Reflector Antenna Developments: A Perspective on the Past, Present, and Future

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Abstract

Reflector antennas confine most of the electromagnetic energy captured over their apertures into a focal plane or redirect the radiated field of the feed into far field. This paper presents a concise history of reflector antenna developments over an extended time span. Representative examples are provided for different periods that impacted various developments of reflector antennas covering past, present, and future. Due to page limitations, not all worldwide aspects of reflector antenna developments are touched upon in this paper, and the authors have confined themselves to the areas that have influenced their research activities.

Keywords: Antenna; communication; history; planetary missions; radar; radio astronomy; reflector; remote sensing; satellite

1. Introduction

Reflector antennas have seen a wide range of applications throughout history since, among other antenna configurations, they provide the highest gain, widest bandwidth, and best angular resolutions at the lowest costs. The primary role of a reflector antenna is to confine or radiate most of the electromagnetic energy over its aperture into a focal plane or far field for communication or energy transfer. Typical reflector antenna configurations are conic sections, the parabola, ellipse, hyperbola, and sphere (see Figure 1), to either focus or efficiently radiate electromagnetic waves. A casual Internet search yields over 3×10^6 hits associated with the phrase "reflector antenna."

Reflector antennas are used in diverse applications, such as satellite communications, radio astronomy, remote sensing, radar, weaponry, and medical applications. Antenna feeds are essential components of any efficient and well-designed reflector antennas; although, unfortunately, due to limited space, this topic is not covered in this paper. Many books, book chapters, and technical papers have been published on the subject of reflector antennas, including feeds [1–11]. Representative reference samples are cited in this paper, and the readers are encouraged to review them for additional references. Again, due to space limitations, many important references are not included in this paper.

Generally speaking, reflector antennas are categorized according to radiation pattern type, reflector surface type, and feed type (see Figure 2). Pencil-beam reflectors are the most popular and are commonly used in point-to-point microwave communications and telemetry, since they yield the maximum gain, and typically, their beam directions are fixed at the time of antenna installation. In satellite communication systems, the uplink pencil-beam is typically steered by moving the reflector, or steering over a limited range using the feed. Recent generations of satellite reflectors have produced other popular types of radiation pattern classifications: contour (shaped) beams and multiple beams. These applications require reflectors with improved off-axis beam characteristics and nonstandard conical shapes.

In this paper, the development of the reflector antenna, from the ancient past to the Renaissance to the present, is

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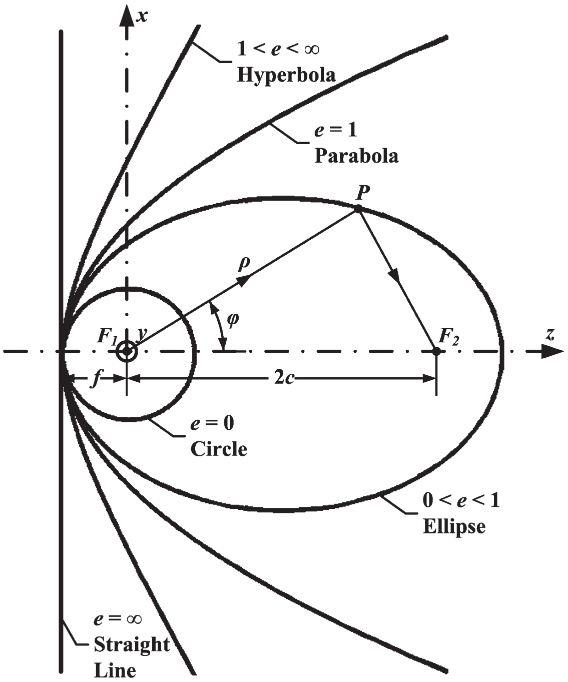

Figure 1. Conic section curves generating conic surface reflector antennas either through rotation about the z-axis or translation along the y-axis. e is the eccentricity.

reviewed in a concise fashion, along with inferences to present and future developments. A conference paper [12] was the starting point for this review paper. The authors decided to collaborate on two historical papers based on presentations they made at the IEEE CLASTECH Symposium and Exhibition on Antennas and Microwave Technology, October 2011, Los Angeles, CA, USA. This paper includes parts of the presentation made by Rahmat-Samii: “The Fascinating Evolution of Reflector Antennas: Past, Present and Future.” A recently published paper, March 2015, covered the history of phased arrays, which was based on the presentation made by Haupt.

2. Marching Through History

2.1 Ancient Legend and Archimedes’ Weapon

Archimedes is credited with using parabolic reflectors to focus the Sun’s heat on attacking Roman ships in order to set them on fire (see Figure 3). An interesting circumstantial account of Archimedes’ use of burning mirrors at the siege of Syracuse (212–215 B.C.) was given by Tzetzes, a Byzantine author of the 12th Century A.D., who claimed to be quoting from the Roman historian Dio Cassius [13]. Assuming that the legend is true, one may conclude that in order for the Sun’s heat to focus on the ships in accordance with Figure 3, the mirror should have been an offset parabolic reflector antenna.

2.2 Early Optical Telescopes in Astronomy

The optical parabolic mirrors resulted in many astronomical discoveries at the close of the Renaissance. James Gregory, a Scottish mathematician at the age of 24 in 1663, published his work titled Optica Promota. In his publication, he described a compound reflecting telescope, i.e., the Gregorian, employing two concave surfaces [14]. In 1672, Sieur Cassegrain, a Frenchman, designed a second compound reflector, differing from Gregory’s in that it employed a convex hyperbolic secondary, placed at a distance between the focus and apex of the main parabolic reflector. Typically, the Gregorian configuration provides higher magnification; however, the Cassegrain configuration is more compact. Around

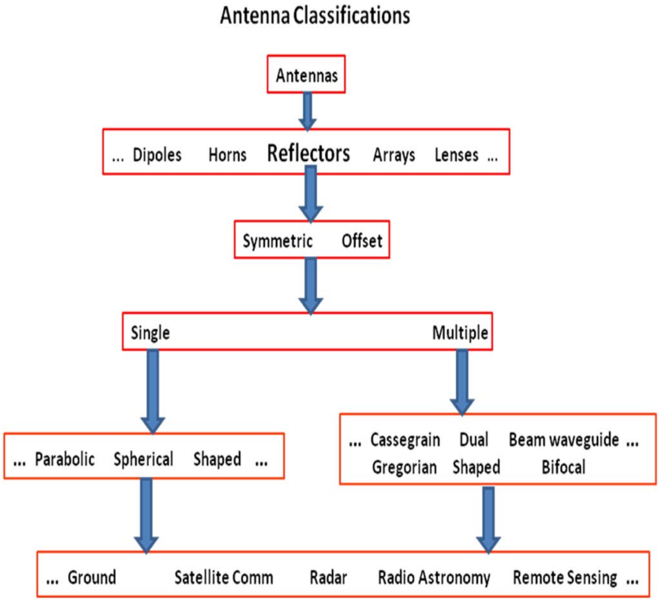

Figure 2. Antenna classifications and various reflector antenna configurations and applications.

Figure 3. Archimedes’ burning mirrors, 212 B.C. Assuming that it worked as legends have it, it must have potentially been an offset parabolic antenna.

Figure 4. Newton's parabolic reflector optical telescope, 1672.

the same time, Newton designed and built a new telescope (see Figure 4) with two reflectors, namely, a parabolic primary and a flat secondary. This Newtonian design became popular with amateur astronomers and still bears his name. All of these designs relied on the geometrical optics properties of conic sections and operated in visible light. Similar designs were subsequently adopted at other electromagnetic frequency bands.

2.3 Maxwell, Hertz, and Marconi—Pioneers

An amazing consequence of Maxwell's discovery of electromagnetic waves was the observation that time-varying currents radiate and travel with the speed of light. Hertz designed a dipole-fed cylindrical parabolic antenna (see Figure 5) along with a spark-gap generator and similar detector [15] to further demonstrate the existence of electromagnetic waves predicted by Maxwell's theory. It is believed that this was perhaps the first reflector antenna operating in nonoptical frequencies. Nobel laureate Marconi also conducted his earlier experiments employing a cylindrical parabola, as described in his first patent in 1896.

3. WWII and Beyond

3.1 RADAR—From Needs to Realities

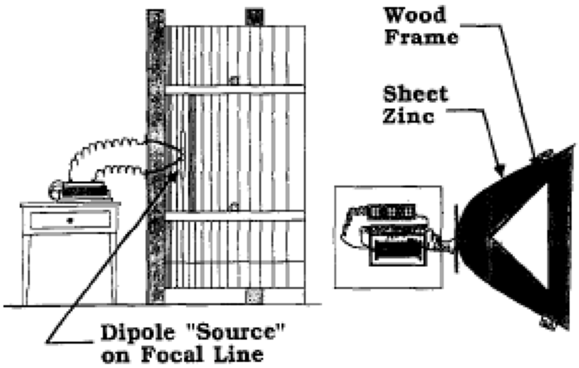

Figure 5. Hertz' parabolic cylinder reflector antenna, 1888.

Figure 6. Wurzberg Riese (Giant) radar antenna (photo taken by R. Haupt outside of the National Electronics Museum).

Germany first deployed the FuG65 Wurzburg Riese (Giant) radar antenna in 1941 to guide night fighters to attack Allied bombers. The example in Figure 6 is 7.4 m in diameter, operates at 560 MHz, and had a radar range of 44 mi. These antennas were mounted on bunkers, rail cars, and even a ship. Subsequently, the strong push for the development of Radio Detection and Ranging in WWII—the U.S. Navy coined the term RADAR in 1942

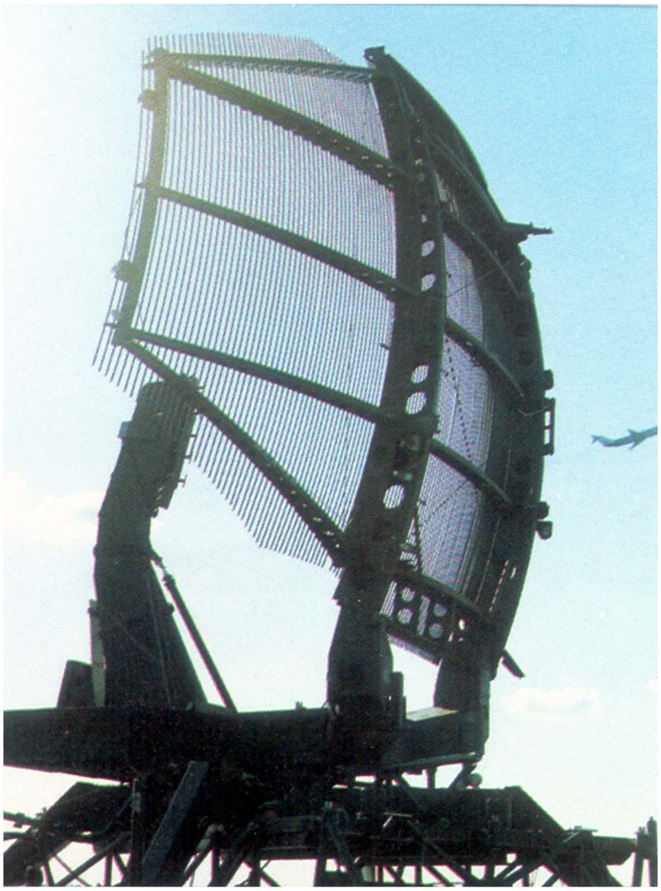

Figure 7. AN/TPS-43 radar (courtesy of the National Electronics Museum).

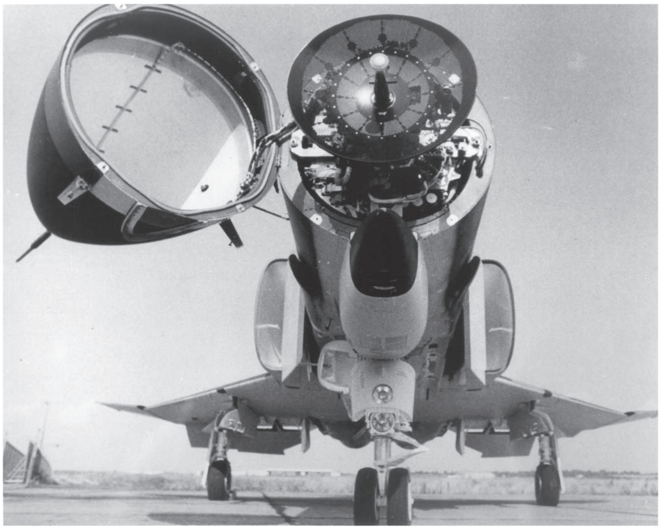

Figure 8. AN/APQ-120 radar (courtesy of the National Electronics Museum).

—led to a unified treatment of reflector antennas, documented in Silver's volume 12, *Microwave Antenna Theory and Design*, of the MIT Radiation Laboratory Series [16]. This Series is perhaps the best starting point to appreciate how the radar technology started and what the critical developments were.

A very important question about how high a frequency a particular reflector antenna surface could efficiently operate was answered by Ruze [17]. He studied the effects of the random surface roughness on reflector antenna gain and showed that there is a shortest wavelength at which the gain of any particular antenna reaches a maximum. Later on, Rahmat-Samii presented many design curves on the issue of random surface errors [18].

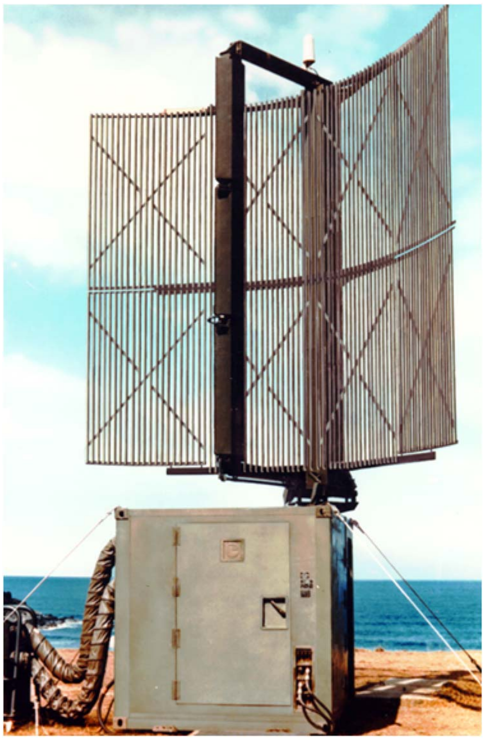

Figure 9. AN/TPS-63 radar (courtesy of the National Electronics Museum).

Radars are important for military aircraft detection. The AN/TPS-43 is a highly transportable surveillance radar that detects, tracks, and identifies aircraft. It first entered production in 1966. It has an ultralow sidelobe dish antenna (see Figure 7) to improve detection when jamming is present in addition to enhancing radar survivability. In the late 1960s and early 1970s, the military also used reflector antennas for aircraft fire control radar. The AN/APQ-120 was manufactured by Westinghouse for the McDonnell Douglas F-4E Phantom II (see Figure 8). Around 1980, the AN/TPS-63 transportable L-band radar system was built for the Marine Corps to detect small low-flying aircraft. A picture of the reflector antenna appears in Figure 9. All airports, i.e., civilian and military, have airport surveillance radar (ASR). In the late 1990s, the ASR 11 was developed by Northrop Grumman (see Figure 10).

3.2 Radio Telescopes—A New Paradigm in Astronomy

Many heavenly objects are not only observable in visible light but also emit radiation at radio wavelengths. Apart from observing energetic objects such as pulsars and quasars, radio telescopes are capable of observing other astronomical objects: galaxies, nebulae, black holes, and even radio emissions from planets.

The first radio emissions detected by Jansky at Bell Labs in the 1930s were from the Milky Way Galaxy. Inspired by Jansky's work, in 1937, Grote Reber built a 9.5-m

Figure 10. ASR 11 radar (courtesy of the National Electronics Museum).

Figure 11. Reber's 9.5-m radio telescope, from haystack.mit.edu.

Figure 13. Effelsberg 100-m radio telescope, with homology structural design.

parabolic reflector antenna in his backyard (see Figure 11) to map the sky in radio frequencies. This was the first radio telescope used for astronomical research, and it was a focal-fed symmetric parabolic dish.

Australians constructed a 64-m radio astronomy antenna at Parkes in 1961. The success of the Parkes project led the U.S. Congress to fund NASA to build a Deep Space Network of large reflector antennas, including JPL's Goldstone 64 m that was later enlarged to 70 m [19] (see Figure 12). These antennas were designed based on symmetric Cassegrain configurations.

The quest for achieving higher resolution resulted in the development of the largest fully steerable reflector antennas, namely, the 100-m symmetric radio telescope of the Max Planck Institute for Radioastronomy at Effelsberg, Germany (see Figure 13), and the 110-m Robert C. Byrd Green Bank Offset Telescope (GBT) at the National Radio Astronomy Observatory in Green Bank, West Virginia (see Figure 14). The designers of the Effelsberg antenna recognized that a completely rigid support structure for their 100-m reflector was out of the question. They furthermore realized that a homologous gravity deformation correcting system could be utilized to preserve a parabolic shape over the range of elevation angle; although, the focal length becomes a function of the elevation angle. This homologous technique provides stable aperture efficiency over its entire elevation range. The GBT utilizes an offset (asymmetrical) reflector antenna system to prevent the feed and support arm blockage of the projected main aperture. The GBT's 2004 panels that make up its surface are mounted at their corners on miniaturized motor-driven pistons that adjust the surface shape. Adjustment of these individual panels provides improved high-frequency performance and stable aperture efficiency over the desired entire elevation range.

The 300-m Arecibo (see Figure 15) is the largest reflector antenna in the world. It is built inside a spherical depression left by a giant sinkhole. A special Gregorian dual-shaped subreflector feed system compensates for the reflector's spherical shape and steers the main beam [20].

The concept of interferometry has been used to construct an array of reflector antennas interconnected by coax, waveguide, or fiber optics to increase the received signal strength and for improved resolution. The Very Large Array (VLA) in New Mexico (see Figure 16) is one example, which has 27 reflectors to provide 351 baselines and achieves a resolution of 0.2 arcseconds at 3-cm wavelength using a correlator implementation. The ALMA is the most recent large radio telescope array. It uses variable configurations and operates at terahertz frequencies

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Figure 12. 70-m JPL Goldstone shaped reflector antenna.

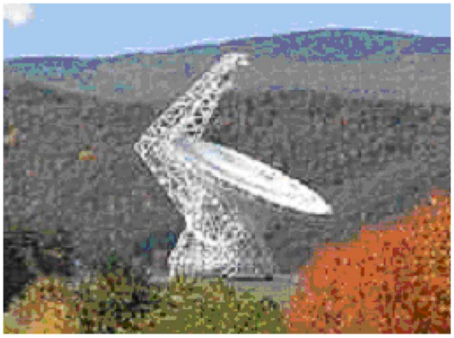

Figure 14. Green Banks 110-m offset Gregorian radio telescope, from www.gb.nrao.edu.

Figure 15. Arecibo 300-m spherical radio telescope.

(see Figure 17) on a mountain top in Chile. There are also many sophisticated reflector antenna systems for radio astronomy in space. For example, the Wilkinson Microwave Anisotropy Probe (WMAP) antenna (see Figure 18) consisted of two doubly shaped offset Gregorian reflector systems operating at frequencies ranging from 20 to 100 GHz and supporting five corrugated feed horns. Detailed descriptions of these classes of antennas can be found in [21].

4. Application of Nonstandard Designs

4.1 Offset Reflectors—Providing Improved Performance

To overcome the undesirable effects of the feed and strut blockages, the various offset reflector antenna configurations displace the feeds and supporting struts outside the projected aperture area of the reflector antenna. Removing the blockage has the advantages of reducing sidelobes and increasing the overall antenna efficiency. Linear polarized cross-polarization is higher in the plane perpendicular to the offset plane, and circular polarization (CP) suffers from beam squint in the same plane. Mizugutch identified a geometric condition for the offset dual reflector, which cancels the undesirable linear cross-polarization [22], [23], and Duan and Rahmat-Samii have provided a simple formula for estimating the CP beam squint [24]. Many useful design curves and equations for offset reflector antennas are provided in [9]. Some representative single and multiple offset reflector antenna configurations are shown in this paper.

Figure 16. VLA in New Mexico.

Figure 17. Terahertz ALMA reflectors on the mountains of Chile.

4.2 Shaped Reflectors—Improving Overall Efficiencies

Considering only the feed spillover and aperture taper efficiencies, a standard Cassegrain reflector antenna efficiency is limited to roughly 80% [25]. Based on the pioneering works of Galindo [26], Williams [27] developed a geometrical optics shaping algorithm to increase the efficiency to nearly 100%. The shape of the initially hyperbolic subreflector is changed to redistribute the feed energy uniformly across the main aperture, taking into account the feed pattern. The shape of the main reflector is changed to ensure uniform aperture phase. More versatile reflector shaping can be achieved using diffraction shaping techniques [28] instead of the geometrical optics shaping. Some representative shaped reflector antenna configurations may be seen in Figures 7, 12, and 18. These shaping techniques have also

Figure 18. WMAP doubly shaped Gregorian reflector antennas.

Figure 19. Cassini spacecraft 4-m antenna with S/X/Ku/Ka-band FSS.

been used to generate nonpencil radiation patterns such as cosecant and contour beams.

4.3 FSS—Providing Frequency Diplexing

A frequency-selective surface (FSS), which is also referred to as a dichroic surface, transmits a set of desired frequencies while reflecting others and, thus, allows spatially separated feeds to illuminate the same reflector antenna (at different frequencies). For example, Cassini mission's spacecraft reflector antenna (see Figure 19) has an FSS operating at S, X, Ku, and Ka bands [29], [30].

Figure 20 shows an FSS populated with tripoles (three-legged dipoles). It reflects frequencies over a certain bandwidth centered about the resonance of the tripole.

4.4 Beam Waveguides to Reposition the Feeds

In a very large antenna system, it is desirable to locate the feed systems in an easily accessible location. A beam waveguide reflector configuration guides the signal using mirrors from its normal focal point near the vertex to a focal point below the structural support where the antenna's feed equipment is housed. This configuration has very low losses between the reflector and the feed equipment (see Figure 21). JPL has developed several beam waveguide antenna systems at its Goldstone facility [19]. More recent developments in beamwaveguide antennas can be found in the literature [31].

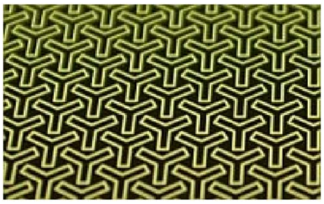

Figure 20. Example of a dichroic FSS, from www.q-par.com.

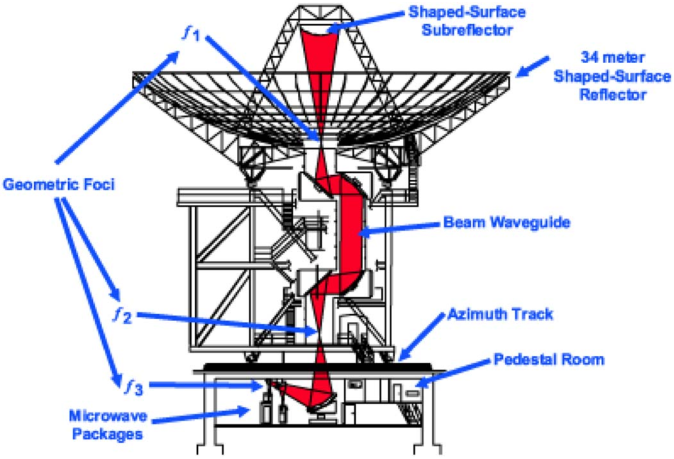

Figure 21. Typical beam waveguide optics routing horn energy into the virtual focus of the subreflector.

4.5 Unfurlable Mesh Surfaces

The quest to deploy large reflector antennas in space necessitated the developments of challenging antenna configurations. A summary of earlier developments may be found in [6]. One concept utilizes an unfurlable antenna that is made from conductive mesh fabrics (typically gold-plated molybdenum with various opening sizes) strung between ribbing and deploys in space similar to a blossoming flower or umbrella. The antenna is transported into space in a closed position that compacts and protects the fabric during shipment. An earlier design of such concept was ATS-6 (see Figure 22).

The Galileo spacecraft utilized a deployable symmetric mesh 4.8-m shaped reflector antenna, as shown in Figure 23. The performance of this antenna was measured at the plane-polar near-field facility at JPL [32]. A deployable 6-m offset reflector antenna and boom assembly on a rotating platform has been used on NASA/JPL's Soil Moisture Active Passive (SMAP) mission successfully launched in January 2015 to map—with increased accuracy, resolution, and coverage—global soil moisture in addition to the freezing and thawing cycles (see Figure 24) [33].

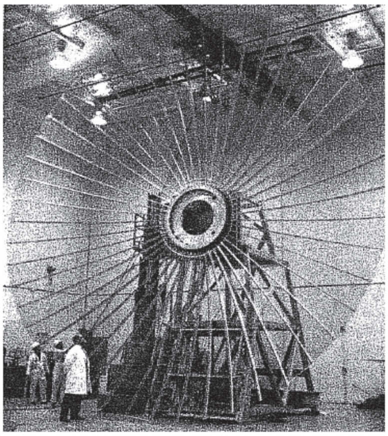

Figure 22. ATS-6 unfurlable 9-m reflector [5].

Figure 23. Galileo high gain 4.8-m deployable mesh reflector antenna at JPL's plane-polar near-field measurement facility.

The Thuraya-3 satellite launched in 2008 with a 12 m × 16 m deployable mesh reflector antenna (see Figure 25) at the L-band provides cellular-like mobile Satcom (GSM-compatible telephone services) over a large geographical region. The Thuraya coverage area encompasses the Middle East, North and Central Africa, Europe, Central Asia, and the Indian subcontinent. The satellites employ state-of-the-art onboard digital signal processing to create more than 200 spot beams that can be redirected on-orbit, allowing the Thuraya system to adapt to business demands in real time.

Alphasat is the largest telecom satellite ever launched by the European Space Agency. It has an 11-m dish that successfully deployed in orbit in 2013 [34].

4.6 Inflatable and Membrane Designs

An alternative to the unfurlable mesh concept is an inflatable reflector antenna that uses conductive membrane instead of the mesh. In 1996, the crew of the Space Shuttle Endeavor released a Spartan Free-Flyer Spacecraft carrying a container about half the size of an office desk. It had a 14-m inflatable reflector, supported by a 15-m diameter torus and connected to the Spartan via three 30-m struts. The reflector and torus were inflated into a reflector shape (see Figure 26). It was the most significant experiment in Space inflatables [35] since the days of the ECHO reflector satellites. A futuristic JPL/NASA concept, i.e., ARISE, of a 20-m inflatable offset Gregorian reflector antenna arrayed with reflectors on earth for imaging black holes at microwave and millimeter-wave frequencies with very high resolution is shown in Figure 27. A potential offset cylindrical membrane reflector antenna design, for future remote sensing applications at the Ku- and Ka-band frequencies, is shown in Figure 28 [36].

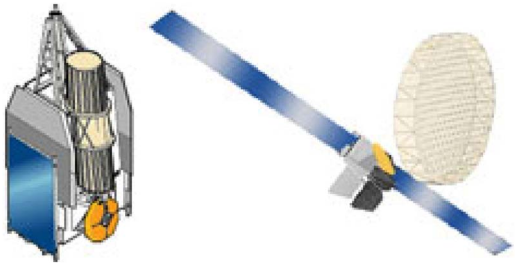

Figure 25. Thuraya satellite shown stowed (left) and deployed (right), from www.boeing.com.

5. CAD and Measurements

Antenna theory is necessarily complex because it involves the solution of electromagnetic wave equations with imposed boundary conditions. Hertz modeled approximate field solutions by deriving the fields of a small oscillating dipole, which is referred to as a *Hertzian dipole*. Many numerical methods used today, such as GTD, PO, PTD, etc., were devised before the advent of the high-performance computers. Implementations of the full-wave solutions can model moderate-size reflector antennas. A descriptive summary of various reflector antenna analysis and synthesis methods, including simple, complex, mesh, and dichroic surfaces, can be found in [9], [10], [11], and [37]. These papers also provide ample other related references.

Reflector antenna measurement techniques have significantly progressed from far-field to indoor to near-field to

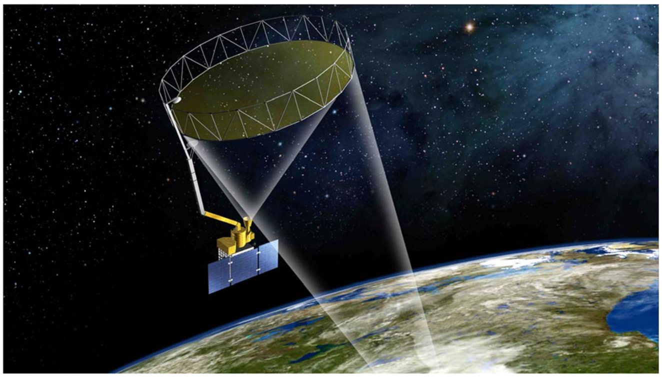

Figure 24. Space-deployable 6m mesh reflector for NASA/JPL Soil Moisture Active Passive (SMAP) mission on a rotating platform, from www.spaceref.com.

Figure 26. L'Garde 14-m offset parabolic shuttle deployed inflatable reflector antenna, viewed from Space Shuttle.

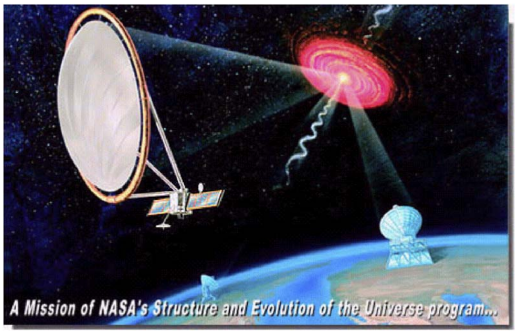

Figure 27. An artist rendition of ARISE inflatable Gregorian reflector antenna arrayed with reflector antennas on earth for microwave and millimeter wave imaging of black holes.

on-orbit measurements. For example, Figure 29 shows the Ku-band DirecTV offset parabolic reflector antenna in the University of California, Los Angeles (UCLA) bipolar planar near-field measurement anechoic chamber. Modern applications of microwave holography and diagnostics have also enhanced the utilization of large reflector antennas by mapping their surface profiles very accurately [38]. Characterizing the surface distortions allows adaptive algorithms to improve performance [9], [39].

Compact ranges use reflector antennas to generate plane waves in the near-field over a large quiet zone. Serrated edges on the compact range reflector mitigate the edge diffraction. More recently, rolled edge compact range reflectors have become popular for reducing edge diffraction.

6. Concluding Remarks

The reflector antenna has significantly influenced astronomy, remote sensing, radar, and weaponry and has always been the workhorse of satellite communication systems. Regrettably, many outstanding aspects of worldwide reflector antenna developments are not touched upon in this paper, and due to page limitations the authors have confined themselves to the areas that have influenced their research activities. Reflector antenna designs have evolved from the early intuitive days of Archimedes and Hertz to the current age of CAD. Advanced mechanical and material developments encouraged the construction of many ingenious designs.

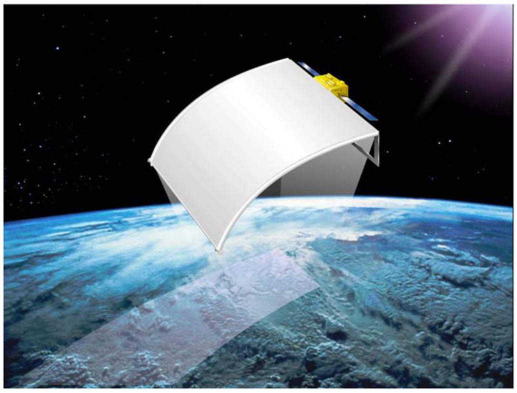

Figure 28. Artist rendition of the remote sensing 6-m offset cylindrical reflector antenna planned to operate at Ku and Ka bands.

Figure 29. DirecTV multifeed offset parabolic reflector antenna in plane-polar near-field measurement facility at UCLA.

It may be interesting to note that Archimedes' burning ship mirrors parallel what today might be referred to as the impulse radiating antennas (IRAs) [40], [41] (see Figure 30) in disabling enemy electronics. This appears to be going a full circle!

Finally, one of the authors, Rahmat-Samii, was so fascinated by a typical reflector antenna shape that when he designed the winning IEEE Antennas and Propagation Society Logo (see Figure 31), he used a rendition of the reflector shape in the artwork of the logo. This depiction of an antenna is the most recognized form of any antenna by the general public.

Perhaps the best way to conclude this paper is by quoting a profound phrase from Goddard, the American father of rocketry: "It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of

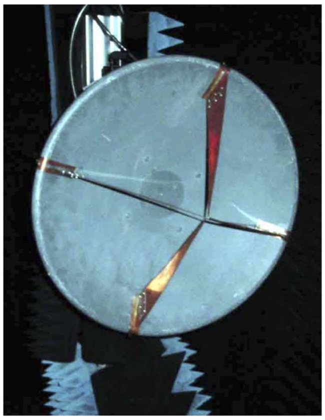

Figure 30. IRA in the spherical near-field measurement range at UCLA.

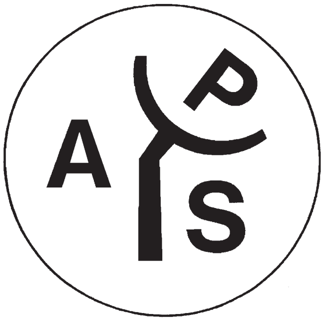

Figure 31. Logo of the IEEE Antennas and Propagation Society, designed by Rahmat-Samii, inspired by the shape of the parabolic reflector antenna.

tomorrow." We are looking forward to many innovative applications of reflector antennas for many years to come.

7. Acknowledgement

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8. References

[1] C. A. Balanis, *Antenna Theory*, 3rd ed. New York, NY, USA: Wiley, 2005.

[2] A. W. Love, "Some Highlights in Reflector Antenna Developments," *Radio Sci.*, vol. 11, no. 8/9, pp. 671–684, Aug./Sep. 1976.

[3] P. J. B. Clarricoats and G. T. Poulton, "High-Efficiency Microwave Reflector Antennas—A Review," *Proc. IEEE*, vol. 65, no. 10, pp. 1470–1504, Oct. 1977.

[4] P. J. B. Clarricoats, "Some Recent Advances in Microwave Reflector Antennas," *Proc. Inst. Elect. Eng.*, vol. 126, no. 1, pp 9–25, Jan. 1979.

[5] A. W. Love, *Reflector Antennas*, New York, NY, USA: Wiley, 1978.

[6] A. G. Roederer and Y. Rahmat-Samii, "Unfurlable Satellite Antennas: A Review," *Annales des Telecommun.*, vol. 44, no. 9/10, pp. 475–488, Nov. 1989.

[7] W. V. T. Rusch, "The Current State of the Reflector Antenna Art—Enter the 1990's," *Proc. IEEE*, vol. 80, no. 1, pp. 113–126, Jan. 1992.

[8] A. D. Olver, "Trends in Antenna Design Over 100 Years," in *Proc. IEEE Int. Conf. 100 Years Radio*, Sep. 1995, pp 83–88.

[9] Y. Rahmat-Samii, "Reflector antennas," in *Antenna Engineering Handbook*, J. Volakis, Eds. New York, NY, USA: McGraw-Hill, 2007, Ch. 15, pp. 15-1–15-63.

[10] W. Imbriale, S. Gao, and L. Boccia, Eds. *Space Antenna Handbook*. New York, NY, USA: Wiley, 2012.

[11] S. K. Sharma, et el., Eds. *Handbook of Reflector Antennas and Feed Systems*. Norwood, MA, USA: Artech House, 2013.

[12] Y. Rahmat-Samii and A. Densmore, "A History of Reflector Antenna Development: Past, Present and Future," in *Proc. SBMO/IEEE MTT-S IMOC*, Belem, Brazil, Nov. 2009, pp. 17–23.

[13] D. D. Simms, "Archimedes and Burning Mirrors," *Phys. Educ. IOP Electron. J.*, vol. 10, pp 517–521, Nov. 1975.

[14] A. Dodd, "An Acre of glass—The History of the Telescope," [Online]. Available: http://ezinearticles.com/?An-Acre-of-Glass—The-History-of-the-Telescope&id=2601009.

[15] D. J. Cickon and W. Wiesbeck, "The Heinrich Hertz Wireless Experiments at Karlsruhe in the View of Modern Communication," in *Proc. IEEE Int. Conf. 100 Years Radio*, Sep. 1995, pp 1–6.

[16] S. Silver, *Microwave Antenna Theory and Design*, New York, NY, USA: McGraw-Hill, 1949.

[17] J. Ruze, "Antenna Tolerance Theory—A Review," *Proc. IEEE*, vol. 54, no. 4, pp. 633–640, Apr. 1966.

[18] Y. Rahmat-Samii, "Effects of Deterministic Surface Distortions on Reflector Antenna Performance," *Proc. IEEE*, vol. 54, no. 4, pp. 633–640, Apr. 1992.

[19] W. A. Imbriale, "Evolution of the Large Deep Space Network Antennas," *IEEE Antennas Propag. Mag.*, vol 33, no. 6, pp.7–19, Dec. 1991.

[20] P.-S. Kildal, L. Baker and T. Hagfors, "Development of a Dual-Reflector Feed for the Arecibo Radio Telescope: An Overview," *IEEE Antennas Propag. Mag.*, vol. 33, no. 5, pp. 2–18, Oct. 1991.

[21] P. F. Goldsmith, "Space antennas for radio astronomy" in *Space Antenna Handbook*, W. Imbriale, S. Gao, and L. Boccia, Eds. New York, NY, USA: Wiley, 2012, pp. 629–663.

[22] Y. Mizugutch, M. Akagawa and H. Yokoi, "Offset Dual Reflector Antenna," in *Proc. IEEE AP-S Symp.*, pp. 2–5, Oct. 1976.

[23] W. V. T. Rusch, P. Aluizio and Y. Rahmat-Samii, "Derivation and Application of the Equivalent Paraboloid for Classical Offset Cassegrain and Gregorian Antennas," *IEEE Trans. Antennas Propag.*, vol. 38, no. 8, pp. 1141–1149, Aug. 1990.

[24] D. W. Duan and Y. Rahmat-Samii, "Beam Squint Determination in Conic-Section Reflector Antennas With Circularly Polarized Feeds," *IEEE Trans. AP-S*, vol. 39, no. 5, pp 612–619, May 1991.

[25] Y. Rahmat-Samii, "Subreflector Extension for Improved Efficiencies in Cassegrain Antennas—GTD/PO Analysis," *IEEE Trans. Antennas Propag.*, vol. 34, no. 10, pp. 1266–1269, Nov. 1986.

[26] V. Galindo, "Design of Dual Reflector Antennas With Arbitrary Phase and Amplitude Distribution," *IEEE Trans. Antennas Propag.*, vol. 12, no. 1, pp. 403–408, Jul. 1963.

[27] W. F. Williams, "High Efficiency Antenna Reflector," in *Proc. Microw. J.*, Jul. 1965, pp 79–82.

[28] D. W. Duan and Y. Rahmat-Samii, "A Generalized Diffraction Synthesis Technique for High Performance Reflector Antennas," *IEEE Trans. Antennas Propag.*, vol. 43, no. 1, pp. 27–40, Jan. 1995.

[29] Y. Rahmat-Samii and A. N. Tulintseff, "Diffraction Analysis of Frequency Selective Reflector Antennas," *IEEE Trans. Antennas Propag.*, vol. 41, no. 4, pp. 476–487, Apr. 1993.

[30] J. Huang, T. K. Wu, and S. W. Lee, "Tri-Band Frequency Selective Surface With Circular Ring Elements," *IEEE Trans. AP-S*, vol. 42, no. 2, pp. 166–175, Feb. 1994.

[31] E. Vassallo et al., "The European Space Agency's Deep-Space Antennas," *Proc. IEEE*, vol. 95, no. 11, pp. 2111–2131, Nov. 2007.

[32] Y. Rahmat-Samii and M. Gatti, "Far-Field Patterns of Space-Borne Antennas From Near-Field Measurements," *IEEE Trans. Antennas Propag.*, vol 33, no. 6, pp. 638–648, Jun. 1985.

[33] P. Focardi, P. Brown, and Y. Rahmat-Samii, "Deployable mesh reflector antennas for space applications: RF characterizations" in *Space Antenna Handbook*, W. Imbriale, S. Gao, and L. Boccia, Eds. New York, NY, USA: Wiley, 2012, pp. 314–343.

[34] Alphasat Fact Sheet, European Space Agency, http://esamultimedia.esa.int/docs/technology/Alphasat_factsheet.pdf.

[35] C. G. Cassapakis, A. W. Love, and A. L. Palisoc, "Inflatable Space Antennas—A Brief Overview," *Proc. IEEE Aerosp. Conf.*, Mar. 21–28, 1998, vol. 3, pp 453–459.

[36] Y. Rahmat-Samii et al., "Advanced Precipitation Radar Antenna: Array-Fed Offset Membrane Cylindrical Reflector Antenna," *IEEE Trans. Antennas Propag.*, vol 53, no. 8, pp. 2503–2515, Aug. 2005.

[37] A. Miura and Y. Rahmat-Samii, "Spaceborne Mesh Reflector Antennas With Complex Weaves: Extended PO/periodic MoM Analysis," *IEEE Trans. Antennas Propag*, vol 55, no. 4, pp. 1022–1029, Apr. 2007.

[38] Y. Rahmat-Samii, "Microwave Holographic Metrology for Antenna Diagnosis," *IEEE Antennas Propag. Newslett.*, vol. 29, no. 3, pp. 5–16, Jun. 1987.

[39] Y. Rahmat-Samii, "Novel out-of-the-box Concepts for Future Spaceborne Antennas," in *Proc. 3rd EuCAP*, Berlin, Germany, Mar. 2009, pp. 836–839.

[40] C. D. Taylor and D. V. Giri, *High-Power Microwave Sytstems*. New York, NY, USA: Taylor & Francis, 1994.

[41] M. Manteghi and Y. Rahmat-Samii, "Improved Feeding Structures to Enhance the Performance of the Reflector Impulse Radiating Antenna (IRA)," *IEEE Trans. Antennas Propag.*, vol 54, no. 3, pp. 823–834, Mar. 2006.

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