities of oblique (stereo) images, e.g. for visualisation or automated building texturing, as well as for the vitality analysis of trees along the roads.

2. PFIFF

PFIFF, a digital airborne remote sensing system, was originally developed by the author to fulfil the special requirements of precision farming (Grenzdörffer, 2005). The special advantage of PFIFF compared to standard photogrammetric frame cameras is the possibility to take oblique images.

The core of the system since 2005 is a digital SLR colour camera, the Rollei AIC45-CIR (Aerial Industrial digital Camera). The CCD-sensor H25 from Phase One has a net resolution of 5.436 * 4.080 pixels (22 Megapixel), see Table 1 for the technical details of the camera.

Table 1: Technical parameters of the digital Rollei AIC-CIR 45 camera

	Rollei AIC 45
Camera type	Rollei AIC with fixed digital back
Resolution [pixel]	5.436 * 4 .080
Pixel size	9 µm * 9 µm
Sensor size [mm]	48.96* 36.72
Colour depth per channel	16 Bit
Colour mode	RGB or CIR
min. exposure interval	ca. 4[1] sec.
Weight (incl. lens)	ca. 1.500 g
Connection to computer	Firewire, Barebone PC
Software	Phase One 3.1

[1] value for two consecutive images under airborne conditions

With the exposure interval of less than 4 seconds under airborne conditions, the Rollei AIC camera enables photogrammetric aerial surveys (60% end lap) with a ground resolution of > 10 cm. The digital back works together with a Rollei AIC-camera body and a Schneider Super Angulon 2,8/50mm HFT lens with a min exposure time of 1/1.000 s. The digital camera is controlled by a barebone PC with a storage capacity of 400 GB which stores all the image data (up to 6.000 images) via firewire connection.

The camera may acquire images either in RGB or in CIR. Therefore the IR-cut filter on the top of the CCD-sensor was removed. The different colour information of the CCD-sensor is gathered via a Bayer-pattern. For a CIR image a band filter is mounted on top of the lens, which filters out the blue light (< 520 nm). The green, red and infrared light up to a wavelength of 1.050 nm passes the filter onto the sensor. As a result the green light and red light sensitive CCD-elements also gather infrared light. These infrared light components have to be separated in the development process. Yet the infrared light sensitivity of the sensor is much stronger than in the visible light. For a similarly enlightened image in the RGB-mode and the CIR-mode the amount of the incoming light has to be lowered by 3 f-stops for the RGB-image.

Other important components of PFIFF are the GPS-based flight management system and a navigation unit that automatically triggers the images during a flight strip according to the pre defined end lap. During the strip the optimal image exposure interval is continuously computed and the camera is triggered synchronously to the PPS-signal of the GPS-clock to ensure a perfect synchronisation with the external high accuracy L1/L2-GPS receiver. The navigation unit records the exposure delay of the camera. With this approach a constant endlap is ensured under all conditions with the most flexibility during an aerial survey. This approach is quite different to the common approach of a photogrammetric aerial survey, because there the image centres become predefined in the flight planning and they are subsequently flown during the aerial survey.

For a photo flight the system is temporarily installed in a Cessna 172 with a small ground hole of ca. 12 cm in diameter. See Figure 1 for the system design.

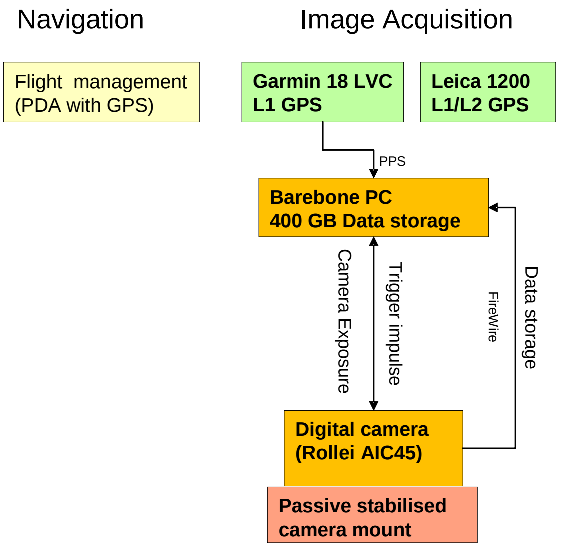

Figure 1: Low-cost remote sensing system PFIFF 2006

For the use of a digital camera in aerial surveys not only the size of the CCD-sensor is of importance, but also many other criteria of the digital camera such as the minimum exposure interval, the external storage capacity, a continuous power source, preview options, the mechanical stability of the sensor (interior orientation), the temporal eccentricity (exposure delay), the reliability and also the radiometric properties have to be considered and determined. Therefore the system has undergone thorough geometric and radiometric calibration procedures. For photogrammetric work the interior orientation of the camera was determined. With the fixed digital back of the AIC45 an on-flight calibration is not necessary. The examination of the linearity, the spectral characteristics of the RGB band filters and the high signal to noise ratio revealed that the radiometric properties of the digital camera are far superior to an equivalent photographic system.

In 2006 a general overhaul of the PFIFF flight navigation system and the flight management system with a fully automatic image triggering was undertaken. The software CartaLinx from ClarkLabs was formerly the basis for the flight navigation, in which the flight lines and the current position of the aircraft were displayed on a laptop to the pilot. The drawbacks of this solution were that the map on the display was always north oriented and the pilot had to rethink left or right on every manoeuvre. Additionally the pilot lacked important information for the navigation, such as current course vs. planned course, critical ground speed etc. Due to these reasons a new software with dedicated features for the pilot was developed. The software runs on a common PDA with GPS. The most important features of the software are automatic rotation of the graphics in the flight direction, automatic zoom functions within and outside the survey area, a graphical display of the current exposure interval of the camera used and most important aerial survey navigation information. The software development was realized in VBA with the GPS-tools vers. 2·31 from Franson S/A.

During the postprocessing the recorded GPS-positions (1 Hz) have to be interpolated to the precise moment of the image acquisition. Due to the long exposure delay of 302 ms (±0.1 ms) of the AIC 45 camera linear interpolation of the GPS-position may be associated with significant errors due to high frequent nonlinear aircraft movements. A comparison of 266 perspective centres, determined either by linearly interpolated 1 Hz GPS-positions and 200 Hz GPS/INS measurement does show this quite well, TABLE 2.

TABLE 2: Deviations [m] of the perspective centres, determined by linear interpolation of 1 Hz GPS recordings and 200 Hz GPS/INS measurements (n = 266)

	X (m)	Y[1] (m)	Z (m)
Average	0.004	0.009	0.015
Standard dev.	0.077	0.104	0.051
Max	0.243	0.581	0.140
Min	-0.175	-0.546	-0.131

[1] East-West, main flight direction of the image strips

With the reengineering of the GPS-based flight management system the exposure delay is now considered during PPS-synchronous image triggering, see Figure 2.

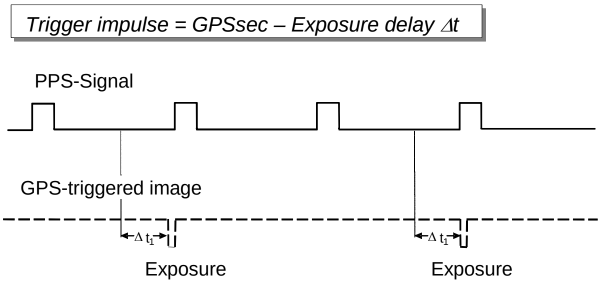

Figure 2: PPS-synchronous image acquisition considering the exposure delay time of the camera

In order to fully automatically trigger images within the survey area, the camera triggering is now tightly coupled with the flight navigation system. The flight management software automatically starts triggering the camera whenever the pilot manoeuvres the aircraft inside the survey area. After the aircraft is outside the survey area the automatic image triggering stops. Because the MS-Windows XP operating system does not support real time applications an additional timer card (NI-6601) from National Instruments was integrated in the computer. The programming of the timer card and the PPS-synchronous triggering was realized with Labview 8.0.

3. OBLIQUE IMAGES

The image acquisition of oblique images requires several changes in the common workflow, from survey planning to image processing and image analysis.

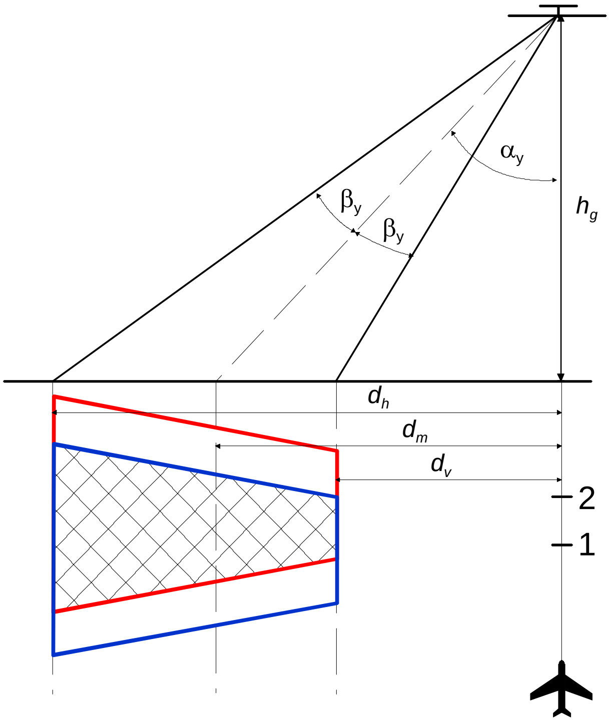

Figure 3: Geometry of oblique images

3.1 Flight planning

In the flight planning for oblique aerial survey several special issues have to be considered. The image scale is not constant throughout the images. In the foreground the ground sampling distance (GSD) is smaller than in the image background. See Figure 3. In the flight planning the altitude above ground and the viewing angle α_y across the flight direction has to be defined. The viewing angle of the lens β_y defines the minimum and the maximum distance d_{max} of the image to the aircraft as well as the image scale for analogue images or the GSD with digital images. The minimum, average and maximal ground resolution is calculated by the following equations.

$$m_{b\min} = \frac{h_g \cos\beta_y}{f \cos(\alpha_y - \beta_y)}$$

$$m_{avg} = \frac{h_g}{f \cos\alpha_y}$$

$$m_{b\max} = \frac{h_g \cos\beta_y}{f \cos(\alpha_y + \beta_y)}$$

The distance of the image foreground and the image background to the aircraft is based on the following equations.

$$D_{\min} = h_g \tan(\alpha_y - \beta_y)$$

$$D_{avg.} = D_{\max} - D_{\min}$$

$$D_{\max} = h_g \tan(\alpha_y + \beta_y)$$

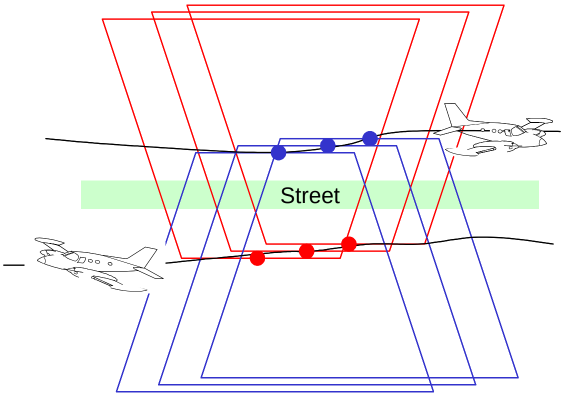

Figure 4: Flight pattern for oblique images of streets, pipelines etc.

3.2 Example oblique images for street trees

On 6th of September 2003 a flight of a 4 km long part of an avenue with trees on both sides was conducted with a ground resolution of approximately 12 cm, Grenzdörffer, 2004. The purpose of the flight was to investigate the possibilities to obtain information of the vitality of trees, the street and the surrounding from nadir looking images as well as from oblique images, see Figure 4 for the flight pattern. Therefore the central flight line along the street was designed to gather nadir looking data. For the oblique images the camera was turned around 90 degrees and held out the window of the airplane manually. On small aircrafts such as a Cessna 172, the wheels of the aircraft maintain outside during the flight. Due to this fact oblique images out of the window could not be taken at the anticipated 45° angle. Instead the looking angle was approximately 60° in omega. To become oblique stereo images with and end lap of 60% the automatic trigger control of the flight management system had to be reset accordingly.

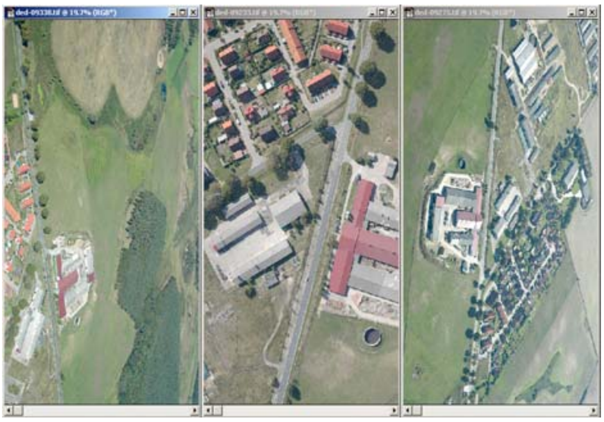

Figure 5: Example of nadir looking and oblique images of a street

At first the nadir looking image strip was processed by means of a standard aerotriangulation. The georeferencing of the oblique images was more complicated, because tie points in neighbouring images could not be found automatically in the first instance. This is related to the fact, that the starting values of ω and φ of the hand held images were unknown. After a manual definition of a minimum number of tie points with a selected number of oblique images, a preliminary triangulation was conducted to obtain approximate angles in ω and φ. Thereafter the automatic tie point generation algorithm worked fine. Due to the apparent differences in the scale within the oblique images the precise determination of the ground control points was difficult. Nevertheless the results of the aerotriangulation of the oblique images were within 60 cm RMS at the GCP's. The most interesting aspect for the interpretation of the trees and other features along the street is the stereo view of the oblique images, because an orthorectification does not yield the full information.

3.3 Oblique stereo images

With direct georeferencing through GPS/INS the problems of manual tie point selection and cumbersome image rectification are overcome and the image data may be used e.g. for texturing of 3D city models or other interesting purposes. See figure 10 for the footprints of a strip of oblique images, generated at a test flight in Rostock, Grenzdörffer, 2005. Due to the big overlap the images may also viewed and analysed in stereo, figure 11.

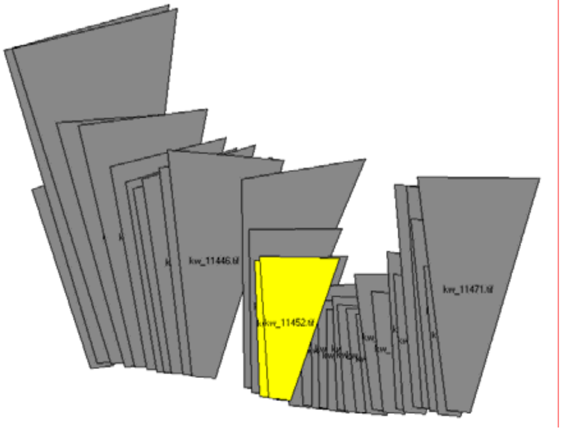

Figure 6: Footprint of strip of oblique images

Due to the highly accurate georeferencing y-parallax is nearly absent (displayed in the lower right part of the screen shot) allowing perfect stereo measurements in the images.

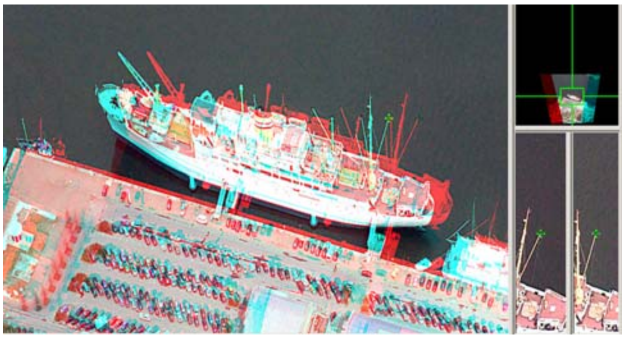

Figure 7: Oblique stereo anaglyph image through direct georeferencing

4. MULTIVISION TEST FLIGHT ROSTOCK

The test flight with oblique images for visualisation and semiautomatic building texturing was undertaken at the 23.11.2006 over the downtown area of the city of Rostock. The complex flight pattern is shown in Figure 8. The average flying altitude was 400 m above ground. The resulting ground resolution in the image center is approximately 15 cm. A total of 78 images with an overlap of approx. 60 % were acquired at the flight.

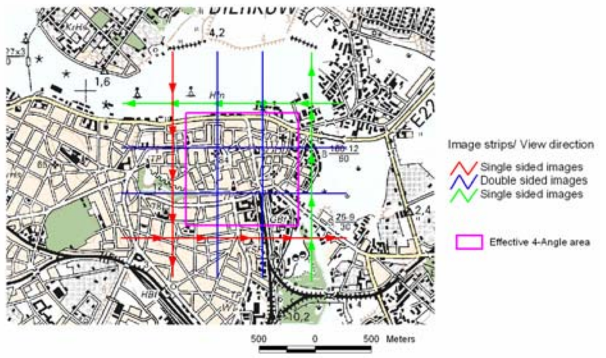

Figure 8: Flight pattern for test flight Rostock 23.11.2006

Due to the low sun angle at the time of flight in late November the image quality in the different view directions is quite different. The radiometric postprocessing included a colour balancing, with individual parameters for each flight direction and a 16 → 8 bit conversion.

5. MULTIVISION

The data analysis of the test flight is done with the Software MultiVision, (Multivision, 2007). Vertical and oblique orthophotos resolved via photogrammetric methods are integrated into a "Site File" to provide an interactive multi-dimension, multi-perspective view of any area, building, structure, and feature. A Site File integrates an orthophoto of a site with its associated oblique photos and DEM. Any selected feature can be viewed in perspective and from any direction. Elements of structured and facades can be accurately be measured for height, width, area, elevation etc. The terrain can be accurately measured for dimension, distances, slopes, elevation and declination.

The determination of the exterior orientation of the oblique images may be by sampling control points, like the method by which orientation is carried out for aerial photos that undergo rectification and orthophoto generation. The program displays an orthophoto and an oblique photo at the same time, so that control points can be sampled on both of them simultaneously. The solution program, MV-SPECIAL ONE, is designated to calculate these parameters efficiently, without requiring any further flight data. The solution is based on the collinearity equations. Control points can be taken from photogrammetric maps, or from any other accurate source. The accuracy of the control points will determine the accuracy of the orientation solution. Orientation of analog aerial photos requires internal orientation, such as input of fiducial marks.

The determination of the exterior orientation of oblique aerial photos can also be carried out using a GPS/INS system. To sum up: Multivision enables a photogrammetric solution for any type of photo/camera. The type of photographic system and solution will ultimately determine the accuracy and resolution of the solution.

The average absolute positional accuracy of the oblique images is related to several factors such as the available ground control points from the orthophoto, the accuracy of the underlying DEM and the accuracy of the interior orientation of the selected camera. For the Rostock project ground control points for the oblique images were derived from the underlying orthophoto with a GSD of 50 cm. The average of the absolute positional accuracy of the images, determined by visual inspection, is generally between 2 - 3 m, while some images are even worse. If the flight is conducted with a GPS/INS the absolute positional accuracy is better, e.g. Grenzdörffer, 2005. The relative accuracy, necessary for the measurement of the height or the width of buildings are only partially related to the absolute accuracy and generally much better.

The program operates in DTM environment, thus enabling to make various calculations for locating the user's relevant oblique photos. Multivision operates in correspondence with a GIS (for example, ArcView). The GIS operator can make geographic queries; once a datum from the GIS is displayed (such as an address, coordinate, polygon, etc.) – four oblique aerial photos for the specific coordinate will appear on screen, Figure 9.

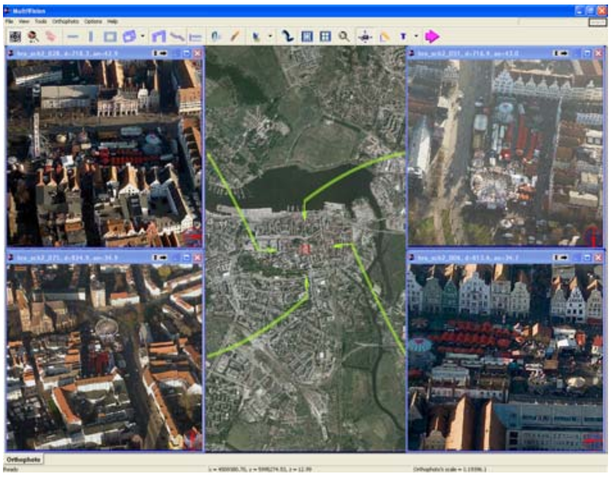

Figure 9: Multivision Main Screen

5.1 Texturing 3D-buildings with aerial imagery

Texturing buildings with the aid of aerial imagery may be done in many different ways. Wide angle vertical images provide an oblique view at their edges, which may be used for automated texture extraction, Zebedin et al. (2007). Alternatively modern 3-line scanners such as the HRSC-A or ADS 40 provide oblique views with their forward and backward looking channels, enabling an automated generation of 3D-textured facades, e.g. Hirschmüller et al. 2006, Woolpert SmartView^{TM} (2007).

5.2 3D-building Data for Rostock

A simple 3D-building model (LOD 1) of the city of Rostock is available on the basis of a HRSC image data and official cadastral information (ALK). Due to the data structure of the ALK, building objects in the ALK may represent more than one building in reality. Therefore buildings were split up based on the true orthophoto of the HRSC. Additionally several landmarks, such as church were modelled individually.

However the usage of a simple block model is limited, e.g. for the determination of road noise absorption of buildings according to new EU regulations (EU Directive 2002/49/EC on Environmental Noise). For city planning and other purposes a 3D-city model should have at least several roof types and textured facades. The common texturing of facades with terrestrial photographs is quite cumbersome. Therefore an aerial survey with automated texturing is the most elegant approach.

The texturing of the single buildings within Multivision is done on a per building approach. Thereby CAD-buildings are incorporated into the software and the facades are clipped automatically from the different views, see Figure 10.

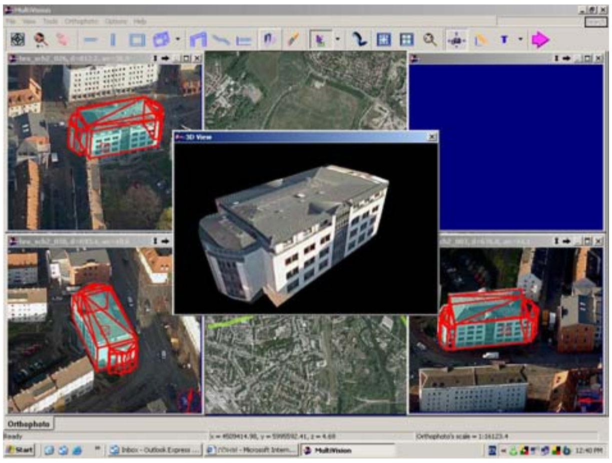

Figure 10: Semiautomatic generation of building textures

Due to a lack of standardized solutions for data transfer between different 3D-software packages 3D-data conversion is always a bottle neck in the development and texturing of 3D-city models. Independent standards such as the CityGML–Standard within OGC (CityGML 2007) are currently under development.

6. OUTLOOK AND FUTURE WORK

The automation of the relative and absolute orientation of oblique images is still an issue of intensive research. Thereby the differences in scale and overlap have to be considered. Läbe and Förstner (2006) demonstrated promising results, also with PFIFF airborne oblique images.

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Possibilities of Pictometry Technology within Kadaster (Dutch Cadastre)

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Summary

This report results from a three-month's research trajectory carried out by Kadaster International in co-operation with GeoTexs, Delft. The provider of Pictometry technology – Blom Group – participated by delivering data, software, (technical) support and discussions. The main aim of the project is to arrive at an understanding how Pictometry might be of benefit to support the tasks and ambitions of Kadaster. Pictometry is a photogrammetric technique of which the sensor system consists of five cameras. The (mutual) geometry of the five cameras is accurately known. One camera is directed nadir (image plane approximately parallel to the terrain surface) and by using a Digital Elevation Model (DEM) ortho-images can be generated automatically from the nadir images. The other four cameras view forward, backward, left and right, resulting in oblique images. With the Pictometry software package Electronic Field Study (EFS) one can navigate through the images while, most importantly, also measurements can be carried out in both ortho and oblique images. The research aim led to the following research questions: (1) what is the accuracy of planar (x,y) coordinates and (2) of the height component (z), (3) what is the information content of the images, (4) what does Pictometry add to conventional airborne photogrammetry, (5) does the technology support determination of preliminary cadastral boundaries, (6) what are the costs involved, (7) which information can be provided by Pictometry technology in view of the future prospects of Kadaster and, finally, (8) which business models are suited?

To conduct the research a laboratory environment has been created, including a stand along computer on which Pictometry image data, map data and EFS software package has been installed. The test images consist of Pictometry ortho-images and oblique images captured at 11th May 2006 and covering the entire territory of Apeldoorn municipality. The map data consists of: (1) boundary lines of objects of Top10Vector and Top25 Raster, (2) feature lines of the Large Scale Base Map of the Netherlands (GBKN) and (3) cadastral map.

Our tests reveal that the accuracy of taking location measurements in ortho-images is 19cm and in ortho-images 86cm, expressed in terms of root mean square error. The accuracy of the elevation component depends on the accuracy of the underlying DEM (AHN: Actueel Hoogtebestand Nederland). The accuracy of AHN is 5cm systematic error and 15cm random error. Although Pictometry technology is presented by the vendor as a visualisation tool, not as a surveying tool, the above measures demonstrate that photogrammetric surveying accuracy can be achieved. For updating topographic data, use of stereo images is crucial. The oblique images provide an advantageous additional information source. In the GBKN

context, Pictometry technology could be used for: (1) checking, editing and completion of the automated created polygons in the process to enhance the GBKN from a line-oriented to an area-oriented database, (2) source to add manually object codes to the polygons, and (3) as additional source for retrieving the location of utility networks. Within a cadastral context Pictometry technology may serve as aid in splitting parcels and carry out parcel formation; it is a suitable tool for preliminary boundary determination. The costs for the present aerial acquisition method used for updating Topographic maps (TOP10) is around Euro 1Million for the entire territory of the Netherlands. The costs of Pictometry technology for covering the urban areas in the Netherlands (50,000+ inhabitants) is Euro 1Million on an annual basis. As a result Pictometry technology can be beneficially and cost-effectively applied when it serves several (future) tasks of Kadaster and in a broader perspective the geo-information needs of the whole of the Netherlands. More importantly, Pictometry technology might serve as an engine and catalyser to fulfil the ambitions of Kadaster to become the principal supplier of real estate and geo-information within the Netherlands. The opportunities offered by this emerging technology should be particularly valued from that perspective. A better understanding of all possibilities and opportunities of Pictometry technology in the context of the present and future tasks of Kadaster, requires further study.

From the list of many applications in which Pictometry technology could be applied successfully, the Board of Kadaster has selected three pilots: (1) identifying preliminary boundaries via notary, (2) building registration and (3) communication between citizens and government. These pilots been chosen because they cover (relatively) new areas, while they fit within the ambitions of Kadaster and have a high degree of actuality.

Contents Page

1. Introduction

This report is the result of a three-month's research trajectory carried out by the Netherland's Cadastre – in the sequel to be called Kadaster – department Kadaster International in co-operation with GeoTexs, Delft, from which firm Dr.ir. Mathias Lemmens has been involved in the project. He is also the principal author of the present report. The main aim of the project is to arrive at an understanding how Pictometry, which is a new aerial photogrammetric technology, might be of benefit to support the tasks and ambitions of Kadaster. Kadaster is a mature organisation providing modern services. According to the long term policy plan (Meerjarenbeleidsplan) 2006-2010, the ambitions of Kadaster are twofold:

1. To be the principal supplier of real estate and geo-information within the Netherlands
2. Authoritative within Europe

Kadaster is also internationally active in particular by providing consultancy to developing countries to establish cadastres or to improve existing ones. The initiative of this project stems from the international branch of Kadaster.

1.1 Pictometry Technology

Pictometry is a new aerial image acquisition and data processing technology developed and patented by US-based Pictometry International Corp, headquartered in Rochester, New York. The essential difference when compared to conventional airborne photogrammetry is that with Pictometry technology not only vertical but also oblique images are taken. The developers have constructed a sensor system consisting of five cameras, one directed nadir (image plane approximately parallel to the terrain surface), the others viewing forward, backward, left and right (Figure 1). The oblique angle for all sideward looking cameras is approximately 40 degrees off-nadir. Figure 2 gives an example of an oblique view. The (mutual) geometry of the five cameras is accurately known, providing, in conjunction with today's advanced computer technology a wealth of new application prospects. The dynamic range of the grey values of the images is 12 bits enabling to carry out surveys under unfavourable light conditions. The present standard aerial surveying method of Pictometry technology stems from homeland security mapping purposes in the US and includes a flying height for neighbouring images of 3,000 feet (1,000m) and for community images 6,000 feet (2,000m) and pixel size 6 inches (15cm) and 1 foot (30cm), respectively. In oblique images the pixel size varies from 10cm at the bottom to 18cm at the top of the image. The standard products captured in Europe are usually neighbourhood images. Mounted on an airplane, up to 16 square kilometre can be acquired per hour. In the standard survey configuration every 1.5 seconds photos are taken. Each image consists of 6MB of data while each square kilometre is covered by around 50 views resulting in around 310mb of image data per square kilometre. Each point on the ground is visible in up to 18 views of oblique (non vertical) images, provided absence of occlusion that means the point is not visible because it is concealed by another object in the line of view. Geo-referencing is done using data gathered by the onboard, integrated GPS and Inertial Navigations Systems from the firm Applanix, a subsidiary of Trimble surveying company.

Figure 1, The Pictometry camera sensor systems consists of five cameras, one directed nadir, the others viewing forward, backward, left and right (Image Courtesy: Blom Group).

In the standard configuration, vertical images have a 30% along track overlap, which is sufficient to ensure that no gaps would be created because of unplanned movements of the airplane due to air turbulence but not enough to allow stereo-viewing and mapping. However, as from October 2006 onwards, Blom Group has modified the standard image capturing configuration for surveying within Europe by using 60% along track overlap, which allows for stereo viewing. To create orthoimages from non-stereo vertical views a Digital Elevation Model (DEM) is required. For creating the ortho-photos, existing DEMs available within a country are used, for the Netherlands this is the AHN (Actuele Hoogtebestand Nederland). In the case of stereo-images, DEMs can be semi-automatically extracted from the overlapping images, using image matching techniques. Pictometry images are provided as an integrated library to be used with a software package called Electronic Field Study EFS, which is a tool to view and take measurements from both ortho and oblique images and to navigate and find a required location. Under an agreement signed in 2005, Blom Group, a geomatics firm based in Norway and with subsidiaries in a variety of countries all over Europe, and focussing on the fields of Geo-information and Offshore Technology (www.blomasa.com) has been exclusively licensed to apply the technology in 23 European countries for ten years, with the option to renew. The department of Kadaster International is co-operating with Blom Denmark. Blom has also participated in the pilot project by delivering data, software, (technical) support and discussions. The support was partly delivered by visiting the Netherlands.

Figure 2, Oblique view from the North on main building of Kadaster in Apeldoorn.

1.2 Cadastral Applications of Pictometry in Europe

Although Pictometry is a new technology it has already attracted the attention of several cadastral institutes in Europe. The Spanish cadastre has started a project in which they use Pictometry ortho images for the detection of illegal buildings along the Mediterranean coast as an aid to monitoring urban growth. Spain has a good mapping record: 40% of urban areas are on scale 1:1,000. No use is made of a standard product, but the images are acquired in dedicated surveys. The ortho images have a Ground Sampling Distance (GSD) of 10cm. Also the Danish Cadastre (KMS) has shown interest in Pictometry. IGN France and Ordnance Survey in England are resellers of the product.

1.3 Aim of the Research

The aim of the present research trajectory is to investigate whether and if yes, how, Kadaster might benefit from the Pictometry technology within the framework of its ambitions and vision on the future. To arrive at feasible insights and understanding within the limited time and resources available the above broad aim has been traced down during the inception stage to the following research questions:

1. What is the achievable accuracy of measuring planar (x,y) coordinates?
2. What is the achievable accuracy of measuring the height component (z)?
3. What is the information content of the images that means which types of objects can be recognized?
4. What does Pictometry add to conventional airborne photogrammetry; i.e. what is the value of geo-referenced oblique images in view of applications, such as Topographic map updating and building registration?
5. Can the technology support the definition of preliminary cadastral boundaries and is it useful for measuring cadastral boundaries, which are newly created by splitting parcels as a result of a transaction?
6. What are the costs involved of incorporating Pictometry technology in existing cadastral tasks?
7. Which information can be provided by Pictometry technology in view of the future prospects of Kadaster?
8. Which business models are suited to establish a sound co-operation between Blom Group and Kadaster?

Since the present research is also directed towards arriving at insight on how Pictometry technology would be of benefit for land administration purposes in developing countries, it would be good to carry out a test in which ortho-rectification is done from the information delivered by the system itself, since most developing countries do not have available an accurate digital elevation model (DEM), as the Netherlands does have in the form of the AHN. That means that the DEM should be created from overlapping Pictometric nadir images by using matching techniques. However, at this moment such a test can not be conducted because the nadir images used in the test do not overlap at the required 60% level.

1.4 Research Strategy

The research methodology is particularly developed to find answers to as many as possible research questions formulated during the inception stage within the limited time and resources available. That means that the methodology focuses on using the most efficient and optimal efforts and paths to arrive from the questions to the answers. It should be stressed that the methodology is not developed to test the feasibility of any operational solution; the emphasis is on finding out whether Pictometry technology can be an aid in present and future cadastral tasks in view of the ambitions of Kadaster. The result of testing the technology provides thus a first estimation on the possible future use of the Pictometry system with recommendations on future pilot studies. To structure the research in feasible parts, work packages have been defined during the inception stage, 21 in total. It was also anticipated that the project could be potentially confronted with a number of risks, partly because of the large number of people involved, with relative few input tasks and also because the project had to be carried out in a short time span. Therefore, a rather large Work Package was incorporated to cope with possible lapses. The appendix provides a list of all people who contributed to the project.

1.5 Methodology

- Research aim 1 requires creation of a test field of points of which the planar coordinates are determined an order of magnitude (say about 10 times) better than coordinates in Pictometry images. As measuring technique GPS is chosen
- Research aim 2 requires insight in the information source used to derive elevation values from, that means the accuracy of AHN
- Research aim 3 requires confrontation of TOP10 and GBKN with ortho images and oblique images
- Research aim 4 requires interpretation of ortho and oblique image by an experienced topographer who is able to identify objects in aerial photographs and who can define the pros and cons compared to the operational method presently in use. An aid during interpretation could for example be the measuring tools, such as measuring heights, within the Electronic Field Study (EFS) software
- Research aim 5 should be done by carrying out a fieldwork in which a surveyor collects cadastral boundaries and using previously acquired cadastral fieldworks as guide to identify cadastral boundaries in the field. Without taking actual measurements the boundaries are drawn, while in the field, on the paper image and next, in the office, the boundaries are manually digitized on the softcopy using the paper map as guide and the

resulting coordinates stored and compared with the corresponding coordinates in the cadastral maps.

- Research aim 6 – costs involved – does not only depend on the price to be paid for a license for using the images but also on the costs involved in deriving value added products from the imagery, in particular labour costs. During the test phase some valuable insights have been obtained about human labour necessary to extract information from the images and to generate value added products. It should however be stressed that the scope of the present project is too limited to obtain in-depth information on the costs aspects; thorough information can only be gained during more in-depth and focused pilot studies
- Research aim 7 has been carried out by conducting interviews with key persons within Kadaster and by studying literature
- Research aim 8 has been carried out by scheduling regular meetings with representatives of Blom group (see Appendix).

1.6 Structure of the Report

The next Chapter treats in greater detail the tasks of Kadaster, gives some background details on Blom Group and discusses the set-up of the research. Chapter 3 presents the test results obtained by field work and laboratory tests, covering research aims 1 to 5. Chapter 4 presents costs considerations and Chapter 5 focuses on research aim 7: which information can be provided by Pictometry technology in view of the future prospects of Kadaster. Chapter 6 focuses on suitable business models. Chapter 7 discusses the results in the framework of the ambitions of Kadaster. Finally, Chapter 8 presents conclusions and recommendations, including proposals for three pilot studies.

2. Background Information

This Chapter treats in greater detail the tasks of Kadaster, gives some background details on Blom Group, and discusses the set-up of the research.

2.1 Kadaster

The tasks of the Cadastre include:

- Registration, management and releasing title information and geo-information
- Land development
- Managing the national geodetic framework
- Providing information products
- Carrying out international activities

Clients of the cadastre include: Notary, National Government, Provinces, Municipalities, Water boards, Ministry for Housing, Spatial Planning and Environment, CBS: Statistics Netherlands, Assurance companies, Citizens, Real estate brokers, Utilities and Financial institutions. Table 1 shows basic numbers on title information for the year 2005. With respect to geo-information Kadaster is the holder of the cadastral map and the topographic map (TOP10) for the whole territory of the Netherlands. The topographic map is hold, maintained and distributed by TD Kadaster. Furthermore, Kadaster is an important stakeholder of the Large Scale Base Map of the Netherlands (GBKN) and will hold the basic register on addresses and buildings (BAG) which is scheduled for being operational in 2009.

Total Number of Parcels Registered in 2006	8,640,000
Number of registered transaction acts in 2006	497.000
Number of acts with new boundaries in 2006	87.000
Number of registered mortgage acts in 2006	748,00
Number of information requests in 2006	30.500.000

Table 1, Facts on Title Registration

Nearly all Kadaster information is available and can be delivered in digital format. When the comprehensive cadastral paper archives, including field survey sketches, have been completely scanned, information of the Kadaster will be completely in digital format. Nationwide Kadaster services are already available in digital format for traditional cadastral information provision; new tools and services will be developed for a series of new tasks related to the registration and information supply for utilities, addresses and buildings.

2.2 Blom Group

Blom ASA, the European exclusive license holder of Pictometry technology, was established in 1954 by Hydrographer Ole H. Blom as a provider within the mapping industry and is now a pan-European company leading in the field of collecting, processing and delivering geo-information. From 2003 onwards, Blom acquired several mapping companies across Europe, including Simmons Aerofilms Ltd, UK, now called BlomAerofilms, and Seficart Group, Spain, now called Blom Sistemas Geoespaciale. The company's turnover in 2006 is around 100 million euros with over thousand employees in eleven countries. The company operates 33 aeroplanes and four helicopters, distributed around Europe enabling to serve the whole continent with digital aerial photography for vertical and oblique images, Lidar and multi-spectral scanning. Microsoft has ordered Pictometry images of all major cities in Europe for a total value of US$ 31M and is an important customer from the private sector.

2.3 European Pictometry Project

Blom's ongoing Pictometry project is currently one of the largest image-acquisition projects in Europe. The aim is to create a standard database of oblique and ortho-aerial imagery covering every town in Europe with a population larger than 50,000 inhabitants, a total of over nine hundred towns. The first and main customer for all the images of the 900 European cities is Microsoft. By the end of March 2007 six cities in the Netherlands are available within Microsoft's Virtual Earth: Breda, Groningen, Kerkrade, Maastricht, Nijmegen, Oss, Venlo en Zwolle (http://maps.live.com; http://local.live.com).

A unique feature of the business model in the context of photogrammetric surveying is that, anticipating growing interest in geo-information on the part of non-conventional users and partly induced by the success of Google Earth, Blom first acquires the images and then approaches potential customers. Anyone can then take out a licence to use the standard image library for a price per km^2. The standard list price is presently set at Euro 250 per square kilometre annually. But this price depends on several parameters, one of which is volume ordered and another is the time span of subscription. Image acquisition without specifically ordering by a customer is a business model that is gaining in popularity; for example, Cyclomedia, which captures terrestrial photographs from a car platform, has also adopted this capture-prior-to-order model. And of course, this model already exists for decades for Earth observation from satellites.

2.4 Pictometry versus Traditonal Photogrammetry

One may ask what does Pictometry technology add to traditional aerial photogrammetry? In principle just oblique images are added, and actually there is nothing new about that. In the past the process of extracting accurate geometric information such as 2D and/or 3D coordinates of points was restricted technologically and could only be done on a production scale by using vertical images. Much emphasis was on using vertical images measuring stereoscopically and the whole image acquisition and measuring process was adapted to this. Compared to carry out measurements in mono nadir images, measuring in stereo images brings the following advantages: (1) acquisition of 3D coordinates without support of a Digital Elevation Model, (2) better interpretation, (3) higher precision is achievable because points can be better identified. Because today the geometry of the sensors can be described accurately, direct geo-referencing can be done by using GPS and inertial navigation systems are available, while the complex geometric transformations can be carried by computer using advanced software solutions and additional information sources, in particular high resolution, accurate DEMs, it is now possible to extract relatively accurate geometric information from oblique images. The biggest advantage of oblique images compared to vertical images is that they enable a better and more intuitive interpretation. The extraction of geo-information from vertical images requires training and craftsmanship while the interpretation and taking measurements in oblique images is much more intuitive and can be done by non-specialists. This statement has been confirmed during our tests. As a result oblique images make aerial information accessible for use by a much larger user group, mainly consisting of non-professional users, such as officers at municipalities, who may use the aerial images just as tool, as they might use Excel spreadsheets, to support their actual tasks. Since the internal and external sensor geometry of the camera system is know and can be described in analytical form and programmed in a computer, measurements can be carried out on the oblique images, such has height, distance, area, location and elevation. Volume of, for example, buildings although in principle possible, can not yet be determined by the Pictometry software. Both the ability to observe the environment from an oblique viewpoint and the ability to measure in the oblique images provides a broad range of new applications for a variety of user groups. A non-limited list of possible applications with the context of Kadaster would include:

- support for orientation purposes - pda, data acquisition by citizens
- overlays with (add on’s to) Top10Vector/NL, CadMap, Large Scale Topographic Map and Address Co-ordinates
- building registration, including additional measurements such as stock counts, extraction of building height

- extracting cadastral boundaries
- mapping (updating with GPS)
- disaster management
- urban planning
- cadastral map quality improvement (map renovation)
- fast acquisition of boundary vertices
- Updating of the topographic map TOP10 Vector/NL
- Updating of the GBKN
- cadastral geometric data acquisition and support in legal/administrative data acquisition in developing countries - also slums and customary area's
- communicating cadastral information to citizens in the framework of the cadastral website www.vindjeeigenhuis.nl

Pictometry technology also enables the semi-automatic texturing of 3D city models. When a wire-frame of buildings is available, the façade textures can be automatically extracted from the oblique images since the geometric sensor model is known and draped on the "empty" facades in the wire-frame. To enhance the 3D model some manual cosmetic operations are necessary. Blom invests much research and development activities in this field, and they have reported promising results.

2.5 Pictometry versus Microsoft's local.live.com

One may put forward the question what does a license for using Pictometry products, which is rather expensive, add to using the same images available at Microsoft's local.live.com website for free? Actually, the two scenarios are not comparable at all. First of all, the availability of images and areas are completely determined by Microsoft; images may be available but not yet included on the website. Furthermore, and more importantly only the oblique images are available, not the ortho-images with as consequence that no stereo-images will be available. Another major drawback is that users are not enabled to carry out measures on the images and to use them as a navigation tool for example to access other data sets. In short: Microsoft's website local.live.com enables just viewing of weakly geo-referenced oblique images.

2.6 Set-up of the Test

To carry out tests a laboratory environment was created, including a stand along computer on which all data and the pictometry software (EFS) was installed. Furthermore, two regular computers with internet connection and email functionality were available.

2.5.1 Test Data Set

The images used in the test consist of Pictometry ortho-images and oblique images covering the urban territory of Apeldoorn municipality captured at 11th May 2006. The ortho-images are derived from nadir images which have been corrected for non-parallelism with the terrain and presence of terrain relief by using the Actuale Hoogtebestand Nederland (AHN). The along track overlap is 30%, which does not enable to view the images stereoscopically (stereoscopically viewing requires approximately 60% overlap). However, from October 2006 and onwards all the Pictometry image capturing is done by Blom with 60% overlap. Each ortho-image is taken at a nominal flying height of 1km and covers an area of approximately 350m x 560m. The Ground Sampling Distance (GSD) is 15cm. The used AHN has a grid spacing of 5m. Since Apeldoorn concerns a built-up area larger than one square kilometre the elevation values include buildings. After installation the coordinates refer to the WGS84 geodetic reference systems.

2.5.2 Map Data

In addition to Pictometry images of Apeldoorn the following digital map data were installed on the test computer; all maps were transformed to WGS84 geodetic reference system. All map data contained geometry of objects; the attribute data were removed to ease testing. The map data included:

- Boundary lines of objects of Top10Vector and Top25Raster
- Feature lines of the Large Scale Base Map of the Netherlands (GBKN)
- Cadastral map.

Figure 3, Cadastral map (black lines) superimposed on Pictometry ortho-image.

3. Test Results

3.1 Accuracy Assessment

To arrive at an estimate of the accuracy of planar (x,y) coordinates (research question 1) that means how well do the coordinates of points measured in the Pictometry images match with the coordinates in reality a comprehensive test was conducted; a test field of single points was created around the Kadaster building of which the x,y coordinates were determined by GPS. Well-identifiable points in particular corners of white roads signs which contrast much with the dark colour of the street asphalt were selected. As a measure of accuracy the root mean square error (RMSE) of the x and y coordinates were determined according to:

$$RMSE_x = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - X_i)^2} \qquad (1)$$

With:

x_i : x coordinate of point i in the Pictometry image

X_i : x coordinate of point i measured with GPS on the ground.

N : Number of points in the test field

Similarly the root mean square error $RMSE_y$ for the y coordinates were computed and finally the overall RMSE as:

$$RMSE = \sqrt{RMSE_x{}^2 + RMSE_y{}^2} \qquad (2)$$

The GPS coordinates were determined in the geodetic reference system of the Netherlands (RD), while the coordinates image points were determined in the WGS84 system. To bring the coordinates in the same system (RD geodetic system) an affine transformation was carried out on the image coordinates:

$$\begin{aligned} X &= a_1 x + a_2 y + a_3 \\ Y &= b_1 x + b_2 y + b_3 \end{aligned} \qquad (3)$$

The six transformation parameters $[a_1, a_2, a_3, b_1, b_2, b_3]$, were determined from a least squares adjustment using four points. The GPS points were measured by a cadastral surveying team under the supervision of the author. From 35 points measured in the terrain, 34 were usable.

The corresponding points in the Pictometry images were both measured in the ortho image and in the oblique images. The coordinates of the points in the ortho-images were measured twice by two independent operators. The coordinates of the two resulting sets were averaged prior to confronting them to the GPS coordinates. Also the coordinates of the points measured in the oblique images were averaged, if applicable, prior to confronting them with the GPS measurements. The results are shown in Table 1.

	$RMSE_x$	$RMSE_y$	$RMSE$
Ortho	17cm	8cm	19cm
Oblique	62cm	60cm	86cm

Table 1, Accuracy assessment of Ortho- and Oblique images.

The points measured in the field with GPS were also measured in the oblique images; one to six measurements of the same point were carried out, depending on the visibility and identifiably of the points in the diverse oblique images. For 31 points we were able to carry out two or more measurements. The standard deviation σ_x for the x-coordinates

$$\sigma_x = \sqrt{\frac{1}{M-1}\sum_{j=1}^{M}(x_{ij}-\overline{x}_i)^2} = \sqrt{\frac{1}{M-1}[\sum_{j=1}^{M}x_{ij}{}^2 - (\sum_{j=1}^{M}x_{ij})^2/M]}$$

With:

x_{ij} : x coordinate of point i in the pictometry oblique image j

$\overline{x}$: Average of the x coordinates of point i in the j oblique images: $\overline{x} = \frac{1}{M}\sum_{j=1}^{M}x_{ij}$

M: Number of images in which point has been measured.

were determined. The average values and other statistics are shown in Table 2.

Oblique	Mean	Minimum	Maximum	Median
σ_x	72cm	17cm	185cm	55cm
σ_y	86cm	12cm	300cm	59cm
$\sqrt{\sigma_x^2+\sigma_y^2}$	112cm			

Table 2, Statistics of measuring identical points in different oblique images.

The achievable accuracy of the elevation component (elevation; research question 2) depends on the accuracy of the underlying DEM. In the present case the AHN (Actueel Hoogtebestand Nederland) has been used. The elevation of points in AHN may systematically deviate from the actual bare ground (maaiveld) on average by 5cm, while the random error is 15cm in terms of one standard deviation, meaning the error in 68% of the measurements is not larger than 15cm. The data acquisition method used for creating AHN is airborne Lidar, which generates a surface model in which the tops of all objects are measured, also of undesired objects such as trees, cars and cattle. These are filtered out but the producers of the AHN acknowledge that this can not be done perfectly. Furthermore, the filtering is carried out by contractors, who also carry out the surveying flight. Each of them has its own filtering technique which one treats as classified. Unwanted objects may thus still be present. In rural areas houses are removed in order to get a representation of the bare ground level. In contrast, in urban areas, when the size of the build-up area is at least one square kilometre, houses are not removed and in the test set of Apeldoorn houses are present. The elevations in the neighbourhood of sharp discontinuities such as facades of buildings may be smoothed.

3.2 Topographic Information Content

Are Pictometry images suited as an aid for updating large scale topographic maps? To arrive at an answer an experienced operator was invited to work for two days with the Pictometry technology. He received the explicit tasks to confront the information contents and functionality of Pictometry technology with the work procedures he was used to at TD Kadaster. To arrive at a proper insight in the findings achieved it is therefore feasible to first have a closer look at the present work procedures at TDN Kadaster.

3.2.1 Present Work Procedures at TD Kadaster

Topographic maps are updated by using two information sources: (1) scanned aerial stereo photographs (scale 1:18,000; resolution 36cm; flying height 3km) and (2) on-site observations by the topographer. Each topographer extracts the information from the aerial images and carries out the field work of that same area, which results in the advantage that he feels to be the owner of the project; it is his/her area. The measurements and interpretation is done in stereo-images, which recently changed from black/white to colour, by using photogrammetric workstations of the Finnish firm ESPA. Stereo view is obtained by making use of the polarization method of stereo viewing: the images are shown to the operator making use of a monitor which is able to change images which a frequency of 100 Herz (in Europe) or 120 Herz in other countries such as the US. So, 50 times per second the left image is presented to the left eye and 50 times per second the right image to the right eye. The images are perceived as separate because of the polarization method used and for which special glasses are required. ESPA, which has now become a subsidiary of the US firm Planar, has taken out of production this system, because one of the core-technologies used in the system is not deliverable anymore. For topographic mapping stereo images do have – compared to ortho-images – the advantage to enable mapping of footprints of buildings. Furthermore, stereo enables to enhance interpretation because 3D view is together with colour one of the most important visual clues. The photogrammetric workstation is flanked by a monitor on which a black/white ortho-image of the same area is projected on which the digital topographic map and the features extracted by the operator in the stereo-images are superimposed. This part of the system is used to assign attributes to the features; the ortho-images are black/white in order to recognize easily the superimposed colour coded features. The manipulation of the features present in the digital map is done by using the GIS software package ArcMap, in the past MicroStation was used. When a feature is not sufficiently visible, sometimes use is made of Google Earth to validate the attribute assignment. Since Google Earth is not classified as an official information source validation/conformation is the only role Google Earth may play in the production process. The ortho-image is used as information carrier during the field work. In summary, the geometric information extraction and interpretation is done by using colour stereo-images while attribute assignment is done using black/white ortho images.

3.2.2 Findings

Advantages:

- With 15cm GSD (ground sampling distance) the resolution of pictometry images is more than twice as high as the images used by TD (36cm). The resulting improvement in sharpness provides an advantage during the interpretation process
- Oblique images add value during interpretation of objects because one can look “underneath” objects which improves the quality of attribute assignment (Figures 4, 5)
- The height measuring tool enables to determine the height of objects which improves attribute assignment
- Operating the Pictometry software package (EFS) is easy and intuitive
- Having available the topographic map on screen improves the work process because of the better orientation capability
- Colour information adds value during attribute assignment

Figure 4, This oblique image enables to recognize that the trees are located at the left side of the ditch.

Shortcomings:

Only use is made of non-overlapping ortho images so that the images can not be viewed in stereo mode. The main disadvantages of viewing images in mono-mode include:

- It is very difficult to reconstruct the footprint of buildings; only the edges of roofs are visible. In some practical situations the footprint and “roofprint” are different
- Discontinuities are difficult to recognize when viewing mono-images. To arrive at an impression of height differences one has to look up several oblique images which is time-consuming
- In general one may state that because in mono images the stereo component is not available one has lost an important visual clue.

Absence of the stereo component is, however, not a characteristic of the Pictometry technology itself, but of the standard products as delivered up to September 2006 and defined mainly in the homeland security framework.

Figure 5, Oblique image showing a corridor connecting two buildings, hanging free in space.

Figure 6, Projection of GBKN lines into oblique image.

Disadvantages with respect to functionality:

- No possibility to extract polygons which is very important for topographic map updating
- When switching from the one oblique image to the other during the attribute assignment process, one often has to scroll to get the concerning object in centric screen view; this is time consuming and labour intensive
- The system enables to project the digital topographic map into oblique images. But this is in general not of much use because the correspondence between image and map may be weak as a result of occlusion of the ground area by mainly buildings, which leads to a confusing view (Figure 6)
- Direct mapping of features and their attributes on colour images is not feasible, because attributes are assigned to features in the form of colour codes which are difficult to observe on colour images. Furthermore, black/white images do have a better contrast.

Parts of the above shortcomings in the software functionality may be resolved by plugging EFS into GIS packages such as Geomedia and ArcGIS, for which plug-ins have been developed. Such plugs-in were not used in the present tests.

3.3 Feasibility as an Information Source for GBKN Updating

The GBKN has been developed as an aid to utilities, public work department of municipalities, water boards and so on, to support the managing tasks of the public domain. The GBKN is a registration of terrain discontinuities both with respect to height discontinuities and discontinuities in material coverage. The discontinuities are measured accurately (20cm) as line objects which are coded according to type, e.g. building façade and concrete edge. The database is not intelligent in the sense that the lines themselves do not know that they may form together a building or another object; the line elements together form thus an unstructured data set. The original GBKN has been acquired by photogrammetric techniques accompanied by field surveys for adding terrain elements which were not visible in the aerial photographs. The updating is done by terrestrial surveying. Today's annual rate of change lies between 8% to 10%, resulting from construction works, erecting buildings, and other changes in the real world. The annual expenses for updating are estimated to be Euro 20 Million.

Photogrammetry is not used anymore as an information source. Nevertheless, in the framework of the Basisregistratie Adressen & Gebouwen (BAG) (Basic Registration Addresses and Buildings), which is presently under development and should be operational in 2009, the GBKN may be used as input source to provide the geometry of the outlines of buildings, just as the GBKN is today's source of building information for the Cadastral map and will be for the TOP10 map. In this framework, a pilot is presently carried out (Test Hulst, Zeeland). Using stereo photographs recorded by the photogrammetric firm Aerodata with the digital camera Vexcel (GSD 7,5 and 15cm) and ortho-photographs of TD Kadaster (GSD 36cm), both recorded in 2005, the contour lines as stored in the GBKN are complemented and updated. The actual measurements of an area covering 5 x 5 km^2 are carried out by two firms in India: Infotech and Rolta. Although the test is still on-going one of the insights gained is that identifying features as building can be performed better using stereo-images than using ortho-images. As with the Topographic map also for the GBKN the availability of stereo-images is thus essential.

Another on-going development is changing the data structure of the GBKN from a set of unstructured line-elements to a set of polygons. In this way the line-elements will know from each other that they form together with other line-elements a polygon. In other words the structure is changed from line-oriented towards area-oriented. Since, the line-elements will keep their original codes this conversion process can be carried out largely automatically. Tests have shown that about 95% of the conversion can be done automatically. Users will be able to add manually object codes to the polygons.

In the GBKN context, Pictometry technology could be used for:

- Checking, editing and completion of the automated created polygons in the process to enhance the GBKN from a line-oriented data base to an area-oriented database. This

can be done manually by superimposing the GBKN on the ortho-images, while keeping the oblique images at hand in the form of thumbnails as an additional interpretation aid
- As source to add manually object codes to the polygons
- As an additional information for the surveyor while being in the terrain for retrieving the location of pipelines, sewerages, telephone line and other utilities. Using the ortho images as a backdrop, the GBKN and the utility map can be superimposed on the images. Since the different data sets can be merged with high accuracy, measures can be derived such as the distance from a road edge visible on the ortho image and an utility line element visible in the map.

3.4 Cadastral Use

When a party buys a part of an existing cadastral parcel, the parcel has to be split into two entities and the boundary between these entities measured. How can Pictometry technology support this process? After signing the transaction act at the notary, the splitting of parcels is usually down in two stages. First the buyer and seller carry out a boundary addressing (aanwijzing) in the presence of a cadastral land surveyor. Next the surveyor measures the boundary in the terrain. Sometimes both actions are carried out simultaneously; immediately after boundary addressing the surveyor measures the boundary. But sometimes there is a (large) time delay between both. Boundary addressing is usually not carried out immediately after signing of the transaction act, there is a time delay which may appear too long for some parties. Therefore, these parties carry out boundary splitting prior to going to the notary. In 2006 the cadastre processed 85,000 transaction acts in which a part of a parcel was delivered to a buyer, thus requiring parcel splitting; 25,000 of these were split prior to establishing the notary act; that means about 30% of splitting is subject to prior land surveying of the boundary.

The measurement and registration of cadastral boundaries serves two tasks. The first one is to enable splitting so that new parcels can be created and registered in the archives of Kadaster. Not only the measurement values are stored but the new boundary is also drawn on the cadastral map which serves as an index entry to the registers. The second task of the measurements is that the boundaries between properties can be reconstructed with sufficient accuracy. Sufficient often means in practice at the centimetre level. Given the accuracy level determined within the accuracy tests described above, Pictometry technology will be unable to serve that aim.

Although Pictometry technology is not suited for replacing terrestrial measurements of the Kadaster, it may serve as aid in splitting parcels and parcel formation by preliminary boundary determination. The reason for prior splitting is usually not to arrive at an accurate boundary description, but to establish the new parcels immediately after passing the notary act. So, the time delay between passing of the transaction act and parcel formation is crucial because it is often undesirable. Furthermore, the separation of boundary addressing and actual boundary measurement is experienced by many as annoying. Given the above practices it would be beneficial when a system would be at hand which enables to carry out boundary addressing and subsequent parcel formation directly at the notary during and as an integral part of the transaction ceremony. The tests we conducted demonstrate that such a procedure could be based on using pictometry technology (Figure 7).

Figure 7, Identification of preliminary boundaries (red and yellow) in Pictometry ortho-image.

The procedure could consist of the following steps:

- The notary sends a request to the cadastre for the required geo-information and is next enabled to download over the internet the concerning cadastral map and corresponding pictometry images (ortho/stereo + oblique)

- The images and map are loaded into the software system on the notary's PC where the cadastral map is superimposed on the ortho-image, while the oblique images are at hand as thumbnails to support better identification
- In consultation with the buying and selling party the notary identifies the new boundary
- Using ortho-images and possibly oblique images the new boundary is drawn making use of mapping tools available within the software. To enable the notary to carry out the preliminary boundary addressing smoothly, more sophisticated drawing tools have to be developed or adopted from GIS software. The resulting measures will not be sufficient for boundary reconstruction purposes, but accurate enough for parcel formation and cadastral map updating
- The data is returned to Kadaster possibly as an attachment to the transaction act
- At Kadaster, an officer checks and, if appropriate, approves the mutation and assigns numbers to the new parcels
- The information is archived in the registers of Kadaster: the preliminary boundary is stored and new parcel numbers attached to the such created parcels.

The accurate boundary measurement can next be carried out at a time which is convenient for the cadastral land surveyor.

Figure 8, Identification of preliminary boundaries (blue) in oblique image. Existing cadastral boundaries are shown in red.

3.5 Non-overlapping Images

The images used in the test set are acquired as a standard product defined by the mother company in the US, where the requirements have been derived from mapping purposes in the framework of US homeland security: neighbourhood images are taken for areas which might be potentially subject to attacks while community images are taken for the relatively save areas. The present standard aerial surveying method does not include capturing of overlapping images to enable stereo-viewing. However, Blom has recorded stereo images since October 2006 and will continue to carry out all Pictometry surveys with 60% overlap. So, in the future in addition to the present capabilities stereo viewing will become available, which would make the technology potentially suited for topographic mapping and as information source for capturing the geometric part of building registration.

4. Cost Considerations

4.1 Introduction

The presented cost considerations are of a general nature, because the present research is not intended to incorporate Pictometry technology as a replacement in an existing production process. We will focus on the registration, management and releasing title information and geo-information tasks of Kadaster, in particular Cadastral map, updating of the Topographic map and GBKN.

Suppose for comparison purposes that the whole of the Netherlands will be flown once in every two years, which is presently the standard schedule for updating TOP10 by TD Kadaster and that the standard list price has to be paid to acquire the images: 250 euro per square kilometre per annum. The land area of the Netherlands is around 35,000 square kilometres. So, the entire territory of the Netherlands can be captured for a cost of Euro 8.75 million per annum. When we restrict cost calculations to the major cities (50,000+ inhabitants), which is the present standard schedule, just 4,300 square kilometres have to be captured resulting in a total investment of around Euro 1 Million per annum.

The Topographic Survey out-sources the aerial surveys necessary to capture the entire territory of the Netherlands by photographs for Topographic Map updating. The costs are around Euro one million for capturing the whole territory of the Netherlands at a resolution which is, more than two times less than Pictometry images (36cm versus 15cm), while the flying height is three times less (3km versus 1km). For that amount the Topographic survey receives stereo film images (black/white or colour) at scale 1:18,000 which are scanned with a GSD of 36cm. In recent contracts the images may also be acquired directly in digital format in colour with a GSD of 27cm. The revisit cycle now is still four years but will become soon two years; the planned year of introducing the bi-annual production cycle was 2006. The images are geo-referenced within the production cycle of TD Kadaster by carrying out an aero-triangulation and in-house the ortho-images are generated using a proprietary Digital Elevation Model.

4.2 Cadastre

Here we will focus on Pictometry technology as a (partial) replacement of the boundary addressing procedure (determination of preliminary boundaries), involving land surveyor, buyer and seller, as discussed earlier. In 2006 the cadastre processed 87,000 transaction acts in which a parcel was partially delivered to a buyer; 27,000 of these were split prior to establishing the notary act, remaining 60,000 to be addressed and surveyed in the terrain after passing of the transaction act. Suppose that boundary addressing (aanwijzing) could be carried out in 50% of the occasions at the notary office using Pictometry technology, which results in an annual boundary addressing totalling 60,0000 x 0,5 = 30,000 boundaries. Let us suppose furthermore that addressing and surveying of 50% of these 30,000 boundaries is presently done in separate actions; first addressing (preliminary boundary determination) and next (weeks or months later) surveying. That means that 30,000 x 0,5 = 15,000 addressings in the terrain could be eliminated by using Pictometry Technology in the notary office. Assuming that one surveyor can address 7 boundaries on average on a daily basis, 2,000 man days could be saved, leading to a saving of approximately Euro 500,000 on a yearly basis, in case of a one-man survey team and Euro 1 million in case of a two-man survey team. In addition, the total number of prior splitting could be reduced because a mean reason for prior splitting is that the new parcels resulting from the splitting are created during transaction. Another, but difficult to assess issue is that preliminary boundary addressing at the notary office using pictometry images may create goodwill among the general public, awareness of the importance of geo-information, and people may recognize the technology because of Google Earth and Microsoft’s Virtual Earth. This would fit within the aim of the Cadastre to become authoritative in Europe.

4.3 Topographic Map Production

The better visibility and interpretability of objects in oblique images and because of the higher resolution of 15cm may result in a reduction of fieldwork as discussed earlier, provided that stereo images are available. Suppose that this reduction will be 20%. At the other hand the consultation of oblique images in the office may slow down the manual processing pace, say with 10%. Remaining advantage will be 10%; with 35 topographers this will result in a benefit of 3.5 man days, or, expressed in money 3.5 x 50,000 Euro = Euro 175,000.

4.4 GBKN

No aerial images are presently used in the updating process of the GBKN. The present costs for updating the GBKN by terrestrial means are Euro 20 Million per annum. Pictometry technology seems to be an aid because the product specifications require that footprints are mapped and not the roof print and the oblique image enables to look and measure underneath objects, although the achievable accuracy in oblique images is just at submetre level. The benefits of Pictometry technology for GBKN should however be viewed in the framework of the BAG, where one needs roof prints of buildings. After finalization of Test Hulst, more can be said about the benefits of photogrammetry in general for GBKN purposes, and deduced from that the benefits of Pictometry technology more particularly. However, the registration of buildings for the whole territory of the Netherlands will be required in the framework of Basic Registration. Since the standard Pictometry library of the Netherlands covers approximately 80% of the buildings, Pictometry would be a suited source of information. A building database is also one of the essential prerequisites for creating 3D city models.

5. Business Models

In view of the ambition of Kadaster to be the principal supplier of real estate and geo-information within the Netherlands it is appropriate to discuss business models (BM) to enable use of Pictometry products at diverse organisational levels within the Netherlands with Kadaster in a pivotal position. Such a discussion is relevant also in view of the fact that to date, major topographic surveys within Europe, more particularly Ordance Survey in the UK and IGN in France, have signed agreements with Blom group as non-exclusive reseller of Pictometry technology of the major cities within their territory. Within the context of this project, several possible BMs have been discussed with Blom Group. Below follows an indicative sketch of the possibilities.

A first BM would be that Kadaster subscribes for internal purposes to the standard Pictometry library of images of the Netherlands, scheduled to capture a total area of 4300km^2 of which presently around 3600km^2 have been captured and around 700km^2 are in the process of capturing. The area covers around 15% of the territory of the Netherlands and approximately 80% of the population and 80% of the buildings. In this BM, the Pictometry images and EFS can be used for enforcing the internal work processes, such as updating of the national topographic database TOP10 and derived products. A business model like this is at present not cost-effective as we have seen in the cost considerations section; Pictometry technology reduces the costs of present work process within Kadaster, but the gain is less than the expenses of licensing Pictometry technology on a yearly basis.

A second possible BM is that the internal application areas as described under BM 1 are extended to use as source for creating preliminary boundaries at notary offices while a transaction act is being passed. A third BM would be that Kadaster becomes provider of Pictometry products for all governmental institutions at state level, including all ministries and their executive institutions such as Rijkswaterstaat. All users would have a plug-in to the images located at a central server located at Kadaster while being able to use EFS possibly linked with the in-house available GIS software package. Help desk support and training would be given by Kadaster, backed by a hot line with Blom. A fourth BM would be to extend the state level users base of BM 3 with users at 50,000+ municipalities.

A fifth and last scenario would be that Kadaster becomes a reseller of the Pictometry products, and would earn a fee of, for example, 25% for every Pictometry product sold. Compared to the first four scenarios, which basically all involve only the public sector, this

BM would also involve establishing relationships with the private sector. This scenario would thus make Kadaster a commercial market party within the Pictometry scene, as Ordance Survey in the UK and IGN in France. It should be mentioned here that also other organisations within the Netherlands are willing to become reseller.

All the above scenarios and their financial consequences have been discussed with Blom group. Indicative costs of the diverse scenarios range from Euro 2 million to Euro 7 million annually.

6. Future Needs of Kadaster

The present section mainly reflects information gathered during carrying out interviews with key persons within Kadaster. Information is also gathered from Kadaster and GBKN reports. Presently, Kadaster is going through an intensive organisation development process in order to stream work processes and to reduce costs. Recently, Topographic Survey of the Netherlands, based in Emmen, has been merged with Kadaster, and is now called TD Kadaster. With respect to its task in the field of registration, management and releasing title information and geo-information Kadaster wants to arrive at further cost reduction and diminishing of production time span by increasing the automation of the registration process and the efficiency of execution of all land surveying processing involved in the splitting of parcels, in which presently around 700 cadastral employees are involved. The office processing of new boundaries was carried out by using the software package FinGIS which is now replaced by Intergraph’s Geomedia.

Kadaster also wants to evolve towards three-dimensional registration of parcels objects, in which both planar and height is recorded. In addition, Kadaster aims at increasing its role in the basis registration, amongst others by acting as the pivotal point for accessing the various basis registrations in co-operation with the owners of the registers. In 2006 Kadaster supplied 30.5 Million information provisions to citizens, charged with € 1.40 per delivery when delivered via internet. By extending its on-line services and centralizing the access over one portal Kadaster wants to improve and increase its service level to citizens. With respect to TOP10 and derived products, Kadaster wants to arrive at one, integrated basic data base, which is scale-less and subject of permanent updating. The updating cycle of four years is scheduled for being replaced by a bi-annual cycle. The scheduled introduction in 2006 is somewhat delayed.

The content of the TOP10 has been prescribed around 150 years, from 1812 onwards, by demands from the military who were also the sole financers. To date the military share for 50% the costs with eight other major clients, including the Ministry of Public Works and Water Management, Water Boards, Provinces, Municipalities and Utilities. Originally all clients were governmental organisations which organisations contribute for the other 50%. This situation has changed as a result of the privatization process. Today the military see themselves as just one out of the nine major clients and want to share costs accordingly. On-going and new developments with respect to the topographic data base include:

- Inclusion of the GBKN buildings into TOP10 starting in 2008. (The accuracy of the buildings on the TOP10 is low as a result of the mapping process. As mentioned earlier, also the cadastral map includes GBKN buildings)
- Addition of street names
- Augmenting the four yearly updating cycle to a two yearly
- Study on the readjustment of the TOP10 contents
- Further integration of TOP10 and GBKN
- (semi-) automatic generation
- Upgrading of TOP10 vector to TOP10NL, which will be part of the basis registration of the Netherlands
- TOP10 is 3D prepared, that means for buildings the height component is an attribute in the database.

It should be mentioned, that one key person within Kadaster acknowledged, when being interviewed, the many possibilities offered by Pictometry and its technological advancements, but doubt whether distribution of Pictometry products to the larger geo-information community of the Netherlands should be part of the future tasks of Kadaster.

7. Discussion

As mentioned in the beginning of the report, this study mainly focuses on arriving at insight in the possibilities of Pictometry technology as an aid to support the tasks and the ambitions of Kadaster. Therefore, the perspectives on the future are presented here, which may be weakly underpinned by the present research results but which emerged as ideas during the course of the research. Possible applications of Pictometry technology in general include:

- Homeland Security
- Urban Planning
- Detection of illegal buildings
- Support to fire departments
- Disaster Management
- Fly-Around simulations, 3D City Models
- *“Our limit is your imagination.”*

Strong strategic points of Pictometry technology are:

- In addition to ortho-rectified vertical images and since October 2006 overlapping images, enabling stereo-view, geo-referenced oblique images are provided which enable better and intuitive interpretation. Furthermore, accurate measurements can be performed, which can be carried out by non-photogrammetrists
- Growth market: all 50,000+ cities in the Netherlands will be available and revisited bi-annually, cadastre Spain is using Pictometry technology and Ordnance Survey UK and IGN are providing Pictometry products to their home market. Microsoft includes the oblique imagery as bird eyes view to their maps and satellite images on local.live.com, used by the millions, in 2006 Pictometry Map Middle East has been established (introduced at Map Middle East), etc.
- Geo-information infrastructure: Pictometry technology could serve as a catalyser for the Geo-information Infrastructure in the Netherlands: it has a wide range of applications, the images are geo-referenced, it’s intuitive interface and high location accuracy enables its use as a navigation tool by laymen providing access to a variety of (geo-) information databases, e.g. building and address register, WOZ data base, and cadastral database. Combined with a building database and Lidar data it has the potential to create realistic 3D City Models fast and for reasonable prices, and can be used as an ‘add on’ to the topographic map
- Survey tool. Pictometry technology is presented by the US mother company as a visualisation tool, not as a surveying tool. Our accuracy tests demonstrate that an

accuracy level at photogrammetric surveying requirements can be achieved with just a few additions

- Pricing of high-resolution, colour standard products: € 250/km^2/annum
- Plug ins of EFS software to various GIS software packages are available, extending the functionality of EFS with the wide range of GIS functionality of ArcGIS, GeoMedia(Pro), MapInfo, Cadcorp and in the near future also Bentley Systems and Autodesk software. ArcGIS is presently used by TD Kadaster and GeoMedia by the surveying department of Kadaster.

Strategic week points are:

- Stereo images: the overlap between vertical images of the present standard product is not sufficient to allow stereo-viewing, which is a prerequisite for updating topographic maps. However, as said, Blom has already recognized the non-stereo viewing capacity of Pictometry products as a weak point and has started surveys (since October 2006) with the necessary along track overlap of 60%.
- The costs of on-going cadastral and established topographic mapping work processes can be reduced by Pictometry technology, but in the short term the gain is less than the expenses

Pictometry technology has the potential to grow out to a technology that could be beneficially used for many geo-information applications in the Netherlands. Diverse, mainly governmental or government supported parties in the Netherlands contract out aerial surveys for their own purposes. As a result, duplications of aerial surveyes are unavoidable and this does not fit well in a proper implementation of a National Geo-Information Infrastructure (NGII). Since standard Pictometry technology provides a bi-annual revisiting cycle, the technology has the potential to become a basic information source for many governmental and non-governmental organisations. As said Pictometry technology may even be approached as an engine and catalyser for co-ordinating the use of geo-information in the Netherlands and support in this way not only the establishment of a proper NGII but also the ambition of Kadaster to be the principal supplier of real estate and geo-information within the Netherlands.

Furthermore, it is interesting to observe that Ordnance Survey has partnered with Simmons Aerofilms Ltd – a subsidiary of Blom Group – to become the sole resellers of Pictometry data for the UK. The Ordnance Survey provides Pictometry technology as a product supporting access to other products in an extended way: “Our OS MasterMap imagery product is a more 2-dimensional vertical view; however, this limits the user’s view of images to roof and treetops. There is no concept of how many floors a building may have, what it looks like from the ground etc.” Furthermore, in April 2007 it has been announced that IGN, the French mapping and cartographic public body, has entered a distribution agreement with Blom (Norway) for distribution of the Pictometry dataset in the French market. A complementary partner in France is Infoterra.

A combination of building footprints or roofprints, detailed digital surface models from Lidar surveys, Cyclomedia images and Pictometry imagery could provide exciting new products – virtual worlds – for affordable prices.

8. Conclusions & Recommendations

8.1 Conclusions

Pictometry technology is a very promising technology when viewed from the broader perspective of the ambitions of Kadaster. The costs of Pictometry technology for covering the urban areas in the Netherlands (50,000+ inhabitants) is Euro 1Million on an annual basis. As a result Pictometry technology can be beneficially and cost-effectively applied when it serves several (future) tasks of Kadaster and in a broader perspective the geo-information needs of the whole of the Netherlands. More importantly, Pictometry technology might serve as an engine and catalyser to fulfil the ambitions of Kadaster to become the principal supplier of real estate and geo-information within the Netherlands. The opportunities offered by this emerging technology should be particularly valued from that perspective.

8.2 Recommendations (Pilot Studies)

A better understanding of all possibilities and opportunities of Pictometry technology in the context of the present and future tasks of Kadaster, requires further study. From the list of many applications in which Pictometry technology could be applied successfully, the Board of Kadaster has selected the following three pilot studies:

1. Identifying preliminary boundaries via notary
2. Building registration
3. Communication citizens and government

These applications have been chosen because they are new or rather new for Kadaster, while they fit within the ambitions of Kadaster and have a high degree of actuality.

8.2.1 Pilot 1

The anticipated results of the first pilot study are: (1) better spatial orientation for all involved parties during transaction, including buyer, seller and notary, (2) in many cases – say 50% - no identification in the field will be required anymore, releasing buyer, seller and surveyor, (3) the splitting and creation of the new parcels can be realized immediately after passing of the act, (4), the cadastral map and graphical indication of the new boundary superimposed on the Pictometry image forms a new template for the surveyor, which can be used prior to and during measurement in the terrain, and (5) an overview of cost savings to be gained. The prerequisites for carrying out this pilot are: (1) one notary office willing to participate, (2) selection of an appropriate sample of deeds, (3) Pictometry images of the concerning sites,

(4) EFS processing software, (5) PC and (6) Human Resources (HR). The costs involved are estimated at € 20.000.

8.2.2 Pilot 2

The anticipated results of the second pilot – building registration – include: (1) understanding of the information required in the building register, (2) insight in which of the required information can be extracted from Pictometry technology, (3) development of a prototype to use Pictometry technology as a navigation tool to access other (geo-spatial) databases, (4) definition of the concerning work processes and (5) an overview of the costs involved. The prerequisites for carrying out this pilot are: (1) stereo Pictometry images of a representative part of a Dutch city, (2) Digital Photogrammetric Workstation as available at TD Kadaster, (3) PC, (4) EFS software, (5) plug in to Geomedia or ESRI software, (6) HR from Kadaster, (7) BAG designers and (8) building register data possibly completed with GBKN data. The costs involved are estimated at € 35.000.

8.2.3 Pilot 3

The anticipated results of the third pilot – Pictometry technology as an aid in the communication citizens and government – include: (1) easier access to data, such as BAG and WOZ data, over the internet, (2) level of appreciation by customers, (3) overview of potential products to be delivered over the internet and applications. The prerequisites for carrying out this pilot are: (1) building an extension (prototype) to Kadaster On Line (KoL), (2) Pictometry images of an appropriate site, (3) HR, (4) PC + software, (5) cadastral data, (6) design of an evaluation test to determine level of appreciation and (7) customers (citizens) who are willing to participate in the test. The costs involved are estimated at € 50.000.

Appendix

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GEOMETRY AND INFORMATION CONTENTS OF LARGE SIZE DIGITAL FRAME CAMERAS

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KEY WORDS: digital aerial cameras, geometry, information contents, self calibration, model deformation

ABSTRACT:

Large size digital aerial frame cameras like Intergraph DMC and Vexcel UltraCam are becoming standard for photogrammetric application. It is difficult to compare the information contents of such cameras with this of analogue photographic cameras. Also the rules for project planning have to be checked if the old relation between photo scale and map scale is still valid. The photo scale has no longer any meaning for flight planning because it is depending upon the pixel size in the camera; the important figure is the ground sampling distance (GSD). The image quality of digital cameras usually is quite better like the image quality of scanned photos, disturbed by photo grain. The comparison of digital images taken with different GSD and scanned analogue photos are leading to the result, that digital images have the same information contents like analogue photos scanned with 20µm pixel size having a GSD smaller by the factor of approximately 1.5. That means 15cm GSD from a digital camera is corresponding to 10cm GSD from analogue cameras scanned with 20µm pixel size. So the information contents of a DMC- and also an UltraCamD-image exceeds the information contents of an analogue aerial photo.

Block adjustments with digital camera images are resulting in sigma0 values of 0.15 up to 0.3 pixels. This high accuracy potential cannot be reached by analogue photos. But it has been shown, that self calibration by additional parameters is still required also for original digital images. Because of the small field of view, the systematic image errors are causing not negligible model deformation. If the systematic image errors can be used in the processing chain, the full accuracy potential of the digital cameras can be used. A program for geometric improvement of the images by the systematic image errors and a program for the improvement of height models by the model deformation have been developed in the Leibniz University Hannover.

1. INTRODUCTION

Large size digital frame cameras are becoming standard for mapping purposes; this also can be seen at the fact that the large size digital cameras in USA are booked during the main flight season and no free capacity is available. The better image quality, high accuracy and the not required scanning of analogue photos supports the change to digital cameras. Because of the better signal to noise relation, CCD- and not CMOS-sensors are used. It is not so simple to compare the information contents of a standard analogue photogrammetric photo with a digital image. In the frame of a diploma thesis, intensive tests of mapping with analogue photos and digital images with different image scales and different ground sampling distance (GSD) have been made in the same area (Oswald 2006). The result was quite clear – the same information contents, that means the identification of details, has been achieved in original digital images having approximately 1.5 times larger GSD than analogue photos scanned with 20µm pixel size, so analogue photos with a side length of 230mm have comparable information contents like digital images, having 7700 x 7700 pixels. This is still less than expected few years ago, but CCD-arrays with such a dimension are not available for affordable price, fast read-out time and suitable image quality. By this reason the Intergraph DMC and the Vexcel UltraCam are based on a combination of smaller CCD-arrays which have to be merged to a virtual image. Another alternative solution is the use of CCD-line cameras like the Leica ADS-40, but with the disadvantage of scene accuracy dependency from the direct sensor orientation, based on relative kinematic GPS-positioning and inertial measurement units (IMU). Under operational conditions the direct sensor orientation is limited to a standard deviation of approximately 15cm. The handling of CCD-line scanner images also requires special software for the photogrammetric workstation. For mapping purposes usually CCD-array cameras are preferred, while for large size ortho images the CCD-line scanner is used more often.

2. INTERGRAPH DMC

The Intergraph DMC is based on 4 convergent arranged sub-cameras (Doerstel et al 2002) (figure 1). This has the advantage of a small field of view for the sub-cameras, optimal for imaging quality. The sub-images are individually merged by tie points in the overlapping area and transformed to a homogenous virtual image. This transformation respects the calibration of the sub-cameras including the lens distortion, so by simple theory the virtual image should be free of any systematic error. But in reality the flight conditions may change the geometry of the sub-cameras even if they are more solid like usual analogue aerial cameras.

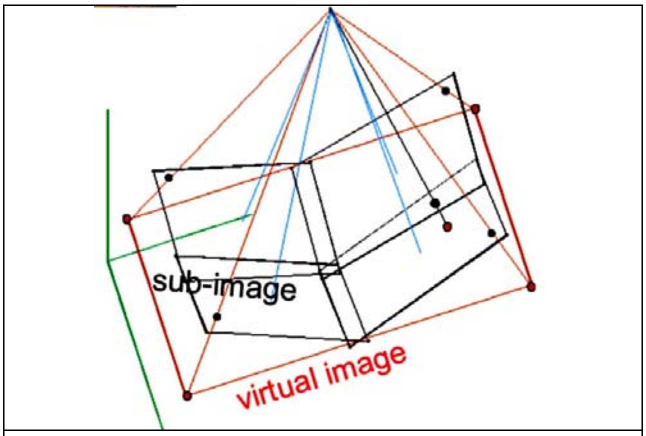


Figure 1: relation of DMC sub-images to homogenous virtual image

3. DMC-BLOCK GHENT

The block Ghent has been flown by Hansa Luftbild, Muenster, Germany over the city of Ghent, Belgium. The block has 80% end lap and 60% side lap; it has been flown in a height level of 796m. Together with the average ground height of 12m the photo scale 1 : 6440 exists, corresponding to 77mm ground sampling distance (GSD). Two crossing flight lines are stabilizing the block, allowing a reduction of the number of control points.

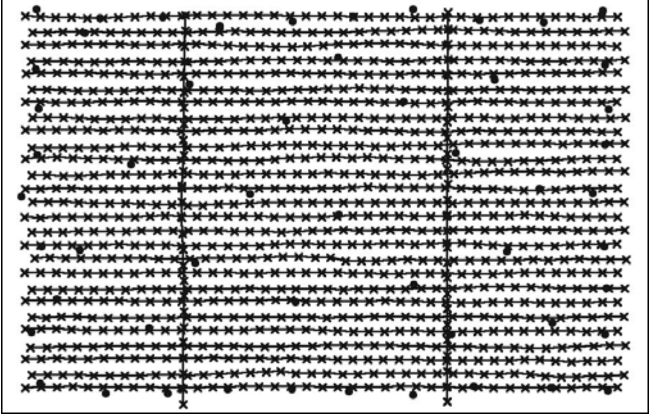


Figure 1: block Ghent 80% end lap, 60% side lap, 77mm GSD 1105 photos, 11899 object points, 102132 image points, up to 21 images/object point

From the original 53 control points, 23 are not used for the block adjustment, instead of this they are used as independent check points. Only with independent check points correct information about the reached object point accuracy can be computed. The inner accuracy of the block adjustment usually is to optimistic and does not respect systematic errors.

A bundle block adjustment without self-calibration leads to not optimal results for the point height. Such effect in a block with not dense control usually is caused by "systematic image errors" – or more precise, the image geometry does not agree with the mathematical model of perspective images. An analysis of the bundle block adjustment residuals – the remaining discrepancies of the image coordinates – indicates systematic image errors. The residuals of all observations are overlaid corresponding to the image coordinates and averaged in small sub-areas to reduce the random image errors. Such averaged residuals only indicate the systematic image errors because parts of the systematic errors are compensated by the adjustment.

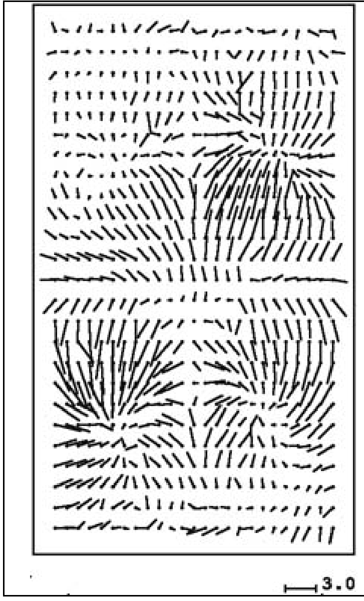


Figure 2: averaged image residuals of bundle block adjustment without self-calibration

root mean square (RMS) values for x and y:
0.8µm / 1.2µm

The averaged residuals (figure 2) indicate systematic errors of the virtual images caused by geometric problems of the sub-images.

4. BLOCK ADJUSTMENT WITH SELF-CALIBRATION

The bundle block adjustment has been made with the Hannover program system BLUH. BLUH handles the self calibration of standard aerial images with 12 additional parameters (Baz et al 2007). For handling the special DMC geometry, special additional parameters have been introduced. The parameter 29 can determine eccentricity errors caused by a not correct introduction of the flying height to the merge of the 4 sub-images (Doerstel et al 2002). This parameter was not significant for all handled data sets, showing that no problem with eccentricity errors exist. The additional parameters 30-33 can determine synchronization errors of the sub-images, the parameters 34 – 41 can determine perspective errors of the sub-images and parameters 74 – 77 can determine radial symmetric errors (r^3) of the sub-images. Under the condition that all 4 sub-cameras are influenced by the same change of the focal length, parameter 78 can compensate the influence of a changed field of view to the virtual image (figure 3a). Also under the condition that all sub-images are influenced by the same radial symmetric error (r^3), parameter 80 can compensate this (figure 3b).

Bundle block adjustments of block Ghent with the following combination of additional parameters have been made:

	additional parameters	
1	0	no self-calibration
2	1- 12	standard parameters of BLUH
3	30-41, 74-77	special DMC-parameters
4	1-12, 30-41, 74-77	standard parameters of BLUH + special DMC-parameters
5	78, 80	common change of all sub-images by field of view + r^3
6	1-12, 79, 80	standard parameters of BLUH + common change of all sub-images

Table 1: used parameter combinations

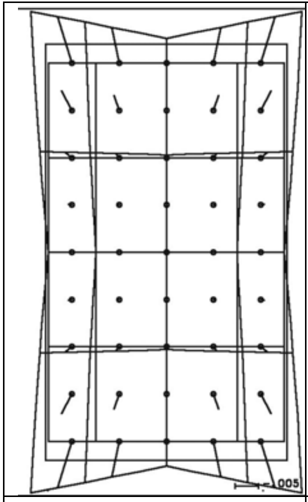


Figure 3a: effect of additional parameter 78

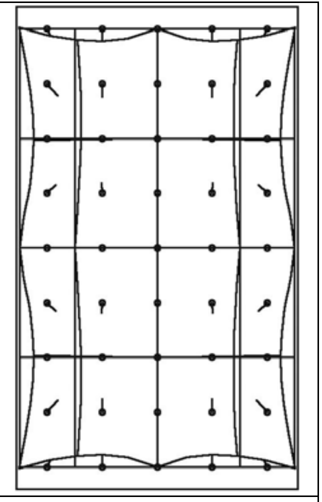


Figure 3b: effect of additional parameter 80

Program BLUH checks the additional parameters for significance, individual and total correlation and removes the not usable parameters automatically from the adjustment. So the final iteration of the bundle block adjustment will be made with a reduced set of additional parameters, guaranteeing the use of only the parameters which can be determined and which are not too strong correlated to each other.

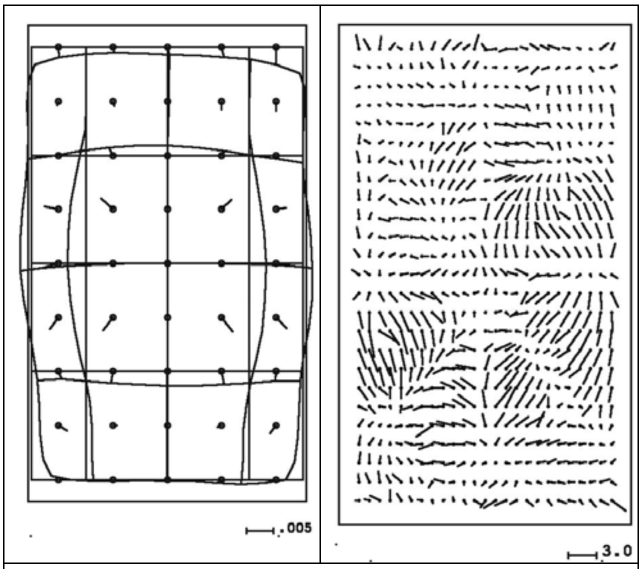


Figure 4: systematic image errors of block adjustment with parameters 1-12 (left) and corresponding averaged residuals (right)

root mean square error (RMS) of residuals: 0.6μm / 0.8μm

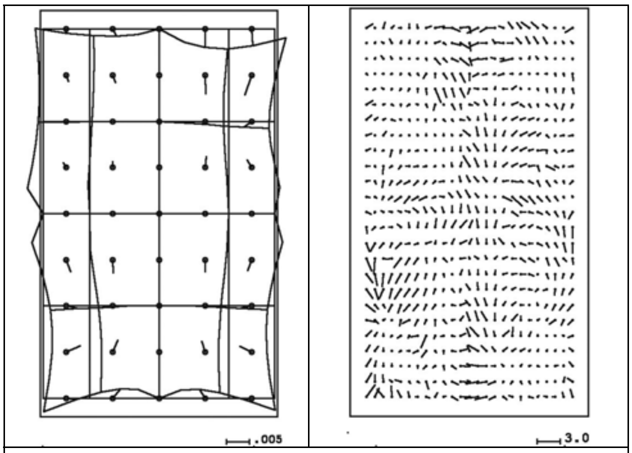


Figure 5: systematic image errors of block adjustment with parameters 30-41 + 74-77 (left) and corresponding averaged residuals (right) RMS of residuals: 0.4μm / 0.5μm

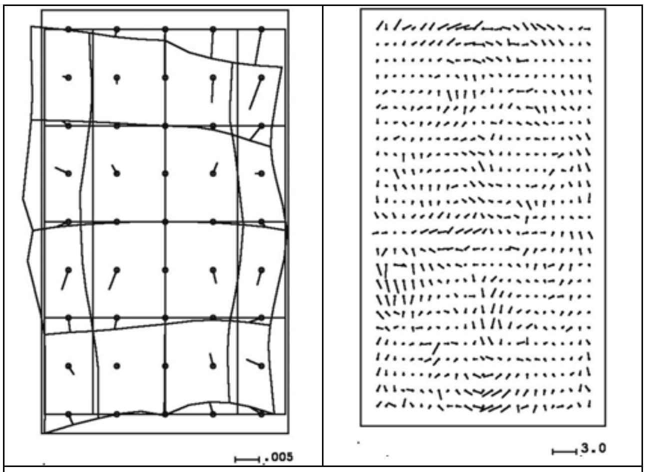


Figure 6: systematic image errors of block adjustment with parameters 1-12 + 30-41 + 74-77 (left) and corresponding averaged residuals (right) RMS of residuals: 0.3μm / 0.4μm

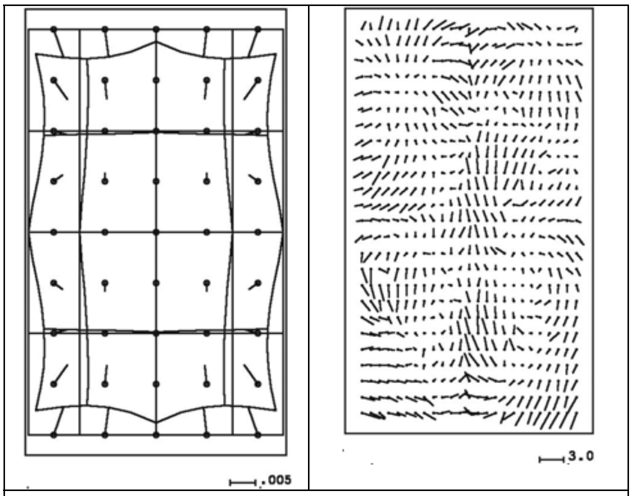


Figure 7: systematic image errors of block adjustment with parameters 78 + 80 (left) and corresponding averaged residuals (right) RMS of residuals: 0.5μm / 0.8μm

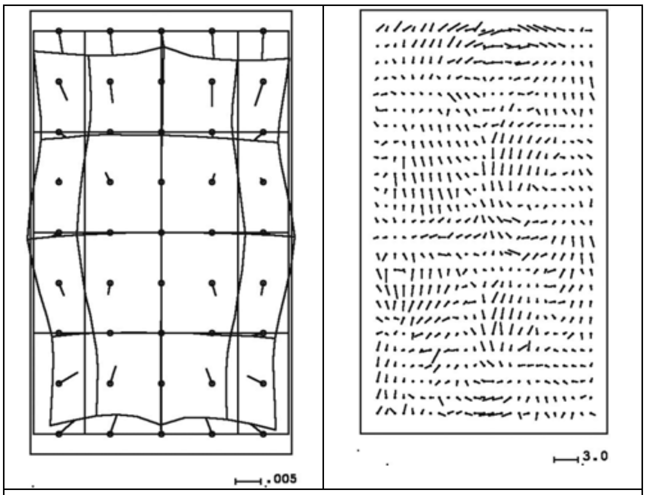


Figure 8: systematic image errors of block adjustment with parameters 1-12 + 78 + 80 (left) and corresponding averaged residuals (right) RMS of residuals: 0.4µm / 0.6µm

It may happen that the systematic image errors are changing within the block. By this reason, the block has been divided into 2 equal parts and the block adjustment has been made for the whole block, but handling the images as taken by different cameras. The systematic image errors of both parts are nearly identical with root mean square differences of the systematic image errors in the range of 0.5µm up to 1µm – this is within the accuracy range under the condition of the correlation to the exterior orientation.

The averaged residuals of the adjustment without self calibration have root mean square values for x and y with 0.8 and 1.2µm. By self calibration with the parameter configuration 1-12, 30-41, 74-77 (configuration 4, table 1) it is reduced to 0.3 and 0.4µm, the other results are within between. But also with configuration 4 small remaining systematic errors exist – neighboured vectors are correlated by r=0.26 for x and r=0.31 for y. At a distance of 15mm in the image the vectors are not more correlated. Without self-calibration, neighboured vectors are correlated by r=0.4 and the correlation goes to 0.0 for a distance of 27mm within the image.

case	control points [cm]		sigma0 [µm]	check points [cm]	
	SXY	SZ		SXY	SZ
0	2.7	9.3	2.08	2.7	15.5
1-12	2.6	2.6	1.75	2.5	5.9
30-41,74-77	2.6	2.6	1.65	2.7	6.1
1-12 + 30-41,74-77	2.5	2.2	1.59	2.5	5.8
78+80	2.6	3.4	1.75	2.7	7.0
1-12 +78 +80	2.5	2.6	1.63	2.5	5.8

Table 2: results of bundle block adjustments DMC-block Ghent

The best results have been achieved with the combination of the general additional parameters (1-12) and special DMC-parameters. It is interesting, that the same accuracy at the independent check points has been reached with the combination of the general parameters with just the 2 additional parameters 78 and 80 like with the individual DMC-parameters. So the same accuracy has been reached with finally 12 parameters in the last iteration like with 24 parameters. That means there is a tendency that there is a simultaneous change of the optics under flight conditions. Intergraph is investigating this and likes to generate improved camera calibrations so that the major influence of the systematic image errors is removed from the virtual images.

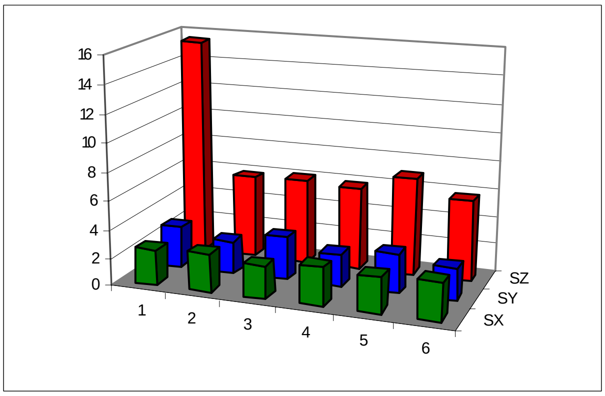


Figure 9: root mean square discrepancies at independent check points – block Ghent, case 1-6 see table 1 and 2

5. DMC-BLOCK RUBI

Also the block Rubi of the Cartographic Institute of Catalonia (ICC), Spain, has been analyzed in detail. The block with 426 photos having 80% end lap, approximately 40% side lap and 3 crossing flight lines, 7763 object and 45464 image points, has been matched with the Intergraph software. The image scale 1:8180 leads with the pixel size of 12µm in the image to 9.8cm GSD. 17 control points with distances up to 12 base lengths, in relation to 60% end lap, are used and 21 independent check points. The control and check points are announced with a standard deviation of 2cm for X and Y and 4cm for Z.

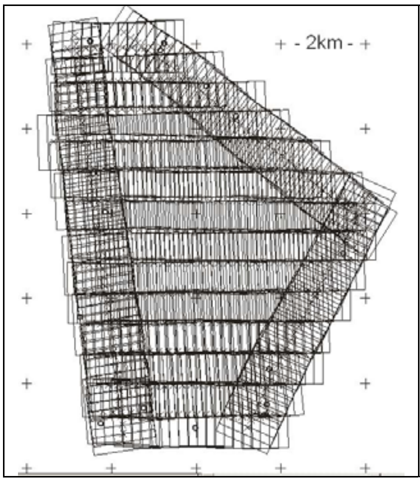


Figure 10: block Rubi
80% end lap, 40% side lap, 98mm GSD
426 photos, 7763 object points, 45464 image points, up to 15 images/object point

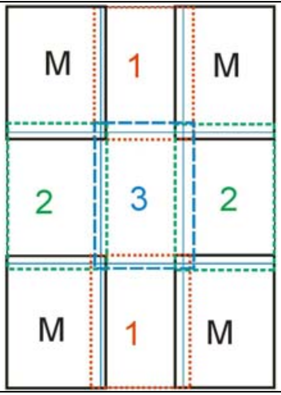
parameters	sigma0	RMSX	RMSY	RMSZ
0	1.87	3.2	2.6	40.3
1-12	1.80	2.1	2.3	6.9
30-41,74-77	1.76	2.5	2.9	7.4
1-12,30-41,74-77	1.73	2.2	2.6	6.9
78 + 80	1.79	2.8	3.3	11.3
1-12 + 78 + 80	1.74	2.2	2.7	6.4

Table 3: results at independent check points, DMC-block Rubi

The results of the DMC-block Rubi are similar to the block Ghent. The sigma0-value – the accuracy of the image coordinates - is in the same range and also the tendency of the dependency upon the additional parameters agrees. But in this case the combination of the general additional parameters (1-12) together with the special DMC-parameters 78 and 80 with the common change of the sub-images are leading to the optimal results. Also some other blocks show the same tendency.

6. VEXCEL ULTRACAMD

For the panchromatic band the Vexcel UltraCamD has 4 separate cameras parallel to each other with 1 up to 4 smaller CCD-arrays (figure 11). The master image includes 4 CCD arrays located in the corners, 1 camera includes the left centre and right centre CCDs, one the upper centre and lower centre and the last camera has just the centre CCD. By means of the overlapping parts, the sub-images of 3 cameras are transformed to the master image with the 4 corner CCDs (Leberl et al 2002).



M = master image
(4 CCD-arrays)
1 = configuration 1
(2 CCD-arrays)
2 = configuration 2
(2 CCD-arrays)
3 = configuration 3
(1 CCD-array)

Figure 11: connection of UltraCam sub-images (Leberl et al 2002)

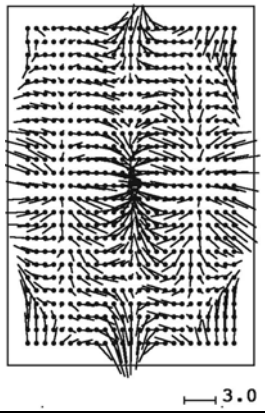
Corresponding to the special parameters for the DMC, the program system BLUH includes special additional parameters for handling the geometric problems of the UltraCam. In relation to the centre image the 8 other sub-images can be changed like a similarity transformation respecting the situation that no gaps between neighboured sub-images are allowed (table 4).

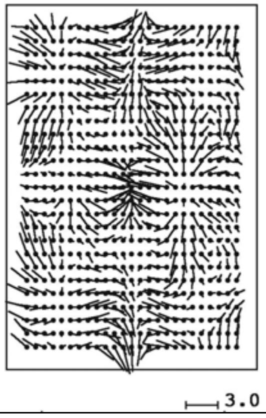
additional parameters	function
42-49	scale parameters
50-57	shift in x-direction
58-65	shift in y-direction
66-73	rotation

table 4: special additional parameters for UltraCamD

7. EXPERIENCE WITH ULTRACAMD

Details of the experience with the Vexcel UltraCamD are shown in Baz et al 2007 and Spreckels et al 2007. With the UltraCamD similar problems like with the DMC exist, that the camera is changing under flight conditions, requiring self-calibration. The standard set of additional parameters (1-12) is not sufficient, so the special UltraCam-parameters have to be used. Like Intergraph, also Vexcel is just investigating possibilities for a-priori corrections or improved camera calibration.





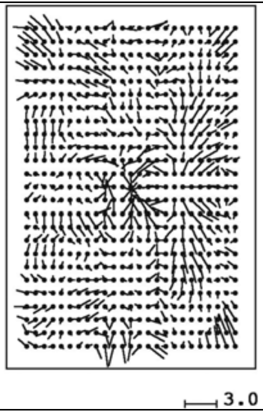


Figure 12: averaged residuals of UltraCamD – German mine site
upper left: without self calibration
upper right: with additional parameters 1 -12
left: with additional parameters 1-12, 42-73 (general parameters + special UltraCam-parameters)

The averaged residuals shown in figure 12 are demonstrating the problem – without self-calibration there is a clear indication of systematic image errors and only with the combination of the general additional parameters (1-12) and the special UltraCam-parameters (42-73) the major part of the systematic errors can be removed.

additional parameters	sigma0	RMSX [cm]	RMSY [cm]	RMSZ [cm]
without	2.66	3.8	3.7	7.6
1 – 12	2.44	3.5	3.4	5.6
1-12,42-73	2.26	3.2	3.0	5.4

Table 5: UltraCamD block mine site, block adjustment with self calibration, 9.0cm GSD, 80% end lap, 60% side lap

additional parameters	sigma0	RMSX [cm]	RMSY [cm]	RMSZ [cm]
without	3.01	2.2	2.8	16.8
1 – 12	2.76	2.2	1.9	7.6
42 - 73	2.85	2.3	2.7	8.9
1-12,42-73	2.75	2.3	2.0	7.5

Table 6: UltraCamD block large scale Istanbul, block adjustment with self calibration, 8.6cm GSD, 80% end lap, 60% side lap (Baz et al 2007)

Also the block Istanbul (table 6), as well as others, shows the same behaviour that for the optimal accuracy a bundle block adjustment with self-calibration, using the general set of additional parameters as well as the special additional parameters for the UltraCam, are required.

8. MODEL DEFORMATION

The bundle block adjustment with self-calibration is not a problem; this can be handled like for analogue photos. The problems appear with the handling of stereo models. For the handling of analogue photos usually systematic image errors are ignored, even if the influence may influence especially the height. For a horizontal mapping the systematic image errors can be ignored for analogue like for the large frame digital cameras. This is obvious in the shown accuracy range – the standard deviation in X and Y is not so much influenced by the self-calibration.

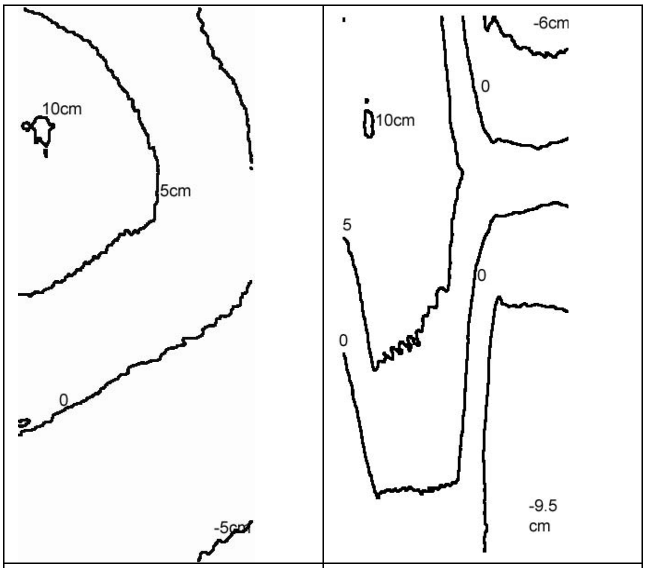
The DMC has for 60% end-lap a height to base relation of 3.26, the UltraCam 3.8. If (like usual) the standard deviation of the x-parallax corresponds to the accuracy of the image coordinates, the vertical accuracy corresponds to the accuracy in X and Y multiplied with the height to base relation (formula 1).

$$SZ = \frac{h}{b} \bullet Spx$$

Formula 1: standard deviation of Z

h=height above ground b=base
Spx = standard deviation of x-parallax

The height to base relation is valid also for the height deformation caused by systematic image errors – this leads to the model deformation. The model deformation is not a new topic for digital images; it exists as well for analogue photos.

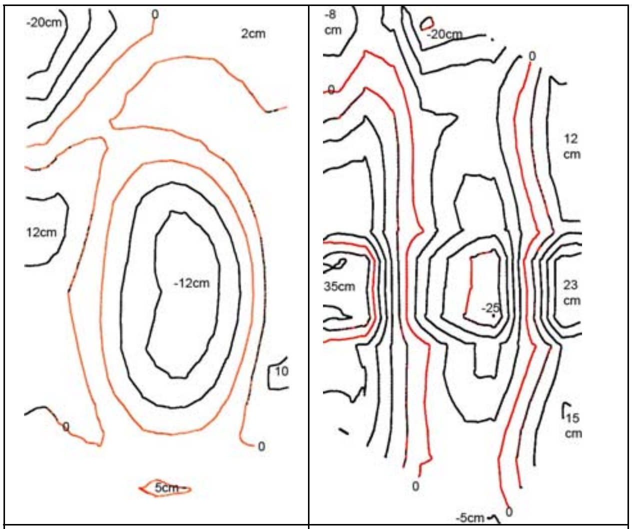


model deformation based on additional parameters 1-12

model deformation based on additional parameters 1-12, 79-80

Figure 13: model deformation in Z: DMC-block Rubi, 9.8cm GSD, end lap 63% 5cm contour interval

The vertical model deformation determined at the DMC-block Rubi is typical for the handled DMC-data sets. The expected vertical accuracy of well defined points corresponds to the sigma0 multiplied with the height to base relation; that means approximately 2µm * image scale * 3.26 = 5.3cm. The average height deformation is in the same range; in the extreme case it reaches 10cm. Of course the systematic image errors could be respected on-line during model handling, but this is not standard for digital photogrammetric workstations. Another possibility is the change of the image geometry by the systematic image errors like possible with Hannover program IMGEO, or a change of the generated digital elevation model like with Hannover program DEMCOR.

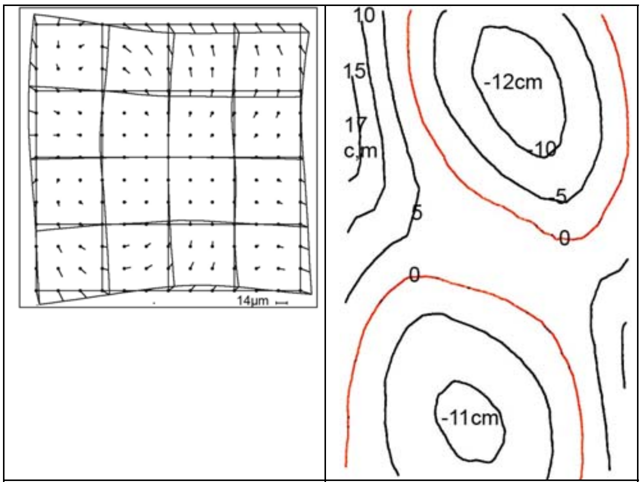


model deformation based on additional parameters 1-12

model deformation based on additional parameters 1-12, 42-73

Figure 14: model deformation in Z: UltraCamD-block mine site, 9.0cm GSD, end lap 66% 5cm contour interval

The model deformation based on the UltraCamD shown in figure 14 are even larger based on a similar GSD. This is also confirmed by other UltraCamD-blocks. As mentioned before, this is not a new thing for digital cameras; it exists also for analogue cameras.



systematic image errors RMK TOP 15
EuroSDR-test Frederiksstad

model deformation RMK TOP 15 Frederiksstad,
end lap 61%, flying height above ground1620m
photo scale 1 : 10 600

Figure 15: model deformation of a modern analogue aerial camera

The model deformation of the block Frederiksstad exceeds the expected vertical accuracy of the RMK TOP 15. As rule of thumb for analogue photos the vertical accuracy is in the range of 0.1‰ of the flying height above ground, corresponding to

16cm for topographic points or 9cm for well defined points (based on +/-5µm for Spx). This demonstrates that the model deformation is not a new problem; it is an old, but mostly ignored problem.

9. INFORMATION CONTENTS OF DIGITAL IMAGES

For mapping purposes in most cases the information content of the mages is the limiting factor and not the accuracy. It is not so easy to compare the information content of analogue with digital cameras. Often this is made based on the resolution of aerial cameras, having under operational conditions a resolution of 40 line pairs / mm, corresponding to 12.5µm pixel size. Under this condition the information contents of an analogue aerial camera would correspond to 80 x 230 pixels or 18 400 pixels in one direction. In reality analogue photos are scanned usually with approximately 20µm pixel size, corresponding to 11 500 pixels in one direction. The major reason for scanning with 20µm pixel size is the disturbance of the detail information by the film grain in the case of smaller pixels. This is not a correct base for comparing the information content of analogue with digital images. By this reason within the frame of a diploma thesis (Oswald 2006) the information content has been compared between analogue and digital images available in the same area with different ground resolution. The possible object identification as function of the ground resolution has been used for the comparison. Digital images are not disturbed by film grain, simplifying the object identification beside better conditions for automatic matching and more information in the shadow areas. As clear result the following relation has been found: the information content of digital images corresponds to analogue images having 1.5 up to 2.0 times larger GSD under the condition of a scan of analogue images with 20µm pixel size. Or in other words: analogue images having 30 – 40µm pixel size correspond to the information contents of digital images. This test was based on DMC and UltraCamD images.

So the information content of an analogue aerial image corresponds to 5750 x 5750 up to 7590 x 7590 pixels. The UltraCamD has 7500 x 11500 pixels while the DMC has 7680 x 13824 pixels. That means the information content of an UltraCamD and a DMC-image is better than the information content of an analogue aerial image. The information content of the UltraCamX has not been analyzed, but here not only the number of pixels is important – smaller pixels may cause a reduced image quality.

10. CONCLUSION

Also the large frame digital cameras Intergraph DMC and Vexcel UltraCamD have some problems with systematic image errors. For reaching the best accuracy, a combination of the standard additional parameters used also for analogue photos and special parameters for the camera type have to be used. The major part of the systematic image errors can be determined and respected with the standard set of additional parameters, the special parameters are only improving the result slightly. In the case of the DMC the systematic errors common for all 4 sub-images together can cover the largest part of the systematic errors, this is an important fact for an improved camera calibration which may reduce the systematic effects in advance.

In the bundle block adjustment no problems exist with the handling of these data, problems may occur with model deformation during model handling. Under operational conditions this is limited to the height determination; the effect to the horizontal position is very limited.

The systematic image errors may be respected as on-line correction in a photogrammetric workstation, but most software solutions do not allow this. Another possibility is a posterior correction of the images or a correction of digital elevation models by the influence of the systematic image error. It should not be forgotten that this is not a special effect for digital cameras, model deformation exist as well also for analogue photos. In addition the possible accuracy which can be reached with digital cameras is quite better than the accuracy reachable with analogue cameras.

The high accuracy level of the digital frame images, as well as the easier increase of the image overlap, allow an extension of the control point distance.

It has been shown that the information contents of a single DMC and UltraCamD image is better than the information contents of a single analogue aerial image.

Intergraph and Vexcel are just working in improved calibration methods, so the described problems may be solved in near future.

Even with the mentioned limitations, also today the potential of the large frame digital cameras is better like the potential of analogue cameras.

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MAPPING CAPABILITY OF A LOW-COST AERIAL DATA ACQUISITION PLATFORM – FIRST RESULTS

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ABSTRACT:

Based on a first prototype, an improved low-cost aerial platform was developed at the Institute of Digital Image Processing in order to be used for immediate acquisition and processing of image data wherever necessary. Typically, such requirements arise in case of natural hazards, where the amount of environmental or infrastructural damage has to be rapidly assessed and quantified. In general, the platform comprises a camera as well as GPS and IMU instruments in order to record the position and orientation of the camera. Using a helicopter, first campaigns have been flown with this platform over various urban and sub-urban test sites in Vienna and Graz in order to map buildings, or – more generally - to create digital surface models. Ground control points were measured and used for these test sites to perform aero-triangulation via block adjustment, and to estimate and validate the potential accuracy with respect to 3D mapping. In this paper, pilot mapping applications are presented, which refer to interactive 3D building extraction using photogrammetric workstation software on the one hand, and widely automated surface model generation using image matching procedures applied to multiple image data on the other hand.

1. INTRODUCTION

Due to an increasing amount of natural hazards in the past years, reliable and up to date image information becomes more and more important, e.g. to monitor environmental changes, to protect and monitor sensitive infrastructure, or for an effective disaster management and decision making processes. As an example, geo-referenced high resolution aerial imagery and 3D surface models can serve as an appropriate information source, in particular if the processing of the acquired data can be carried out in ‘near real time’.

The Institute of Digital Image Processing has set up an airborne platform for a low cost data acquisition and fast product generation. The platform allows rapid and versatile data acquisition whenever and wherever needed. Applications being typically envisaged are mapping of disaster events like flooding, land slides, storm damage and the like. Thereby, the objects and areas of interest can be imaged by as many over-flights and as many repetitive images as deem to be reasonable. Rapid mapping of such events is an obvious objective, requiring automated execution of individual data processing steps.

In order to launch first data acquisition campaigns, the platform has been mounted on a helicopter. Images were captured over selected urban and sub-urban areas in or in the vicinity of the cities of Vienna and Graz. Forward and backward over-flights were made, each of them leading to about 5 coverages of the objects on ground. Hence, a highly redundant image material was achieved, which can be utilized in manifold alternatives for 2d and 3d mapping tasks.

In the following the aerial data acquisition platform is described in more detail. For 2 selected test sites, the procedures and the results of mapping experiments devoted to building and surface mapping are presented. On the one hand, this platform setup was used to provide image data within a project that required a 3D building reconstruction for a wave propagation simulation. On the other hand, surface mapping procedures utilizing, which utilize multiple image coverage as provided by a high overlap of sequential images, were applied for 3D surface mapping for a selected test site. The benefit and the algorithmic issues of these procedures are presented and discussed.

2. AERIAL DATA ACQUISITION PLATFORM

Prior to a decision on the specific components of the platform the basic requirements have to be outlined. The final version of the aerial data acquisition platform should provide multiple overlapping images for a 3D surface reconstruction and the feasibility of a quasi true-ortho image and mosaic generation. For disaster monitoring near ‘real time’ image processing is required, implying geo-referencing without using ground control points for optimization and validation purposes. Further requirements refer to low cost, easy operating and high flexibility. This flexibility requires a low weight platform that can be mounted on an aircraft (helicopter or airplane) or can simply be operated hand-held also from a non expert. The camera resolution should be as high as possible in order to assure a reasonable trade-off between resolution on ground and area being covered

2.1 First platform prototype

The first platform prototype was realized by a high resolution digital camera (12 mega pixels), which was further connected to a L1/L2 GPS phase receiver and operated from board of a helicopter (see also Table 1). A related data acquisition experiment was made in the context of landslide mapping. After a period of intensive rainfall at the end of August 2005 in the area of Gasen (located in the north eastern part of the Austrian province Styria) several landslides caused severe damages on houses and infrastructure. Above all one person was killed by a collapsing house.

For this area, aerial images were captured with an overlap of at least 70 % to enable the generation of a 3D surface model. The images had to be taken in an oblique (off-nadir) viewing direction with respect to the area of interest. The average height above ground was 400 meters, which yielded to an image resolution of about 15 cm. In total more than 200 images were necessary to cover the entire area. The procedures and results achieved for this mapping experiment were presented in Raggam et al. (2006).

2.2 Current platform conception

Based on the experiences of the mapped landslides near Gasen the platform setup was changed. The capacity of the 12 mega pixels camera is low in case that a larger area is to be covered by images of high pixel resolution. Higher data acquisition efficiency hence requires a higher camera capacity. Therefore the camera was replaced by a Hasselblad H2D with 39 mega pixel. In addition a low cost IMU (inertial measuring unit) was mounted on the camera, thus providing approximate values of the camera's exterior orientation (see Table 1).

Platform configuration	First prototype	Current conception	Future conception
Camera system	consumer camera	high end consumer camera	high end consumer camera
Camera resolution	12 Mp	39 Mp	39 Mp
GPS system	L1/L2 Phase receiver	L1/L1 Phase receiver	L1/L2 Phase receiver + EGNOS
IMU system	-	X-Sense	Novatel
IMU accuracy	-	low	high
Stabilization	-	-	yes
Image processing	post processing	post processing	near real time

Table 1. Airborne data acquisition platform concepts (EGNOS: European Geostationary Navigation Overlay Service)

3. DATA ACQUISITION

3.1 Image data

First data acquisition campaigns based on the current platform conception were driven by a project of the European Space Agency (ESA), which was devoted to the characterization of the satellite to indoor channel at S band. Therefore, 3D building models together with material attributes were required. These data should be derived by interactive stereo data processing. Image data were acquired for six selected test sites in Austria, representing prominent buildings like the airport, the millennium tower or the FFG building in Vienna, or the airport, the shopping city "Seiersberg" or a prefabricated house park in Graz. Each of the test sites has an extension of about 500 by 500 meters and was covered with images at 80 % overlap and a ground resolution of 8 cm from board of a helicopter. In total, some 25 images were captured for each site (image example see Figure 1).

In addition to the six sites the sub-urban test site "Mariatrost", which is located near Graz, was captured. Here, the overlap of sequential images was in the order of about 70 % (image example see Figure 2).

3.2 Ground control

For the determination of the exterior orientation a couple of ground control points (GCPs) and verification points were measured for each of the test sites by means of a GPS survey. For the verification of the GPS positioning accuracy a second survey of GCPs was carried out for the shopping city "Seiersberg" test site one week after the first measuring campaign. The average horizontal and vertical deviation of these points measured in two epochs was 2.5 cm and 4 cm, respectively.

For the test site "Mariatrost" no GPS measurements were made. Instead, GCPs were measured using available ortho-photo maps and an existing elevation (terrain) model, implicating a reduced GCP accuracy in an estimated order of a few decimetres in planimetry and about 1 meter in height at the best.

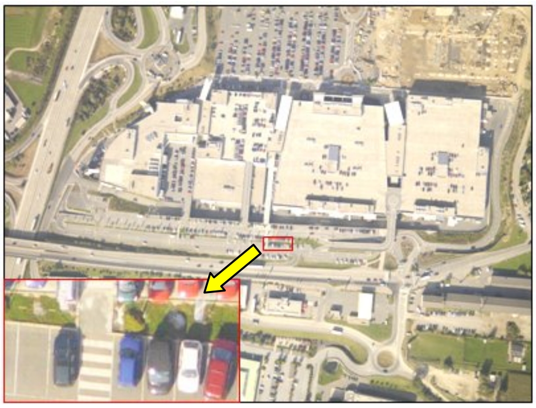

Figure 1. Aerial image of test site "Seiersberg"

Figure 2. Aerial image of test site "Mariatrost"

3.3 Mapping Objectives

According to the objectives of the ESA project on the one hand, and in order to test the developments made at the institute with respect to the utilization of multi-image coverage for surface mapping on the other hand, the following tasks and experiments were applied to these data sets:

- Interactive mapping of selected buildings. Therefore, the commercial *Leica Photogrammetriy Suite (LPS)* was used. In this paper, results achieved for the “Seiersberg” test site are presented.

- Automated surface mapping utilizing multiple image data sets. Therefore, recently developed approaches included in the *Remote sensing Software package Graz (RSG)* were used. In this paper, first results achieved for the “Mariatrost” test site are presented. RSG is a development of the Institute of Digital Image Processing with a strong focus on 3D mapping using optical as well as SAR image data.

For these first mapping tasks, still un-calibrated image data have been used due to unavailability of reliable calibration parameters, e.g. to cope for radial image distortions. As will be shown, this leads to distinct mapping discontinuities, which become particularly obvious if not only single stereo pairs are treated.

4. BUILDING EXTRACTION

For the characterization of the satellite to indoor channel at S band 3D building models together with material attributes were required. To generate the CAD building models 3D points needed to be measured in the stereo images. Finally the models were setup within the commercial *Autocad* software. In the following, results achieved for the test site “Seiersberg” are presented.

4.1 Block Adjustment / Seiersberg

For this test site, a core of 18 images was collected into an image block and imported into *LPS.* Using 17 GCPs which were measured appropriately in the images and numerous automatically detected tie-points a block adjustment was carried out to determine the exterior orientation of the images. From the control points, 3D setup/mapping accuracy in planimetry and height could be estimated as follows (bias/mean and standard deviation values given):

Mean: $m_E=$ 0.00[m] $m_N=$ -0.02[m] $m_H=$ 0.05[m]
Std.Dev.: $s_E=$ 0.07[m] $s_N=$ 0.10[m] $s_H=$ 0.26[m]

These accuracy estimates can be considered to be sufficient in order to meet the accuracy requirements for the intended building mapping.

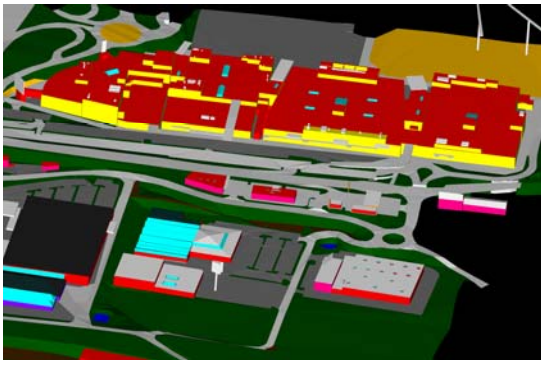

Figure 3. 3D model of the shopping city Seiersberg

4.2 3D Modelling

In the following the images were imported into *Leica’s Stereo Analyst*. The shapes of all relevant building features as well as the terrain were stereoscopically measured in individual stereo models. The 3D point cloud which was captured in that way was transferred into *Autcad* in order to finally create a surface/building model (see Figure 3).
Road tracks and parking areas are shown in gray, the terrain in green, a building activity area in light brown, and building blocks appear in different colours depending on the materials of the façades and the roofs.

5. SURFACE MAPPING APPROACHES UTILIZING MULTIPLE STEREOSCOPIC COVERAGE

5.1 Background

As mentioned above, the low-cost aerial data acquisition platform can be operated in a way that highly overlapping sequential images are achieved for an object or an area of interest, either in a single or in multiple over-flights. This leads to multiple stereoscopic coverage, which further on may be utilized for surface reconstruction purposes with distinct benefit in comparison to standard stereo pair utilization. At the Institute, first implementations and experiments have been devoted to image triplets (Raggam, 2005), while a set of 5 UltracamD images over the forested area mentioned above was used by Ofner et al. (2006) in order to carry out a multi-stereo image surface mapping experiment.
The benefit of multiple stereoscopic coverages, i.e. more than 2 overlapping images for a target point on ground, may be discussed by means of Figure 4. Here, sequential image pairs may be matched and 5 lines of sight be achieved from 4 matching results in the ideal case. On the one hand, the utilization of 5 lines of sight instead of only 2 makes the point intersection procedure to determine the ground coordinates of a target point more robust and leads to a distinct increase of surface model quality. On the other hand, the occlusion effects caused by trees or buildings are reduced in comparison to standard stereo pairs. Forest gaps may for instance be imaged from 2 neighbouring images (e.g. images 2 and 3 in Figure 4), while they might be invisible for a standard stereo disposition (e.g. images 1 and 5). Besides, neighbouring images in general show a higher similarity, leading to a superior matching performance in comparison to the more diverging standard stereo images.

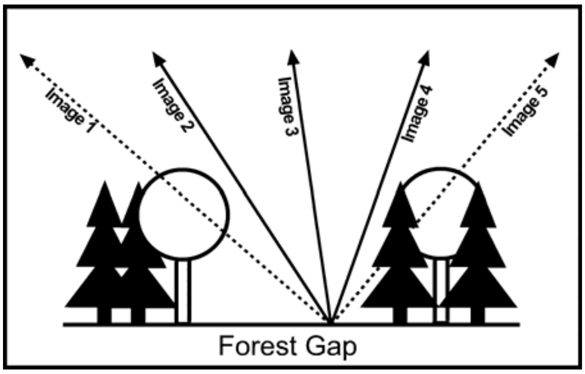

Figure 4. Multi-image mapping scenario

5.2 Image registration

In order to facilitate image matching, a (coarse) registration of the respective image pair is reasonable. The surface mapping procedures which are at present implemented in the *RSG* software can deal with the following options:

- Utilizing stereo images: One image is coarsely registered with respect to the other by means of a linear (and hence invertible) point transformation, which may be derived from a set of tie-points. These points either may be measured manually, or may be determined automatically using the imaging equations and a coarse elevation (terrain) model. The images may be physically registered in advance, or the registration may be implicitly considered during image matching.
- Utilizing stereo ortho images: The images are ortho-rectified using a coarse terrain model. It is an obvious benefit that image matching can then make use of well registered input image pairs in order to determine the remaining ortho image disparities, which are due to features like vegetation and buildings, which are not represented in the terrain model.

A comparative analysis of standard stereo mapping versus ortho-image based stereo mapping is given by Gutjahr et al. (2005) for glacier mapping using Eros and Ikonos image pairs. These 2 general approaches to extract 3D information from overlapping stereo images were expanded with respect to the utilization of more than one image pair, i.e. multiple matching results originating from sequential stereo pairs as indicated in Figure 4 are to be used simultaneously in order to reconstruct the terrain surface. The approaches to utilize multiple stereo ortho image disparity maps and stereo image disparity maps are described in the following sections.

5.3 Image Matching

The dominating proposition for image matching is to allow matching of individual image pairs as most convenient and promising. It is suggestive to match image pairs sequentially, i.e. the first with the second, resulting in a disparity map DM-12 according to Figure 5, the second with the third (DM-23) etc. according to the sequence of image acquisition. This strategy assures that image pairs with highest similarity are used in the matching procedure. Nevertheless, also matching results achieved from e.g. the first with the third image (DM-13) etc. should be applicable to the follow-on surface reconstruction procedure.

5.4 Disparity Map Tracking

A key task to utilize multiple disparity maps resulting from a matching strategy as indicated above is to collect corresponding matching results, i.e. those referring to the same target point. The multiple matching results lead to multiple lines of sight for this target point. Spatial intersection of these lines of sight yields the target point coordinates on ground.

5.4.1 Tracking Stereo Ortho Image Disparity Maps:

The collection of corresponding matching results over a sequence of disparity maps is done as follows:

1. The first disparity map (resulting from matching the first and the second ortho image) being included defines 2 lines of sight to those targets which were matched successfully. Each disparity vector determined for a target point in image 1 (P1) points to the corresponding location P2 with respect to ortho image 2.
2. Then, all matching results where ortho image 2 was used as reference image are investigated, e.g. those resulting from matching ortho image 2 and 3, 2 and 4 etc. A disparity vector is interpolated at location P2 of these disparity maps, again pointing to the corresponding location of the search image (e.g. image 3) and defining a location P3.
3. The procedure is continued with remaining disparity maps.

This procedure to collect all corresponding matching results is supposed to deliver in a first instance multiple ground coordinates (P1, P2, etc.) of a certain feature on ground. These may be more or less severely different due to the displacement of this feature in the individual ortho images. These ground locations are back-projected into the individual images to achieve multiple image coordinates, defining a couple of lines of sight.

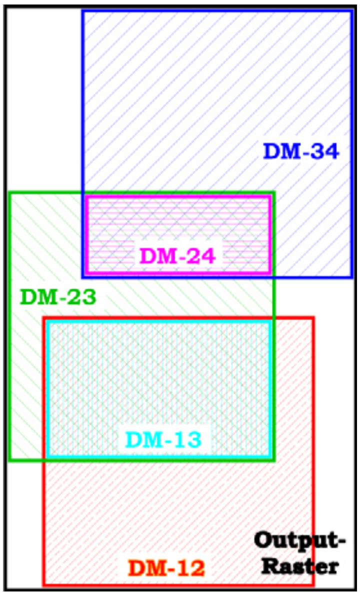

Figure 5. Scheme of multiple image overlaps

5.4.2 Tracking Stereo Image Disparity Maps:

While ortho image based disparity maps can be tracked via the ground coordinates being defined by the pixel and the disparity as such, auxiliary means have to be used in the approach which was implemented in order to track stereo image disparity maps. The following facts and preparatory steps are considered:

- The coarse (linear) transformation between 2 images (see section 5.2) is used for tracking, as it also gives a link between individual (specifically consecutive) disparity maps. E.g., the transformation between images 1 and 2 also defines the relationship between disparity map DM-12 and disparity map DM-23.
- Consequently, appropriate (linear) transformations can be established between arbitrary disparity maps by merging/chaining individual transformations. E.g., a transformation between images 1 and 4 becomes feasible by merging the transformation between images 1 and 2, 2 and 3, and 3 and 4.
- For tracking, a reference disparity map is selected (e.g. the first in the sequence, like DM-12), and

transformations with respect to all other disparity maps being involved are established.

- Only disparity maps, where the reference images is either the same as for the reference disparity map, or where the reference image corresponds to the search image of another disparity map can be utilized. E.g matching result using images 1 and 2 (DM-12) cannot be linked immediately with the matching result using images 3 and 4 (DM-34), while it can be linked with the matching results using images 2 and 3 (DM-23), or 2 and 4 (DM-24).

Disparity map tracking is done using the above mentioned transformations in order to collect all matching results corresponding to the same target from the individual disparity maps. In its general workflow, this procedure is equivalent to the one applied for stereo ortho image disparity maps (see section 5.4.1).

5.5 Spatial Point Intersection

Multiple matching results, which are collected by disparity map tracking, result in multiple lines of sight, which are then subject to spatial point intersection. Here, a least squares approach is applied in order to determine the location of the corresponding feature on the ground. It is to be noted that projection lines resulting from a single matching result of neighbouring images would represent a weak geometric disposition to determine the corresponding point on the ground due to their small intersection angle. However, the collection of several corresponding matching results in general yields a comparably wide-spread bundle of multiple projection lines, assuring numeric and geometric stability for the determination of ground coordinates.

The spatial intersection procedure further includes several mechanisms to identify and reject erroneous or highly uncertain matching results. Such unreliable matching results for instance use to occur in or close to areas which are occluded in one of the images to be matched. Back-matching thresholds and/or thresholds of the point residuals resulting from the least squares intersection procedure are applicable to reject doubtful matching results. Based on the results of spatial point intersection a raster surface model can finally be generated.

6. MULTI-IMAGE SURFACE MAPPING RESULTS

The approaches to extract surface models from multiply overlapping - optionally ortho-rectified - stereo pairs as described in section 5 were applied to the test sites “Seiersberg” and “Mariatrost”. In the following, results achieved for the sub-urban test site “Mariatrost” are presented.

6.1 Block adjustment

For this test site, 17 images were collected into an image block. Using a set of 31 GCPs and 39 additional tie-points, which have been measured for the images of this test site, a block adjustment was applied yielding the following results with respect to 3D setup/mapping accuracy:

Mean:	m_E= -0.09[m]	m_N= -0.01[m]	m_H= -0.13[m]
Std.Dev.:	s_E= 0.22[m]	s_N= 0.21[m]	s_H= 0.84[m]

These results are distinctly worse than those achieved for e.g. the “Seiersberg” test site. However, they correspond well with the accuracy potential/limits induced by the used reference data.

6.2 3D Surface Mapping

For a first test of the surface mapping approaches outlined in section 5, 4 sequential images were selected for this test site (see Figure 6). Matching was applied to the 3 sequential (ortho) image pairs and surface models generated from the matching results. The matching disparities as well as the surface models are shown in Figure 7 for the stereo image and for the stereo ortho image based approach. The disparities are shown in yellowish colour, while blue colour indicates areas of poor matching reliability, like typically forest or building borders, or at the image borders.

The stereo image disparity maps as well as the stereo ortho image disparity maps were then tracked in order to collect corresponding matching results, to perform spatial point intersection and to finally generate a surface model. The surface model resulting for both approaches are shown in Figure 7.

In general, the 2 surface mapping results are well comparable. Many of the unreliable matching results can be removed in the over-determined least squares point intersection procedure by introducing appropriate thresholds for the backmatching distance and or point intersection residuals. Major problem areas or features, however, still can be observed. Besides, there are obvious discontinuities in the surface models, which exactly correspond to the borders of individual disparity maps, or stereo coverage. The observable height discontinuities are in the order of a few meters.

Although a proof could not yet be made, it can be assumed with high confidence that these artefacts are due to the missing image calibration. Image calibration tests, which have been carried out meanwhile, have shown that (radial) image distortions of some 20 pixels in length have to be accounted for at the image borders. This undoubtedly can lead to height errors in the above mentioned order of magnitude.

7. CONCLUSIONS

Based on the first results, which have been achieved by interactive as well as automated 3D mapping procedures, the following major conclusions can be made with respect to the mapping capabilities of the low-cost data acquisition platform:

- 3D mapping using image data acquired by this aerial platform can be done with sufficiently high quality and accuracy
- The multi-image based surface reconstruction approaches have an obvious potential to circumvent problems inherent to standard stereo mapping. Provided that images are acquired with a high overlap, these approaches use to facilitate image matching, to reduce unreliable matching results and to reject such results in case they occur.
- Image calibration is an essential prerequisite to assure high quality as possible.

As a consequence, instantaneous activities are devoted to the latter issue in order to

- either compensate for the image distortions by generating calibrated input image data, which are not affected by distortion effects,

- or to include and consider the respective distortion parameters resulting from the calibration activities within the underlying imaging equations.

The surface mapping experiments then shall be reproduced and continued including other test sites, in order to comprehensively evaluate the 3D mapping potential of the low-cost data acquisition platform in its present conception.

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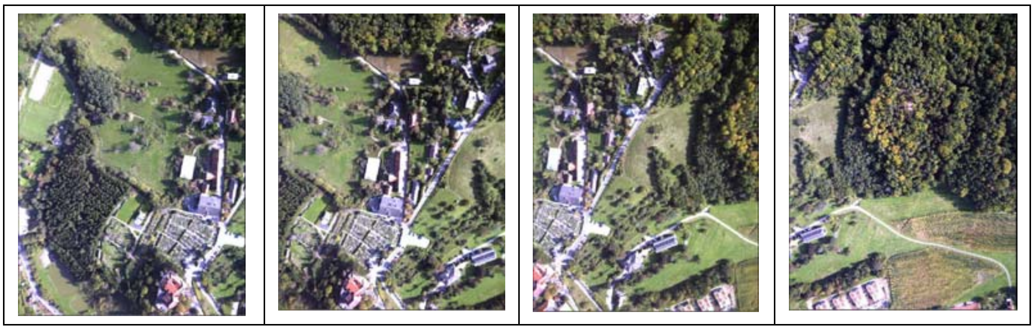
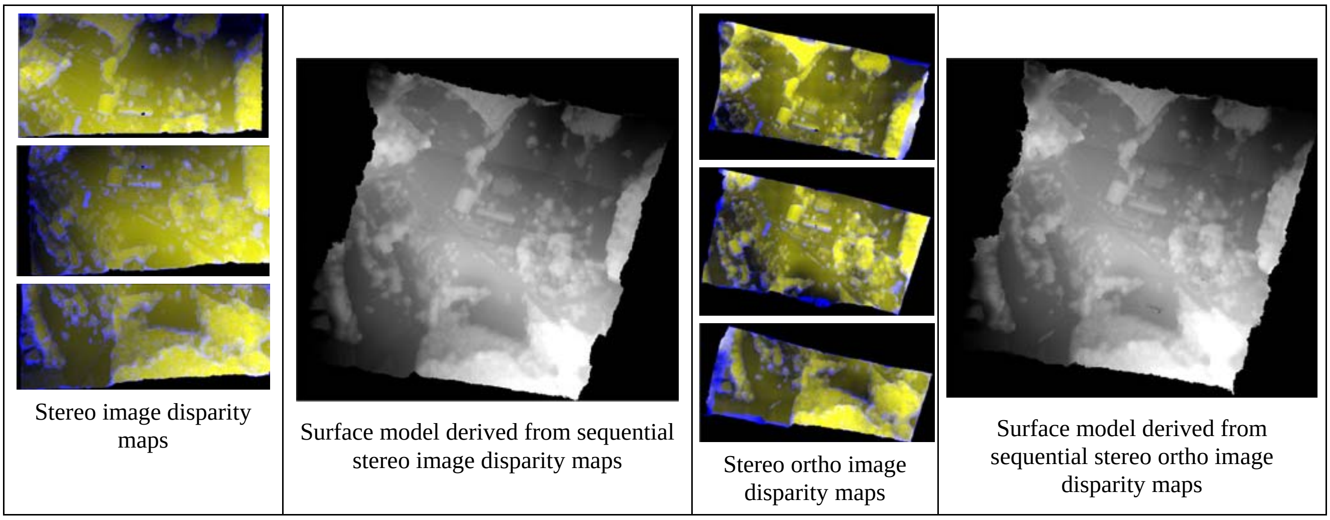


Figure 6. Example of 4 sequential images of test site “Mariatrost” (flight direction left to right).



Stereo image disparity maps

Surface model derived from sequential stereo image disparity maps

Stereo ortho image disparity maps

Surface model derived from sequential stereo ortho image disparity maps

Figure 7. Surface models derived from multiple stereo image pairs (left) and multiple stereo ortho image pairs (right).

Stereo-matching Techniques

Automation in photogrammetry is largely made possible by stereo-matching techniques that enable (semi-)automatic aero-triangulation and creation of digital elevation models. Matching: I know what it is, I know what it does, but how does it work?

The aim of matching is to identify corresponding phenomena in two or more sets. In photogrammetry the sets are the left and right image of a stereo pair, and the problem in corresponding them is to trace and locate in the right image the conjugate of a point in the left image. Ever since images could be stored in a computer as pixels stereo-matching algorithms have been being developed, there are many and new ones emerge on a regular basis. The methods may be categorised into two broad classes depending on how the image is approached. From the signal-processing perspective an image is regarded as a set of grey values or colour representing the intensity of reflected electromagnetic signals. But an image may also be seen as a representation of features present in object space where each feature, such as the corner of a building, a road crossing or tree, is represented by an irregularly shaped group of pixels.

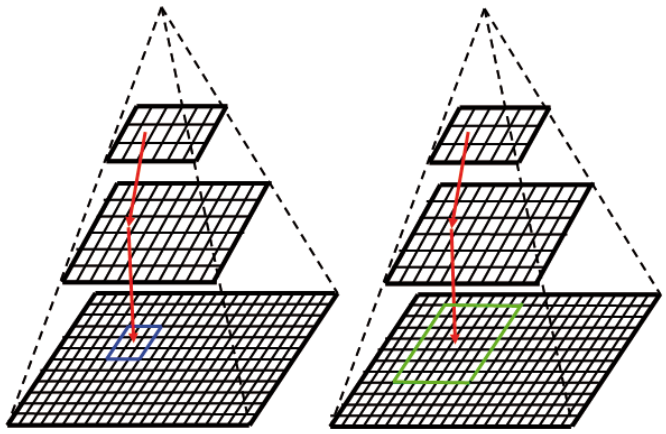


Image pyramids of a stereo pair, at base the original image. Blue border in image (left) marks target patch, search patch is marked green. In the multi-resolution approach matching starts at course level and plummets to higher resolutions until the original image is reached.

In the signal-based approaches, also called area or intensity-based, correspondence is sought using intensity values in a regularly shaped patch. A target patch the size, for example, of 9x9 pixels, is defined and shifted over a search patch in the other image the size of which depends on how well the approximate location of the conjugate point is known. For each position a similarity measure is computed, for example, the normalised cross-correlation, resulting in a connected set of similarity measurements, one for each pixel. The highest similarity value determines the corresponding patches, their centre pixels selected as corresponding points. Acceptance of the match depends on whether the similarity value exceeds a predefined threshold; the value can be selected in a heuristic way or, when using normalised cross-correlation, on a statistically sound basis using student t-testing. Sub-pixel accuracy can be achieved by fitting a function, for example a second-order polynomial, through the correlation values and then determining the maximum of that function.

Correlation techniques allow at best a linear difference (gain and shift) between the intensity values of the left and right image, but a shift only in geometry. Since geometric differences do exist as a result of differences in exterior orientation and presence of relief, these are tackled through an iterative least-squares approach. These usually model the geometric differences as affine transformations. However, gain comes at a cost: the approximate location of the conjugate point has to be known accurately in advance, even down to the level of a few pixels. This problem can be coped with along two lines. The first by establishing an approximate match with feature-based matching, whereby first points, line or areas are detected in both images using differential operators such Marr-Hildreth, Sobel, Moravec or Förstner. Next, attributes are assigned to the features, such as average and variability of grey values. Knowing the search range, corresponding features in the left and right images are found by comparing attributes. A consistency check is then performed, based on the assumption of smooth object surfaces, to remove faulty assignments. The location of features serves as an approximation for least-squares matching.

Another way to tackle the approximate value problem is by adopting a multi-resolution approach in which an image pyramid is created with at its base the original, full-size images and at subsequent higher levels images generated from uniting 2x2 pixels. This may be repeated until an image of just one pixel remains. By selecting a hierarchical level that best reflects the approximate position of the conjugate point least-squares matching is carried out at that level. The resulting correspondence is now used to track the matching down through the image pyramid until the original image has been reached.

High computation load requires reduction of search space. This is achieved by using information on relative position and orientation of the stereo pair and characteristics of the terrain topography. The first enables use of epipolar geometry, which reduces matching to a problem of 1D; the latter might avoid starting at too high a level in the image pyramid.

The above has been compiled from Lemmens, M.J.P.M., 1988, A survey on Stereo-matching Techniques, International Archives of Photogrammetry and Remote Sensing, Vol. 27, part B8, pp 11-23.

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Chapter 5

Lidar Technology

By Mathias Lemmens

5.1 Introduction

Lidar is a rapidly evolving surveying technology for collecting 3D point-clouds both from airborne platforms and in land-survey settings. Lidar has gained widespread recognition as the main source for the reconstruction of real-world surfaces. Its many applications include the creation of accurate Digital Elevation Models (DEM) and 3D-city models for planning purposes. It offers benefits for planning, design, inspection and maintenance of infrastructure. From the air, dunes, beaches, dykes and floodplains can be captured accurately and with a high level of detail, enabling coastal-erosion modelling, monitoring and flood-risk management. The goal of surface reconstruction is to approximate geometry, topology and features of a surface using a finite set of sampled points. Lidar is without doubt a most successful data-acquisition technique. As an acronym of Light Detection and Ranging - some prefer to read Lidar as Laser Imaging Detection And Ranging - the term has become a 'proper name', spelled like your own first and surname with the initial letter the only capital. Laser scanners are, like Radar, active sensors that emit laser beams for measuring the distances to objects without human/object contact.

5.2 Terrestrial Lidar

Terrestrial Lidar, also called Terrestrial Laser Scanning while Leica Geosystems calls it High Definition Surveying (HDS) makes possible the swift measurement of millions of points by automatically scanning the scene at high speed. In the resulting dense point-cloud objects can be easily identified, allowing the creation of 3D-models with a level of detail impossible to achieve within a reasonable space of time using traditional technologies. TLS thus opens up new dimensions in surveying, including surveying for land administration purposes.

The principle of terrestrial laser scanning (TLS) is based on either time-of-flight or phase-shift. In the time-of-flight technology the sensor emits a laser pulse in the direction of the object; the time taken by the part of the pulse reflected back to reach the instrument is measured. Distance is calculated by multiplying this travel time by the speed of light and dividing the result by two. In phase-shift technology the sensor emits laser beams which are modulated as sine waves. The phase of the reflected part of the laser beam is measured and compared to the phase of the outgoing one, and distance then calculated from the difference in phase (phase-shift). Point density is usually so high that by recording the strength of the reflected signal quasi images can be created.

The application areas from which manufacturers diverge into production of TLS fall into three categories:
high-precision measurement and detailed 3D reconstruction of industrial objects such as cars
measurement of outdoor scenes featuring objects of complicated shape (construction, architecture, civil engineering)
land survey; the Trimble VX , for example, is based on the total-station concept, modified in an advanced way.
One of the most important features of a TLS is measurement range because range determines to a large extent types of application. A distinction can be made between short-range (up to 25m), medium-range (up to 250m) and long-range (larger than 250m). Manufacturers too recognise range as a decisive factor, some therefore encoding it in the name of the system. For

example, the CPW 8000 has a range of 8000cm or 80m, the CP3200 a range of 32m, and the ranges of Faro's LS 420, 440 and 480 are 20m, 40m and 80m respectively. Maximum range does not depend only on the TLS itself but, since laser scanners operate in non-contact mode, also on object reflectivity. Some manufacturers indicate this by accompanying the range with a reflectivity percentage, also called Albedo. Only time-of-flight systems, which make use of pulsed laser, are suited for long-range applications. Phase-shift systems are particularly suited for high-precision short-range and medium-range applications, for which high point densities are required. Phase-shift systems are not suited for airborne applications.

Phase-based scanners, on the market for about fifteen years, were initially aimed at close-range, high-accuracy industrial applications. These scanners are characterised by a precision ranging from sub-millimetre to sub-centimetre level, and high scan rates of up to half a million points per second; they are thus able to capture objects at very high density. However, these favourable precision and scan rate numbers come at the cost of maximum achievable range, which is less than 100m. In contrast, time-of-flight systems may measure distances up to 1km and even more, but their precision is usually limited from sub-centimetre to centimetre level, while scan rates are 10kHz.

Laser scanners are often compared to reflectorless total stations and, as far as the measurement principle is concerned, this is fine. Both instruments measure distances using pulsed laser light or phase shifts. Total stations can achieve higher precision because many measurements, even up to thousands, to the same point are taken and averaged, while laser scanners measure each distance only a few times, sometimes just once. To determine the X,Y,Z coordinate, the coordinates of the position of the instrument have to be known as well as the horizontal and vertical angles of each outgoing laser beam. The 3D coordinates of each point are calculated in a local or national reference system, from the laser distance, the known X,Y,Z coordinates of the instrument, and horizontal and vertical angles of each outgoing laser beam. The coordinates of the position of total stations are usually determined by centring the instrument above a known point. The position of a laser scanner is usually determined indirectly by placing special targets in the scenes the three coordinates of which are measured using traditional survey instruments such as total stations. The similarity in measurement technology inspired manufacturers of traditional survey instruments to modify their total stations into a quasi laser scanner able automatically to scan areas of interest at predefined intervals, despite scanning rate being significantly lower than that of laser scanners.

At product level, similarity between laser scanners and reflectorless total stations bounces. A land surveyor is used to interpreting a scene as a collection of characteristic points each of which has to be measured individually; connecting the characteristic points correctly allows reconstruction of the boundary of the object. Using a laser scanner, no selection of individual points takes place during scanning; it is a matter of chance which points are hit by the laser beam. As a result, unwanted objects, such as crossing pedestrians, are also captured. The actual measuring is done in the office by fitting geometric primitives such as lines and planes through parts of the point-cloud. Boundaries and characteristic points are computed from intersecting neighbouring geometric primitives. Laser scanners can collect points for hours on end without human intervention, making them particularly suitable for capturing hostile environments such as nuclear plants, where placing the instrument needs to be done fast.

Laser scanners and total stations are also compared at time-efficiency level. Indeed, surveying with a total station is only feasible when the object can be modelled by a limited number of characteristic points. Laser scanning enables capturing scenes consisting of objects of complex shape, such as chemical plants, cultural-heritage and traffic-accident sites. Some vendors of laser scanners posit the idea that if a laser scanner acquires 8,000 points per second while it takes a survey team ten seconds to measure a single point, using the scanner is equivalent to working with not one but 80,000 teams; a faulty and misleading comparison. Surveyors select their points intelligibly, while laser scanners take points blindly, without identification, interpretation and selection. These activities have later to be carried out in the office. As such, laser scanning bears more comparison with photogrammetry than with surveying. Laser scanning may thus bring land surveyors and photogrammetrists closer together. Or even result in the merging of the two professions.

Vendors of terrestrial Lidar scanners often proudly present the operation of their instruments in the field as “a piece of cake”. And they are right; it is convenient. One just needs to place the instrument in front of the object, level it roughly, enter the area and push the button. It’s as simple as that. Or at least, as far as the instrument side of the survey is concerned. But the snag lies not in operating the instrument but in the prelude to this, and in scene monitoring during capture.

Before placing the instrument the operator has to ensure that no objects intervene between instrument and scene that might occlude essential parts of it. This means no cars, lampposts, traffic signs, vegetation, people or donkeys. No ‘alien objects’, as Prof. Heinz Ruther called them in his discussion of the challenges posed by terrestrial scanning of heritage sites (GIM International May, 2007, pp 14-17). Potential sources of failure may also be hidden in the scene; lapses may result especially from the reflectance characteristics of the surfaces of objects. Hitting a surface, a laser beam may interact with it in three ways: it may be reflected, absorbed or transmitted. Only reflected beams will reach the instrument and thus be of use, but one reflection is better than another. Ideally, a surface behaves as a diffuse reflector, so that the resulting reflections are of like strength in all directions. In this case most of the signal returned from the surface reaches the instrument. But when parts of an object have a specular surface the reflection is deflected and little or no signal is returned to the instrument. Therefore mirrors, shiny metal and brackets of neon lights present in the scene have to be removed or covered. Signal strength, recorded in addition to time of flight of the laser beam, provides the operator with a helpful means of detecting lapses in reflectance during processing of point-clouds.

Laser beams may be transmitted through windows; this can happen, for example, with buildings, and results in the recording of objects on the other side of the glass. To avoid problems in reconstructing the final scene, windows have to be covered, or special caution must be exercised in processing the point-cloud. Highway police, when using scanners to record the site of an accident, spray special powder on car windows to prevent the scanner “looking” through them. Indeed, we live in a dynamic world full of people continually on the move, so that pedestrians tend to cross a scene whilst it is being captured, and the same is true of animals, cars and bikes. The surveyor must thus close off the scene area to all traffic before pushing the button. This might sound self-evident, but how often are ground-control points for aerial surveys invisible because they lie beneath trees or just a few metres from a thirty-storey building? And in practice closing the scene to moving objects often proves much more problematic than it sounds.

In addition to covering objects and preventing things crossing the scene, the surveyor also has to place and identify objects in it prior to pushing the button. Objects may be markers, such as nails, or marked existing points, such as sharp corners. They are used as control points, necessary for the conversion of range data to X,Y,Z coordinates in a national or local reference system. The location of the points has to be selected with care and unambiguously indicated to avoid mistakes. Most commonly, four control points are used at the edges of the scan, although three is enough for geo-referencing; the fourth is used for reserve and check. Large objects require scanning from several positions, and adjacent scans have adequately to overlap. Once a control point has been identified in one scan, identification in the overlapping scans can be done semi-automatically.

5.3 Airborne Lidar

'Airborne Laser-scanning' is a term used in Europe; other parts of the world have generally adopted the term 'Airborne Lidar'. Although the rise of airborne Lidar as an operational system began just a decade ago, its history dates back to the sixties when it was first tried out. In the 1970s experimental systems were developed. Accurate positioning remained a bottleneck until, in the early nineties, GPS became a reliable, stable and precise positioning technology. Today Lidar is recognised as an advanced technology with many beneficial characteristics: high rates of data capture (up to 100km2/h) and levels of automation, right up to 3D-reconstruction of the real world. Lidar also features low cost per point, high accuracy and precision and a high level of detail (up to millions of points per square kilometre), while the final solution is largely independent of terrain type, characteristics and daylight/weather conditions.

Millions of Points

Airborne Lidar systems are multi-sensor, usually consisting of a reflectorless laser sensor, a positioning system and a digital camera. The laser sensor determines distance from the platform to arbitrary points on the Earth's surface by measuring the time interval between transmission of a train of pulses (up to 250,000 pulses per second!) and return of the signals. A rotating or nutating mirror enables scanning perpendicular to flying direction. To compensate for mechanical instabilities and guarantee constant alignment, fibreglass optics may be mounted in front of the mirror. A positioning system is required to transform range measurements into 3D terrain coordinates, and this comprises two coupled main parts: GPS and Inertial Measurement Unit (IMU). The aim of the GPS is to measure the position of the laser sensor. Sampling frequency is in the order of a few Herz. The IMU, also called Inertial Guidance System (IGS), uses a combination of accelerometers and gyroscopes to detect rate of change in acceleration and attitude; the latter usually defined as pitch, roll and yaw. Position is calculated by two times integration of accelerations along the three perpendicular axes. Accumulation of measurement errors means an IMU suffers from drift, resulting in discrepancy between its true and apparent position. IMU positions are, however, not useless: since sampling frequency lies in the order of several hundreds of Herz, IMU positions may fill GPS gaps. To compensate for drift, IMU position is updated every time a GPS position becomes available. Integration of GPS and IMU measurements is done using Kalman filter technology. In contrast to GPS, IMU does not require external aid. As an autonomous system it is immune to any interference from the outside world, such as jamming. Integration of the two systems improves accuracy of positioning and precision.

The Real World

Depending on system, flying height, speed and number of flyovers, point densities up to some dozens per m2 can be acquired. Helicopters are better suited for high-resolution coverage because they can easily limit their speed. Since Lidar is an active system, data acquisition is independent of sun illumination, while no shadows are generated. Weather and visibility only slightly affect flown survey. Height values may be effortlessly obtained in areas of low textural variation, such as beaches and dunes. Wavelengths in the near infrared part of the spectrum (typically 900nm, 1,060nm and 1,500nm) are non-penetrative, so that pulses will be reflected from forest-stand foliage and other vegetation. Since the footprint is of limited extent (typical beam divergence being a few milli-radials to sub-milli-radial) some of the signal may reach the ground if vegetation is not too dense. The last part of the return signal may thus represent distance to the ground and the first part canopy height. Some systems, in addition to the first and/or last part of the return signal, collect four or eight samples, or even the entire return pulse, enabling determination of vertical surface structure such as roughness, height and shape of objects, canopy density and height of trees, and reflectivity.

Applications

The value of Lidar data appears to full advantage when combined with other datasets such as aerial and satellite imagery and topographic data. Lidar provides useful information for all stages of infrastructure works, such as corridor planning, environmental-impact simulation, optimal movement of earth works, determination of (rail)road deformation and detection of obstructions such as fallen trees after storms. Lidar also provides information for the creation of 3D-digital city models and aerial monitoring of electricity power-lines. Other applications include flood-hazard zoning, river-flood modelling and assessment of post-disaster damage. The accuracy and resolution of Lidar are so high that geo-scientists are apparently being forced to adjust their erosion and floodplain models.

The result of a Lidar survey is a dense cloud of irregular, distributed 3D points characterised by XYZ coordinates associated with attributes such as intensity of return signal. The central issues when dealing with Lidar data concern archiving and management of the data, generation of output suitable for use within GIS and CAD software, filtering of data for reconstruction of bare-earth surfaces and features such as buildings and trees, and visualisation of the data. The main focus here is on generation of GIS and CAD output.

5.4 Interpolation

Representation of elevation data within a GIS and CAD environment is carried out preferably in raster format, elevation values being stored in the cells of a 2D regular raster. The transformation of an irregular point-cloud into a regular raster requires interpolation: computation of elevation values for non-sampled terrain points from sampled points. Reconstruction of the continuous surface requires definition of a function that passes through the sampled points. An infinite number of functions will fulfil this constraint and, unfortunately, no simple rule exists for determining which is best suited to a given dataset. Additional conditions have thus to be defined, which has resulted in the development of a wealth of interpolation techniques. Some conditions are based on geostatistical concepts (kriging) and others on locality. The latter assumes a relationship between the elevation of each point and other points in the vicinity, up to a certain distance away. One of the most simple and available methods is ‘inverse distance-weighted interpolation’. This assumes an inverse relationship between elevations of neighbouring points and their distance: the greater the distance, the less the elevation of a sampled point will contribute to computation of the elevation of the non-sampled point. There are also conditions based on smoothness and tension (splines) or ad hoc functional forms. Selection of the method of interpolation is often based on experience, experiment and availability of algorithms in the GIS system. But it must be kept in mind that results produced by the various methods may differ considerably and appropriate selection is crucial; wrong information may lead to potentially wrong decisions and faulty simulation results.

5.5 Data Swaps

The hundreds of millions of points generated by each Lidar survey cause computational complications during interpolation since it is not possible to store all this data in the internal memory of even the most sophisticated computer. As a consequence the data has to remain on larger but significantly slower disks. Operational weakness arises from data swaps between disk and RAM rather than computation when processing such massive volumes of data. Many practical algorithms therefore perform ‘segmentation’, breaking down the point-cloud into a set of non-overlapping sub-clouds each containing a small number of sampled points. The points in each segment are then independently interpolated. Based on this principle a vast number of segmentation methods have been developed, including simple breakdowns and ones based on Voronoi diagrams. An algorithm that copes efficiently with data swapping minimises the times a disk is accessed and spectacularly reduces runtime. Researchers are still looking for algorithms that reduce data swaps. Agarwal and co-authors1, for example, recently developed a scalable approach based on quad-tree partitioning of data into a set of non-overlapping segments, going on to confront the performance of their own approach with that of commercially available software. They found their own method was able to process nearly 400 million points using less than 1GB of Ram, while QTModeler 4 from Applied Imagery, processing approximately 50 million points using 1GB of RAM, performed best of the other methods.

5.6 Conclusions

Laser scanning is a generic data-acquisition technique. A large range of different types of objects may be captured three-dimensionally by a laser scanner. Sometimes the user may expect too much of an exciting new technology, and it may come as a surprise even to the manufacturer in which fields the technology finds its main application. Each application, whether 3D-mapping of a chemical plant, monitoring of bridges and other civil-engineering applications or land administration, requires specialisation in capturing and processing technology, and such experience can only be gained by trial and error. There is no magic button that has simply to be pushed after acquisition of 3D point-clouds to produce perfect reconstruction. It takes time before a new technology becomes a well-established tool within a certain field of application.

Chapter 6

Satellite Images

By Mathias Lemmens

Due to the low Ground Sampling Distance (GSD) of earlier generations of satellite imagery, the use of satellite data in the surveying field has been limited. Argentina and Nicaragua, for example, have carried out tests with SPOT 4 and compared the results with fiscal and physical cadastral plans but could not achieve accurate boundary maps because of poor GSD of SPOT 4 imagery. The launch of SPOT 5 improved the geometric performance. In Guatemala, SPOT 5 imagery has been compared with data from total stations, GPS and orthoimages for different types of parcels. Good results were obtained for large and medium parcels; although the results for identifying small parcels, peri-urban and urban estates showed limited accuracy. The accuracy of identification depends directly on the size and shape of the property, the topography of the area, the type of fences and vegetation coverage present on the study area as well as the scale of the orthoimage used in the identification process. The Guatemalan research recommended the use of SPOT 5 orthoimage as an input that can be considered in countries regarding cadastre with less strict precision.

From the turn of the millennium, however, the GSD of satellite images has gradually improved with the launch of high-resolution satellite sensors, including Ikonos, Quickbird and WorldView-1. The last, WorldView-1, a satellite weighing 2,500 kilograms, was sent by a Boeing Delta II rocket into 496km sun-synchronous orbit from Vandenberg Air Force Base in California, USA on Tuesday 18th September 2007 at 11:35 am Pacific Daylight Time. WorldView-1 was the thirteenth earth-observation satellite blasted beyond earth's atmosphere in 2007; indeed, such hardware is currently being constructed and launched at breakneck speed. Remarkably, this was the first US earth-observation satellite this year, while China and Japan have each already put two such satellites into space. The launch of US GeoEye-1, earlier scheduled to take place in the third quarter of 2007, has already been postponed to late First Quarter or early Second Quarter 2008.

Features

QuickBird has panchromatic and multispectral sensors with resolutions of 61- 72cm and 2.44-2.88m, respectively, depending upon the off-nadir viewing angle (0- 25 degrees). The sensor covers 16.5-19km in the across-track direction. In addition, the along-track and across-track capabilities provide stereo geometry and a revisit frequency of 1-3½ days. Worldview-1 is part of the National Geospatial-Intelligence Agency (NGA) NextView programme. The first images become commercially available at the beginning of 2008. When fully operational WorldView-1 will provide panchromatic imagery with a ground-sample distance (GSD) of 50cm at nadir and dynamic range of 11 bits per pixel. A larger GSD could technically have been achieved, but US regulations require that satellite images offered to commercial customers have a GSD no better than 50cm. The swath width at nadir is 17.6km and one day of data acquisition may result in up to 750,000km^2 being captured. During a single pass, contiguous areas of 60x110km can be covered in mono and 30x110km in stereo. The platform is so stable and the positioning sensors so accurate that an accuracy of 3m to 7.6m can be achieved without using ground-control points, 2m with them. The same area on earth can be captured within just six day of a previous visit, so that if a GSD of 1m suffices, revisit frequency may rise to 1.7 days. High-resolution satellite images are a new geo-data source from which man-made structures such as walls, ditches and road borders may be extracted.

These features make high resolution imagery suited for map creation and cadastral purposes. When satellite imagery have a GSD of 2m or better they are useful for supporting most cadastral applications, which threshold has been reached with the turn of the millennium.

Compared to aerial photographs advantages of satellite images from a user's perspective include (1) less expensive, (2) no need for: flight plan development and arrangement, and formal approval of the flight mission, and (3) less ground work is needed for the creation of Ground Control Points (GCP). Furthermore, when the aerial images are only available in hardcopy (paper) format the recurrent need of enlargement, increases the costs rapidly. Satellite images are more convenient and provide a wider flexibility to manipulate the scales.

In many developing countries, including Kenya, Preliminary Index Diagrams (PID) have been introduced as a temporary measure to speed up land registration pending preparation of more accurate documents. PIDs are land parcel index maps traced from unrectified aerial photographs. As it happens so often, temporary is often not temporary at all in the long run as it might last much longer than envisaged and today, half a century later, PIDs are still actively in use. Though the PIDs have satisfied the immediate need in the provision of title to land, there is a growing concern about the boundary information obtainable from these maps for purposes of land administration, land valuation and planning. High-resolution satellite imagery might be an alternative for cadastral surveying.

High spatial resolution satellite images are often available as geo-referenced rectified images; geo-referencing is based on known position and attitudes of the satellite. By using ground control points, and a digital elevation model (DEM), which introduce, of course, additional costs, the images can be transformed as orthorectified images into the national reference framework. Often parcel boundaries are marked by trees, fences with presence of vegetation, roads or foot paths and ditches with the presence of low altitude vegetation. This translates to about 2m width at the usual PID scale of 1:2500. In flat terrain, boundaries can be easily identified in enhanced orthoimage. The accuracy of the determination of area of parcels from orthoimages depends particularly on the size of the property. Medium properties between 10-20ha show a deviation from the reference area of 0.22%, estates of 5–10ha a deviation of 1.77% while small estates in flat areas deviate 3.7% from the actual value of the area.

Land Registry and Cadastre of Turkey carried out an accuracy test on the suitability of Ikonos images, taken in 2002, for cadastral purposes (Oguz and Sezgin, 2006). The GSD of Ikonos images of the panchromatic band and the multispectral bands are one meter and four meter respectively. By merging the panchromatic band with the multispectral bands a pan-sharpened image was created with GSD one meter. To geo-reference the image of the test area eight signalized ground control points (GCPs), measured by GPS, were used. The size of the test area was two by two kilometre; field survey of such an area requires two weeks. The GPS coordinates appeared to have an accuracy of better than 10cm. ERDAS 8.6 was used for carrying out the geo-referencing, using polynomials as geometric transformation models.

Ikonos image overlaid with boundaries obtained by field survey (red). Visual inspection demonstrate already that correspondence is modest.

Assuming that property boundaries coincide with topographic features, one cadastral map was created from a terrestrial survey and another of the same area from the satellite image. Boundary extraction from the satellite image could be done much faster than the two weeks necessary for the terrestrial survey. The two maps were overlapped in ERDAS environment and the differences in location of identical boundaries determined. Assuming the field survey as the truth (error-free) the resulting Root Mean Square Error (RMSE) for the satellite image was 3m. So it is not possible to extract property boundaries with high accuracy maps from satellite images. Furthermore, as stated, only boundaries which are visible as topographic features can be measured.

Conclusions

High-resolution satellite imagery with its utility for surveying large areas in a time and cost effective manner, can thus be an interesting input for establishing a countrywide cadastral information system for the rural part of the country provided that the accuracy requirements are modest.

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GIM Interviews Dr Rainer Sandau, Chairman, International Academy of Astronautics (IAA)

Potential of Small Satellites

Small satellites for earth observation are an important ongoing development in space research. How can mapping and disaster management benefit from small-satellite systems? What is the potential and what the challenges? Are small satellites an inferior alternative for developing countries that cannot afford large satellites? This month's interviewee, Dr Rainer Sandau, provides answers to these and other questions.

By Mathias Lemmens, editor-in-chief, GIM International

What are mission, scope and organisational structure of IAA?

IAA encourages international scientific co-operation through scientific symposia and meetings and through the work of six commissions dedicated respectively to Space Physical Sciences, Space Life Sciences, Space Technology and System Development, Space System Operation and Utilisation, Space Policy Law and Economy, Space and Society Culture and Education. A major initiative is the development of a series of 'Cosmic Studies' and 'Position Papers' dealing with science, engineering, social and policy aspects, including the Study on Cost-effective Earth Observation Missions. Here we use the outcomes of the symposia on Small Satellites for Earth Observation, a biannual conference that takes place in Berlin hosted by DLR. The 6th Symposium is scheduled to take place from 23rd to 26th April 2006.

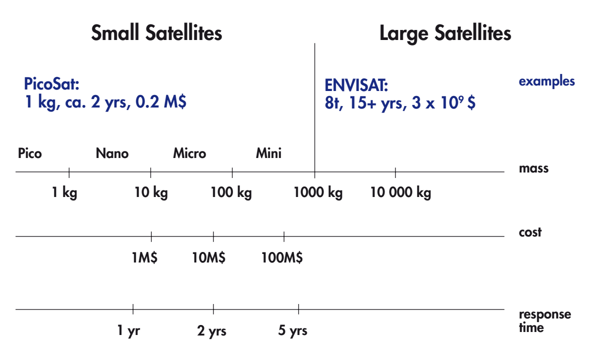
Please elaborate upon your own role and involvement in IAA.

Elected as a member in 1997, I from the beginning promoted small satellites by initiating and organising IAA symposia in Berlin and the Small Satellite Session at the annual IACs. I chaired the study on Cost-effective Earth Observation Missions carried out by a group of 36 experts with various backgrounds and from differing disciplines such as science, engineering, application and management. These people originated from fifteen countries and five continents, ensuring unbiased results. I also organised the student prize paper competition and I co-chair the IAA symposium in Berlin, and the Small Satellite Symposium, with seven sessions at the annual IACs. As chairman of the IAA commission IV 'Space Operations and Utilisation' I am in charge of all academic activities dealing with (1) space activities and new concepts in space operations and utilisation, (2) communications, remote sensing, and navigation satellites, (3) small satellites for developing nations, countries emerging in space technology, and earth observation, (4) safety, rescue and quality, (5) EVA protocols and operations and (6) use of space facilities.

What markets do you expect for small-satellite missions?

Developing countries in particular use the possibilities of small satellites and restrict their requirements to the available technologies. But NASA and ESA are

Dr Rainer Sandau is chief scientist at the German Aerospace Center (DLR) in Berlin, Germany. He has accumulated over 25 years experience in space activities, involved along the way in the instrumentation for missions to Venus, Mars and Earth. He has also worked on instruments for small satellites ranging from earth-observation to comet-lander. The stereo camera designated WAOSS (Wide-Angle Optoelectronic Stereo Scanner) that he developed for the Russian Mars 96 mission flew on the DLR micro-satellite 'BIRD', dedicated to forest-fire detection and assessment. WAOSS formed the basis for the Leica ADS 40. Dr Sandau is (co-)author of over 160 publications, holds more than twenty patents and is (co-)editor of thirteen books and conference proceedings.



Comparison: mass, cost and revisit time of small and large satellites.

also increasingly considering the potential, which includes more frequent missions resulting in faster return of science and application data, a wider variety of missions and thus more diverse use and more rapid expansion of the technical and/or scientific knowledge base. Smaller countries also want to involve local and small industry in the projects. Interest on the part of the military would lie in short assembly and launch times, while the private sector would step in whenever profit comes into view. For the latter I see two application areas: mapping and disaster management. Other potential areas of commercialisation include low-Earth orbit systems enabling low-energy communication covering populated areas, and medium-Earth orbit systems for navigation in traffic, search and rescue. In the future all large systems such as ENVISAT with a development time of more than fifteen years will probably be replaced by small satellites. Large-satellite systems can be complemented by small satellites making specific measurements, such as the Normalized Difference Vegetation Index (NDVI), which could be corrected for aerosols and clouds using data from NASA's A-Train: a series of research satellites (Aqua, CloudSat, CALIPSO, PARASOL, Aura and OCO) that fly in formation.

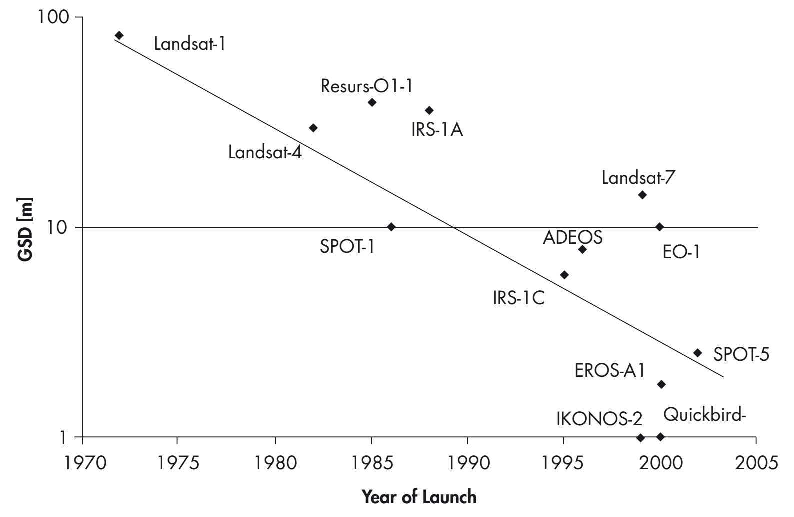
International Academy of Astronautics (IAA)
IAA, with its current approximately 1,100 full and corresponding members in 65 countries, was founded on 16th August 1960 in Stockholm, Sweden, during the eleventh International Astronautical Congress (IAC). Since then IAA has regularly brought together the world's foremost experts in astronautics to explore and discuss cutting-edge issues and issue guidance on the non-military use of space and exploration of the solar system. IAA is an independent non-governmental organisation recognised by the United Nations in 1996. Current president is Prof. Edward C. Stone, USA. IAA aims to foster the development of astronautics for peaceful purposes, to recognise individuals for their good work in the field, and to enable contribution to international endeavours and co-operation. IAA disseminates a diverse list of publications including *Acta Astronautica*, a monthly journal in English, a *Newsletter*, Proceedings of Symposia, and a *Yearbook*. It also releases electronic dictionaries in sixteen languages, *Weekly News*, *Position Papers* and *Cosmic Studies* and a scientific-paper database on the IAA website.

What do you mean by small satellites complementing large ones?

A mission can be cost-effective and meet the needs without making all the measurements itself. NASA's 'A-Train' makes individual measurements that support cross-platform science. Many sensors also use ancillary information, such as digital elevation models, to add context. One could readily envision a small-satellite mission that was intended to provide some niche product, such as crop-yield forecasting, in a particular region. Such a small satellite could produce a very specific measurement, such as NDVI, corrected using data from the A-Train. In such cases the spacecraft resource requirements could be quite small. Another approach is to decrease the ground-repeat delay by forming a co-operative that shares data produced by the elements of the constellation. Each member of the co-operative then gets the benefit of a much shorter revisit time, economies of scale being revealed as more members join the co-operative.

For such a future to become reality literally hundreds, or even thousands, of satellites would have to be rocketed beyond Earth's atmosphere. Wouldn't that be too costly?

Over the last ten years the availability of small launchers has increased and the prices are reasonable compared to the cost of small satellites; as a consequence small-satellite missions will no longer be constrained by launch costs. Most new launch systems are designed to serve an international commercial market. The entry of Russian and Ukrainian launch systems operated as joint ventures with US or European companies, marks a major shift. Although some nations still insist on the use of a 'national' launch capability, the general trend is towards the use in new launch systems of major components built in other countries, blurring national divisions. The increasing availability of these low-cost launchers and the development of dispensers have opened up possibilities for single launches of a constellation and individual payloads. The launch of the

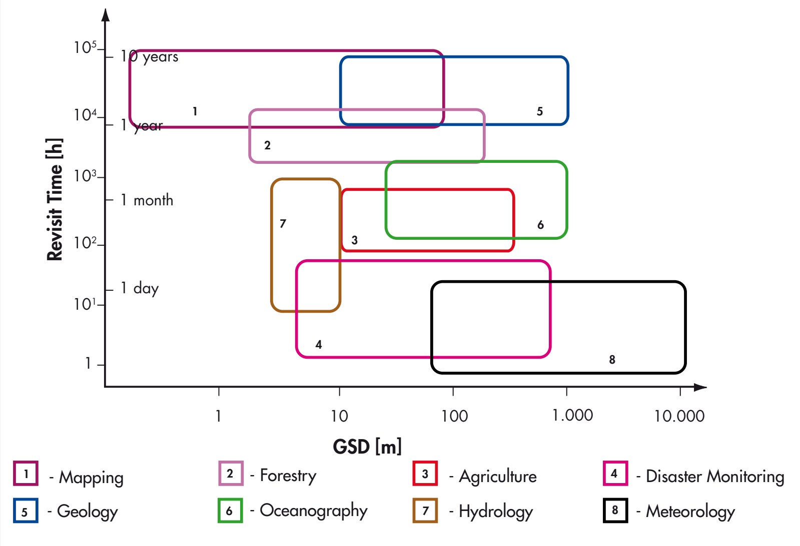


Trend in decreasing GSD (ground sampling distance or spatial resolution) of some civil earth-surface imagers from the early seventies onwards.

NASA/DLR GRACE satellites used Eurockot Launch Services, the joint venture owned by Astrium and the Russian company Khrunichev, to place two satellites in a closely controlled formation via a dispenser. This launch was the first commercial use of the Russian SS-19 ICBM, which provides the two booster stages for the Rockot launch vehicle, with a heritage of 150 flights. At the other end of the spectrum, Ariane 5 has been used to launch six auxiliary payloads along with the primary Helios satellite. This included Nanosat, Spain's first small satellite, with a mass of less than 20kg. Development of small launchers is also stimulated by 'space tourism'. On 4th October 2004 Burt Rutan and Paul Allen built and flew the world's first private spacecraft to the edge of space to win the $10 million Ansari X Prize. Perhaps the early history of aviation foretells the next twenty years of space access. Initially air travel was risky and expensive, but with the growth of a commercial market costs and risks dropped. Now air transport is so cost-effective that bulky agricultural goods such as apples are shipped halfway around the globe at prices competitive with local transport and production.

What is the feasibility of small-satellite missions for topographic mapping purposes?

Small-satellite missions are suited for topographic mapping, but the main question is how far the ground resolution can be increased. High ground resolution is connected to large focal length and often also large aperture, and satellite stability needs to support this. The high data volume generated at high rates needs to be transmitted to the ground within mass, volume and energy budget, which requires careful design of small satellites. Resolutions better than 10m can be achieved, as proven by TOPSAT (UK) with its 2.5m, and EROS-A1 (Israel) with its 1.8m. RapidEye, with 6.5m resolution, also belongs to this high-resolution category.



Earth observation requirements with respect to Ground Sample Distance (GSD) and revisit time for eight application areas ranging from Mapping to Meteorology.

Mission	S/C mass	Instrument	Instrument Mass/Power	GSD [m]	Launch
EROS-A1/ Israel	250 kg	PIC	36 kg/140 W	1.8 m	2000
TOPSAT/ UK	120 kg	HCROC	30 kg/30 W	2.5 m	2005
EROS-B/ Israel	350 kg	PIC-2		0.82 m	2005
Rapid Eye/ Germany	150 kg	REIS	62 kg/73 W	6.5 m	planned
Diamant-1/ Germany	250 kg	MSRS	70 kg/120 W	5 m	planned

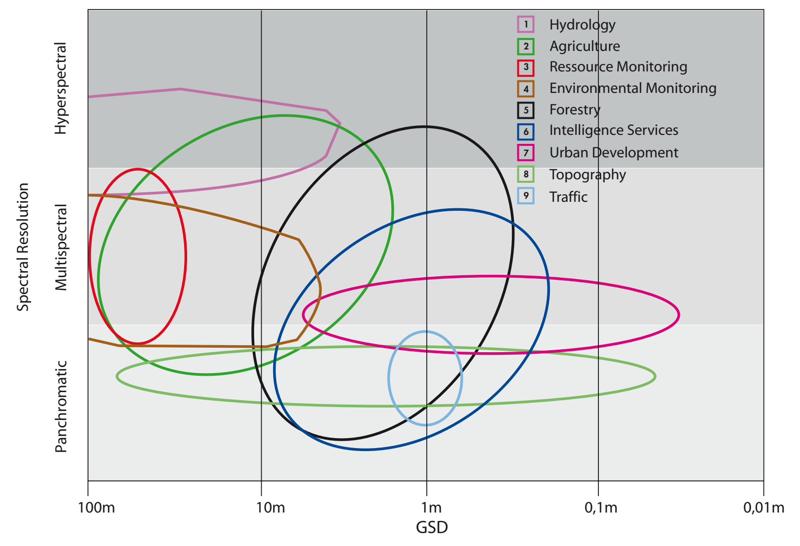
***Table 1**, Overview of topographic mapping missions using small satellites.*

In addition to mapping you have also mentioned disaster-management as an important application area. What are the crucial developments for this application?

In disaster-management we find application fields such as cyclone and storm, El Nino, flood, fire, volcanic activity, earthquake, landslide, oil slick, environmental pollution, industrial and power-plant disaster. The technology developments in the space segment from which disaster management would benefit result first of all from higher performance of the satellites themselves and secondly from the on-board sensors. Better performance of satellites can be achieved by ongoing improvements in subsystems such as board computers, data-handling systems, transmitters, solar arrays, batteries and GPS receivers. On-board sensors will grow in resolution both geometrically and radiometrically and will have more spectral channels. The feasibility of passive radar (SAR) micro-satellites flying in formation with an active radar satellite is being investigated. Furthermore, the costs of launching and operating small satellites will drop, making them affordable for dedicated constellations. Data stemming from different satellites and constellations will increasingly be used in an integrated fashion, increasing revisit time and information content. There will be increasing onboard processing of acquired data, resulting in high-level data products suited for direct use as soon as data reaches ground stations.

What do you see as the biggest long-term challenges?

The increasing world population will demand new or better methods to provide food and water in sufficient quantity and quality, despite higher risks of pollution and shrinking agri-



Earth observation requirements with respect to spatial resolution (GSD) and spectral resolution of nine application areas ranging from Hydrology to Traffic.

cultural areas. This will demand global observation and control of resources using specialised satellite systems. Small-satellite missions can contribute to disaster management, agriculture, forestry, ocean and coastal zones, atmosphere, weather and climate, ice and snow, land-use and land-cover change and mapping. In this context, the biggest long-term challenge is developing a robust commercial market that supports the manufacture of small satellites. Small satellites appeal to the pride of some nations and provide a means for enforcing the industrial base and attracting students into high-tech industry. After the first few satellites, however, investments may no longer be justified by the nation eager to gain space-faring status; manufacture should remain relevant and cost-effective. In many markets space technology has entered the era of diminishing returns; for example, are there market gains in imaging at one centimetre when imagery of 1m is available? This 'plateau effect' means that more vendors can aspire to provide the same product. How many suppliers can the market support? It may be that the market can support more suppliers of imagery if revisit time is a key driver. The user draws products from several independent sources and understands enough about each to produce the product. Raw data products, though, are not likely to capture many more users; small satellites can supply tailored products that address specific needs. Vertical integration of the industry to provide instruments, data and integrated data products is likely to spur significant growth.

If there is a topic we have not already covered and upon which you would like to elaborate, please feel free to do so now.

Most of the key points elaborated here are based on the results of the IAA study group on Low-cost Earth Observation Missions, published by A. A. Balkema Publishers, a member of Taylor & Francis Group plc, Leiden, The Netherlands, 2006. ISBN 10: 0-415-39136-9, ISBN 13: 9-78-0-415-39136-8, 160 p.◆

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3)Topographic mapping requires careful design of small satellites

4) Biggest challenge is developing a robust commercial market

Information Content of High-resolution Satellite Images

Mapping with OrbView-3 Images

The information content of OrbView-3 and Ikonos imagery is compared, using the Zonguldak area in Turkey as test area. Although OrbView-3 images are qualitatively slightly inferior to Ikonos panchromatic scenes, they can be used for the generation of topographic maps at scale 1:10,000. However, they are not suited for 1:5,000 mapping, for which scale Ikonos images also show limitations.

By Hüseyin Topan, Gürcan Büyüksalik, Zonguldak University, Turkey and Karsten Jacobsen, Leibniz University, Germany

In operation since 2004, OrbView-3 is one of the recent very high-resolution space sensors, offering images of 1m panchromatic and 4m multispectral Ground Sampling Distance (GSD). In mapping terms both geometric accuracy and information content are important, but the required geometric accuracy can be reached without difficulty provided that images are not degraded by atmosphere and sun-elevation effects. As a rule of thumb, the GSD should be at least 0.1mm of the map scale, corresponding to scale 1:10,000 for 1m GSD.

Visual Comparison

Examination of information content has to be done by visual inspection (Figure 1). OrbView-3 and Ikonos have approximately the same resolution, but comparison shows that edges are sharper in the Ikonos image and that whilst OrbView-3 shows cars only as blobs, structural elements are visible in Ikonos. The GSD of 0.62m offered by QuickBird enables identification of more detail. On the other hand, the 5m GSD of Spot 5 limits the use of these images to the creation of maps of smaller scale. Buildings are still visible but they cannot be mapped in detail, and sometimes back-gardens will be identified as streets. Many of these differences result from sensor configuration, radiometric resolution, recording conditions and terrain characteristics.

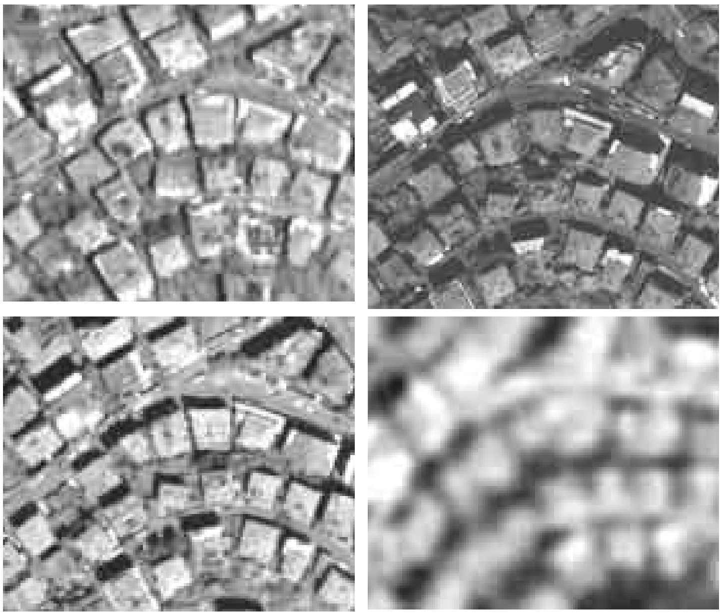

***Figure 1,** Information content of satellite images depends mainly on Ground Sampling Distance (GSD). All images cover the area of Zonguldak, Turkey: (from left to right, from top to bottom) OrbView-3 (GSD: 1.07m), Ikonos (GSD: 1.00 m), QuickBird (GSD: 0.62m) and Spot 5 (GSD 5m).*

Sensor Configuration

OrbView-3 uses staggered CCD-lines; two CCD-lines are shifted by 0.5 pixels against each other so that the pixel size projected on the ground for nadir view is 2m and adjacent pixels overlap 50% in both directions (Figure 2). The effective GSD of 1m resulting from such over-sampled pixels differs from nominal GSD of 1m. OrbView-3 takes 2,500 double lines per second, but the satellite footprint speed is 7.1km/sec, which requires permanent change of view direction to slow down angular speed. The resulting slowdown factor is 1.4 (Figure 3). The effective GSD as determined by point-spread analysis of sharp edges does not show loss of resolution against the nominal GSD, but it can be manipulated by contrast enhancement.

Radiometric Resolution

OrbView-3, Ikonos and QuickBird have a radiometric resolution of

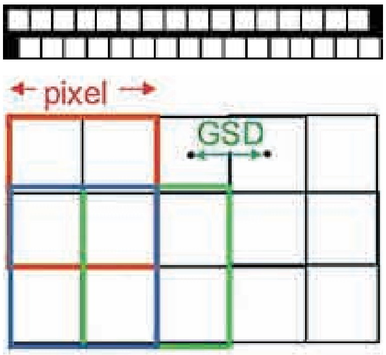

***Figure 2,** OrbView-3 sensor characteristics: staggered CCD-lines (top) result in over-sampled pixels (bottom).*

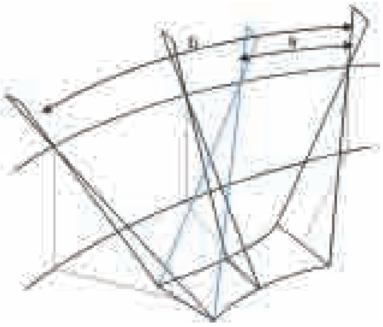

***Figure 3,** Slowdown imaging by permanent change of view direction: slowdown factor b/a 1.4.*

***Figure 4,** OrbView-3 image represented in original 11bit radiometric resolution (left) and in 8bit radiometric resolution (right).*

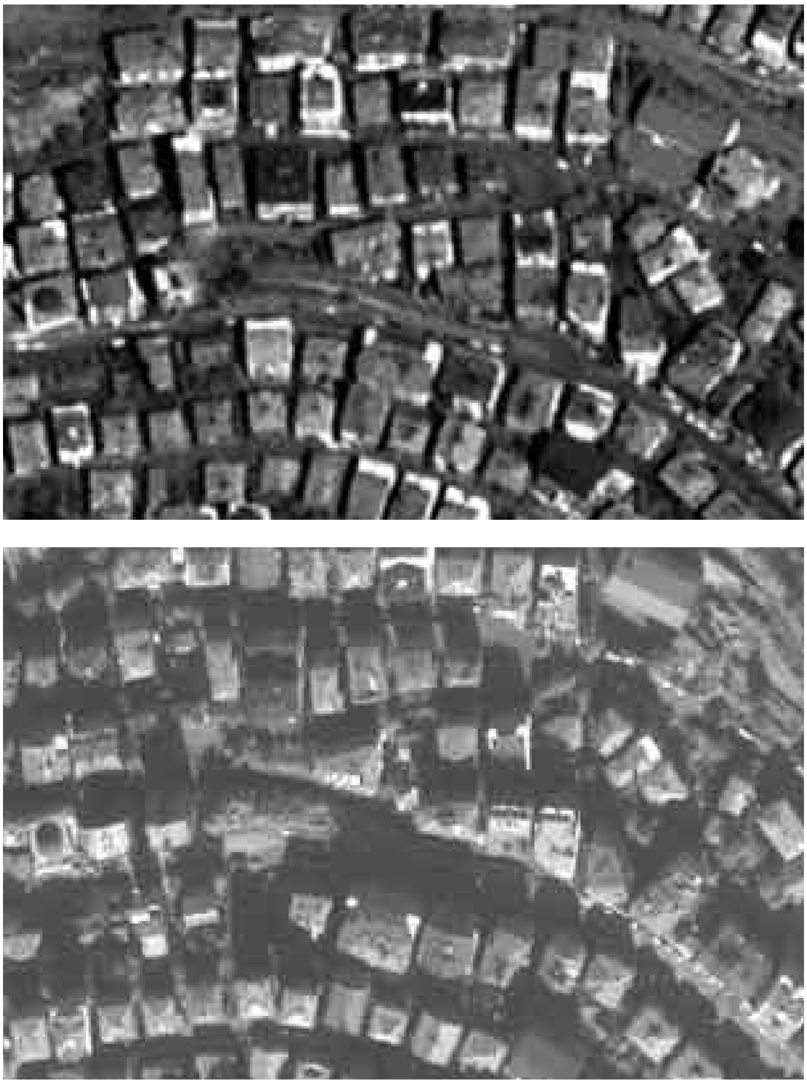

***Figure 5,** (Top): OrbView-3 with 63° sun elevation, (bottom): Ikonos with 41° sun elevation.*

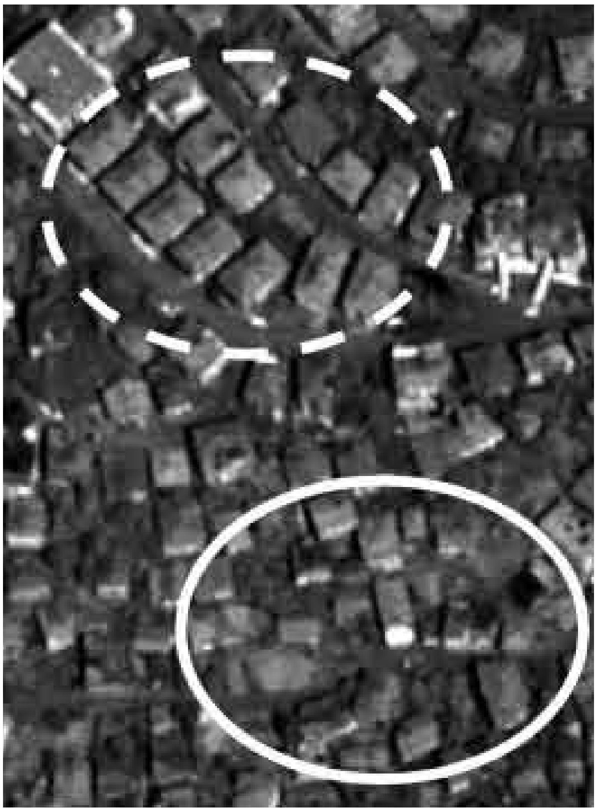

***Figure 6,** OrbView-3 showing planned built-up areas (dashed ellipse) and unplanned ones (solid ellipse).*

11bit, with which 2,048 grey values can be represented. However, the grey values within one scene will not cover the whole range and a qualified change from 11bit to 8bit grey values does not lead to significant loss of information. Only in some crucial areas do differences appear between the original 11bit and the derived 8bit grey values. Figure 4 shows more details in the roof in the original 11bit image than in its 8bit counterpart. This may be important for automatic image matching, but for mapping purposes it is unimportant because in both cases the building can be sufficiently well identified in all required detail.

Recording Conditions

Haze, clouds and smoke may reduce contrast; enhancement is possible but the resulting image quality will not approach that of images taken under optimal conditions. Sun elevation and azimuth cause shadows that hinder identification of details (Figure 5). With a sun elevation angle of 63°, shadows in the OrbView-3 image are not so long as in the Ikonos image with a sun elevation angle of 41°. Shadows cause identifi-

Shadows hinder identification of details but sometimes support object identification

Object	Image	Det	Rec
Large individual buildings	OV	***	***
	IKO	***	***
Small individual buildings	OV	***	**
	IKO	***	***
Wide roads	OV	***	***
	IKO	***	***
Small roads	OV	***	**
	IKO	***	***
Sport grounds	OV	**	**
	IKO	***	***
Cemetery area	OV	**	**
	IKO	***	***
Coast line	OV	***	***
	IKO	***	***
Sideline of roads	OV	**	**
	IKO	***	***
Wall	OV	**	*
	IKO	**	**
Pavement	OV	**	**
	IKO	***	***
Footpath	OV	**	*
	IKO	**	**
Pool	OV	*	*
	IKO	***	***
Grass land	OV	**	**
	IKO	***	***

Table 1, *Summary of detection (DET) and recognition (REC) possibilities of OrbView-3 (OV) panchromatic and Ikonos (IKO) pan-sharpened images. Good:***, Medium:*, Difficult: **

cation problems in scenes with narrow streets, high buildings and terrain inclination, as is the case in the north of the Zonguldak area, but sometimes shadows may support object identification. For example, a helicopter landing-pad might at first sight look like a roof, but missing shadow may indicate that it is on the same level as surrounding grassland.

Terrain Characteristics

Contrast is the dominant component of image interpretation, but identification of objects also depends on their characteristics. Planned areas, with larger, well-arranged buildings can be more easily mapped than unplanned areas with smaller and irregular objects, especially when the latter occur in hilly terrain (Figure 6). Identification of objects in planned areas does not result in significant differences between OrbView-3 and Ikonos panchromatic images, while in unplanned areas the better image quality of Ikonos resulted in a larger number of identified objects. Not every building has a rectangular shape and, particularly in hilly terrain, walls may not be parallel. Figure 7 shows a building of irregular shape (a), a rectangular building (c) and a low building throwing little shadow (b). The latter has not been identified during the mapping exercise, mainly because of missing shadow. OrbView-3 cannot take panchromatic and colour images simultaneously as do Ikonos and QuickBird, so no direct pan-sharp-

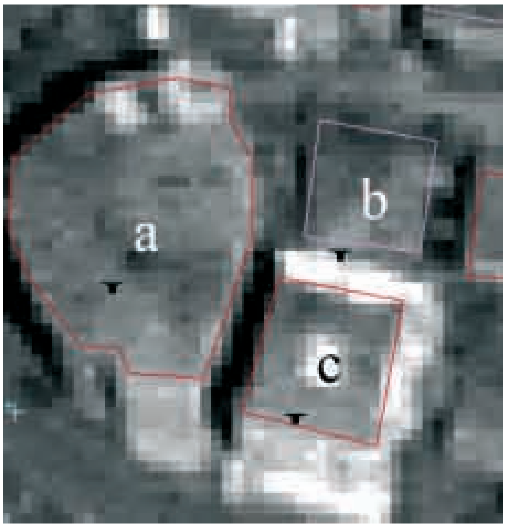

Figure 7, *OrbView-3 image showing building of irregular shape (a), unrecognised building (b) and building of usual shape (c).*

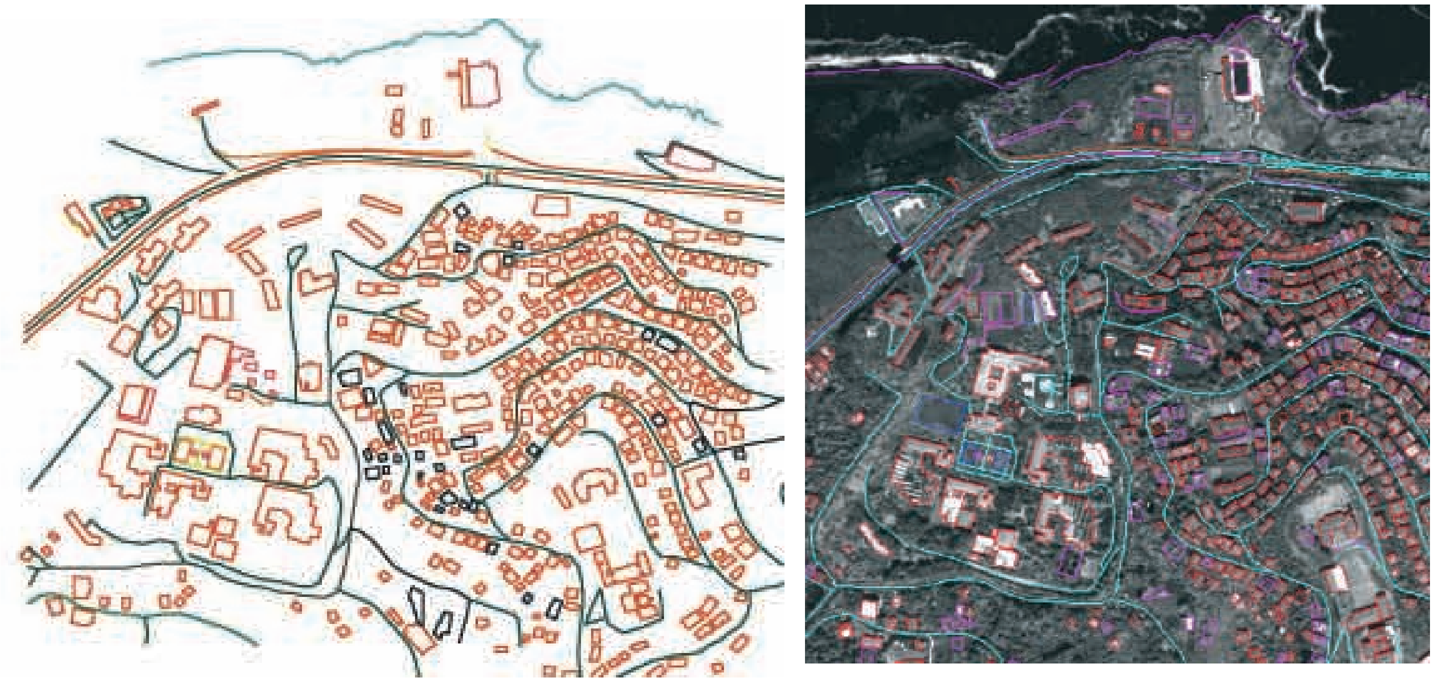

Figure 8, *Mapping based on panchromatic OrbView-3 image (left) and on panchromatic Ikonos image (right).*

ening was possible. Mapping with pan-sharpened Ikonos and QuickBird images simplified object identification, but this does not mean that more objects can be identified; the number was insignificant.

Results

Table 1 summarises the detection (DET) and recognition (REC) possibilities of features and objects in OrbView-3 and Ikonos imagery. Figure 8 shows maps created from panchromatic OrbView-3 and Ikonos images. All buildings and nearly all roads have been recognised in the Ikonos image; a few roads in shadowy areas have not been recognised. In the OrbView-3 mapping 93% of the buildings and 96% of the roads mapped with Ikonos are seen, while only 33% of the pavements could be identified. These results demonstrate that OrbView-3 images are well suited for creation of 1:10,000 topographic maps.◆

Biographies of the Authors

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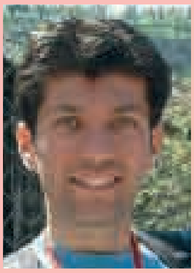
Karsten Jacobsen received a PhD in Photogrammetry from Leibniz University, Hanover, Germany. He is academic director of the Institute of Photogrammetry and Geoinformation at the same university. His main research area is numerical photogrammetry, especially the use of space imagery.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ORTHORECTIFICATION AND GEOMETRIC QUALITY ASSESSMENT OF CARTOSAT-1 FOR COMMON AGRICULTURAL POLICY MONITORING: FINAL RESULTS

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KEY WORDS: CARTOSAT-1, geometry, digital elevation model, errors, quality, agriculture

ABSTRACT:

The European Union uses remotely sensed data in a large operational programme to monitor subsidies given to farmers and to identify irregularities in claims. The trend over the last few years has been in sharp increase in the use of very high resolution sensors, with a number of different sensors being used in a complementary manner. For instance, whilst instruments able to provide imagery with a ground sampling distance (GSD) of <1m make up the primary use (with acquisition in 2006 of around 150,000 km2), sensors acquiring data with around a 2m GSD are in general used as a back-up in case of primary instrument acquisition failure. Cartosat-1 test data, which falls into this 2nd category and potentially could provide useful data in the main programme, was imaged in the framework of the Cartosat-1 Scientific Assessment Programme (C-SAP).

This paper presents the final results of sensor model and DEM extraction for Cartosat -1 full dataset (two stereo pairs) for a test site located near to Mausanne-les-Alpilles (France), used since 1997 with a time series of reference data for the checking of farmers' aid applications. The chosen approach was to: First, determine the best method for image rectification and model adjustment; this was verified by undertaking a series of orthorectifications and comparing results with independent check points. Off-the-shelf software (PCI Geomatica 10 and LPS) was used for the evaluation. Second, upon selecting the chosen model creation approach, undertake the extraction of the DEM using the stereo pairs, and proceed with the DEM quality assessment. Moreover, for the assessment of the DEM generation purpose fully automated models were prepared based on GIS techniques. In brief, the full DEM covering the study site is compared with a reference DEM (of higher quality), and assessed according to the land cover and slope categories thus enabling application specific assessment of the DEM generation and potential for image use. Lastly, the quality assessment of SRTM (open source) for the same AOI was prepared and compared with obtained results form Cartosat – 1 DEM extraction process evaluation.

1. INTRODUCTION

1.1 Study aim

The European Union (EU) uses remotely sensed data in a large operational programme to monitor subsidies given to farmers and to identify irregularities in claims. In 2005, 24 EU member states were involved, checking around 163,000 farms on 210 sites (Chmiel et al., 2004). The so-called "Control with Remote Sensing" operation utilises a mixture of high and very high resolution. Details of the technical specifications and methodology can be found at the project web site (European Commission, 2006a).

The instruments with GSD being around the 2m to 3m range (e.g. EROS 1A, Formosat, etc.) are used in the control operation as back-up instruments, in case of VHR non-acquisition for the site due to technical or meteorological problems. CARTOSAT-1 was tested here with the prospect of performing in such a role.

However, due to two-stage plan of the project, the analysis has been divided into two parts based on 31Jan2006 and 06Feb2006 image pairs, respectively. A first part was completed on the 31Jan2006 image pair and results published (Kay and Zielinski, 2006). The present paper summarizes the whole project including selected results of the first study.

The study objectives were:

1. to determine a reliable, operational, approach for orthorectification of the CARTOSAT-1 scenes provided for testing;
2. to assess the performance of the instrument for production of orthoimagery;
3. to assess the suitability of the stereoimagery for DEM generation;
4. to check the suitability of Shuttle Radar Topography Mission (SRTM) data (open source) for the same area of interest.(USGS, 2007)

1.2 Study site

The study site located near to Mausanne-les-Alpilles (France) has been used by the European Commission Joint Research Centre since 1997 (Spruyt and Kay, 2004). It therefore comprises a time series of reference data (DEMs, imagery, ground truth) and presents a variety of agricultural conditions typical for the EU (Kay and Zielinski, 2006).

1.3 Instrument, imagery acquired

CARTOSAT-1 (NRSA, 2006) carries two state-of-the-art Panchromatic (PAN) cameras that take panchromatic stereoscopic pictures of the earth in the visible region of the electromagnetic spectrum. The swath covered by these high resolution PAN cameras is 30 km and their nominal instantaneous geometric field of view is 2.5 metres.

The images acquired for this study consist of two sets of stereo pairs, provided as Orthokit GeoTiff format, referenced to the WGS84 ellipsoid and datum. Other specific data are given in Table 1 below.

Instrument	Fore	Aft
Acquisition date	31 Jan 2006	
Image ID	065103300601	065103300602
Scene Centre Roll	-13.6degs	-13.6degs
Sun Azimuth	157,9degs	156,5degs
Sun Elevation	26,0degs	28,9degs
Acquisition date	06 Feb 2006	
Image ID	065103300501	065103300502
Scene Centre Roll	+4degs	+4degs
Sun Azimuth	159,8degs	158,2degs
Sun Elevation	28,3degs	31,0degs

Table 1. General characteristics of imagery acquired for the Mausanne-les-Alpilles site

The location and overlap of the two datasets is given in Figure 1 below. The two image pairs almost fully cover the selected area of interest with a significant overlap.

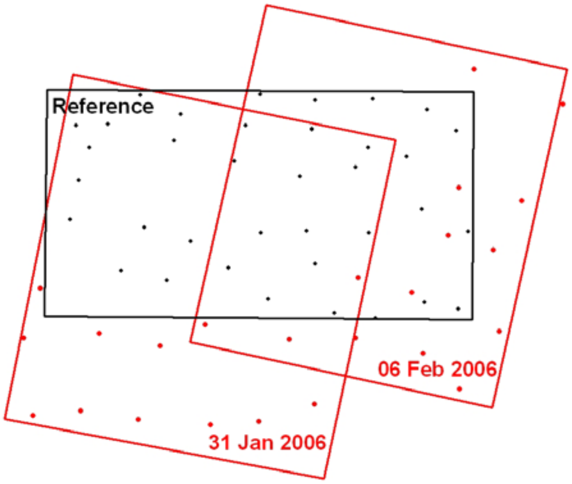

Figure 1. Location of imagery acquired for the Mausanne-les-Alpilles site (presented in UTM zone 31N projection). The black rectangle defines the reference data range and nominal study area of interest. New ground control points collected specifically for the study are shown.

1.4 Reference data

The study site comprises a number of higher quality images and digital elevation models, as well as a set of high quality (centimetre precision) GPS points were available for the test site. Nevertheless, due to the specific characteristics of the instrument in question, it was considered necessary to undertake further field work and acquire (using dual frequency GPS) a new series of 25 points at specific locations, chosen on the CARTOSAT-1 imagery (red marked points, Figure 1). Additionally, higher quality imagery, acquired in 2003 using an airborne digital instrument (Spruyt and Kay, 2004), was used to photointerpret a new set of 35 points (black marked points, Figure 1).

The DEM (surface model derived from airborne imagery, with a posting of 2m) presents a verified quality (linear Root Mean Square Error [RMSE] in the vertical axis, Z) of better than 0.60m on well defined points.

2. METHODS

2.1 Software

Only off-the-shelf software was applied in the test, in accordance with the main objective of the study, i.e. to determine the operational use of CARTOSAT-1 imagery. Specifically, Geomatica 10.02 and the Leica Photogrammetric Suite (LPS v9.0) were tested for orthorectification performance. Geomatica 10 permitted the testing of both physical and RPC approaches to orthorectification; LPS by contrast allowed only the RPC method. Since both approaches are mainstream in the operational programme, all three methods were tested.

DEM creation was made using the LPS software. All assessment of the results was made in a separate GIS environment, to ensure compatibility of results.

2.2 Orthorectification

The chosen approach was to determine the best method for image rectification and model adjustment; this was verified by undertaking a series of orthorectifications and comparing results with independent check points. The basic approach applied for geometric assessment is the standard method developed by the JRC (European Commission, 2006b). This method applies the strict use of independent check points in the evaluation of image correction performance, permitting the comparative benchmarking between different instruments and different processing methods.

The orthorectification approaches applied are the mainstream RPC bias method and physical model (Toutin, 2004). In all cases, the image pairs were (where possible with the software) corrected together using tie points. All ground control points used, check points and tie points were identically chosen for each test, to ensure that comparisons were not complicated by different selection. Furthermore, the transfer of image coordinates was achieved via file import, to ensure interpretation errors were constant between tests.

Note that we specifically opted to use the best available DEM for the orthorectification process in order that any influence of the DEM would be eliminated at this stage.

2.3 DEM extraction and quality assessment

The automatic DEM extraction based on area base matching in LPS was undertaken. The extraction process based upon selecting the chosen model creation for both image pairs. Additionally, all parameters have been set equally including search area, correlation size, coefficient limit pixel size for both image pairs.

The assessment of the DEM generation was made using a complex method developed during the testing of SRTM, Reference3D products (Kay et al., 2005).

Additionally, for the project needs a full automatic processing chain was applied based on IDL script and ArcGis batch models. In general, the processing chain allows the comparison of the full DEM dataset covering the study site with a reference DEM (of higher quality). The approach allows the full assessment by three broad land cover categories (derived from CORINE land cover classification) and four slope categories (supplied from the reference DEM), thus enabling application specific assessment of the DEM extraction and potential for image use.

Furthermore, identical processing was applied for the SRTM (open source) data (USGS, 2007). To assure statistical compliance of tested data samples, the SRTM DEM was resampled to the same resolution as DEM generated from Cartosat 1 image pairs (GSD=10m).

Using the above methodology, the area of interest was divided into the land cover and slope stratification. The importance of each stratification category is given in Table 2 below.

Land cover classes				
Contribution of the class [%]	Arable	Forest	Urban	Water
	64	30	5	1
Slope classes				
Contribution of the class [%]	0–10%	10–20%	20-40%	> 40%
	71	7	9	13

Table 2. Importance of the land cover and slope strata for the study site. Note that the water class were excluded from the analysis (from, Kay and Zielinski, 2006)

3. ORTHORECTIFICATION RESULTS

This chapter presents the orthorectification results of the Cartosat 1 imagery pairs (Table 1) evaluated in the project. Most of the results here refer to the February image pair whilst results from the January image pair (Kay and Zielinski, 2006) are included for comparison.

3.1 Geomatica software

3.1.1 Physical model rectification

A series of rectifications were carried out, using identical ground control points and the highly accurate reference DEM. In accordance with the software documentation (PCI, 2006), the minimum number of ground control points (GCPs) required for the use of this model is only 6. We therefore started tests using six well distributed ground control points; extra GCPs were progressively added. However, the regular distribution was maintained.

Figure 2 shows the performance of this test series for each image (fore, aft) for the image pair 06 Feb 2006. The results are presented for each image, with the check point linear RMSE value presented for the Easting (X) and Northing (Y) value separately.

The results show the decreasing tendency of RMS values with an increased number of GCP used in the tests. We can see that single RMS values of Nothing (Y) are shifted and twice bigger than Easting (X) for aft image (2.9m, 5.0m respectively) and opposite for image forte (4.6m, 2.7m respectively) of February dataset where 11 GPC were used. In reflection the previous test based on the January image pair the best performance (2-3.5m of RMSE$_{1D}$) was achieved for the two images tested only when a minimum of 11 GCPs were used (Kay and Zielinski, 2006).

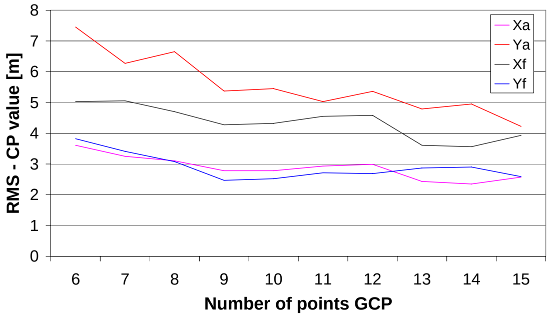

Figure 2. Number of GCPs required to orthorectify using the Geomatica physical model – February image pair.

3.1.2 RPC rectification

The RPC approach in Geomatica 10 applied was the bias method, applying the coefficients supplied with the imagery. We prepared the test using a 0, 1st order and 2nd order adjustment but in this paper only the results of 1st order adjustment are presented. Again, the testing began with the use of the same six GCPs, identical to the physical model test. The identification of the points was done via a file import of image coordinates, thus ensuring that no interpretation differences exist between the two tests.

The results of February image pair (Figure 3) show a very good performance of the RPC method in this software compared to the physical model. We can observe that results are stable, but the RMSE value imperceptibly increase while the number of GCP increase and they do not exceed the 3.5m RMSE value (in either X or Y). In comparison with the earlier results, performance in the Easting (X) direction was the same, however errors in the Northing (Y) direction were considerably worse for the January image (more than 20m with first test - 6 GPCs).

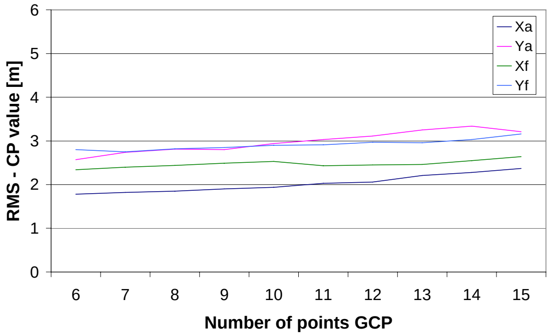

Figure 3. Number of GCPs required to orthorectify using the Geomatica RPC model. Stable condition was reached starting from six GCPs.

3.2 LPS Software: RPC

No physical model for the CARTOSAT -1 was available in the LPS software used for testing. We therefore applied exclusively the RPC approach, again undertaking a series of rectifications, using identical ground control points and the highly accurate reference DEM.

Figure 4 (below) shows that the rectification of February image set performance very similar to January data set. Linear RMSE (that is, either X or Y directions) was reduced to around 1 pixel, even when only 6 GCPs were used for the rectification. The RPC approach showed stable results for both test data.

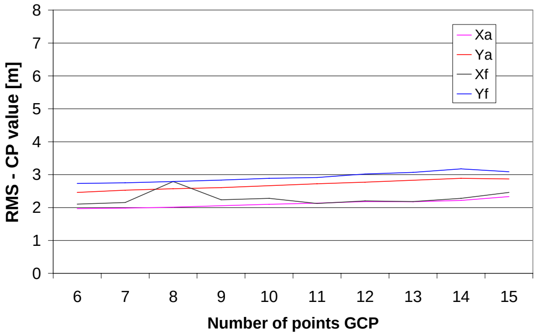

Figure 4 Number of GCPs required to orthorectify using the LPS RPC model. Stable condition was reached using six points.

3.3 Orthorectification, summary

Like in the first paper, the results demonstrate that it is already possible to perform good orthorectification using standard off the shelf software packages. It should be recalled that in both cases, the CARTOSAT-1 specific satellite models used were relatively new and therefore it is likely that they will improve.

With both packages it was feasible to correct the imagery to within the specifications required for the operation of the EU Control with Remote Sensing program.

As after processing of the first image pair, we chose to proceed using the LPS software package, applied with the RPC model block solution and just 6 ground control points.

4. DEM PROCESSING

4.1 DEM Extraction

The DEMs were extracted from the full overlap area available for the test site stereo pairs (Table 1) using the model built from the RPC approach using 6 GCPs per image pair, in the LPS software. The grid sizes for the DEM generation were 10m, and were generated for the full overlap of the image pairs. However, the assessment presented here is only for the area for which a reference DEM was available (Figure 1).

For both image pairs, during the creation of the DEM, all six GCPs and tie points (15 for each image pair) were used as seed vertices. This input enhances the relative position of the DEM generated and improved results. Moreover, all parameters were carefully set for the January and February image pairs equally (e.g. search area, correlation size, coefficient limit, pixel size, etc.) to avoid that any additional factors influenced processing results. Furthermore, no filtering or post-processing of the DEM to change the result of the automatic extraction was applied.

Note that image data delivered were acquired in the first months of 2006 (January and February) and characterize very low sun elevation angles (Table 1) and strong, long shadows. Moreover, image contrast is low, strongly influencing the correlation of image pair results. It can be easily seen on the so-called General Mass Point Quality reports (internal report of LPS) where matched thresholds are established as follows; “Excellent” in the range (1-0.85), “Good” (0.85-0.70), “Fair” (0.70-0.50) and two categories of “Isolated” and “Suspicious”. For the January image pair, 58% of the generated vertices were considered “Excellent” matches according to the internal software quality reporting, 23.5% were considered “Good”, and with some 18.4% considered “Suspicious”. For February we obtained slightly better correlation results in the above categories; 67.3%, 19.7% and 13.0%, respectively.

Rather than filter the DEMs to eliminate peaks and spurious vertices, we used this information as a mask and the results relate to vertices classed as “Excellent” or “Good”. In total we examined 81.5% of January and 87% of February images pairs generated vertices.

4.2 DEM assessment

The chapter presents the overall results of the comparison with the higher-grade reference DEM. An automatic “raster to vector” approach (Kay et al, 2005) was applied using bilinear interpolation to determine the elevation of each Cartosat-1 DEM 10x10m cell position in the reference data set. The processing chain delivers the standard deviation and mean of the elevation differences (between the Cartosat-1 DEM point and corresponding interpolated vertex) and stores the raster results for further analysis.

In next stage of the process we continued by analysing the performance of the DEM generation first by land cover category and then by slope category, separately. Note that in the results presented, the values for the land category include all slope categories, and vice versa.

As can be seen in Figure 5, the comparison of the AOI overlapping DEMs generated from two Cartosat-1 image pairs (January and February) gives good performance expressed by Standard Deviation [SD] values, 3.80m for the Arable category (64% of AOI), well inside the required quality for the Control with Remote Sensing program (established as 5m $RMSE_Z$). Again the Urban (5% of AOI) category also presents for both image pairs a similar result (SD between 3.80m and 3.90m),

The forest areas (31% of AOI) result, presents slight increases between January and February image sets, from 5.12m to 6.59m, respectively. We recorded that the mean values for both image sets within all three categories are not significantly different from zero with respect to the Standard Deviation results presented, although the Forest category shows a bigger shift (trees height) than the Urban or Arable categories. Most noticeable for the breakdown by slope category for January and February image sets (Figure 6) is the stability of the Standard Deviation result, which exceeds 5m only for the steepest category (>40%, covering 13% of the study vertices).

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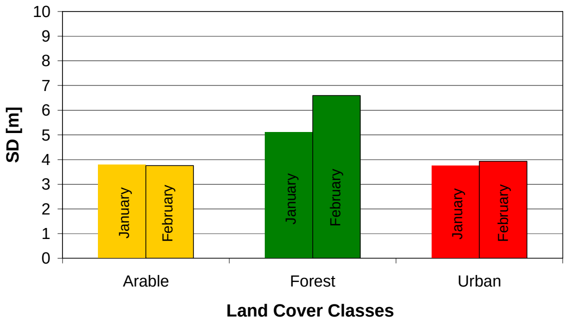

Figure 5. Overall results of the DEM comparison, by Land Cover category

Again it should be recalled that these results mix all land cover categories for each slope category. For this reason we further detailed (Figure 7-8) the analysis by splitting each land cover category by slope category for each image pair separately.

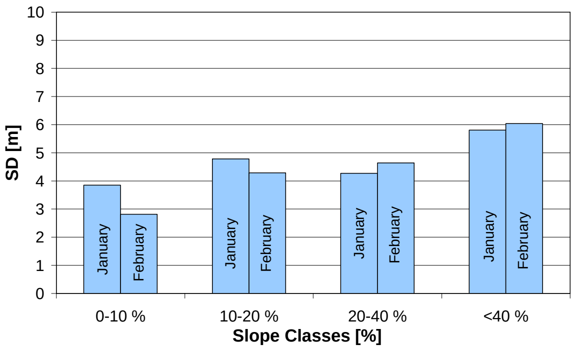

Figure 6. Overall results of the DEM comparison, by Slope category

Figure 7 and Figure 8 presents these results graphically, where the results are split for each land cover category by slope category for January and February, respectively. Generally, we can see that the results degrade with increased slope, for all types of land cover category.

However, the results obtained on February image pair are slightly better (Figure 8), probably caused by correlation performance. Nevertheless, for all but the steepest of categories, the DEMs created are inside the requirements of the Control with Remote Sensing program.

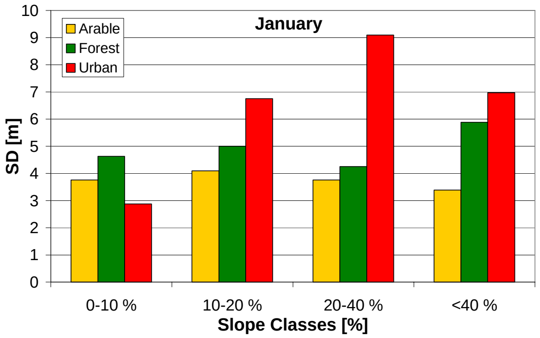

Figure 7. Results of the DEM comparison of January image pair, by Land Cover and Slope category
(Kay and Zielinski, 2006)

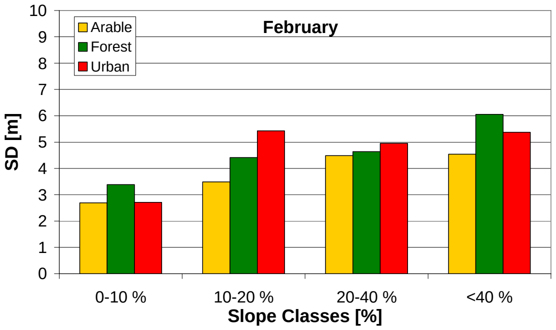

Figure 8. Results of the DEM comparison of February image pair, by Land Cover and Slope category.

We conclude that for normal agricultural and forest area applications, the performance is in general compatible with the stated performance of the instrument (NRSA, 2006) and inside the required performance for the Control with Remote Sensing program.

4.3 SRTM assessment

We noted previously that, whilst these results appear promising, they also seem comparable or slightly worse than the publicly available SRTM data set (Kay, et al 2005, Rodriguez et al., 2006) with a reported Standard Deviation result well under 5m. It was worthwhile, therefore, to complete this statement with a similar analysis of the SRTM data available for the test site in question.

The same process chain described above was applied to SRTM (open source) data. However, the original data was resampled to 10x10m grid size to assure the statistical compliance of volume tested data samples.

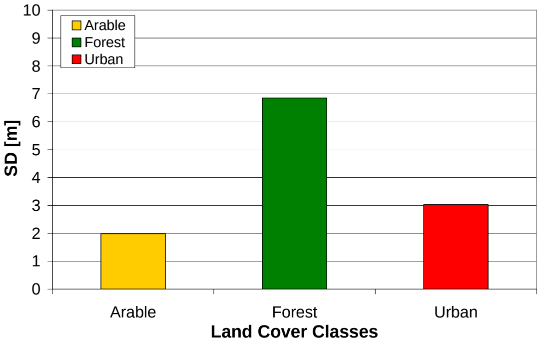

Figure 9. Overall results of the SRTM comparison, by Land Cover category

Figure 9 presents graphically results obtained on SRTM data against the reference DEM. We found that for the two classes (urban and arable area – 69% of AOI) the SRTM performance was better than our Cartosat-1 based product. However, for the forest class we received a bit worse SD value due to a product sampling (3 by 3 arcsec) in relation to terrain changes inside the origin pixel.

The SRTM product has a predictable performance in the site tested, working better on terrain that is of lower slope angles (Figure 10). Within first two slope classes (79% of whole AOI) the SD values are inside the required performance but again, the results of slope categories include all land cover categories.

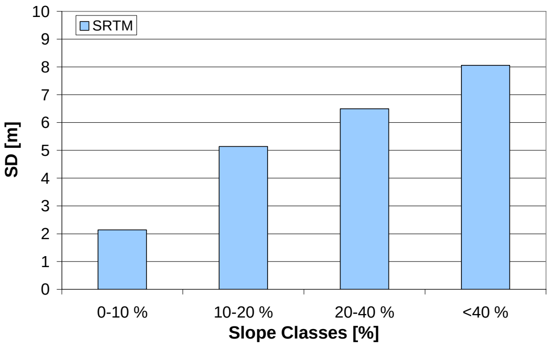

Figure 10. Overall results of the SRTM comparison, by Slope category

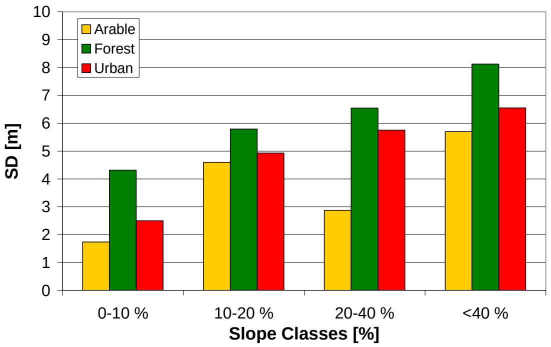

Figure 11. Results of the SRTM comparison, by Land Cover and Slope category.

5. CONCLUSIONS

In the project the series of orthorectification tests were completed to evaluate the operational performance of the CARTOSAT-1 sensor for the production of orthoimages. Our tests show that it was comparatively straightforward to produce reliable products, well inside the expected performance of a modern satellite instrument, from 2 to 3m $RMSE_{1\text{-}D}$ (i.e. in either Northing or Easting directions) mainly using RPC bias method in LPS with just 6 GCPs.

Some difficulties were encountered when using the Geomatica 10 RPC method and physical model approach (for February image pair), but these are not thought to be directly related to the RPC coefficients provided with the imagery.

After choosing the LPS method for sensor geometry modelling, the extraction of the corresponding DEMs produced good results that again are suitable for the operational purposes of the EU Control with Remote Sensing program, i.e. better than 5m $RMSE_Z$ for typical agricultural areas.

The results of SRTM product preformed better than their standard specification with stable behaviour for the test site and the product is a useful alternative or even the preliminary source for operational EU programs.

We concluded that the data provided for the test were very suitable for use as a back-up instrument, compatible with the requirements of the EU control program and commensurate with the technical characteristics (spatial and spectral resolution) of the sensor.

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Chapter 7

Quality Issues

By Mathias Lemmens

The aim of this chapter is to get acquainted with quality issues. A measure of quality often used is Root Mean Square Error (RMSE). In the previous chapters, more specifically in Chapter 4, we have extensively treated the role and computation of RMSE and therefore we will skip further treatment here. An important data handling technique when processing quantitative data is least squares adjustment; a technology which has been developed as a standard data handling technique within surveying. Below we will give a short introduction to the concepts of Least Squares. During a practical we will apply the technique for determining the transformation parameters of a coordinate transformation. Other quality issues treated in the chapter are accuracy standards and examples of data spatial quality degradation.

Least Squares Adjustment

Having many applications in math, science and engineering least squares adjustment is a mathematical procedure that uses redundant measurement to determine a "Most Probable Value" for some unknown parameter or parameters by "minimizing the sum of the squares of the residuals of the measurements." Redundant here means that in the mathematical model used to link observations with unknown parameters, there are more observations than unknown parameters. It is commonly used in geodesy, photogrammetry and surveying. Surveyors use least squares methods to verify the reliability of their measurements, and to "fit" their observations onto known positions. Most GPS users rely on a least squares adjustment for distributing the error in their measurements throughout a network of observations. For the user, however, these calculations are invisible because they are carried out by software. In surveying and mapping, least squares is normally used to perform network or traverse adjustments or to estimate the transformation parameters that "Best Fit" a set of observations. Least squares is a flexible adjustment technique that can be adapted to any mathematical model, whether it relates measurements to unknown parameters in a linear, quasi linear, or non-linear sense.

Least squares also takes account for the quality of the measurements in the adjustment procedure. Some measurements may have a better quality (lower standard deviation) than others. By weighting the measurements according to their quality, their contribution to the determination of unknown parameters can be controlled. Thereby the parameters receive some portion of the error that relates to the quality of the measurement. A second advantage of a least squares adjustment is the analysis of precision of the adjusted measurement data. Additional statistical tools present in most least squares adjustment software will enable the user to determine the level of precision attained in the survey.

It is common knowledge to all surveyors that every measurement, whether collected using conventional surveying equipment or GPS equipment, contains error. These errors can be classified as random errors (inescapable errors due to the precision of the equipment being used), systematic errors and blunders (mistakes in the measurement). It is extremely important that blunders are detected and removed from measured data, otherwise, the results will be unreliable. Least squares also enables to evaluate whether there are errors present in the measurements and to remove these errors. As stated above, when the statistical model of random errors of the measurements are known, least squares allows in addition to calculate the random errors present in the calculated parameters. Performing a least squares adjustment has been proven as the best method to detect blunders in survey measurements. Blunder detection is accomplished through statistical analysis of the measurements. These statistical tools help point to data suspected to contain a blunder.

Although detection of blunders and survey precision can be performed through other means, using least squares will give users the best tools to ensure that final adjusted measurements are devoid of blunders. Consequently, least squares adjustment has been developed as a standard data processing and data handling technique in surveying.

The following paper, “Cadastral Survey Accuracy Standards”, by Belle Craig and Jerry L. Wahl, is published in Surveying and Land Information Science.

http://www.acsm.net/publist.html

Direct comments on this paper may be emailed to Bob Dahl at

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Cadastral Survey Accuracy Standards*

Belle A. Craig and Jerry L. Wahl

ABSTRACT: The fields of land surveying and mapping have benefited from technology innovations. New technology has not changed the boundary surveyors' core responsibility, which is to locate, mark, and document the boundary in a legally defensible matter, for their clients, the adjoiners, all future owners of real property, and interests in real property adjoining the boundary. Nonetheless, the global positioning system and computers have changed the way land surveyors measure, analyze, and calculate data. Land owners and land managers have turned to geographic information systems to make complex ecological and economic decisions. Boundaries are often the first line of evidence of the extent of an interest held in land. Survey accuracy standards need to address all types of cadastral spatial data and be consistent with the Federal Geographic Data Committee standards to facilitate data sharing. Current cadastral survey accuracy standards are inadequate and need to be changed to reflect the way modern land surveys are conducted and address the fact that geospatial data, once incidental to the survey process are now one of its primary products.

Introduction

This paper will examine the impacts of changing technology on the accuracy of cadastral boundary surveys, and how those changes can affect the actual terms in which accuracy is expressed. It also explores the changing roles and responsibilities of the cadastral surveyor and the private sector survey community in defining, developing, and managing survey data for inclusion in a National Integrated Lands System.

The rapid rate at which advances in technology are occurring have outpaced the ability of many individuals and organizations to react quickly and appropriately to change. It will take years to fully understand the impact of emerging technology on the land surveying profession. The fields of land surveying and mapping have benefited from technology innovations in personal computers, total station instruments, and global positioning system (GPS) equipment, to name just a few. New tools for rapid acquisition of measured data are continually being developed and refined, and the Internet has provided the means to share such data with people worldwide.

Most of the public land in the U.S. is in the western states and in Alaska. Many socio-economic changes have occurred in the western U.S. that challenge the multiple-use philosophy of government agencies managing federal lands. Recreation and tourism on public lands have increased and often collided with the interests of ranchers and miners. Increased awareness of the environment and the sensitivity of natural ecosystems to external influences have changed land management policy on federal lands. Federal land management agencies have turned to technology, specifically Geographic Information Systems (GIS), as an aid to make complex management decisions about federal lands.

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The Public Land Survey System (PLSS) is the basis of land tenure in 30 of the 50 states in the U.S. The boundaries of public land, often legally defined by the PLSS, are a federal land management agency's first line of evidence of the existence of a federal interest in the lands they are tasked with managing. In response to the GIS needs of land managers, the Bureau of Land Management, Cadastral Survey has diversified its mission. Charged with establishing, marking, and maintaining boundaries of public lands, Cadastral Survey is participating in the development, design, and implementation of a National Integrated Land System (NILS).

The increased need for better tools to manage complex issues in a GIS environment has spawned

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* This paper on the need to change the terms in which cadastral survey accuracy is expressed is currently under review by the Chief Cadastral Surveyor, Bureau of Land Management. If adopted, the recommended changes could have ramifications outside federal lands and beyond the survey of federal land boundaries. Direct comments on this paper should be e-mailed to Bob Dahl at <robert_w_dahl@blm.gov>. To stay current with BLM's preparation of the next edition of the *Manual of Survey Instructions,* visit the Bureau of Land Management Cadastral Survey Manual Next Edition web site at: http://www.blm.gov/cadastral/Manual/nextedition.htm.

the need for Cadastral Survey to develop and manage a Geographic Coordinate Data Base (GCDB) (http://www.blm.gov/nhp/what/lands/title/cadastre.htm). This database will serve as a spatial representation of the Public Land Survey System in a GIS environment, which will actively be managed by cadastral surveyors. The database is still incomplete in some states and, currently, the accuracy of the GCDB data is of a map quality. The database has been designed to allow for ongoing improvements to the accuracy of the spatial data with repeated inclusion of modern survey data. The GCDB will be the foundation of the National Integrated Land System.

When conducting surveys of federal lands, cadastral surveyors reference boundary surveys to the National Spatial Reference System (NSRS). This system is a network of Continuously Operating Reference Stations (CORS) and horizontal and vertical control stations maintained by the National Geodetic Survey (NGS). Geodetically referenced survey data are used to define the link between the Public Land Survey System and natural resources managed by federal land management agencies. Inclusion of accurately measured geographic data will serve to further refine the overall accuracy of the Geographic Coordinate Data Base, as well as provide accurate project control for future boundary surveys of public lands.

Current Cadastral Survey accuracy standards are inadequate and need to be changed to reflect the way modern field surveys are conducted and to be consistent with the Federal Geographic Data Committee (FGDC) standards for spatial data to facilitate data sharing (FGDC 1998). This paper will address the responsibility of Cadastral Survey to redefine accuracy standards for control surveys, which reference boundary surveys to the NSRS, and the accuracy standards for boundary surveys of federal lands.

Cadastral Survey Limits of Closure

Traditionally the reporting of accuracy in the various editions of the *Manuals of Surveying Instructions* has defined survey accuracy in terms best expressed by precision ratios. This method for evaluating survey accuracy is well known and published in many textbooks. Generally speaking, the allowable limits of closure for surveys of federal lands are derived from the summation of all of the latitudes and departures along the surveyed lines of a closed traverse. The purpose of establishing limits of closure is two-fold. The most important reason is to make sure all surveys meet a standard for accuracy. This allows for the orderly establishment of a uniform Public Land Survey System, which is, by definition, a rectangular system of survey. Standards must be established and met to maintain the general rectangularity of the system. Table 1 provides a summary of limits of closure documented in the *Manuals of Surveying Instructions*.

This look at historical instructions demonstrates that cadastral survey has gradually increased the expectation of the accuracy of field surveys and also changed the manner in which a standard for accuracy is expressed. The changes were based on refinements made in survey instruments and field survey techniques (*The Manual of Survey Instructions, 1947*):

> In reference to accuracy of surveys ...The question relates to the matter of the dependability of the record direction and lengths of lines as currently returned, or the reliance that can be placed on those values. To what extent can those values be incorporated safely into other surveys that presume to set up definite standards of accuracy, or mapping purposes of various classes. ....This is a test that bears directly on the improved technique, which is now practiced in the making of public land surveys (3-234:238).

It should be noted that the standards of accuracy documented in manuals of survey instruction were created primarily for application to original and completion surveys. The General Land Office did not officially allow for dependent resurveys or retracements of original surveys of the PLSS until the passage of the Resurvey Act of March 3, 1909 (35 Stat. 845) as amended June 25, 1910 (36 Stat. 884: 43 U.S.C. sec. 772).

The Manual of Survey Instructions, *1947* refined a standard of accuracy that offered varying “classes of surveys.” These survey classes addressed issues such as the difficulty of terrain and the value of the land being surveyed as having merit in the determination of what an expected standard of accuracy would be. The issue of land values is still very important. A hundred years ago the value of public land in mountainous terrain, in a wilderness, may have been considered negligible. Many Americans currently feel that the value of our public land that has remained a wilderness is priceless. Consideration of land value and terrain should continue to play a role in the development and application of any new cadastral survey standards. The difference in land values in urban and

Manual	Limits Applied
1855	p. 21: Limits of closure for a township was stated at 3 chains, and 50 links, or 1:548. p. 24: Closures of interior sections state that the east and west section lines must be within 100 links of 80 chains, and the north and south section lines must be within 100 links of equal length, or 1:320.
1864 Instructions	p. 11: The only significant change from the 1855 Manual is a re-wording that the east and west section lines must be within 100 links of the most southerly line in that tier of sections.
1881	p. 39: Limits of Closure of township exteriors were reduced to 3 chains, 1:640. Closures of interior sections state that east and west section lines must be within 80 links of 80 chains, and the north and south section lines must be within 80 links of equal length. Which equates to a precision ratio of 1:400.
1890	p. 40: Limits of Closure of township exteriors were 3 chains, 1:640. Closures of interior sections state that east and west section lines must be within 80 links of the actual distance established on the south boundary of the township controlling the width of the tier of sections, must lose within 50 links north or south of the true corner: and the north and south section lines must be within 80 links of equal length. Which equates to a precision ratio of 1:640.
1894	p. 59: Same as the Manual of 1890.
1902	p. 66, section 175: Same as the 1890 Manual.
1919 advance sheets	p. 159. Section 174: The same as the 1902 manual, but describes the limit of closure as a precision ratio instead of using fallings, as 1:640 in latitude or departure when computed separately or 1:452 when combined.
1930	p. 222, section 234 same as 1919. 1:640.
1947	p. 234: same as 1919. This manual also refers to the limits of closure such as "the rectangular limit," "limit for control of new surveys," "limit relating to defective exteriors and section lines," and the "limits for subdivision."
1973	p. 98: The current Manual of Survey Instructions for Public Lands. Limits of Closure change to 1:1280 for latitude or departure or 1:905 combined.

Table 1. Manual limits of closure by edition.

rural areas should be taken into consideration when analyzing errors associated with boundary surveys (3-234:238-9).

Direct and Indirect Measurements

Measurements are made to determine unknown quantities. All measurements contain error. There are two methods—direct and indirect—by which measured quantities are determined. Direct measurements are made by applying an instrument directly to the unknown quantity and observing its value, such as measuring a distance between two points with a tape. Surveyors make indirect measurements when, for example, they measure angles and distances directly to a point to compute station coordinates. From these "directly obtained" coordinates other angles and distances may be derived indirectly by computation.

Public domain surveyors have historically used direct methods of measurement; they measured boundary lines by staying as close as possible to the true line. Most surveyed lines were measured directly with a chain. Off-line traverse methods only increased the amount of chaining needed to measure a line. Indirect methods of survey, such as triangulation, were used to make measurements across canyons or other obstacles and were generally an exception as a primary method of survey.

Today the most common method of survey measurement is indirect. With the introduction of the Electronic Distance Meters (EDMs), chaining as the dominant method of measuring distances became obsolete. Programmable calculators have simplified the task of survey calculations, and surveyors use combinations of field methods such as traversing and radial survey techniques to measure lines. The Global Positioning System (GPS) is by its very design an indirect method of determining a measured quantity. Conceptually similar to a conventional resection, the GPS method enables surveyors to determine the unknown horizontal position of a station from measurements made from GPS satellites whose positions are precisely known.

Both the direct and the indirect method of measuring surveyed lines have their advantages and disadvantages. For example, if the intent of a survey is to post and mark the lines of a timber sale, then direct measurements along the lines to be posted are the best method. However, the direct survey method is often more susceptible to propagation of errors such as transfer of azimuth and a general lack redundant measurements. In the case of indirect measurements the surveyor can minimize the number of instrument occupations made during the course of the survey. This, unlike direct measurement methods, allows the surveyor to minimize the propagation of error during the course of a survey. Indirect survey methods do, however; require more redundant measurements to validate survey data. Varying terrain and vegetation influence the choice of survey method and equipment, particularly if the goal is to optimize survey efficiency in the field. This notwithstanding, it is at the surveyors' discretion whether they employ indirect or direct methods of survey and which combination of survey instruments they use to complete the survey.

It should be noted that the current *Manual of Surveying instructions, 1973* was issued prior to the common use of the electronic distance meter. Many significant advances in survey technology have occurred in the last two decades. New technology has not only changed the field methods used or ways survey lines are measured, but refinements in instrumentation and use of GPS has provided the means to make more accurate survey measurements. Today instrument specifications for accuracy are better, and when the equipment is used properly, it will produce more reliable results. In order to further develop the concepts of accuracy of modern surveys, we need to examine how measured survey data are reduced and evaluated.

Methods of Survey Data Reduction

To understand the impact of new technology on the survey profession, we need to look at the evolution of reducing survey data in the public land survey system. This aspect of surveying has been radically redefined by the personal computer.

The PLSS is a unique survey system, continental in size and rectangular by definition. The PLSS has many unique characteristics, as described in "*Geodetic Aspects of Land Boundaries in the PLSS Datum in a Cadastral Computation System*" (Wahl et al. 1992):

> Many boundaries and most elements of the Public Land Survey System are defined in a geodetic sense, for example lines of constant true bearing, latitudinal arcs, meridians, long, straight lines, parallel and other equidistant lines. (p.1) …. Straight lines on the ground are lines of constantly changing bearing. (p.4) ….Lines of constant bearing in the PLSS datum will be "curved" on the ground. (p. 5)

These "curved" lines would include state boundaries, standard parallels, township exteriors, section lines, subdivisional lines of sections, and many grant and reservation lines. There are exceptions where boundaries are not lines of constantly changing bearing or curved, which might include portions of grant or reservation boundaries and some portions of state boundary lines.

> In the current world of surveying there are two widely varying computational methods in common use. The first method is a simple plane survey computation performed on a local orthogonal coordinate system. Another method in use for control survey applications utilizes geodetic systems with spherical or ellipsoidal coordinate systems (latitudes and longitudes). A common variation of geodetic computations is the use of any number of coordinate projections or grids (Wahl et al. 1992, p.1).

Of the computational methods commonly available in existing software is the use of plane computations based on local orthogonal coordinate systems. Yet, it is the responsibility of cadastral surveyors to lay out of lines which require what is best described as a geodetic computational system. The methods that surveyors are to follow to achieve intended results are described in the current *Manual of Survey Instructions, 1973*:

> Details of the plan and its methods go beyond the scope of textbooks on surveying. The applications to large-scale area requires an understanding of the stellar and solar methods for making observations to determine the true meridian, the treatment of the convergence of the meridians, the running of true parallels of latitude, and the conversion of the direction of lines so that at any point the angular value will be referred to the true north at that place (pp 1-3).

According to Wahl et al. (1992):

> It is generally understood by surveyors that the use of simple plane methods while convenient, is not necessarily suitable for large-scale surveys. Why this is so is not usually so well understood. Plane survey computations have become associated with almost all boundary and construction surveying while geodetic methods are most often associated with control surveying, mapping, and route survey. However there are many large-scale surveys where this distinction between computational systems cannot be maintained. In many large-

> scale surveys it becomes necessary to deal with some geodetic aspects of the survey (p. 1). … A good example of a survey system with significant geodetic components is one used throughout the western United States, the Public Land Survey System (PLSS)...during the course of the first original surveys... it became apparent that the term "rectangular" is a generality that cannot be effectively maintained over a large survey extent (p. 2).

Various editions of the *Manuals of Survey Instructions* tell the surveyor how to interpret certain mathematical results obtained when surveying on a sphere or ellipse using a simple plane orthogonal coordinate system. Among them is the "apparent misclosure" due to the convergency of meridians. Addressing this issue, Wahl et al. (1992) wrote: "A theoretically perfect survey will appear to misclose in the PLSS datum" (p. 6).

The common availability of personal and handheld computers has allowed cadastral surveyors to move beyond the simple plane orthogonal coordinate system to spherical and ellipsoidal coordinate systems that reflect the true geodetic nature of the Public Land Survey System. Computers became available to cadastral surveyors before adequate computer software. Working with the University of Maine, BLM's Cadastral Survey developed a Cadastral Measurement Management (CMM) software. This software was developed specifically for dependent resurveys, but can be used for original surveys as well. At the time of its development there were no commercially available software systems that fully met the computational needs of the cadastral surveyor in the field. This software has allowed the cadastral field surveyor to work using a spherical or ellipsoidal coordinate system.

When using a continental or global coordinate system, such as latitude and longitude, the surveyor is able to spatially relate his boundary survey to the rest of the world. The premise of directly and accurately relating different types of spatial data, through the use of common coordinate systems, is a fundamental principal of a Geographic Information System. With the widespread development and uses of GIS there are now many software vendors that employ the use of geodetic coordinate systems. Global Positioning Systems and the software to reduce GPS data also use global coordinate systems.

The development of the CMM software made another important tool available to the cadastral field surveyor—the ability to analyze survey measurement data using a statistical method called least squares analysis. At the time CMM was developed many other software vendors employed this tool for data and error analysis. In the field of surveying the focus of other software applications was on control surveys, not large-scale boundary surveys. Currently, commercially available software does not include capabilities for doing specialized computations related to dependent resurveys of the PLSS, but it will soon.

Although the least squares analysis is a relatively new tool for the cadastral surveyor, this method of error analysis as developed in the eighteenth century. The first published article on the subject was written by Adrian-Marie Legendre in 1805, entitled "Methode des moindres quarres" (http://www.history.mcs.st.andrews.ac.uk/history/Mathematicians?Legendre.html). Originally developed for analyzing celestial observations, the method was first investigated by Pierre-Simon who laid its foundation in 1774 (http://www.history.mcs.st.andrews.ac.uk/history/Mathematicians/Laplace.html). Carl Gauss extensively used the method as a student at the University of Gottingburg in 1794 and is accredited with its development (http://www.history.mcs.st.andrews.ac.uk/history/Mathematicisans/Gauss.html). Concurrent, with the work of Laplace, Legendre, and Gauss, the first public land surveys, covering parts of Ohio, were made by the Geographer of the United States in compliance with the Ordinance of May 20, 1785. Using a least squares method for the analysis of survey measurements would have been impractical at that time. The Cadastral Survey did not apply adjustments to raw measured data in the past because most adjustments were biased. It has taken over two hundred years for the least squares method to be fully appreciated but with new technology, using least squares for the adjustment and analysis of measured data has become common practice.

Least Squares Analysis vs. Precision Ratios

All measurements contain errors, and all references in this discussion refer to random error. The treatment of systematic error and blunders is excluded from this discussion. There is a recognized distinction between the terms accuracy and precision. Precision measures the degree of consistency between measurements and quantifies the size of the discrepancies. Accuracy is the absolute nearness of a measurement to the true value of a measured quantity. For the sake of this discussion the term accuracy will refer to relative, not absolute, accuracy because, as reported by Wolf and Ghilani (1997, 1.3:2):

- No measurement is exact;
- Every measurement contains errors;
- The true value of a measurement is never known; and
- The exact sizes of the errors present are always unknown.

Past survey manuals expressed survey quality standards in the form of a closure precision ratio. Using a precision ratio to evaluate survey error has a well defined place in determining the relative precision of past surveys. It is a well understood principle that during the course of a dependent resurvey the limit of closure or standard in place at the time of the original survey is how past survey measurements are judged today. It is because of this that surveyors need to continue to evaluate resurvey data and calculate precision ratios, or loop closures for their work. The role of the surveyor is not to improve upon the work of historic surveys but to generally evaluate the quality of those surveys made in good faith.

Using precision ratios to evaluate survey work preformed today is mandated by the current *Manual of Surveying Instructions, 1973*. This method of quantifying error makes no attempt to identify measurement mistakes, or impart any information as to the positional error associated with any particular corner point of a survey or dependent resurvey. Precision ratios serve only to imply the general quality of the relative precision of a closed traverse. The loop closure has minimum redundancy and does not evaluate scale or rotational errors. The professional surveyor who is tasked with evaluating the accuracy of his work can easily find better tools suited to produce unbiased results.

Numerous general methods are available to disclose error in survey measurements. For instance, three angles measured in a plane triangle must equal 180 degrees. The sum of the angles measured around the horizon at any point must equal 360 degrees, and the sum of latitudes and departures must equal zero for closed traverses that begin and end at the same point. Each of these conditions involves one redundant measurement. In the case of three angles of a plane triangle, if only two angles were measured, angle A and B, the third angle, C, could be computed as C=180°- A-B. The actual measurement of the angle is redundant but allows the surveyor to assess the errors in the measurements made. The total angular error could be distributed by adjusting the angles and forcing the sum of the angles of the triangle to equal 180 degrees. This adjustment of the measured data would result in statistically improved precision. There are many different ways to adjust survey measurement data; some are more arbitrary than others.

In surveying, redundant measurements are very important. Prudent surveyors check the magnitude of the error of their work by making redundant measurements. These extra measurements allow the surveyor to assess errors and accept or reject measurements. They also make valid adjustment of survey measurements possible. The more a measurement is validated by additional direct or indirect measurements, the greater the likelihood of the measurement approaching the true value of the measured line. While the process of adjusting a plane triangle is relatively simple, the process becomes much more complex when analyzing large survey networks. Adjustments correct measured values so they are consistent throughout the network. Many methods for adjusting data have been developed, but the least squares method has significant advantages over all of them.

Least squares adjustment is based on the mathematical theory of probability and the condition that *the sum of the squares of the errors times their respective weights is minimized.* The least squares adjustment is the most rigorous of adjustments yet, it is applied with greater ease than other adjustments because it is not biased. Least squares enable rigorous post-adjustment analysis of survey data and can be used to perform pre-survey planning. These data-processing functions are greatly improved when least squares are used to compute a set of errors that have the highest probability of occurring.

The most important aspect of using least squares is that surveyors can analyze all types of survey measurements simultaneously. This could include horizontal and slope distances, vertical and horizontal angles, azimuths, vertical and horizontal control coordinates, and GPS baseline observations. Least squares adjustments also allow for the application of "relative weights" to properly reflect the expected reliability of different measurement types. An example would be weighting a line measured with a tape differently than one measured with GPS.

Least squares analysis has the advantage that after an adjustment has been finished, a complete statistical analysis can be made from the results. Based on the sizes and distribution errors, various tests can be conducted to determine if a survey meets acceptable tolerances or whether measurements must be

> repeated. If blunders exist in the data, these can be detected and eliminated. Least squares analysis enables precisions for the adjusted quantities to be determined easily, and these precisions can be expressed in terms of error ellipses for clear and lucid depiction (Wolf and Ghilani 1997, 1.7:9).

When computing loop closures of a closed traverse, precision ratios can only imply the general magnitude of the error. The "clear and lucid depiction of precision expressed as error ellipses" has radically changed the way a surveyor can look at survey error. Using least squares adjustments surveyors can express error in terms of positional tolerance of a single point, the relative error of all of the points in a network, or the range of precision within a large network.

As all new alternatives to long-standing practice, least squares adjustment of data has its own detractions. This notwithstanding, common availability of computers has made the use of least squares practical to achieve the same results regardless of the user. Even the most basic knowledge of statistical methods for data analysis will greatly aid field surveyors and prevent the misapplication of this data adjustment. The following serves to remind the surveyor that least squares can assist in identifying mistakes or blunders in survey work, but the need to remove them is critical to maintaining the overall integrity of the work. Results of least squares adjustments of survey data are applied only to the random error, which is generally small in magnitude. No adjustment is final until all blunders are removed (Hamming 1986).

> Probably the major fault with least squares is that a single very wrong measurement will greatly distort the results because in the squaring process large residuals play the dominant part- one gross error 10 times larger than most of the others will have the same effect in the sum of the squares, as will 100 of the others. Great care should be exercised before blindly applying any result (as is so often done); at least look at the residuals, either by eye or by some suitable program, to see if one or possibly a few measurements are wildly off (25.1 p. 431).

The least squares method of analysis of survey measurements is now commonly used in all aspects of surveying. Every cadastral surveyor who surveys the boundaries of public land has computer hardware and software available to perform least squares analysis and adjustment of survey data. Real-time Kinematic (RTK) GPS makes use of this process in the field to resolve baseline measurements on the fly. Root mean square error is evaluated in the RTK GPS survey data logging device in the field. Statistical methods of data analysis are also used in many natural resources related professions. When the various data from different sources are combined in a GIS, one of the first questions that comes to mind is how accurate are the data? How closely does the virtual picture of reality mimic the real world or actual conditions in the field?

Requirements of a Cadastral Standard

Before we get too involved in a discussion of the applicability of a given standard we would like to define what we want the standard to do. For our discussion we will distinguish between a "standard" and a "specification." Simply put, a standard attempts to define the quality of the work in a way that is ideally independent of the equipment or technology in use. A specification describes how to achieve a certain standard with a given set of tools, equipment or technologies.

We believe that any new cadastral standard should *be technology neutral*. The standard should be developed with the idea that it can be applied to new technology; the first test, however, is that the standard can be applied to current technology. This goal seems to fit the way most standard-making exercises are conducted, including the FGDC standards formulation. Another goal is that a new standard should be *inclusive*, i.e., it should not exclude major technologies that are currently considered acceptable. At the same time it should not permit the quality of the work to decrease from current standards. A standard should also be *understandable* and *useable* rather than confusing, ambiguous or difficult to apply.

What someone wants from a standard depends on how the data are used. For example, for mapping and GIS purposes the primary concern may be the positional accuracy of the corner locations, whereas for a boundary survey relative location accuracy from the adjacent parcel monumentation is critical and often of highest concern. However there are other survey aspects that are often overlooked, and this seems to be the case in all the standards we reviewed. Apart from the survey network used, procedures for how monuments are set need to be checked and evaluated. Another critical element is the actual stability of the monument itself. If a monumentation procedure only assures placement of the monument to the 3-cm level there are diminishing returns to evaluation the survey network at the 2-mm level. It is also clear that if the monument is subject to soil movement, frost heave, or man-made disturbances of a few centimeters, its use for future work is affected. Accuracy standards perhaps need additional elements to describe these factors.

Twenty years ago positioning accuracy needs were minimal; not even the U.S. Geological Survey (USGS) used cadastral data on a regular basis to depict land boundaries on their mapping products. At the typical USGS map scale of 1: 24K, 40 feet of accuracy was sufficient to conform to the National Map Accuracy Standards. The PLSS monuments found on the ground were the primary fiducial marks that related the cadastral survey to the map. Recently, and particularly over the past five years, we have seen a radical shift in the demand for and use of accurate spatial representations of cadastral surveys. Since about 1985 Cadastral Survey has began to require geodetic ties to ongoing surveys. With the advent of CMM, surveys are performed on a geodetic basis, while also integrating GPS (both static and RTK) in the new surveys. As a result of these changes BLM surveys are linked to other geospatial data directly instead of through their map depiction.

The modern BLM Cadastral Survey is a specialized subset of the traditional control survey. While it is useful (if not necessary) to advise users of the spatial accuracy of its products, the Cadastral Survey has the ability to perform surveys to meet a particular spatial need, such that what was once only incidental to the survey process is now an integral part of the execution of public land surveys, and these surveys produce spatial data as one of the primary outputs.

Application Modes of a Standard

A standard can be applied as a design tool, a requirement, and an evaluation tool. Used as a *design tool,* a standard will enable us to assess what equipment and methods we need to use on a particular project in order to achieve the standard. This application is part of planning for new work. If viewed as a *requirement,* a standard is applied during the duration of the project to ensure that the work complies with stipulated quality requirements. And lastly a standard can be applied as an evaluation tool to work of any source and vintage in order to "classify" the work so that various users can make best and proper use of the data from that source for varying purposes.

There are other terms that are sometimes used to describe these modes. An *a priori* method is one that is applied before the work is done, and it usually defines specific procedures and equipment to use. An *a posteriori* method is a standard or process that can be applied after the work has been done. This method is based on specific analysis of the survey data.

We may need to reiterate here why we want a standard in the first place. We are primarily involved in the original or subsequent location of land boundaries. The purpose of any standard is to assure a product or process meets a particular level of quality. The products that a cadastral survey produces are monuments and lines established on the ground, a written public record of the measurements, and evidence and reasoning behind any survey decision in the form of plats and field notes. There has been an increasing demand for a variety of additional products that derive from a spatial depiction of the survey lines and parcels.

There are three different types of spatial data that Cadastral Survey collects. These are the Boundary data in the form of bearings and distances between points, data that ties boundary surveys to the National Spatial Reference System (NSRS), and historical record data that is collected for inclusion in the BLM's Geographic Coordinate Data Base, GCDB. Each one of these types of data has very different expectations of accuracy, and as such should be classified differently. The GCDB data accuracy will not be considered in this discussion, but it is recognized as being dependent on the accuracy of cadastral surveys and NSRS control data from recent surveys.

In the early days of the Public Land Survey System the Act of February 11, 1805, was passed. This law declared that the original survey and its monuments are as if they "were without error" in the eyes of the law. This codification of a common law concept forgave a myriad of sins but also allowed the surveys to be completed expeditiously. Does this mean that there is no need for accuracy standards for Cadastral Surveys? We say *no* even though the same forces are in play today as then. First, we are predominantly not involved in performing original surveys. Today our primary role is as retracement surveyors. Whether doing original or resurvey work there has to be a compromise between scientific perfection, which usually takes longer and costs more, and low-accuracy work and methods that take much less time to produce. It must be recognized that low-quality work affects the actual use of the boundaries down the road.

Current technology allows us to approach accuracy with high scientific precision for little or no incremental cost over a merely adequate accuracy. The advantages of doing so for current and future generations of boundary survey users abound.

There will always be a compromise between accuracy and practicality, but the compromise is much closer to the ideal than ever before in history.

If one were to prioritize a list of the components of a cadastral survey, one would probably place good monumentation at the top of the list. Next would be the act of recording good descriptions of the monuments and the measurements relating to them. In the case of restored corners, documenting the decisions that were made about what and how the point was established is important. Following that would be the description and measurement of accessories to the monuments, and next would be measurements between a monument and surround monuments of the same survey describing the lines of the survey. Last would be the tie relating the survey to the National Spatial Reference System (NSRS).

This prioritization reflects our traditional and natural hierarchy of importance. In part this relates to the sanctity of the original monument, but a good portion of our ranking is derivative from the concepts of error propagation. For example, it was originally assumed that short line distance measurement was more accurate than long distance measurement, and that ties to accessories in the immediate vicinity of a corner would be more trustworthy than those from the nearest corner perhaps a half mile or a mile away. Similarly, measurements to nearby corners of the same survey were assumed to be more reliable than ties to distant control points. However, in the current technological climate, the difference between these levels has shrunk if not almost disappeared. In fact, it may be possible that the measurement in a cadastral survey to a bearing tree, taken to the nearest degree, and rounded to the nearest link or half link in distance, is less reliable or accurate than that to the nearest other monuments of the survey, and even on occasion to its coordinates relative to NSRS.

The monuments and lines of a survey or resurvey are the primary physical manifestation of the survey on the ground. If the physical evidence cannot be found because of inaccurate measurement, then they are of no use. If the monuments and lines become obliterated, then any method used to restore them will only be as reliable as the measurements left behind in the record or on the ground. A sloppy bearing to an accessory will lead to ambiguity and confusion at the very least, and it may lead to restoring the corner to the wrong place. The same can be said for the procedures defining restoring lost corners. If the record being used is inaccurate, then the procedure suffers.

The reason for going into this discussion is that accuracy (to the degree that it can be achieved economically) assures more stable boundaries. The boundaries, when in need of rehabilitation, can be restored in almost the same place. The stability that derives from good measurements has obvious real economic value. If the survey is related through standard procedures to the NSRS there is yet another level of stability added to the others we are familiar with; it is like an additional layer on the onion of information which may someday be evidence that contributes to the stability of boundaries.

Having accurate measurements is a good thing, and reasonable accuracy is now economical. If a monument is destroyed, it can reasonably be restored from its accessories to within a small spatial tolerance, generally less than the size of a monument cap. If its accessories are lost, then proportionate methods will restore it to nearly the same location. In addition, spatial representation in GIS systems will be relatively accurate, such that decisions about the locations of improvements and resources on the land will not be subject to costly errors and assumptions.

Possibly the most quoted book on land surveying in this century, Mulford's Boundaries and Landmarks, addresses some of these concerns about defining accuracy. The point we wish to make is well stated by surveying educator and author Ben Buckner in his article on accuracy standards published in the *Professional Surveyor* magazine (1997), and it refers to the "Mulford effect." Commenting on Mulford's view that, "It is far more important to have faulty measurements on the place where the line exists, than an accurate measurement where the line does not exist at all," Buckner wrote:

> I don't think Mulford intended for surveyors to disregard measurement accuracy. Yet, I have heard many surveyors quote this…and scoff at the idea of correcting for systematic errors or doing any kind of measurement analysis other than proportionate measurement. My own perspective on the subject, and what I would like to think Mulford would say now if he knew how many surveyors have misused his earlier statement, is that it is important to first locate the corner from [an] analysis of all relevant evidence bearing on its original position, applying common law rules and principles and, after the corner is thus located and monumented, to perform accurate measurements between the monuments, to analyze the measurement uncertainty, and to make appropri-

> ate and theoretically correct statements about this uncertainty.
>
> In this statement, the use of measurements in the first phase of restoring the corner is implicit. If measurements are cited in a description or on a plat, they are part of the evidence. Where monuments are "called for," the case law dictates that measurements are secondary or informative, but they must be considered nevertheless. Therefore, analysis of their precision and accuracy becomes involved in the process of analyzing the evidence. Furthermore, when all other evidence of the corner is lost, measurements rise to the status of "controlling." Thus, the importance of accuracy and error control, both in the original measurements and in retraced measurements, cannot be denied.
>
> Professional surveyors cannot ignore measurement accuracy and analysis of measurement uncertainty for three reasons. The first is explained in the previous paragraph. From a practical and legal standpoint, measurements are part of the evidence. The second is a more philosophical. Measurements embody the very meaning of surveying. Ignoring measurement accuracy and analysis is tantamount to a doctor ignoring medicine or a lawyer ignoring rules of evidence. Third, accuracy in measurement helps preserve the evidence for future generations. This may be the most important reason, since it affects both the public and the profession. It leaves the survey in better shape than before, to everybody's benefit. It is simply the professional and the "right" thing to do (Buckner 1997).

Our own corollary to the Mulford's famous quote, is: *An inaccurate* measurement even if on the correct line is a source of unending mischief. The best of all worlds is an accurate measurement on the correct line.

Examples of mischief abound. For example the confusion which surrounds the obscured monument that has conflicting measurements from accessories, or the monument that is lost and there are now conflicting or inaccurate measurements from the nearest corners. Coordinates and boundaries incorrectly depicted on maps and in GIS systems, and decisions made upon incorrect restorations based upon defective measurements do not aid in providing certain and permanent boundaries, unless all monuments last forever and are well and properly described and known to all adjoiners, a situation that seems to seldom exist for long.

The National Spatial Data Infrastructure

The National Spatial Data Infrastructure (NSDI) was created as a result of an *Executive Order 12906* by President Clinton in 1994. The reasons that prompted the creation of NSDI have been spelled out in "Coordinating Geographic Data Acquisition and Access: The National Spatial Data Infrastructure" (http//:www.fgdc.gov/publications/documents/ geninfo/execord.html), as follows:

> Geographic information is critical to promote economic development, improve our stewardship of natural resources, and protect the environment. Modern technology now permits improved acquisition, distribution, and utilization of geographic (or geospatial) data and mapping. The National Performance Review has recommended that the executive branch develop, in cooperation with state, local, and tribal governments, and the private sector, a coordinated National Spatial Data Infrastructure to support public and private sector applications of geospatial data in such areas as transportation, community development, agriculture, emergency response, environmental management, and information technology.
>
> *Section 1. Definitions*
>
> "National Spatial Data Infrastructure" (NSDI) means the technology, policies, standards, and human resources necessary to acquire, process, store, distribute, and improve utilization of geospatial data.
>
> "Geospatial data" means information that identifies the geographic location and characteristics of natural or constructed features and boundaries on the earth. This information may be derived from, among other things, remote sensing, mapping, and surveying technologies. Statistical data may be included in this definition at the discretion of the collecting agency.
>
> *Section 2. Executive Branch Leadership for Development of the Coordinated National Spatial Data Infrastructure*
>
> The Federal Geographic Data Committee ("FGDC"), established by the Office of Management and Budget ("OMB") Circular No. A-16 ("Coordination of Surveying, Mapping, and Related Spatial Data Activities") and chaired by the Secretary of the Department of the Interior ("Secretary") or the Secretary's designee, shall coordinate the Federal Government's development of the NSDI. (Clinton 1994)

This executive order defines the charter of NSDI and that charter includes the task of defining the types and quality of spatial data that will be used in Geographic Information Systems (GIS). As a result of this executive order, the FGDC has been charged with the responsibility to develop spatial data standards. Draft proposals of standards and final standards are available for public comment on the FGDC web site [http://www.fgdc.gov/standards/status/swgstat.html]. The purpose of the FGDC standards is to define a method to adequately report and define the positional accuracy of geospatial data. Many state governments and agencies have adopted these standards. A number of technical boards of registration for Professional Land Surveyors have adopted them through the legislative process.

Geospatial Positioning Accuracy Standard

Only a portion of the standards developed by FGDC apply to Cadastral Survey; it was the Geodetic Subcommittee which developed spatial accuracy standards for surveying. The surveying standards are entitled *Geospatial Positioning Accuracy Standards, Part 1: Reporting Methodology* and *Geospatial Positioning Accuracy Standards, Part 2: Standards for Geodetic Networks* [http://www.fgdc.gov/standards/status/sub1_2.html].

The draft FGDC Geodetic Subcommittee standard describes a general scheme of classification that is based on reporting coordinate data, with associated positional tolerances, specifically the relative error circle reported at 95 percent confidence (see appendix A). The FGDC national standard for spatial data accuracy insures flexibility by omitting threshold values that data must achieve; instead spatial data can be described as falling within an expected bandwidth or range of accuracies. This flexibility is well suited to the variety of methods and instruments used by cadastral surveyors. Agencies are encouraged by FGDC to establish pass–fail criteria for acquisition of spatial data by contractors. Developing pass–fail criteria would require careful consideration of many factors, and the criteria would need to be broad and inclusive rather than exclusive. They would also need to be independent of the methods used in making measurements, field conditions, or the survey instruments used.

The current draft of the FGDC standard describes two sets of values to be reported: "Network Accuracy" and "Local Accuracy." Local accuracy is also referred to as relative accuracy in some sources. The results are reported in ranges of accuracy. The values are defined thus:

> **Network Accuracy** of a control point is a value that represents the uncertainty in the coordinates of the control point with respect to the geodetic datum at the 95-percent confidence level. For NSRS network accuracy classification, the datum is considered to be best expressed by the geodetic values at the Continuously Operating Reference Stations (CORS) supported by NGS. By this definition, the local and network accuracy values at CORS sites are considered to be infinitesimal, i.e., to approach zero.
>
> **Local Accuracy** of a control point is a value that represents the uncertainty in the coordinates of the control point relative to the coordinates of other directly connected, adjacent control points at the 95-percent confidence level. The reported local accuracy is an approximate average of the individual local accuracy values between this control point and other observed control points used to establish the coordinates of the control point.

The standard that is probably best suited to Cadastral Survey boundary surveys is a statistical method of analysis referred to as local accuracy. The draft FGDC standards for geodetic networks (FGDC 1998, Part 2, Section 2.2, pp. 2-4) contend that:

> By supporting both local accuracy and network accuracy, the diverse requirements of NSRS users can be met. Local accuracy is best adapted to check relations between nearby control points. For example, a surveyor checking closure between two NSRS points is mostly interested in local accuracy (or in the case of the cadastral surveyor, a local control point relative to other survey points along a traverse or in a network of RTK GPS baselines). On the other hand, someone constructing a Geographic or Land Information System (GIS/LIS) will often need some type of positional tolerance associated with a set of coordinates. Network accuracy measures how well coordinates approach and ideal, error-free datum.

The current draft of the FGDC standard does not define the specific statistical methods used to derive local accuracy or the relative error ellipses on which it is based. It is important to note that the local relative error ellipse is not the same thing as the network or project error ellipse. A more complete technical discussion of the local error can be found in Appendix A of the 1996 Canadian Standard reproduced here in appendix A (Geomatics Canada; http://www.geod.nrcan.gc.ca/index_e/products_e/publications_e/Accuracy_Standards.pdf).

The Geomatics Canada standards document closely parallels the FGDC standard in most respects, and its appendices also correlate with earlier drafts of those for the FGDC standard. Information about the computation of the FGDC values is still lacking, as online comments from reviewers on the most recent (4/2003) FGDC standard indicate. The FGDC has indicated that some of these specifics may be included in the final draft or placed in additional referenced documents when finalized.

Other Standards

Over the past 15 years there have been numerous attempts to create new standards to reflect both current accuracy needs and new technology. Various approaches have been tried, including loop closures, theoretical uncertainty, positional tolerance, and other mixed standards which have evolved towards the FGDC type of a standard. One example is the standard published by the American Land Title Association (ALTA; http://www.acsm.net/alta.html), which follows an error propagation type model. The 1999 ALTA Standard defines positional uncertainty and positional tolerance thus:

> "*Positional Uncertainty*" is the uncertainty in location, due to random errors in measurement, of any physical point on a property survey, based on the 95 percent confidence level. "*Positional Tolerance*" is the maximum acceptable amount of positional uncertainty for any physical point on a property survey relative to any other physical point on the survey, including lead-in courses.

The standard, which is expressed as 20 mm plus or minus 50 ppm (parts per million), is based on controlling error propagation. The ppm component can be expressed as 1:20,000. The positional error is a function of distance from a given point; the larger the distance from the point the larger the positional error allowed. The ALTA standards are brief but seem to rely extensively on the surveyor's judgment rather than on a defined *a posteriori* analysis. For example, one of the few paragraphs in the standard is:

> The surveyor should, to the extent necessary to achieve the standards contained herein, compensate or correct for systematic errors, including those associated with instrument calibration. The surveyor shall use appropriate error propagation and other measurement design theory to select the proper instruments, field procedures, geometric layouts and computational procedures to control and adjust random errors in order to achieve the allowable positional tolerance or required traverse closure.

And later, under Computation of Positional Uncertainty:

> The positional uncertainty of any physical point on a survey, whether the location of that point was established using GPS or conventional surveying methods, may be computed using a minimally constrained, correctly weighted least squares adjustment of the points on the survey.

It appears that there are different and sometimes multiple approaches to applying the ALTA standard. Many other standards of this type allow the user to meet a choice of criteria, or to meet the standard by *a priori* evaluation of methods or by *a posteriori* evaluation of the results. As a result they are relatively easy to apply, but may produce less rigorous results. The Canadian Standard discussed above makes this commentary on loop closure and error propagation based standards:

> Precision measures are relatively simple to compute and are often used to estimate accuracy. They provide useful estimates of accuracy only if the data are unaffected by biases due to blunders or uncorrected systematic effects. Without some assurances that such errors do not exist, a precision measure provides information that is of limited use. ….For instance, a horizontal position may have been determined using the most precise GPS measurements and processing techniques, but if the positioned point is misidentified as one that is actually ten meters away, the precise position for the wrong point is of little use. While the precision measures may indicate that a precision of ten centimeters has been achieved, the bias introduced by misidentifying the point limits its accuracy to ten meters.

The FGDC format, like the Canadian example quoted, replaces ratio formats with a combination of network and local accuracy. We think this is an appropriate solution but cannot be completely sure what practical difficulties we may encounter implementing them until we are able to perform testing. There is currently not much software available that computes local error based on the FGDC draft approach. We are concerned therefore that while the draft FGDC standard may be appropriate for a number of our needs, it may have some weakness in the *ease of use* aspects. To quote the Canadian Standard document again:

> Local accuracy indicates how accurately a point is positioned with respect to other adjacent points in the network. Based upon computed relative accuracies, local accuracy provides practical information for users conducting local surveys between control monuments of known position. Local accuracy is dependent upon the positioning method used to establish a point. If very precise instruments and techniques are used, the relative and local accuracies related to the point will be very good. … While a point may have good local accuracy it may not necessarily have good network accuracy, and vice versa. Different positioning applications will have varying objectives that emphasize either network or local accuracy, or have specific requirements for both types of accuracy.

Here is where one logical test of applying the FGDC standard raises questions. For a directly observed traverse network constrained to static GPS, it is certainly possible to develop a program to compute the network and local error values, however, at present we do not have software that does so. Another potential issue relating to the usability of the FGDC standard applies to use of RTK techniques. If the RTK procedure is used to obtain positions, possibly with error data, and check shots, then while we can say something about the relative accuracy of the coordinates from the RTK base, we will not be able to perform direct *a posteriori* statistical analysis of either the network or local accuracy values as defined by FGDC. This is particularly the case when the surveyor does not collect RTK GPS baseline data to analyze them in a network. A complete implementation of the FGDC standard, as we understand it, would require collection of baseline information and subsequent vector analysis of the data with least squares before the coordinates are included in the project network and evaluated for local error. The question then becomes, “Does this impose an unworkable burden on current practice and procedures?”

We have two initial concerns regarding the application of the FGDC local accuracy standard: 1) availability of software that will compute and report the standard, and 2) use of RTK techniques that do not easily allow for network evaluation. Where the network accuracy meets the local accuracy standard, a partial solution may be available for the first issue. Assuming that a properly computed network or local (project) **network** error value will always represent the upper limit of the **local** error values, then these values represent the worst case scenario for the local error. However this assumption still requires that the data be computed in a network. One solution apparent to solve the RTK issue is to collect baseline information and analyze the vector data in the project network using least squares. The other solution would be to use *a priori* error analysis that would be analogous to adding up the error values that contribute to the overall coordinate errors for the RTK coordinate. Another approach would be to define and test a specified set of procedures that are known to meet the FGDC standard.

From the discussion here it is clear that the draft FGDC standard network accuracy component can be used to define the positional accuracy of boundary surveys of federal lands and geodetic reference or control ties to the NSRS. Network accuracy should be applied when describing data that reference boundary surveys to the NSRS, such as when geodetic control measurements are made to PLSS survey monuments or cadastral project control monuments. The local accuracy component of the draft FGDC standard seems more applicable to boundary surveys, however the primary concern with this method is the lack of tools to compute the error values so that the standard can be applied.

Conclusions

The Cadastral Survey of BLM has historically taken full advantage of new technology to improve the efficiency of survey crews in the field. We must continue to recognize that accuracy has value, and the ability to define and describe the accuracy of our current and future products is essential to a variety of applications for which the data may be used.

Precision ratios which have been used in the past serve only to imply what the general quality of a closed traverse is. This method of evaluating error does not serve to identify measurement mistakes or impart any information as to the positional accuracy of any point along a traverse. Until recently, adjustments to survey measurements have not been used in cadastral survey. Rather, direct methods of measurement such as prolongation of line and chaining on true line to survey boundary lines and precision rations have been the preferred field methods. Indirect methods of measurement with GPS are, however, becoming more and more common, and statistical methods are proving to be the best for evaluating the accuracy of these measurements.

The most rigorous of data adjustments and the easiest to apply without bias are least squares. Computers and BLM's Cadastral Measurement Management software based on least squares have made the application of adjustments to large-scale networks extremely practical.

The most constant of issues is one of responsibility. It is the responsibility of federal agencies and the Cadastral Survey to define and describe threshold values and pass–fail criteria for accuracy of modern cadastral surveys performed to locate and protect federal interest lands.

The authors feel that for cadastral applications, a dual or a "mixed" standard may be appropriate. The FGDC-defined network accuracy standard is suitable for classifying the spatial products of a cadastral survey, but local accuracy may be too difficult to compute or apply to boundary surveys at this time. Further work needs to be done to evaluate the possibilities of obtaining tools that will compute the local accuracy components of the proposed FGDC standard. Until then consideration should be given to a standard with options that would look more like the ALTA standard—as at least an alternative form of the local accuracy portion of the FGDC standard—that would complement positional tolerance of a point such as an error ellipse at 95 percent confidence. What is needed is an inclusive accuracy standard that reflects modern survey practices with regard for the needs of the cadastral survey professional and public.

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Appendix A

Pages extracted from the Canadian Appendix A that appears to be largely equivalent to the old FGDC appendix "D".

COMPUTATION OF CSRS ACCURACIES

The network and local accuracies for points in the national network of the Canadian Spatial Reference System (CSRS) are based upon the results of a least squares adjustment of the survey observations used to establish their positions, where the network accuracy values refer to the origin of the CSRS.

The network and local accuracies of the horizontal coordinates and ellipsoidal heights of points in the CSRS can be computed from elements of a covariance matrix, as described in the following sections. This covariance matrix of the adjusted parameters, denoted $C_{\hat{x}}$ must have been produced from a least squares adjustment where the known CSRS control coordinate values have been weighted using their one-sigma network accuracies. Matrix $C_{\hat{x}}$ is a symmetric matrix where the elements along the diagonal are variances of the adjusted parameters and the off-diagonal elements are covariances between the different adjusted parameters.

The adjusted parameters of interest to this discussion are corrections to estimated a priori coordinate values for the observed points. These corrections are determined in the local geodetic system at each point, and therefore expressed in units of metres along each of the x, y and z axes (Steeves, 1984).

Three-Dimensional Positioning Accuracy

For three-dimensional adjustments of high precision GPS position difference observations, the evaluation of the data should include the computation of relative and absolute 95% confidence ellipsoids. While these measures are not included in the present standards, their computation and analysis is an important phase in the evaluation of specialized projects carried out for geodetic or other scientific applications. A thorough treatment of the computation of confidence ellipsoids appears in Vaníček and Krakiwsky (1986).

Horizontal Coordinate Accuracy Computations

Network Accuracy 95% Confidence Ellipse

The standard ellipse representing the one-sigma network accuracy of the adjusted horizontal coordinates at point i, is defined by its major (a) and minor (b) semi-axes. Using the elements of the covariance matrix $C_{\hat{x}}$, these can be computed from:

$$a = [\ (\sigma^2_{\phi i} + \sigma^2_{\lambda i})\ /2 + q]^{1/2}$$
$$b = [\ (\sigma^2_{\phi i} + \sigma^2_{\lambda i})\ /2 - q]^{1/2}$$

where

$$q = [\ (\sigma^2_{\phi i} - \sigma^2_{\lambda i})^2\ /4 + \sigma^2_{\phi i \lambda i}\ ]^{1/2},$$

and where

$\sigma^2_{\phi i}$ is the variance of latitude (m^2),
$\sigma^2_{\lambda i}$ is the variance of longitude (m^2), and
$\sigma_{\phi i \lambda i}$ is the covariance of latitude and longitude (m^2).

The orientation of the network accuracy ellipse is given by the following expression:

$$\tan 2\theta = 2\sigma_{\phi i \lambda i}\ /\ (\sigma^2_{\phi i} - \sigma^2_{\lambda i})$$

where θ is the azimuth of the major semi-axis. The quadrant for 2θ should be chosen such that $\sin 2\theta$ has the same sign as $\sigma_{\phi i \lambda i}$ and $\cos 2\theta$ has the same sign as $(\sigma^2_{\phi i} - \sigma^2_{\lambda i})$.

The computed values of a and b must be multiplied by the appropriate expansion factor to convert the standard ellipse to a 95% confidence ellipse (Leick, 1995). For large adjustments where the degrees of freedom are quite high, the factor 2.45 for infinite degrees of freedom is used. For adjustments where the degrees of freedom are less than or equal to 120, the expansion factor corresponding to the actual degrees of freedom should be used (Surveys and Mapping Branch, 1978).

The semi-axes of the 95% confidence ellipse representing the network accuracy at point i are generally computed as:

$$a_{95} = 2.45a$$
$$b_{95} = 2.45b.$$

Further information on the computation of confidence ellipses may be found in reference texts, such as Mikhail and Gracie (1981) and Mikhail (1976).

Network Accuracy 95% Confidence Circle

The 95% confidence circle is another representation of horizontal coordinate accuracy. It will be used in the United States to describe the horizontal accuracy of points, as described in FGCS (1995). The 95% confidence circle is introduced here to serve users who may be accustomed to using a circular expression of positional uncertainty.

The 95% confidence circle is centred on the estimated horizontal coordinates of the point as illustrated in Figure 4. The true position is unknown and can only be estimated through the measurements. The 95% confidence circle describes the uncertainty or random error in this estimate, resulting from random errors in the measurements. There is a 95% probability that, in the absence of biases or other systematic errors, the true value will fall within the region bounded by the circle.

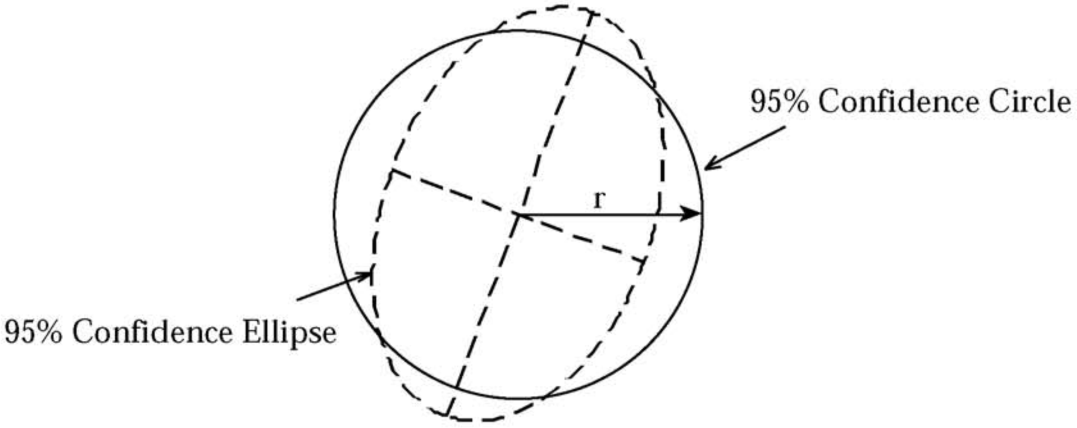

Figure 4: The 95% confidence circle

The 95% confidence circle is closely approximated from the major (a) and minor (b) semi-axis parameters of the standard ellipse and a set of coefficients. For circular error ellipses, the circle coincides with the ellipse. For elongated error ellipses, the radius of the circle will be slightly shorter than the major semi-axis of the ellipse. The radius r of the 95% confidence circle is approximated by:

$$r = K_p \, a$$

where

$$K_p = 1.960790 + 0.004071\,C + 0.114276\,C^2 + 0.371625\,C^3,$$

$$C = b/a.$$

Note that the coefficients in the above expression are specific to the 95% confidence level, such that when the major semi-axis of the standard ellipse is multiplied by the value of K_p, the radius of the 95% confidence circle is obtained directly, and no further conversion is required (FGCS, 1995). Details on the circular confidence region may be found in Leenhouts (1985).

Local Accuracy 95% Confidence Ellipse

The local accuracy at a point is based upon an average of the individual local accuracies (or relative accuracies) between that point and other adjacent points. The standard relative ellipse, representing the one-sigma local accuracy of the horizontal coordinates of point i with respect to another selected point j, is defined by its major (a) and minor (b) semi-axes. The semi-axes are given by:

$$a = [\ (\sigma^2_{\Delta\phi\,ij} + \sigma^2_{\Delta\lambda ij}\ )\ /2 + q]^{1/2}$$
$$b = [\ (\sigma^2_{\Delta\phi\,ij} + \sigma^2_{\Delta\lambda ij}\ )\ /2 - q]^{1/2}$$

where

$$q = [\ (\sigma^2_{\Delta\phi\,ij} - \sigma^2_{\Delta\lambda ij})^2\ /4 + \sigma^2_{\Delta\phi\,ij\Delta\lambda ij}\ ]^{1/2},$$

and where

$\sigma^2_{\Delta\phi\,ij}$	is the variance of the difference in latitude between points i and j,
$\sigma^2_{\Delta\lambda ij}$	is the variance of the difference in longitude between points i and j, and
$\sigma_{\Delta\phi\,ij\Delta\lambda ij}$	is the covariance of the differences in latitude and longitude between points i and j.

The variances and covariance of the position difference are obtained from the elements of the covariance matrix $C_{\hat{x}}$ as follows:

$$\sigma^2_{\Delta\phi\,ij} = \sigma^2_{\phi i} + \sigma^2_{\phi j} - 2\sigma_{\phi i\phi j}$$

$$\sigma^2_{\Delta\lambda ij} = \sigma^2_{\lambda i} + \sigma^2_{\lambda j} - 2\sigma_{\lambda i\lambda j}$$

$$\sigma_{\Delta\phi\,ij\Delta\lambda ij} = \sigma_{\phi i\lambda i} + \sigma_{\phi j\lambda j} - \sigma_{\phi i\lambda j} - \sigma_{\phi j\lambda i}$$

where

$\sigma^2_{\phi i}$ is the variance of i-th latitude (m^2),
$\sigma^2_{\lambda i}$ is the variance of i-th longitude (m^2),
$\sigma_{\phi i \lambda i}$ is the covariance of i-th latitude and i-th longitude (m^2),

$\sigma^2_{\phi j}$ is the variance of j-th latitude (m^2),
$\sigma^2_{\lambda j}$ is the variance of j-th longitude (m^2),
$\sigma_{\phi j \lambda j}$ is the covariance of j-th latitude and j-th longitude (m^2),

$\sigma_{\phi i \phi j}$ is the covariance of i-th latitude and j-th latitude (m^2),
$\sigma_{\phi i \lambda j}$ is the covariance of i-th latitude and j-th longitude (m^2),
$\sigma_{\phi j \lambda i}$ is the covariance of j-th latitude and i-th longitude (m^2), and
$\sigma_{\lambda i \lambda j}$ is the covariance of i-th longitude and j-th longitude (m^2).

The orientation of this local accuracy ellipse is given by:

$$\tan 2\theta = 2\sigma_{\Delta\phi ij \Delta\lambda ij} \,/\, (\sigma^2_{\Delta\phi ij} - \sigma^2_{\Delta\lambda ij}).$$

The computed values of a and b must be multiplied by the appropriate expansion factor to convert the standard relative ellipse to a 95% confidence ellipse, as described above for the network accuracy 95% confidence ellipse.

The semi-axes of the 95% confidence ellipse representing the local accuracy between points i and j are generally computed as:

$$a_{95} = 2.45a$$
$$b_{95} = 2.45b.$$

Local Accuracy 95% Confidence Circle

The 95% confidence circle representing a local accuracy can be derived from the major and minor semi-axes of the standard relative ellipse between two selected points. The expressions for estimating the radius of the local accuracy 95% confidence circle are the same as for the network accuracy computation, substituting the standard relative ellipse a and b parameters into the formulae provided in the Network Accuracy 95% Confidence Circle section above.

Appendix B

Terms

Land tenure: The system by which interests held in land are identified, described, displayed, conveyed, and protected.

Geospatial data: Information that identifies the geographic location and characteristics of natural or constructed features and boundaries on the earth.

Cadastre: An official register of the quantity, value, and ownership of real estate.

Cadastral: of or relating to the records of a cadastre; concerned with an assembling or keeping of records necessary to a cadastre; of a map or survey, showing or recording property boundaries, subdivision lines, buildings and other details.

Bench Marked

American Land Title Association Standard
Bureau of Land Management and *Manual of Instructions for the Survey of the Public Lands of the United States, 1973*
Canadian Spatial Reference System Accuracies
Federal Geographic Data Committee
Geospatial Positioning Accuracy Standards
National Geodetic Survey and National Spatial Reference System
U.S. Geological Survey Maps with National Map Accuracy Standards

■

About the Bureau of Land Management

The BLM, an agency of the U.S. Department of the Interior, manages more land—262 million surface acres—than any other federal agency. Most of the country's BLM managed public land is located in 12 Western states, including Alaska. The Bureau, which has a budget of $1.8 billion and a workforce of 10,000 employees, also administers 700 million acres of sub-surface mineral estate throughout the Nation. The BLM's "multiple use" mission is to sustain the health, diversity, and productivity of the public lands for the use and enjoyment of present and future generations. The BLM accomplishes this by managing for such resources as outdoor recreation, livestock grazing, and energy and mineral development that helps meet the nation's energy needs, and by conserving natural, historical, cultural, and other resources on the public lands. Additionally, the BLM is responsible for and manages the survey and title records of the public domain, private land claims, and Indian trust lands.

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Real-life Examples from Jordan

Spatial Data Quality Degradation

The competitiveness of an organisation is negatively affected by poor data quality, as introduced through the multitude of transformations and transfers carried out on original data. One risk involves uncontrolled exchange of data between organisations and departments within them. The author uses real-life examples from Jordan to demonstrate the impact of resolution, vector-to-raster conversion, scale, generalisation, classification of remotely sensed images and file exchange upon data quality.

By Samih Al Rawashdeh, Balqa Applied University, Jordan

Data acquisition is the most important step in any GIS and Geomatics project. All results are influenced by the quality of the original data and subsequent steps involving transformation, transfer and exchange. Principal spatial data sources are satellite imagery, aerial photographs, field surveying and scanned maps and documents. Original data cannot normally be used directly in GIS projects. For example, satellite images have to be corrected for atmosphere and Earth-curvature effects, among others. And georeferencing has to be applied to bring them into a preferred reference system. All these transformations introduce error and degradation of quality.

Image Resolution

Figure 1 shows two satellite images of different resolutions: on the right is part of a Landsat image of 30m resolution; the left image stems from an Ikonas image of 1m resolution. Both were taken in the same year. Much information present in the left-hand image is absent in the right-hand one. The number of mixed pixels (mixels) in the low-resolution image causes degradation in shape and in a number of recognisable features. In the high-resolution image one can identify three pools, whereas in the low-resolution image only one is visible. Different resolutions will also result in differing values for areas, as shown in Table 1. The expansion in the urban area of Greater Amman, and the runoffs in the Walla and Habisse, were computed from 30m and 15m-Landsat data and from a digital vector map. The computations summarised in Table 1 demonstrate how course resolutions introduce overestimation of area size.

Vector to Raster

Vector-to-raster (V-to-R) transformation also introduces degradation, depending on resolution: i.e. size of raster cells. A point in the vector database, for example, becomes a square of the size of one pixel or raster cell. V-to-R transformation can be carried out either by central-point or by dominant-unit rasterisation. To demonstrate the effects on shape and size, we in Figure 2 transformed a vector polygon (A) to raster (B) and back again to raster mode (C). The resulting polygon overlaid on the original (see D) shows how severe degradation can be.

Scale and Detail

A map feature must be visible and easily identifiable under normal conditions; that is, at a distance of 30cm from the eyes and under normal light conditions.

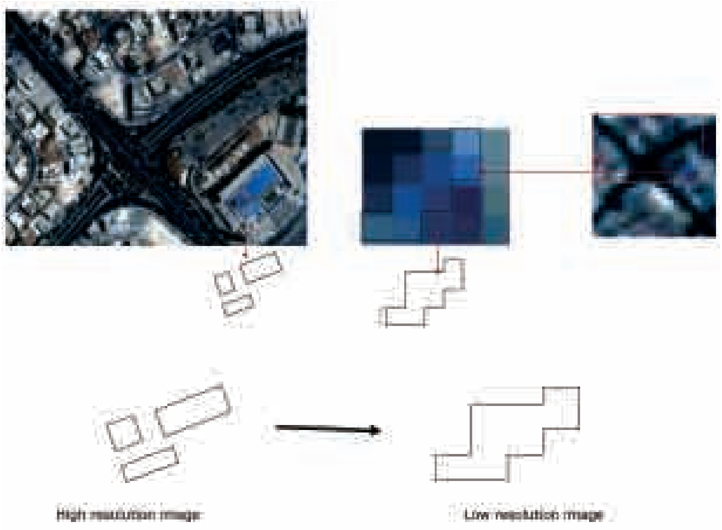


***Figure 1,** Swimming pool, extracted from high-resolution satellite image (left) and from low-resolution satellite image (right).*

	Resolution	Area [km2]	σ
Greater Amman	30 m	621.9996	4.2288
	15 m	619.8976	2.1020
	Vector	617.7708	0.0000
Wala Basin	30 m	2073.86	3.1800
	15 m	2071.45	0.7734
	vector	2070.6766	0.0000
Habisse Basin	30 m	192.78	2.1000
	15m	191.86	1.1800
	vector	190.6800	0.0000

***Table 1,** Comparison of areas derived from different resolutions.*

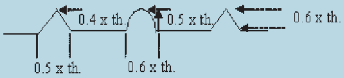
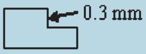
Geometric element	Practical dimensions	
point	Diameter 0,1 mm	
Simple line	Thickness 0.1 in drafting	
Space between two lines: 0.2 mm		
Space between two polygons signs: 0.2		
Bends of a line:		
Squares and rectangular forms	Filled square 0,4 x 0.4 mm Empty rectangle 0.6 x 0.6	■ □
	Filled rectangle 0.4 x 0.6 Empty rectangle 0.6 x 0.8	■ □
	Recess	
	Shed 0.6 x 0.8 mm	

Table 2, Minimal dimension of map features.

The number of features that can be visualised is proportional to scale. Not only number, but also the shape of features depends on scale. Smaller details will appear only when the scale becomes large enough. Whether certain details will be represented or not depends on the rules of legibility, which include:

- *visual acuity of differentiation*: in general, the factors which determine the recording of an image by eye are colour, lighting conditions and size of objects
- *visual acuity of alignment*: ability of the eye to see whether two lines are aligned to each other
- *parting threshold*: the eye requires a minimal space between two features in order to distinguish them as separate. This space depends on the thickness of the lines with which the features are drawn; for thick lines the parting threshold is 0.15mm
- *differential threshold*: ability of the eye to record differences in size of features.

The minimal dimensions that the eye can record without ambiguity, under natural conditions, are shown in Table 2. When the dimension of a map feature is smaller than the minimal dimension this feature cannot be represented at its true size and has therefore to be represented by a conventional sign. For example, a building of 25 x 25 meters can be represented at scale on maps of scales better than 1:50,000. But it cannot be represented in its true size at a scale of, for example, 1:500,000, because then the map dimensions of this building would become 0.05 x 0.05mm.

Generalisation

Figure 3 shows a curved line represented at different scales. Details are lost when represented at medium-scale (B), and become a straight line when represented at small-scale (C). Suppose this curved line is a segment of a road; then the length would vary according to scale and the expected error could exceed 100%. Figure 4 shows the effect of three types of generalisation of a group of islands: elimination of the small islands (top), regrouping the small islands into one island (middle) and regrouping the small islands to become part of the large island (bottom). All three generalisations show large degradation in area, shape and number of features.

Classification

When classifying remotely sensed

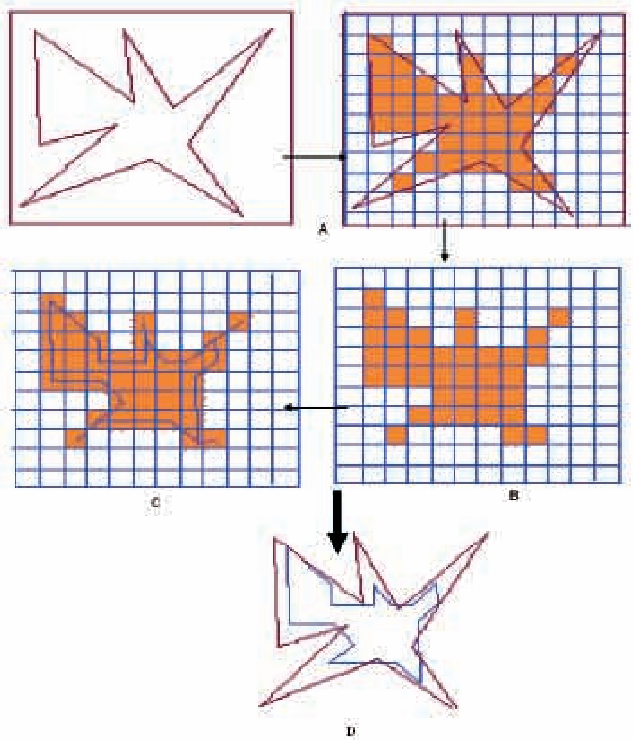


Figure 2, *Degradation caused by vector-to-raster-transformation.*

Figure 3, *Degradation caused by generalisation of linear feature.*

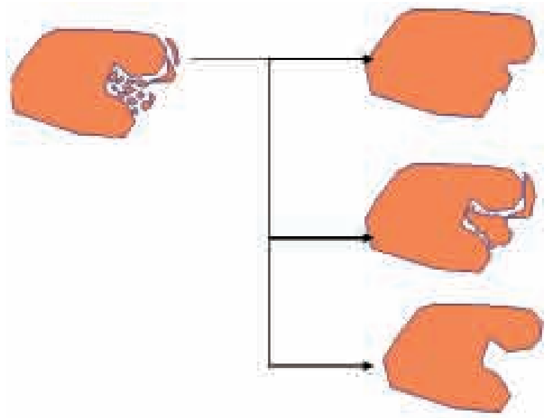


Figure 4, Degradation caused generalisation of area feature.

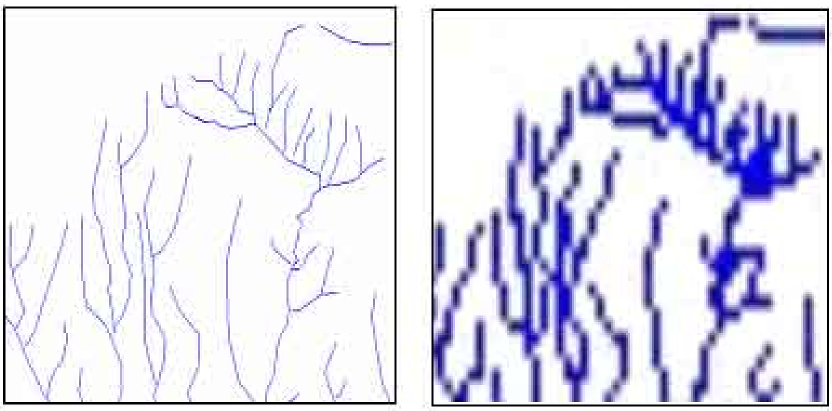


Figure 5, Effects of transformation of vector representation, of part of Walla basin network, into Tiff and JPG format.

images, degradation may be introduced resulting from:

- limited number of classes: only a limited number of classes can be selected, while in reality the number of classes may be much larger; features which would not belong to any selected class will be erroneously allocated to one of the selected classes
- percentage of pixels correctly classified is generally less than 100%
- mixed pixels: a pixel cannot belong to more than one class at a time; a mixed pixel will belong to one class only, leading to area and shape errors
- unclassified pixels: pixels that are not allocated to any of the selected classes.

Further, geo-referencing introduces degradation: the root mean square (RMS) error is rarely equal to zero, and re-sampling causes spectral degradation. The likihood of degradation increases with increasing transfer of data between organisations; for example, when the format is changed during transfer from vector to image format, such as Tiff or JPG (Figure 5).

Concluding Remarks

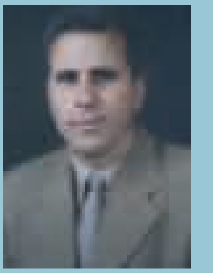
Organisations must standardise data formats to avoid multiple transfer of formats, some of which may be of low quality. A history file must accompany data, so that some estimation may be made of the quality of the data, as good-quality data can be never obtained from poor-quality data.

Further Reading

- Burough, P., A., 1986, Principles of Geographical Information Systems for Land Resources Assessment.
- Comber A.J., Fisher P., and Wadsworth R., 2004, Integrating land cover data with different ontology: identifying change from inconsistency, International Journal of Geographical Information Science 18 (7), pp 691-708.◆

Biography of the Author

Dr Samih Al Rawashdeh is lecturer and head of the Engineering Surveying and Geomatics Department at Balqa Applied University, Jordan.



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DEMs and Ortho-imagery from Dual-band Side-looking Radar

Mapping a Colombian Oil Pipeline

Adverse weather and terrain conditions meant the Cano-Limon oil pipeline in Colombia had never been accurately mapped until orthorectified images and digital elevation models covering an area of 94,000km^2 were created using airborne dual-band interferometric IFSAR simultaneously acquired X and P-band data. The authors report on main aspects of the project.

By Joseph Allen and James Reis, EarthData, Maryland, USA

The Cano-Limon oil pipeline extends nearly 780km from the Cano-Limon oilfield in Colombia's Arauca region along the north-western border with Venezuela to a port in Covenas. When fully operational the pipeline can carry up to 20% of Colombian petroleum production, a major source of national revenue. In collaboration with the Colombian Government, the US National Geospatial-Intelligence Agency (NGA, formerly NIMA) took the lead in obtaining new map data. Thick cloud cover makes optical remote sensing inoperative, and ground surveys are impractical due to a combination of multi-layer tropical vegetation and rugged terrain in the Northern Andes. Therefore interferometric IFSAR was successfully used as a mapping alternative.

GeoSAR Project

The Cano-Limon pipeline mapping effort, known as the GeoSAR Latin American Demonstration Project (GLAD-P), is the first commercial use of the Geographic Synthetic Aperture Radar (GeoSAR) system by NGA, following nine years of development. GeoSAR is a dual-use development programme managed by NGA, integrated by EarthData International of Frederick, Maryland, USA and designed by the Jet Propulsion Laboratory (JPL) in California, which engineered the components of the mapping system and ground-processing segment using custom and off-the-shelf technology. EarthData's responsibility was to transform this technology from engineering grade into an operational system. This involved mounting antenna pods on the wings of a Gulfstream II business jet, installing the radar system inside the aircraft and getting flight certification from the Federal Aviation Administration. Figure 1 shows a schematic view of GeoSAR data-collection configuration.

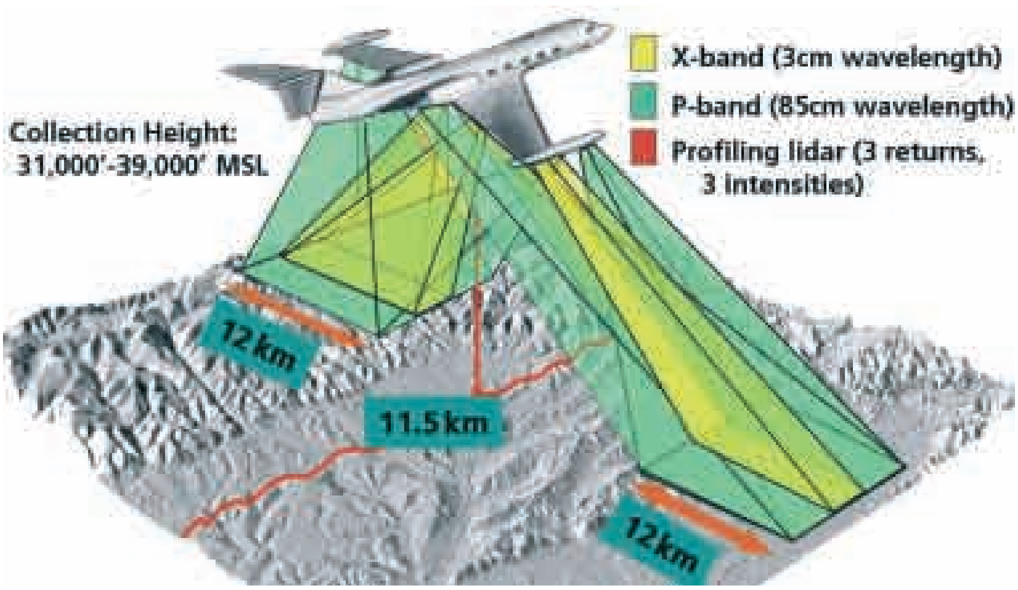


Figure 1, *Dual-band antennas mounted under each side of the aircraft, Lidar profiler mounted at aircraft centreline: data-collection configuration enables simultaneous collection of IFSAR X-band data, IFSAR P-band data, and continuous nadir-terrain profiling.*

Penetrating Vegetation

The GeoSAR programme aimed at designing, building and deploying a commercially viable IFSAR mapping system capable of simultaneously acquiring the X and P bands. IFSAR uses two antennae, the fixed distance between them precisely known. These emit and receive radar pulses. By measuring phase differences between the reflected signals at the two antennae surface elevations can be calculated. X-band, operating at a frequency of 9,630-9,790MHz, is commonly used in airborne IFSAR mapping systems. Its relatively short wavelength (3cm) acquires highly detailed data from the first reflective surface encountered, such as tree canopy, man-made structures and bare ground. P-band operates in the 270 to 430MHz range. The wavelength

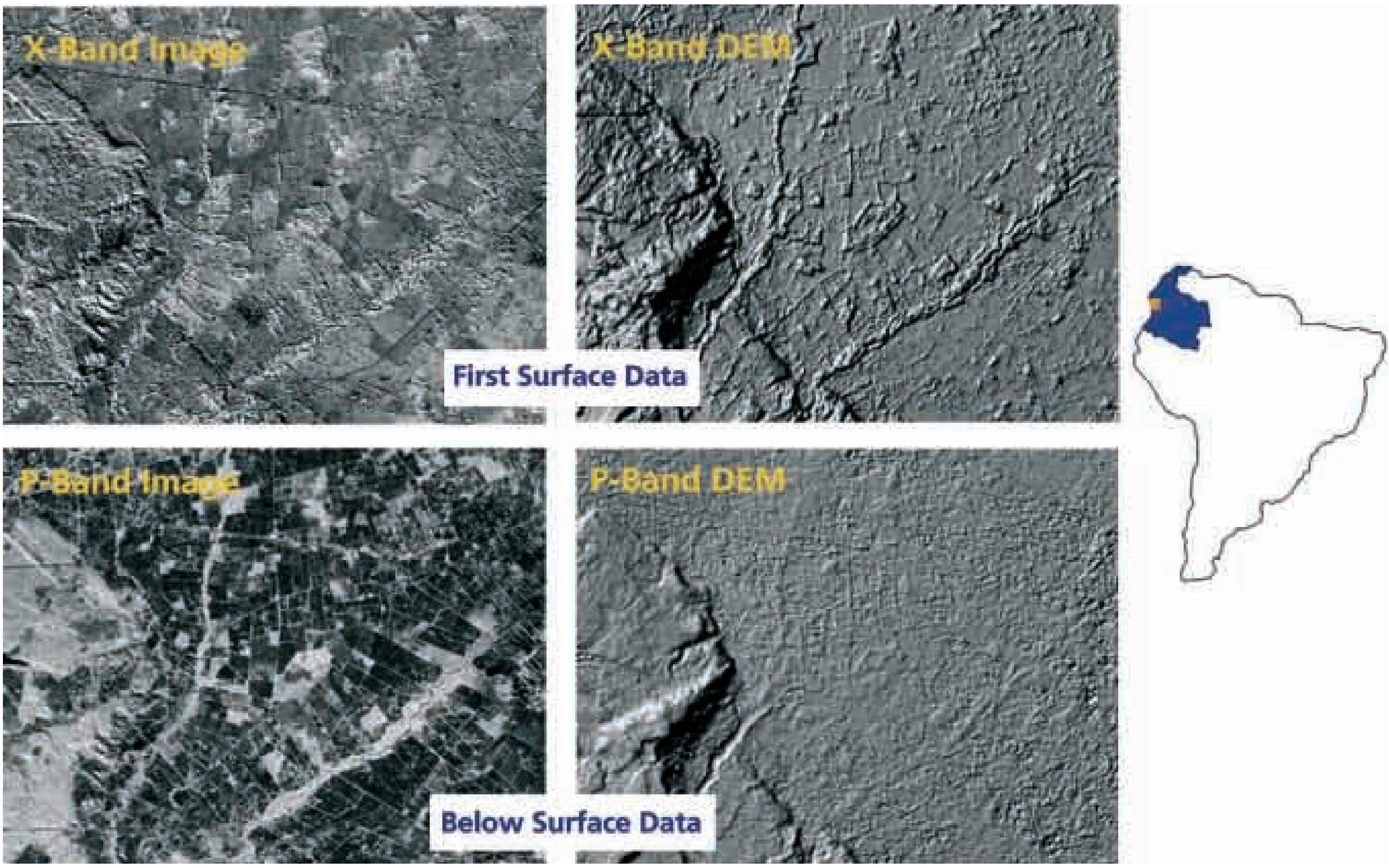


Figure 2, *Differing reflection characteristics of X-band and P-band (see section Penetrating Vegetation).*

Optical remote sensing inoperative, and ground surveys impractica

of 1m is capable of penetrating vegetation and top layers of soil or sand in arid regions.

The simultaneous use of both short and long-wavelength radar enables mapping a variety of surface and sub-surface features in virtually any environment, regardless of the presence of vegetation. These are very beneficial properties for mapping the Cano-Limon pipeline, which passes through grassland, jungle, mountain and coastal terrain. Figure 2 shows X-band and P-band images of the same area, and the associated Digital Elevation Models (DEM) as derived products. X-band scatters off the first surfaces of vegetation, buildings and bare earth. The 3m-posted X-band image (Figure 2, top left) is rich in first-surface details. The vegetation is seen in the X-band DEM (Figure 2, top right) along rivers and fields. P-band penetrates vegetation and scatters off substructure, showing details otherwise hidden beneath foliage. The P-band image (Figure 2, far left) reveals road networks, buildings, and features not apparent in the X-band data. Edges of features such as rivers and roads are clearer in the P-band image because the longer wavelength deeply penetrates overhanging vegetation. Absence of vegetation in the P-band DEM results in a smooth appearance that more closely follows the terrain relief. GeoSAR is the only system in the world to operate single-pass X and P-band IFSAR simultaneously from both sides of the same platform.

Dual-side Looking

Selection of the P-band was not arbitrary. Several low-frequency bands offer penetrative capabilities but the P-band is the longest that could function on a cost-effective aircraft. In airborne IFSAR the antennae pairs are separated by many wavelengths to maximise phase differences of return signals, and hence elevation measurement accuracy. Of the civilian jets that can affordably be used for mapping, the Gulfstream-II has the longest wingspan. The 20m distance between wingtips dictated that P-band was the lowest frequency that could be used without compromising interferometric performance. For this reason the P-band pods are located on the wingtips for maximum separation and the X-band antennae are contained under the wings closer to the fuselage. In each pod one antenna points to the left and the other to the right-hand side, providing simultaneous X and P-band acquisition of the same 10km-wide swath coverage on either side of the flight path. This antenna configuration is known as ‘dual-side looking’. Redundant collection of data necessary for the creation of DEMs is obtained by overlapping flight lines covering the nadir hole of the previous flight line (Figure 3). Along each flight line the system looks at

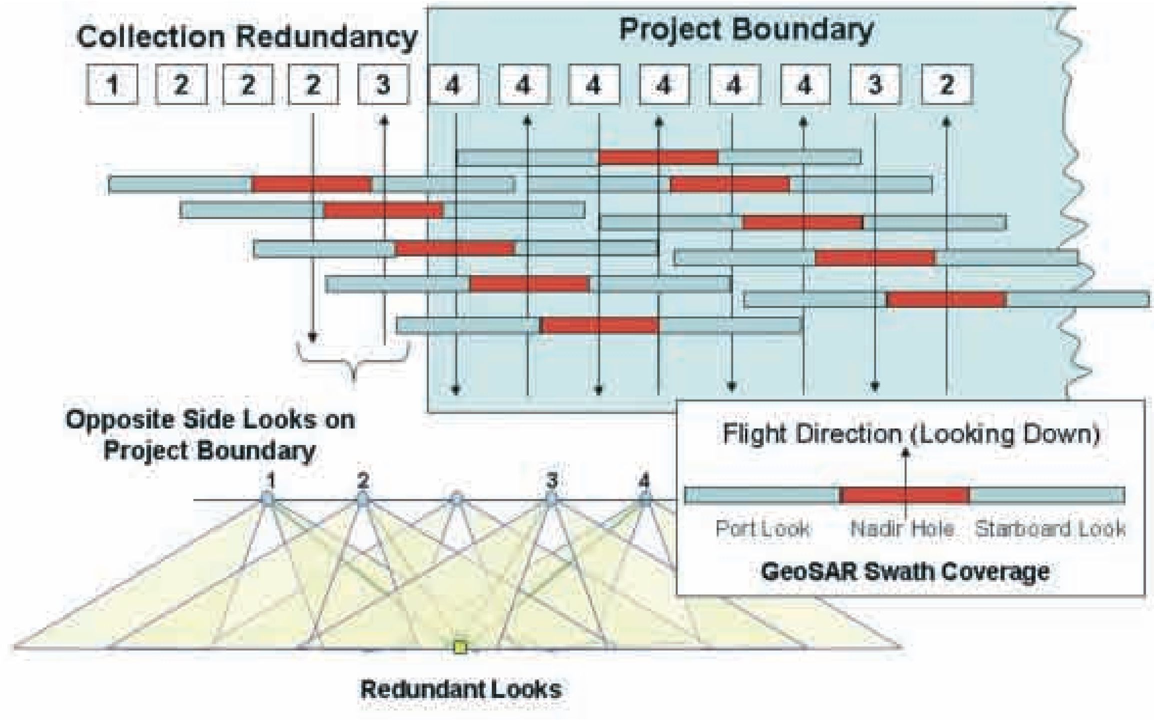


Figure 3, Redundant collection of data obtained by overlapping flight lines.

each ground point twice from the left and twice from the right, at a steep and a shallow angle which covers areas otherwise obscured by radar shadow, specular reflection and foreshortening. EarthData prefers never to 'interpolate' ground points.

Forbidden Area

The two-sided raw-collection rate at nominal acquisition altitude of 10km is 240km^2 per minute per band. In comparison to a standard single-sided IFSAR, dual-side-looking IFSAR collects more looking angles, so that surface elevation values can be calculated more accurately. The distance between two subsequent flight paths is usually 5km, or half the swath width. The multiple and opposite 'looks' of each point on the ground much improves elevation calculation and reduces the number of ground surfaces hidden behind tree shadows, hills and mountain peaks in rugged terrain. Dual-side-looking IFSAR also makes it possible to cover twice as much terrain on one pass as covered by a standard, single-side-look system. The elevation varied by 5,000m from the coastal area through the Andes along the pipeline route, with ground cover varying just as drastically. Nevertheless, the system was operated at standard altitude and power throughout the project. Airspace restrictions, however, required many modifications to normal flight-path planning. The aircraft was not permitted to fly over neighbouring Venezuela, creating the risk of voids resulting from mountain peaks shadowing lower terrain from radar illumination. To minimise data voids the flight path spacing was tightened, increasing the number of 'look' angles and swath overlaps.

Wavelength of 1m capable of penetrating vegetation and soil

Wing flexure causes antennae to continually shift

Radar Notching

Use of the P-band potentially introduces frequency interference. This is because the P-band transmits in the UHF (Ultra-High Frequency) part of the electromagnetic spectrum: the part dedicated to many government radio communications, including air traffic control, aviation instrument-landing systems and emergency locator beacons. In the US many UHF bands are reserved for military communications. To avoid interference the radar emission in government-specified segments has to be significantly reduced (notching). Close co-operation with the National Telecommunications and Information Agency (NTIA) was necessary. NTIA facilitates co-ordination with local communications users to determine where notching should occur in each flight path. The frequencies are programmed for automatic notching during data acquisition. Fortunately, there were few stationary UHF systems operating in the region, so notching was not needed. However, there was occasional interference, probably from mobile communications devices in the jungle. The impact of such interference on data quality was minimal thanks to the acquisition redundancy and adaptive filtering technology that is a unique feature of the system.

Twisting Wingtips

IFSAR requires that the baseline, that is the distance between the two antennas, be precisely known. However, during flight wing flexure causes antennae positions to continually shift with respect to the fuselage. Therefore a motion-measurement device was mounted on the fuselage centreline between the wings. This device, the first of its kind deployed in commercial IFSAR, uses lasers and optical cameras to measure to a fraction of a millimetre the attitude of the antennae pods with respect to the body of the aircraft. The measurements were transmitted daily together with onboard-collected GPS data by internet to EarthData's Maryland (USA) headquarters, where the datasets were analysed to ensure that excessive turbulence had not ruined the data. On the rare occasions when this occurred re-flights could be planned for the next day, before the aircraft left the area.

P-band reveals topographic structure, homes, streets and paths

End Products

The entire project included 187 flight paths. Stored on Sony 19mm data cartridges with 100-gigabyte capacity, the IFSAR data was processed by a SGI 2400 computer at the Maryland facility. Six months after acquisition the end products were ready for delivery. They included 3m-resolution X-band and 5m P-band orthorectified radar imagery and DEM of the same spatial resolution (Figure 4). Comparison of the X and P-band images illustrates the advantages of simultaneous acquisition of the bands. The X-band image readily shows the pipeline, holding tanks, smaller pipes and other infrastructure not obscured by vegetation. By comparison, P-band peaks beneath the foliage and reveals topographic structure, homes, streets and paths barely visible in the X-band. Linear features such as fences and field boundaries pop out of the P-band data. Together these complementary images provide a complete picture of natural and manmade features. Comparing the dual-side-looking imagery to standard single-side IFSAR, a striking difference was the low level of speckling. Filtering reduces speckle noise but also reduces the resolution or sharpness of the imagery. Dual-side-looking imagery enables averaging of the different 'looks', which decreases the level of speckle noise. All GLAD-P deliverables received first-time acceptance from NGA.

Two Upgrades

The Cano-Limon project provided an opportunity to identify system features that could be refined to improve operational efficiency, resulting in two upgrades. Firstly, there was installation of a solid-state digital data-storage system capable of storing 4,000 gigabytes (four terabytes). The 100-gigabyte capacity of the onboard data storage cartridges limited flight lines to 22 minutes, which necessitated changing in-flight tapes. Now the path lengths are no longer limited, yielding greater cost-effectiveness. Secondly, there was addition of nadir-looking profiling Lidar for generating accurate bald-earth profiles for ground-control purposes. The placement of multiple radar reflectors used earlier for this purpose proved dangerous when operating in a jungle, and at least one disappeared before the flight mission began. These upgrades have been completed and tested and are operational.

As a result of this project and the upgrades, NGA has contracted EarthData to deploy GeoSAR for other mapping efforts in other parts of South America where accurate, up-to-date map data has up until now been lacking.

Further Reading

◆ Scott Hensley, Riadh Munjy, and Paul Rosen, 2001, Interferometric Synthetic Aperture Radar in Digital Elevation Model Technologies and Applications: The DEM Users Manual, editor: David F. Maune, Chapter 6, ASPRS.◆

Figure 4, *One end product is 3m-resolution orthorectified X-band imagery.*

Biographies of the Authors

Joseph Allen has over 37 years experience in mapping, charting and management of international mapping programmes. He has been with EarthData for the past three years as Program Manager for Defense/Intelligence Programs, after previously working as a NGA senior production manager. His educational background includes college courses in cartography and photogrammetry, and image interpretation and terrain analysis training at the Defense Mapping Agency.

James Reis holds MS degrees in Electrical Engineering from California State University at Long Beach and Technology Management at Pepperdine University. He has more than thirty years experience in systems engineering and information technology and has been with EarthData for the past five years as chief technology officer. He has managed the transformation of GeoSAR technology into a commercially viable airborne mapping system and data production centre.

Joseph Allen and Jim Reis, EarthData International, Corporate Headquarters, 1825 Connecticut Avenue NW, Suite 320, Washington DC, 20009 USA, e-mail: jallen@earthdata.com and jreis@earthdata.com

Web-based Solution for GPS Data

NOAA OPUS

Since March 2001 the National Geodetic Survey (NGS) has operated the Online Positioning User Service (OPUS) to provide end-users with easy access to the US National Spatial Reference System (NSRS). This popular web-based application provides accurate, reliable and consistent geodetic coordinates with minimal user input. A submitted GPS data file is usually processed within a few minutes and the computed coordinates are accurate to a few centimetres.

By Neil D. Weston, Tomás Soler, Gerald L. Mader, National Geodetic Survey, NOAA, USA

Although in principle the OPUS system can process GPS data collected from any part of the world, the majority of submissions are from North America. OPUS currently processes between 15,000 and 18,000 datasets per month and annual growth rate is around 70%. One consideration during the design phase was to keep the web-based interface simple. OPUS can presently accept GPS data files from any dual-frequency, geodetic-quality receiver, either in native receiver format or in Receiver-INdependent EXchange format (RINEX). Multiple GPS data files can also be submitted in a zip file, each GPS data file being processed sequentially and independently to produce a set of coordinates for each occupation.

User Input

The main upload page is currently limited to four input fields but does contain several buttons and links to information on OPUS, how to use the system, what policies govern its operation, and a link to Frequently Asked Questions (FAQ). The input fields are used to identify a user's email address, to which the results are sent, GPS data file, antenna type and height. The third input field has a drop-down menu that provides a list of all supported GPS antennas. Once an antenna is selected this option ensures use of the correct antenna phase patterns. Antenna height in metres can be entered in the final field. If zero is entered here the returned coordinates will be for the Antenna Reference Point (ARP), usually at the base of the antenna. The OPUS page has an option for the selection of additional parameters such as State Plane Coordinates (SPC), reference stations during processing and request for an extended report. Another option is to save to the email address antenna type and height, SPC code, selected base stations and extended option choices. This feature is handy if a user has performed multiple occupations with the same antenna etc and would like to use the same information to process each data file. After filling in all fields, the file can be uploaded.

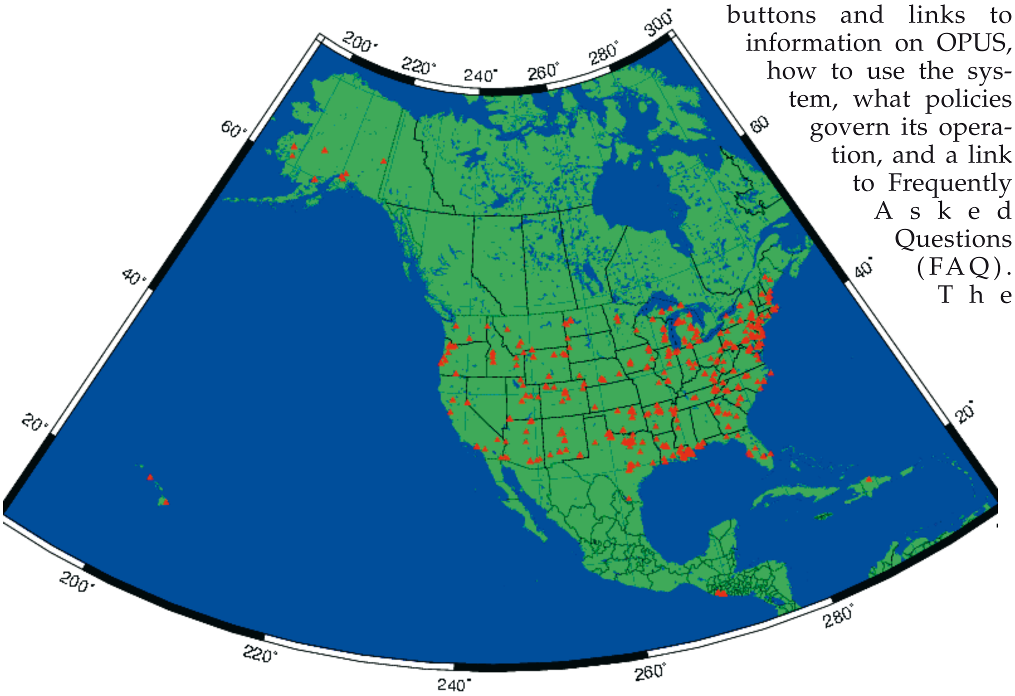
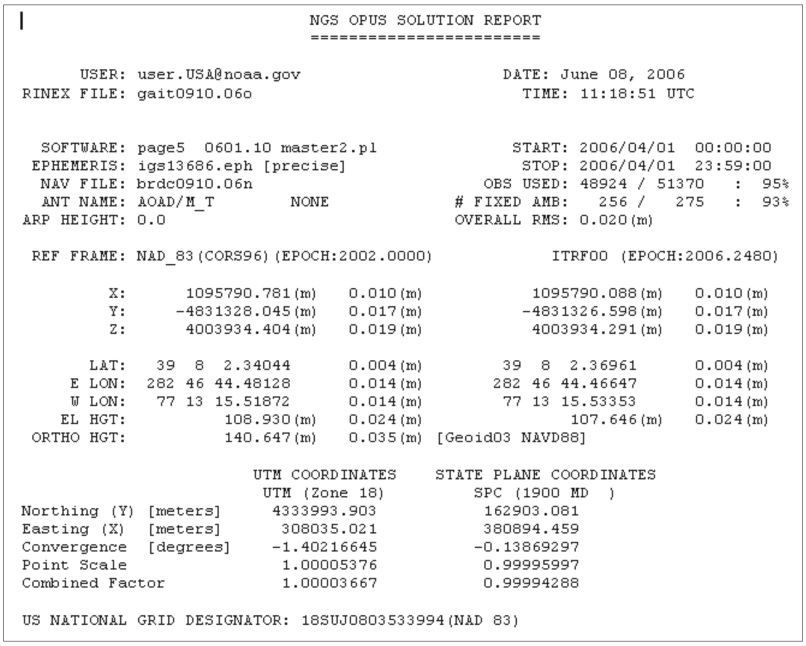


Figure 1, *Geographic location of OPUS solutions processed on 6th June 2006.*

Processing Steps

After uploading to OPUS the first step is to determine the date of occupation and the station's approximate location. The date is used to retrieve ancillary information from the International GNSS Service (IGS), such as the broadcast and precise ephemeris. The location is used to select up to three neighbouring reference stations from the IGS or CORS network, each of which will participate in a single baseline solution with the user's station. In the second step, three, independent, double-difference solutions are performed within the ITRF reference frame, between the user's station and each reference station. The results are compared and averaged, but if any section fails to meet the quality criteria



```
|                             NGS OPUS SOLUTION REPORT
                              ========================

      USER: user.USA@noaa.gov                          DATE: June 08, 2006
RINEX FILE: gait0910.06o                                TIME: 11:18:51 UTC


  SOFTWARE: page5  0601.10 master2.pl                 START: 2006/04/01  00:00:00
 EPHEMERIS: igs13686.eph [precise]                     STOP: 2006/04/01  23:59:00
  NAV FILE: brdc0910.06n                           OBS USED: 48924 / 51370   :  95%
  ANT NAME: AOAD/M_T        NONE                # FIXED AMB:   256 /   275   :  93%
ARP HEIGHT: 0.0                                 OVERALL RMS: 0.020(m)

 REF FRAME: NAD_83(CORS96)(EPOCH:2002.0000)              ITRF00 (EPOCH:2006.2480)

         X:       1095790.781(m)   0.010(m)            1095790.088(m)   0.010(m)
         Y:      -4831328.045(m)   0.017(m)           -4831326.598(m)   0.017(m)
         Z:       4003934.404(m)   0.019(m)            4003934.291(m)   0.019(m)

       LAT:   39  8  2.34044       0.004(m)         39  8  2.36961       0.004(m)
     E LON:  282 46 44.48128       0.014(m)        282 46 44.46647       0.014(m)
     W LON:   77 13 15.51872       0.014(m)         77 13 15.53353       0.014(m)
    EL HGT:           108.930(m)   0.024(m)                107.646(m)   0.024(m)
 ORTHO HGT:           140.647(m)   0.035(m) [Geoid03 NAVD88]

                        UTM COORDINATES    STATE PLANE COORDINATES
                         UTM (Zone 18)         SPC (1900 MD  )
Northing (Y) [meters]     4333993.903           162903.081
Easting (X)  [meters]      308035.021           380894.459
Convergence  [degrees]    -1.40216645          -0.13869297
Point Scale                1.00005376           0.99995997
Combined Factor            1.00003667           0.99994288

US NATIONAL GRID DESIGNATOR: 18SUJ0803533994(NAD 83)
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Figure 2, *OPUS solution report for GPS data collected on 1st April 2006.*

an additional reference station is selected for a fourth baseline. In the third and final step the ITRF coordinates are transformed into the NAD83 datum and other mapping projections such as UTM and SPC, before producing the final solution report. These three steps typically take about three to four minutes but can vary depending on occupation length.

The report sent to the user in ASCII text format via email

Output to User

The report sent to the user in ASCII text format via email consists of three main sections. The first contains information on user's dataset, such as start and stop time, antenna type and height, number of observations and overall accuracy. The second section reports positional information in the ITRF at the observation epoch, and NAD83 and UTM at the datum epoch. Peak-to-peak values are also stated and are useful in determining the level of agreement between the three individual baselines. The orthometric height at the station is computed from a geoid model produced by NGS and reported if GPS data was collected in the conterminous US. The third section contains information on the three reference stations used in the solution and the distances to each reference station and to the nearest NGS-published control point. If the extended output option is selected, additional reference-station information is given. Figure 1 shows the geographic location for a number of processed datasets submitted on 6th June 2006. Figure 1 shows a typical solution report for 24 hours of data collected at a station (gait) on 1st April 2006. The extended output is also compatible with many post-processing applications from other third-party vendors.

Performance

To determine performance, two hours of GPS data from approximately two hundred CORS sites across North America were submitted and processed and their solutions compared with the published coordinates. The standard deviations were 0.8, 1.4, and 1.9cm for the local north, east and up components, respectively (Figure 3).

Further Reading

- Mader, G.L., Weston, N.D., 2006. NGS Online Positioning User Service, GeoIntelligence Jan/Feb, pp 16-19.

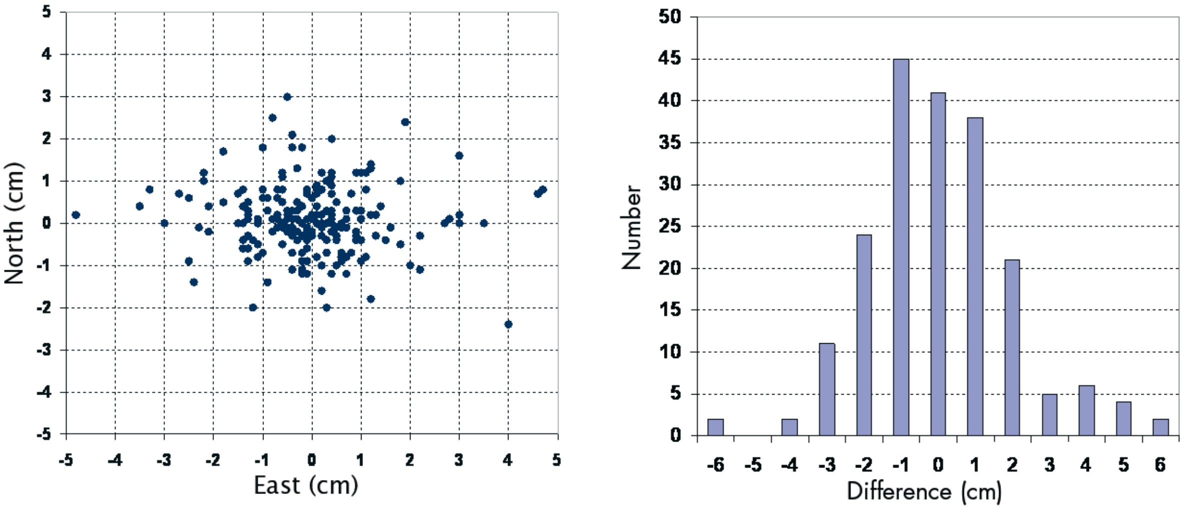

Figure 3, *Horizontal (left) and vertical (right) distributions of OPUS solution differences from accepted ITRF values shown for two hundred CORS stations using two hours of data, the minimum required by OPUS.*

- Mader G.L., Weston N.D., Morrison M.L., and Milbert D.G., 2003. The On-line Positioning User Service (OPUS). Prof. Surv. 23(5): 26, 28, 30.
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Biographies of the Authors

Neil D. Weston holds an MS in Applied Physics and will receive his PhD in Physics in May 2007. He is currently OPUS programme technical manager but also has an interest in 3D imaging and motion analysis.

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UK Commercial GPS Network Solution

From OSNET to SmartNet

On 20th December 2005 Leica Geosystems announced a partnership with Ordnance Survey to offer commercial delivery of a GPS network solution across Great Britain. The network now consists of over 110 reference stations based on GPS and GPS, and GPS/Glonass receivers, creating a full national GNSS RTK solution for over two hundred users.

By Mark Burbidge, Leica Geosystems, United Kingdom

Built upon the leading GPS Spider reference station software, SmartNet enables a further increase in GPS and GPS/Glonass productivity and reliability with reduced hardware costs.

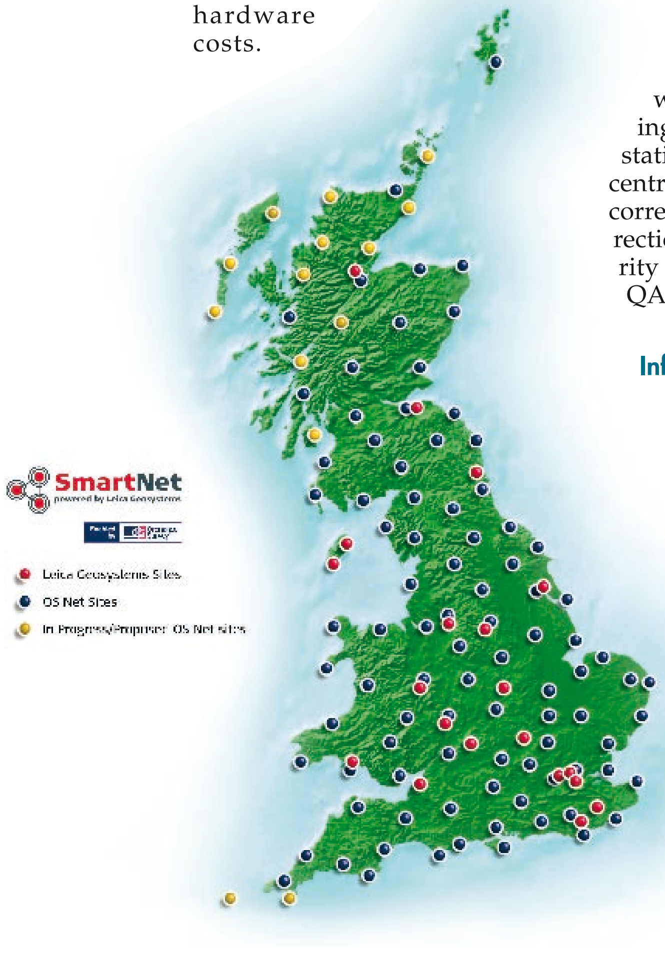


***Figure 1,** SmartNet Reference Stations as per Decemeber 2006: red spots, Leica Geosystems net sites; blue spots, Ordnance Survey net sites; yellow spots, ordnance survey sites in progress or proposed.*

The 24/7 National GNSS Network solution (see textbox for abbreviations) is based on a common datum and covers entire Great Britain (Figure 1). Users can expect centimetre-level Network RTK accuracy, through to sub-metre DGPS, or raw data for post-processing. The network consists of the following sub-systems: (1) reference station infrastructure, (2) control centre, (3) generation of network corrections, (4) delivery of corrections and support, (5) security and backup and (6) network QA/QC.

Infrastructure

The reference station infrastructure, the most important part of any network, is built in partnership with Ordnance Survey (OS) which has its own internal RTK network known as OSNET and available only to internal staff. However, OS has made available raw data from OSNET to participating commercial partners who are able to supply network software, control centre, communications and expertise on a national scale. The network will be further strengthened to create a high-density, high-redundancy network, and 'active' Leica reference stations will be added in co-operation with TSA members so as to deploy the latest GPS and Glonass reference stations receivers. In co-operation with Nottingham University's Institute of Engineering Surveying & Space Geodesy, the full GNSS RTK system will operate up to fourteen Quality Monitoring reference sites. SpiderNET software at the control centre handles and disseminates all corrections.

Corrections

A cluster is a sub-network of stations processed together to achieve a common level of ambiguity. One small network may consist of one cluster. Larger networks such as SmartNet, where performance, redundancy and reliability are at issue, consist of several clusters, and individual sites may be in more than one cluster, allowing overlap (Figure 2). Each cluster may or may not be on the same integer level. A cell is a selection of sites from a cluster consisting of one master station and several auxiliary stations, used to generate master-auxiliary corrections (Figure 3). Since SpiderNET processes all data together, every site in the cluster is reduced to the same ambiguity level and, in contrast to other approaches, no artificial limit of three reference stations is imposed. Use of more than three reference stations can improve network geometry, helps estimation of larger-scale atmospheric effects and prevents the rover from losing its fix if one reference station drops out due, for example, to unreliable communication links. Using two-way communications SpiderNet can also decide from rover location which site or cell is best suited. After receiving the position of the navigated rover SmartNet will collect all reference sites (reduced

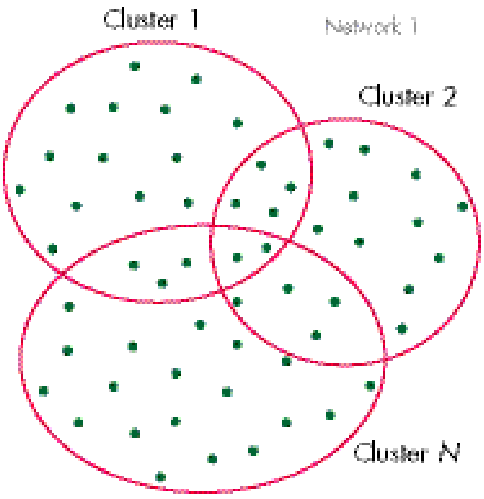


Figure 2, *Reference network comprising a number of clusters.*

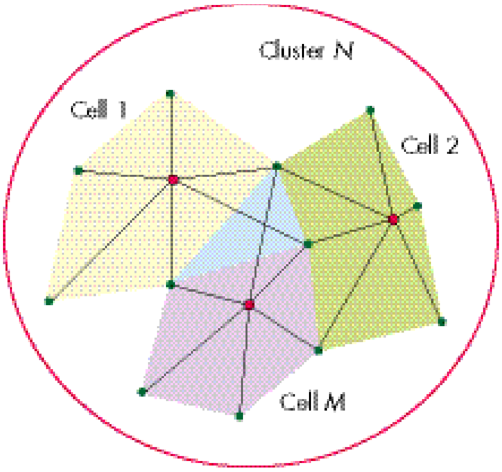


Figure 3, *A cluster provides master-auxiliary corrections to several rovers, with each rover using an appropriate cell based on its location.*

to a common ambiguity level) relevant for that position. Six stations are typically selected: the nearest as master station with full corrections and the others as auxiliary correction differences. Corrections are then returned to the user via Nearest, MAX or iMAX products, in appropriate formats (Figure 4). The GPS Spider solution enables new modules to be added, such as additional support for modernised GPS, Glonass and Galileo.

Glossary of Abbreviations

DGPS	Differential GPS
GGA	Global Positioning System Fix Data
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GSM	Global System for Mobile communication
IMAX	Individualised Master-Auxiliary Corrections
MAC	Master Auxiliary Concept
NMEA	National Marine Electronics Association
OSNET	Ordnance Survey Network
QA/QC	Quality Assurance/Quality Control
RINEX	Receiver-Independent Exchange Format
RTCM	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematic
TSA	The Survey Association
NTRIP	Networked Transport of RTCM via Internet Protocol

Delivery and Support

Each client rover is authenticated and administrated either by Internet GPRS or GSM Cell. The user can either negotiate their own sim card tariff from providers or, for subscribed rovers, obtain one from SmartNet administration. For GPRS access the user will be given an IP address, a unique user ID and password, which will normally be entered under the standard NTRIP options on manufacturer's software. For the GSM the user will require only user ID, password and phone number to dial. Flexible subscription plans have also been arranged, users not being restricted to one licence per rover system. In fact, as long as there is only one connection at a time, users will be able to switch their single licence between multiple users. Full network support is provided to users subscribing to SmartNet, with guidelines for setting up different types of rover receivers.

Security and Backup

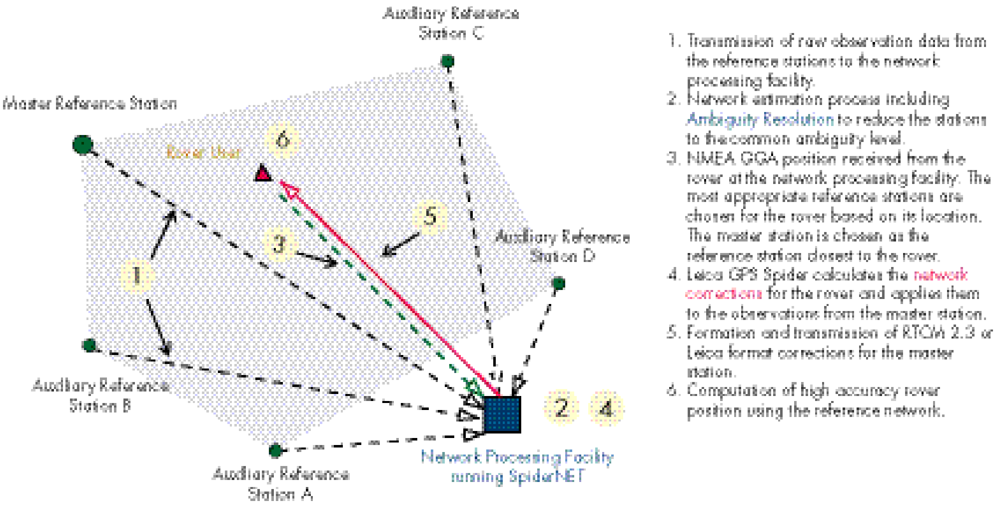
The software architecture is based on a secured site of network servers, streaming raw data from reference stations and computing corrections to a proxy server or web-server for dissemination to users by NTRIP GPRS, access router GSM or RINEX file web downloads. Full security systems, including multiple firewalls, full network redundancy and backup servers, are also supported. The security concept separates the network operation and computation from data dissemination, thereby protecting the key infrastructure and sensitive user and billing information. The architecture is situated in a high-security, co-location data centre in London's Docklands. There is full system redundancy with backup servers at the data centre. Should any problem arise within network mechanisms a full switch to backup systems is immediately implemented.

Quality Control

Leica GNSS QC software is installed at the control centre to continuously monitor data within the network and make regular audits of station multipath errors etc. Leica SpiderWeb software is fully integrated with GNSS QC, enabling real-time reports and statistics to be pushed to the web-server and giving users the ability to view network performance and statistics by way of real-time live charts on the SmartNet website. Full 1-30 second Rinex downloads are also available for service subscribers.

MAX and iMAX

Leica Geosystems has for many years been researching, promoting and realising Network RTK solutions and working towards an industry standard for Network RTK corrections. The company has jointly with other RTCM members developed and driven MAC, the future of networked RTK and basis for the newly approved RTCM 3.1 Network RTK messages. Up until now there have been no official internationally accepted standards for network RTK corrections. At the May 2006 RTCM SC104 meeting the proposed new network RTK messages for RTCM V3 were approved and the decision taken to release them with the next update of RTCM in V3.1; in October 2006 RTCM 3.1 version was formally released for Network RTK. The RTCM V3.1 network RTK messages provide an open, unambiguous and manufacturer-independent standard for network RTK corrections. The new standard, in addition to promoting increased compatibility and innovation, offers some distinct user advantages over previous non-standardised methods. Users of older receiver types are not restricted; to provide access to the entire GPS community corrections known as iMAX are available. These require two-way communications, may be transmitted in RTCM 2.3 or RTCM 3.0 format, and provide the same performance as a rover fully supporting MAX.



1. Transmission of raw observation data from the reference stations to the network processing facility.
2. Network estimation process including Ambiguity Resolution to reduce the stations to the common ambiguity level.
3. NMEA GGA position received from the rover at the network processing facility. The most appropriate reference stations are chosen for the rover based on its location. The master station is chosen as the reference station closest to the rover.
4. Leica GPS Spider calculates the network corrections for the rover and applies them to the observations from the master station.
5. Formation and transmission of RTCM 2.3 or Leica format corrections for the master station.
6. Computation of high accuracy rover position using the reference network.

***Figure 4,** Generation of master-auxiliary corrections (MAX) for rover.*

Concluding Remarks

To date, the network services over 200 RTK users. Figure 5 demonstrates that on working days on average nearly half of these are connected, and even the weekends show GNSS surveying activities.

Further Reading

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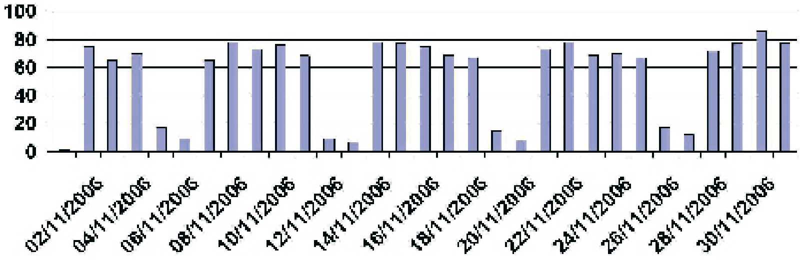

***Figure 5,** User Graphs Nov '06. RTK users do not hesitate to continue measuring activities over the weekend!*

Biography of the Author

Mark Burbidge is currently UK GNSS Network & Technical Support Manager for Leica Geosystems. He is a Chartered Surveyor member of RICS, the Royal Institution of Chartered Surveyors and full member of the Institute of Civil Engineering Surveyors. He has also participated on the RICS Geomatics faculty board and the Mapping and Positioning Panel in the UK.

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