Displaced-Axis-Ellipse Reflector Antenna for Spacecraft Communications

Aluizio Prata, Jr., Fernando J. S. Moreira, and Luis R. Amaro

***Abstract*— This work discusses the electrical characteristics of axially-symmetric dual-reflector antenna systems based on the Axially Displaced Ellipse (ADE) configuration, with emphasis on its application in compact high-gain high-efficiency spacecraft communication antennas. Relevant ADE electrical properties are compared with the corresponding characteristics of the Cassegrain geometry (a configuration commonly used in high-gain spacecraft applications). It is shown that the ADE is capable of operating efficiently with electric apertures considerably smaller than the Cassegrain geometry, an important feature for small spacecraft. To demonstrate the outstanding electric performance that can be expected from the ADE, the predicted and measured results of an X-band 1250 mm aperture diameter prototype are presented.**

***Index Terms*— Reflector antennas, Axially-displaced ellipse antennas, high-gain antennas, spacecraft antennas, communication antennas.**

I. Introduction

As the technical sophistication of the instruments used in deep-space missions increases, so does their demand on the communication channel data rates required to relay the acquired information back to earth. Increased data rates require increased signal-to-noise ratios. Among the multitude of engineering parameters that can be used to improve the communication channel signal-to-noise ratio, increasing the antenna gain is an obvious choice. However, since the gain of any antenna is directly proportional to its collecting area, the current trend towards smaller spacecrafts provides a conflicting requirement that severely limits the maximum tolerable antenna aperture dimensions. The end result is an increasing need for relatively small and efficient aperture antennas.

Since the early days of space exploration, most spacecraft high-gain antennas have employed axially-symmetric dual-reflector Cassegrain geometries [1]. Although not without problems, this ubiquitous configuration derived from the classical Cassegrain telescope of optical fame is robust, relatively simple, and capable of providing high gain and high efficiency as long as its reflectors have a reasonable size relative to the operational wavelength. In this article another dual-reflector antenna configuration is discussed: the displaced-axis dual-reflector antenna (usually referred to as the axially displaced ellipse, or ADE, antenna). This and other comparable antenna geometries have been studied by the authors during the last five years [2]. It has been found that the ADE provides an excellent choice for compact high-gain spacecraft antenna applications. As the result of this study, the ADE geometry was recently selected for use as the X- and Ka-band high-gain antenna of the NASA's Mars Reconnaissance Orbiter spacecraft (MRO), currently scheduled for launch in 2005.

Several relevant electric aspects of the ADE configuration are discussed below. Since this antenna is presented here as an alternative to the typical Cassegrain geometry, when a relatively small electric aperture size is needed, we start with an overview of the Cassegrain geometry and the corresponding difficulties that occur when its electric aperture is reduced. With this background, the ADE is introduced and its significant aspects are discussed. Also, whenever appropriate the characteristics of the ADE and Cassegrain antennas are compared. To demonstrate the ADE antenna, as well as to validate the tools developed for its design and analysis, a prototype X-band ADE with an electrically small 1250 mm diameter aperture (about 30 wavelengths at 7.145 GHz, which is considered a small diameter for dual-reflector antennas) was successfully constructed and measured as part of the NASA's Mars Surveyor 2001 Program. This article concludes with a discussion of this early example of a compact ADE antenna, which although never used in space, is the precursor to the NASA's Mars Reconnaissance Orbiter spacecraft ADE antenna currently being made.

II. The Ubiquitous Cassegrain and some of its Limitations

The classical Cassegrain configuration is shown in Fig. 1. In order to provide a realistic example, this is a scale drawing of a compact practical geometry. This antenna employs an electrically large paraboloidal main reflector (diameter D_M and focal length F) illuminated by a relatively smaller confocal coaxial hyperboloidal subreflector (diameter D_S and inter-focal distance $2c$). In the transmit mode of operation a high-gain feed horn located at the system focus excites the subreflector, which on its turn scatters the feed energy towards the main reflector (the main reflector is then illuminated from the virtual focus located behind the subreflector). Having the feed horn as near as possible to the main reflector vertex allows the associated communications electronics to be placed just behind the main reflector, minimizing the length, and hence the

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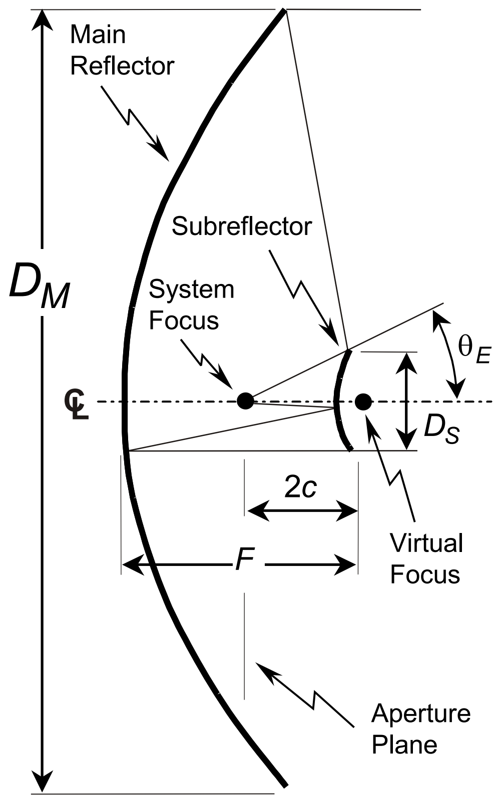


Fig. 1. Axially-symmetric Cassegrain antenna geometry.

associated loss of the waveguide runs connecting the amplifiers to the feed horn. In this geometry the main reflector provides the desired gain with the subreflector operating as a relay mirror that spreads the horn radiated energy over the relatively large main reflector angular extension.

The basic principle of operation of the Cassegrain, and almost any other reflector antenna, is geometrical optics (i.e., their operation assume that the electromagnetic field can be described by rays). In this light, Fig. 1 can be scaled up to any physical dimension, as long as all its relative proportions are preserved. However, to assure proper operation when scaling down, the reflecting surfaces cannot become smaller than several wavelengths in extent—practical experience indicates that about 7 wavelengths is a reasonable lower limit for most geometries. If excessively small surfaces are used, the electric performance of the antenna proportionally degrades significantly. Also, since the subreflector is always substantially smaller than the main reflector, as the antenna electric dimensions are reduced, the subreflector will reach the above wavelength limit before the main reflector. As a consequence there is a tendency to increase the D_S/D_M ratio if the above limitation needs to be circumvented. However, this approach also increases the aperture blockage by the subreflector, causing performance degradation. Although reasonable variations of the basic Cassegrain antenna geometry of Fig. 1 can be implemented in practice, for X-band spacecraft antennas a typical compromise of all the above discussed effects leads to $D_S \approx D_M/8$ and $\theta_E \approx 25°$ (this edge angle requires a feed horn with about 19 dBi directivity). Assuming a minimum subreflector diameter of 7 wavelengths, one then concludes that the main reflector of the Cassegrain should have at least 56 wavelengths in diameter.

The two reflecting surfaces depicted in Fig. 1 are classical (i.e., a paraboloid and a hyperboloid). As a consequence, the feed directivity must be both sufficiently high to minimize the energy spillover past the subreflector as well as sufficiently low to maximize the antenna efficiency. An optimum is typically achieved when the feed radiation along the subreflector rim direction is about 11 dB lower than towards the subreflector vertex (i.e., the feed taper $F_t = -11$ dB). As Fig. 1 indicates, an obvious difficulty with classical surfaces is the fact that the feed energy reflected by the subreflector vertex region goes back into the feed instead of illuminating the main reflector. The feed aperture then blocks some of the subreflector scattering, increasing the antenna return loss and reducing its efficiency. However, to a certain extent this problem can and should be corrected using instead a variation of the Cassegrain called the axially-displaced Cassegrain (ADC) geometry [2]. Basically this modified Cassegrain configuration employs a slightly pointed subreflector vertex that diverts the reflected energy away from the main reflector axis. Ignoring conductivity losses and mechanical errors, in the high-frequency limit the ADC reaches an efficiency of about 83% (see Fig. 2). Further efficiency improvement can be obtained by completely departing from classical surfaces and using shaped surfaces [3]. In addition of also having a pointed subreflector vertex, shaped surfaces also allow the use of an even higher gain feed. The subreflector can then be illuminated with an amplitude taper F_t significantly larger than 11 dB, reducing the spillover to a small level while simultaneously achieving a near-uniform main-reflector illumination. Since with shaped surfaces about 98% efficiency can be achieved in the high-frequency limit (again ignoring conductivity losses and mechanical errors, and assuming $D_S \approx D_M/8$), any high-gain spacecraft Cassegrain antenna should use shaped surfaces.

Now let's return to the design of compact Cassegrain antennas. To better appreciate the difficulties encountered in this endeavor, consider a typical X-band deep-space spacecraft application (lowest operational frequency of 7.145 GHz) with a gain requirement translating into $D_M = 2400$ mm. This diameter corresponds to about 57 wavelengths at 7.145 GHz, which according to a previous paragraph is about the minimum diameter for an X-band Cassegrain. Although this conclusion is somewhat open to dispute, this example should nevertheless clearly indicate that designing small efficient Cassegrain antennas (e.g., with $D_M = 1500$ mm) is not a simple task. With such a small subreflector the unavoidable diffraction effects will significantly reduce the Cassegrain antenna efficiency. Although in this situation shaped surfaces will still provide some efficiency improvement, the control of the main-reflector illumination is severely compromised, and the benefits of a pointed subreflector vertex become almost insignificant. Furthermore, since the feed horn dimensions cannot be reduced as the antenna dimensions are scaled down, the blockage caused by the feed horn quickly becomes a significant problem. Clearly then a different reflector antenna geometry is needed for compact reflector-antenna applications.

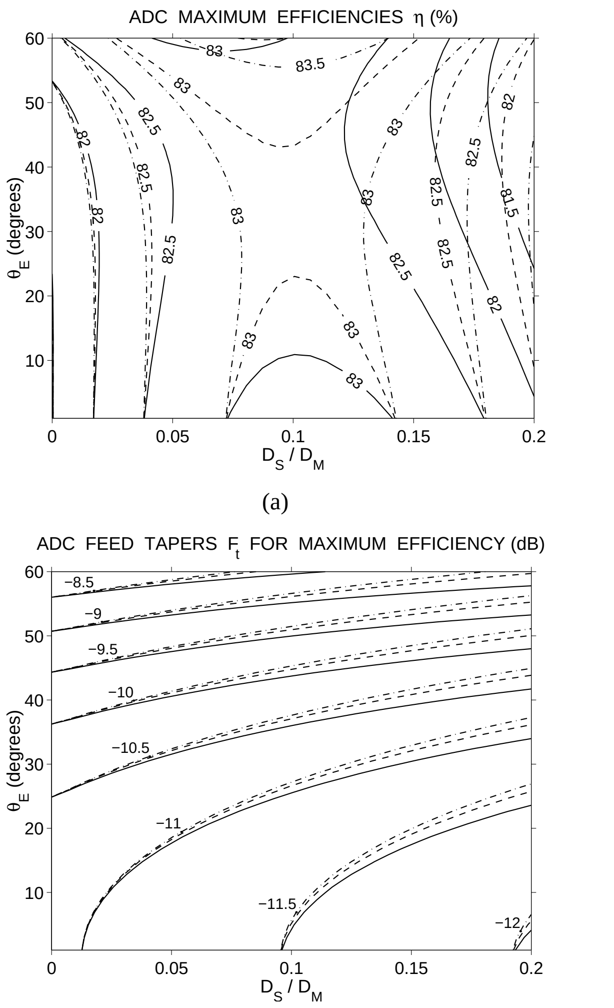


Fig. 2. Axially-displaced Cassegrain (ADC) a) maximum effi ciencies η and b) corresponding feed tapers F_t: $\ell_o/D_M = 0.5$ (solid lines), 1 (dashed lines), and 2 (dash-dot lines), where ℓ_o is the total path length of a ray propagating from the system focus to the aperture plane.

Since the minimum subreflector size provides one of the dominant limitations of electrically small Cassegrain antennas, an obvious alternative would be to remove it and place a low-gain feed horn at the paraboloidal main reflector focus. This alternative—the paraboloidal reflector antenna—is widely used in many antenna applications and is well covered in the available literature. However, it also has its own limitations when used to implement compact high-gain spacecraft antennas. In a nutshell, two main difficulties stand out: it is very hard to efficiently illuminate paraboloidal reflectors of small relative depth (i.e., small F/D ratios) due to the lack of high performance feed horns capable of producing the required broad angular radiation; and a single reflecting surface limits the design flexibility. As a consequence this alternative also does not produce a highly efficient antenna.

III. The ADE Antenna and its Advantages

An alternative dual-reflector antenna design that minimizes several of the problems discussed above is the ADE geometry

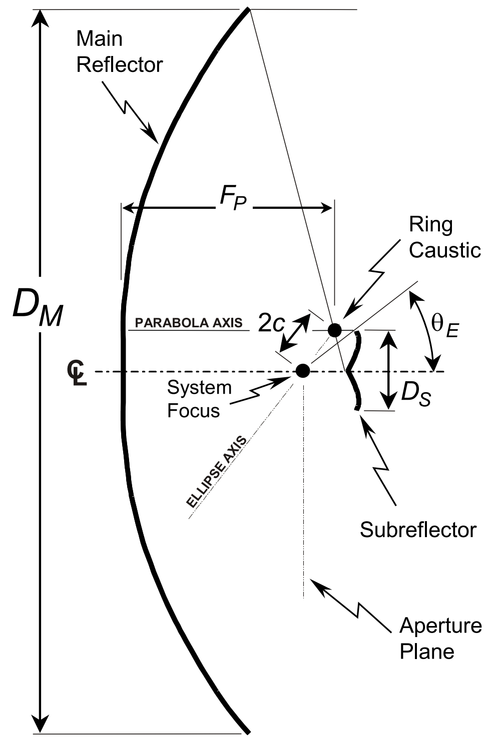
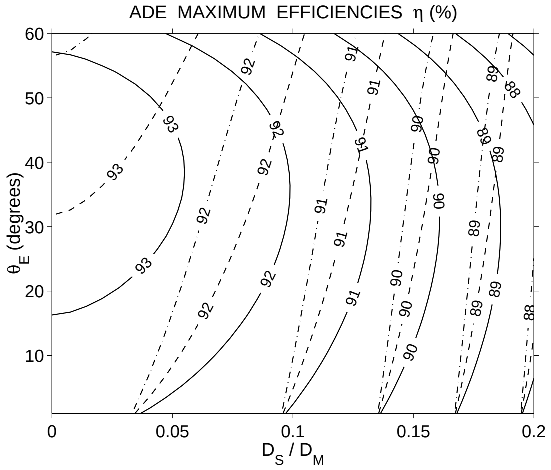


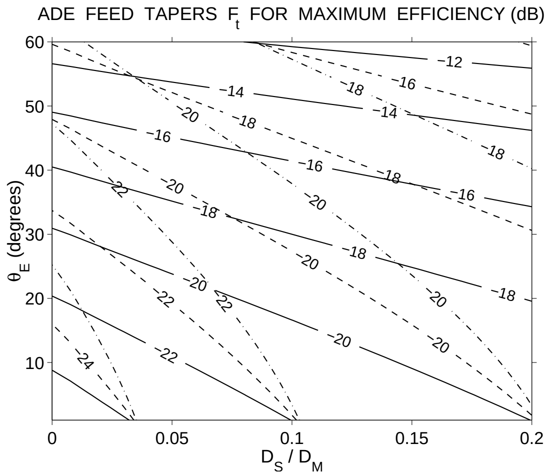
Fig. 3. ADE antenna geometry.

(shown in Fig. 3 together with a few relevant rays). Although this antenna was originally proposed nearly forty years ago [4], its use in compact high-gain spacecraft antenna applications only begun to be exploited in relatively recent times. The basic characteristics of this antenna configuration, as well as its design procedure, have recently been discussed in the literature [2]. Its main reflector is produced by spinning an offset section of a parabola, of focal length F_P, about the antenna axis of symmetry. This creates a main reflector with the ring caustic shown in Fig. 3. To appropriately illuminate this main reflector, a subreflector with a coinciding ring caustic and a focus (the system focus) is needed. This can be achieved starting with a displaced section of an ellipse with tilted axis and interfocal distance $2c$ (hence the name ADE), and spinning this ellipse about the antenna axis of symmetry. The final geometry produced by this process is the ADE antenna.

Observing Fig. 3 one notes two outstanding features of the ADE antenna. First, the subreflector has a pointed vertex that directs the feed radiation along the antenna axis towards the main-reflector rim. This assures minimum reflection of energy towards the feed horn, even when the subreflector diameter D_S is relatively small in terms of the operation wavelength. And second, the illumination of the main reflector central region comes from the feed rays that reflect near the subreflector rim, which also stay away from the region occupied by the feed horn aperture. In sharp contrast with the virtual focus of the Cassegrain geometry (see Fig. 1), the ring caustic of the ADE allows the feed horn to move closer to the subreflector without significant deleterious blockage effects, as the overall dimensions of the antenna are scaled down as needed to produce a compact geometry.



(a)



(b)

Fig. 4. ADE a) maximum effi ciencies η and b) corresponding feed tapers F_t: $\ell_o/D_M = 0.5$ (solid lines), 1 (dashed lines), and 2 (dash-dot lines), where ℓ_o is the total path length of a ray propagating from the system focus to the aperture plane.

Another significant characteristic of the ADE geometry becomes evident when ray-tracing techniques are used to obtain its aperture field [2], which yields Fig. 4. In the high-frequency limit, and ignoring conductivity losses and mechanical errors, efficiencies around 91% can be obtained without shaping, with $D_S \approx D_M/10$ and θ_E values in the 20° to 60° range, provided that an appropriate feed taper F_t towards the subreflector rim is used (i.e., between 20 and 12 dB, respectively). Furthermore, again in the high-frequency limit, the ADE efficiency increases as the D_S/D_M ratio decreases, further favoring compact antennas with small subreflectors.

Although the above characteristics indicate that the ADE geometry is a strong candidate for compact high-gain antennas, it is well known that the high-frequency limit performance predictions become increasingly less reliable as the electric dimensions of the antenna are reduced. Hence, in order to provide reliable performance predictions, numerical tools based on rigorous electromagnetic analysis techniques were developed to analyze the performance of generalized classical axially-symmetric dual-reflector antennas and applied to model ADE antennas [5]. The results obtained confirmed the expectations, and were further validated by the ADE demonstration model discussed in the next section.

IV. Compact X-Band ADE Antenna Demonstration Model

A prototype X-band ADE was constructed and measured in order to confirm the outstanding electric characteristics of this antenna geometry for compact high-gain spacecraft antenna applications. Since this antenna was also designed targeting a particular mission (i.e., the NASA's Mars Surveyor 2001 Program), it incorporated a few mission-specific constrains that unfortunately reduced its final gain. However, this fact did not significantly detract the prototype from serving as an ADE demonstration and validation model.

The antenna (shown in Figs. 5 and 6) was designed to operate in both receive and transmit deep-space spacecraft communication bands (center frequencies of 7.167 GHz and 8.420 GHz, respectively). It has an aperture diameter $D_M = 1250$ mm, and a subreflector diameter $D_S = 140$ mm, which are only about 30 and 3.3 wavelengths at the lower operation frequency, respectively ($D_S \approx D_M/9$). In fact, Fig. 3 is a scale drawing of this antenna. The subreflector illumination is provided by a simple two-corrugations corrugated horn with about 14 dBi gain and -23 dB return loss. This return loss value does not change significantly when the horn is placed in the reflector system, since the subreflector backscattering into the feed is very small in the ADE geometry. The subreflector was supported by a tripod that provided two choices of main-reflector attachment points: at the rim and at 2/3 radius (the figure depicts the struts at their 2/3 radius attachment position). Calculations indicated that about 0.2 dB gain reduction is produced by the subreflector supports, in either one of the two attachment choices (this positional insensitivity was confirmed by measurements).

With the exception of the subreflector supporting struts, the complete antenna (including feed horn) was modeled using the rigorous numerical tools mentioned in the previous section. The predicted directivity of the antenna was 38.0 dBi and 39.3 dBi, at 7.167 GHz and 8.420 GHz, respectively (ignoring mechanical errors, strut effects, and conductivity losses). This corresponds to efficiencies of 70% and 72%, respectively. The measured gain results agreed well with these numbers once the impact of mechanical errors, ohmic losses, and strut effects were accounted for (within an estimated probable measurement uncertainty of 0.5 dB), Typical predicted and measured linearly-polarized radiation pattern results are shown in Fig. 7. The cross-polarization shown is a measurement artifact, and the discrepancies observed in the sidelobes are attributed to the scattering produced by the subreflector supporting struts as well as to mechanical inaccuracies.

V. Summary and Conclusion

The basic characteristics that render the axially-displaced antenna (ADE) attractive for compact high-gain spacecraft communication applications have been reviewed and compared

Fig. 5. ADE antenna prototype.

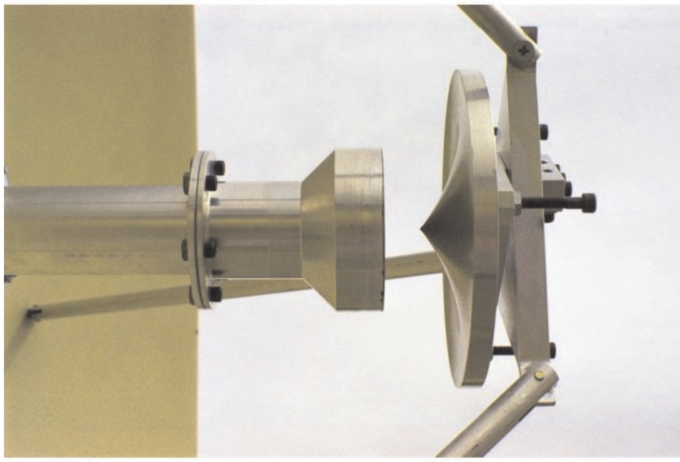


Fig. 6. Subreflector and feed of the ADE antenna prototype.

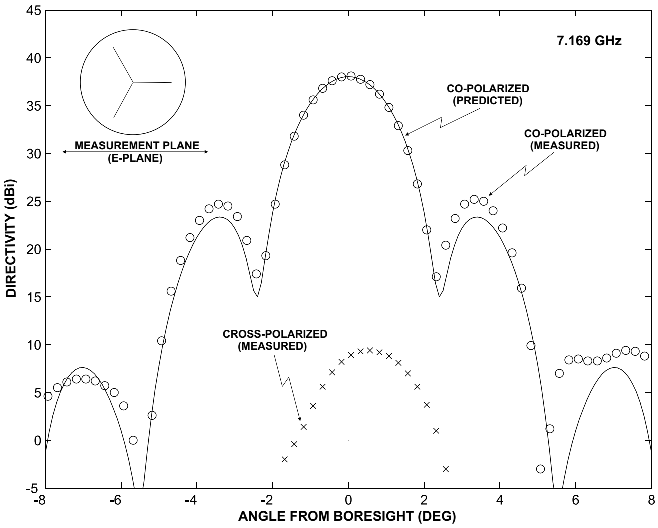


Fig. 7. Prototype ADE antenna radiation pattern (insert shows antenna aperture with supporting struts).

to the corresponding characteristics of the Cassegrain antenna geometry. In contrast with the Cassegrain, the ADE geometry allows the implementation of considerably smaller apertures (i.e., diameters of 30 wavelengths or less) while yielding higher efficiency. The predicted and measured results of an ADE validation and demonstration prototype were presented. The performance obtained confirms the excellent performance that can be expected from this antenna configuration.

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