Reflectarray Antennas for Space Applications

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Abstract— **In this paper, the advantages and recent developments of reflectarray antennas for space applications are reviewed. Basic requirements for space antennas, and the limitations and challenges of conventional designs are discussed. Various advantages of reflectarray antennas over reflectors and phased array antennas are reviewed and it is shown that reflectarray antennas can be a suitable low-cost choice for the new generation of space antennas.**

Keywords- beam-scanning, multi-beam, reflectarray, shaped-beam, space antennas.

I. Introduction

Reflectarray antennas are similar in principal to parabolic reflectors, while the bulky curved surface of the parabolic reflector is replaced with a planar antenna array. Thus, the reflectarray antennas have low-profile, low-mass and low-cost, and therefore are more suitable for deployment particularly for space applications. The concept of the reflectarray was initially introduced using waveguide technology in the 1960's, but the reflectarray didn't receive much attention until the development of microstrip reflectarrays in the late 1980's [1]. Since then microstrip reflectarray antennas have slowly emerged as the new generation of high-gain antennas [2].

This article presents a review of the advantages of reflectarray antennas for space applications. First the basic requirements for space antennas are reviewed, and the limitations and challenges of conventional space antennas are discussed. In the next stage, basics of reflectarray design and analysis, and the advantages of reflectarray antennas for space applications are discussed. The aim of this study is to stimulate and promote reflectarray research for future space applications.

II. Antennas for Space Applications

A. Requirements for Space Antennas

Space antennas mounted on satellites or space shuttles are arguably the most diverse part of spacecraft technology, which vary with frequency, coverage, resolution, and flexibility of operation [3]. However, the common considerations for space antennas are size, weight, and power (SWaP) because of limitations imposed by the satellite launch capabilities. In terms of the antenna requirements however, deep space communications require high-gain antennas. This is generally a main challenge since the antenna gain is directly proportional to its aperture size; therefore large size antenna technology plays a critical role here. Four types of antennas are commonly used for space applications which are reflectors, lenses, arrays, and hybrids [4]. In addition to the high-gain requirement for space and radar antennas, they are required to have multiple beams, shaped beams, and beam-scanning capabilities [5].

Reflector antennas are perhaps the most common high-gain antenna in use today for space communications. They are simple, well developed, and with proper feed networks they can achieve electronic scanning [6]. However the major disadvantage of reflector antennas is the high mass and volume, which increases the launch costs. To mitigate the high launch costs, membrane or mesh reflectors are typically used for space applications. To reduce the volume, the reflector antenna is folded depending on the number of segments for the design, and once in space it is then fully assembled. Lens antennas on the other hand have some advantages over reflector antennas, such as wide-angle scan, lower sidelobe levels, and more tolerance towards dimensional errors. However, what has prevented the widespread use of these microwave lens antennas in space applications is their large mass and volume [7].

Printed antenna technology has opened a new horizon for space antennas. Microstrip array antennas [8] are low-profile, low-cost, low-mass, and the planar geometry of the antenna allows for foldable small package designs that are easy to deploy and assemble in space. In addition phased microstrip arrays offer the functionality of achieving high-speed electronic scanning [9]. However, the major disadvantage of printed antennas is the requirement of a complicated feed network which in most cases is quite lossy. This becomes more challenging for high-gain beam-scanning, since transmit/receive (T/R) modules are a necessary requirement for phased arrays which significantly increases the complexity of the design [10].

B. Advantages of Reflectarrays for Space Applications

As discussed in the previous section, the ideal system parameters for space antennas are light weight, small packaging, and low cost. In addition to these requirements that are mainly due to launch and space deployment considerations, a space antenna must have the functionality to achieve a high-gain, with multiple or shaped beams and also beam scanning.

Reflectarrays are basically a hybrid of reflector and planar array antennas and as such offer advantages over both designs [1]. In comparison with bulky reflector antennas, a reflectarray has a planar aperture, that is low-profile, low-mass, and can easily be folded and deployed in space. In addition the fabrication process for a reflectarray antenna relies on printed antenna technology which is not only cost effective, it is relatively fast and simple. In comparison with array antennas, the spatial feeding scheme eliminates the design complexity and energy losses of a feeding network in traditional array antennas, resulting in a higher efficiency. Furthermore, phased reflectarray antennas eliminate the need for T/R modules which will also reduce the system cost.

As a result this hybrid design, combines the favorable features of conventional parabolic reflectors and phased array antennas, and become an excellent antenna candidate for high-gain space applications.

III. Design and Analysis of Reflectarray Antennas

Similar to a reflector, a reflectarray antenna consists of an aperture illuminated by a feed source. On the reflecting surface, there is an array of printed antenna elements whose reflection phases are individually controlled to produce a planar phase front. The required phase for the reflectarray elements is determined using ray tracing. For the reflectarray system shown in Fig. 1, the reflection phase for the i^{th} element is calculated using

$$\phi_i = k_0 (R_i - \bar{r}_i . \hat{r}_o) + \phi_0 . \quad (1)$$

Once the phase requirement is known for the reflectarray elements, it can then be realized with various phase tuning approaches such as phase- or time-delay lines, variable size elements, or element rotation techniques [1]. Accurate characterization of reflectarray elements reflection phase is critical for the design and therefore it is usually obtained with a full-wave simulation technique using an infinite-array approach.

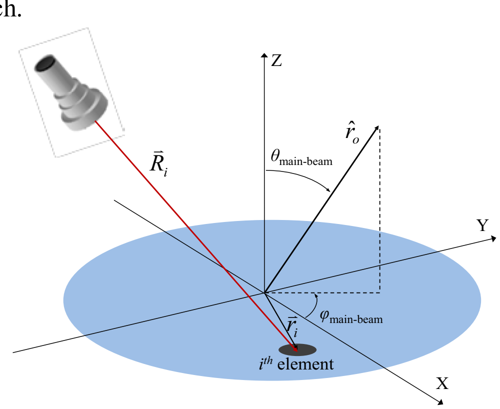


Fig. 1. The geometrical model of a reflectarray antenna.

Various approaches have been developed over the years to calculate the radiation characteristics of the reflectarray antenna. They can be categorized in two groups: classical analytical approaches, and full-wave simulations. The classical methods use array summation or far-field transformation of currents to calculate the radiation pattern of the reflectarray antenna [11]. The main advantage of these analysis methods is the fast computational time; however due to the approximations in the analysis, some discrepancy with practical results may be observed. Full-wave analysis methods on the other hand can provide accurate results, although the drawback is that they are computationally quite challenging [12].

Numerical and experimental results have shown that the classical methods can accurately calculate the main beam direction, beam-width, and side-lobe and cross-polarization levels in the main beam area, which make them efficient tools for the initial design. Additional stages of optimization may be required for a reflectarray antenna design. However, it should be recognized that the classical approaches have limited accuracy, and when accurate radiation pattern in the entire 3-D space is required, full-wave simulation of the reflectarray system is necessary.

IV. Space Applications of Reflectarray Antennas

A. *Multi-Band Reflectarrays*

Antennas for space communication systems are typically required to provide multiband operating frequencies. For example the downlink and uplink Ka-bands for NASA Deep Space Network (DSN) are 31.8-32.3 GHz and 34.2-34.7 GHz, respectively. While in some cases, the bandwidth of the entire frequency range could be covered with the antenna, multiband spot coverage is actually an advantage in terms of reducing the out-of-band interference.

Various designs of multi-band reflectarrays have been developed over the years. Single or multi-layer reflectarrays have been designed to achieve single-band and multi-band performance from microwave frequencies up to the THz range [1]. Considerable improvements have been made to these designs over the years and many practical designs have been demonstrated. A two layer reflectarray with dual frequency operation was demonstrated in [13]. More notably a single-layer tri-band circularly polarized reflectarray was demonstrated by researchers at the University of Mississippi [14]. For this design, variable size elements are used for the C-band, whereas the X- and Ka-band elements are designed using the element rotation technique. A summary of the measured performance of this tri-band reflectarray is given in Table I.

TABLE I. Measured Data for Multi-Band Reflectarray

Frequency Band	Peak Gain (dB)	Center Frequency (GHz)	1 dB Bandwidth
Ka	38.7	32	6.3%
X	29.1	8.4	2.0%
C	28.4	7.1	1.8%

B. *Multi-Beam and Shaped-Beam Reflectarrays*

In many cases, space antennas are required to provide multiple beams and/or tailored earth coverage. Reflectarray elements have the flexibility to achieve, in general, any value of phase shift by controlling the geometrical parameters of the elements. Utilizing this direct control of phase shift for every element, a reflectarray antenna can achieve shaped beam patterns or simultaneous multiple beams without a complicated fabrication processes and additional costs.

For multi-beam reflectarray antennas various design approaches are available which in general can be categorized into two groups: direct methods and optimization methods. Both methods can be used for the design which typically depends on the requirements for the antenna. While it is implicit that the optimization method can achieve a better performance, in some cases the direct methods may be used for the design [15]. For the optimization methods, typically the alternating projection method (APM) is used for the design [16]. The flowchart in Fig. 2 provides an overview of the APM optimization process.

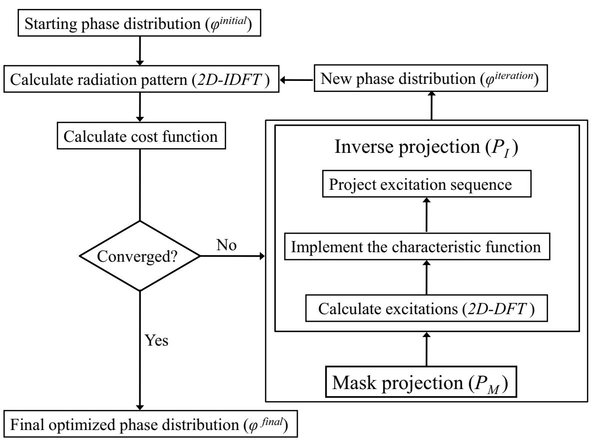
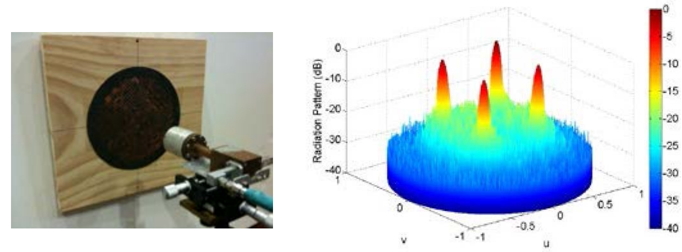


Fig. 2. Flowchart of the alternating projection optimization method.

For more complicated multi-beam designs, such as multiple asymmetric beams, it may be necessary to apply a more powerful optimization routine such as particle swarm optimization (PSO) for the design. In comparison with other high-gain multi-beam antennas such as reflectors with feed-horn clusters or large phased arrays which require beam-forming networks, reflectarray antennas offer a low-mass and low-cost design, with less fabrication complexity, and easier deployment for space applications. For example a Ka-band single-feed quad-beam reflectarray antenna was recently designed and fabricated at the University of Mississippi [16]. The fabricated prototype and the measured radiation pattern for this design are shown in Fig. 3.

For shaped beam reflectarrays typically a synthesis process, is implemented to determine the required phase of every element in the array [17]. Optimization methods such as APM or PSO can be used to determine the required phase shift on the reflectarray aperture. Once the required reflection phase for every element in the array is known, design and fabrication of a shaped beam reflectarray follows the same procedure as a single-beam design. The advantage of shaped beam reflectarrays is the simplicity of the design and fabrication, relative to the large solid reflectors that are the common choice for shaped-beam space antennas and generally require expensive custom molds.



(a) (b)

Fig. 3. Single-feed quad-beam reflectarray antenna: (a) fabricated prototype, (b) measured radiation pattern at 32 GHz.

C. Beam Scanning Reflectarrays

Several space applications, such as precipitation or hurricane radars, require high-gain antennas with beam-scanning capabilities. In recent years beam-scanning designs have added a new dimension to reflectarrays by enabling them the capability to achieve a dynamic radiation pattern. As discussed earlier, the spatial feed and individual element phase control scheme of the reflectarray antenna is low-loss and eliminates the need for T/R modules, which makes it a suitable choice for high-gain beam-scanning. The beam of a reflectarray antenna can be scanned by means of the reflector nature or the array nature of the antenna. In addition it is possible to utilize both approaches in a single design to improve scan performance or reduce system cost.

In the first approach, one changes the phase distribution on the reflectarray aperture by changing the spatial delay. This beam scanning technique is similar to what one uses to scan the beam of a reflector antenna, and is categorized as the feed displacement approach. Feed-displacement beam-scanning reflectarrays can themselves be categorized into two groups: multiple feed array and phased array feed [18]. A multiple array feed can achieve a beam-switching performance, while a phased array feed can provide a continuous beam-scanning. In addition to the feed design, reflectarrays with apertures designed based on the principle of bifocal, dual reflector, or spherical reflector systems can significantly improve the scan performance [19].

Similar to phased array antennas, a reflectarray antenna with individual phase control for each element can also achieve a dynamic pattern. Since each element in these systems can be equipped with a low-loss phase shifter; they are capable of wide angle beam-scanning. The phase of the reflectarray elements can be controlled mechanically, electromechanically, or electronically, which is typically chosen based on the scan speed requirement. Various designs of phase tuned beam-scanning reflectarrays have been demonstrated over the years using micro-machines [20], MEMS [21], PIN diodes [22], and exotic materials [23].

The choice between these two approaches for beam-scanning reflectarrays is typically based on the scan range requirement, where feed-displacement designs are more suitable for narrow angle scanning, and aperture phase tuned systems are desirable for wide angle scanning. In particular for space applications, beam-scanning reflectarrays offer notable advantages over phased arrays or reflector antennas, since they can provide high-gain high-speed beam-scanning with a much lower cost and more flexibility in the design.

V. CONCLUSIONS

Recent developments in reflectarray antenna technology for space applications are reviewed. The basic requirements for space antennas, and the limitations and challenges of conventional designs are discussed. Various advantages of reflectarray antennas over conventional high-gain space antennas are discussed. It is evident that reflectarray antennas can be a suitable low-cost choice for the new generation of space antennas.

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