Review and Prospect of the Development of Multi-beam Reflector Antennas

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Abstract: This paper mainly introduces the development trend of multi-beam reflector antenna system in recent years. Starting from L/S band, the typical multi-beam satellite antenna systems in Ku/Ka band in various countries are reviewed. The development of high-throughput satellite communication antenna and some new technologies of reflector structure are also introduced. Finally, the future trend of multi-beam reflector antenna is prospected based on the demand of future satellite communication development.

Key words: Multibeam reflector antennas, high throughput satellite, beam coverage.

1. Introduction

Multi-beam antenna, which emerged in response to the rapid growth of modern satellite communication capacity and the demand of multi-target regional communication, is the most widely used in the current satellite communication field. Since Intelsat IV-A, an international communication satellite launched in 1975, first adopted multi-beam antenna, the technology of satellite-borne multi-beam antenna has developed rapidly. Especially in the past ten years, with the rapid growth of communication services, High Throughput Satellite System (HTS) has become a major research hotspot in the field of space communication technology. As a key component of the system, HTS antenna using multi-beam technology is a good solution. As a result, the research on multi-beam antenna is rapidly warming up in the field of space technology in the world, and has become an important direction of the development of space-borne antenna technology in the world.

2. S/L-Band Reflector Multi-beam Antennas

Inmarsat-4, a communication satellite of Inmarsat, operates in L-band and has an antenna aperture of up to 9 m. It can form a global beam, 19 wide-point beams and 228 narrow-point beams, as shown in Fig. 1 and Fig. 2 [1].

The Satellite Garuda-1, developed by Lockheed Martin, has two umbrella L-band antennas with a diameter of 12 m, which are used for receiving and transmitting respectively. The advantage of using two pairs of antennas is to reduce the influence of passive intermodulation and the risk of antenna failure. Each pair of antennas has 88 feeders to form a feeder array. By adjusting the amplitude and phase of each feeder signal to achieve the goal of controlling beam pointing, a total of 140 point beams can be formed, of which 8 beams can be dynamically adjusted.
The L-band multi-beam reflector antenna for the Satellite Alphasat-I-XL launched by Astrium’s MDA Company in 2013 consists of 120 helical radiation units with an aperture of 2.5 meters and an 11-meter deployable mesh reflector [2]. The antenna structure is shown in Fig. 3. The antenna uses digital beamforming technology, which can form 400 variable beams and share the functions of receiving and receiving. Although the antenna satisfies the design requirements in the aspects of directional graph, phase tracking, power allocation and passive intermodulation (PIM), its biggest disadvantage lies in the use of single circular polarization beam, which greatly limits the communication capacity of the satellite. With the advancement of related research, some research institutions in Europe and the United States have not only realized the common function of sending and receiving of MFB in S-band feed, but also made the feed in L/S band have the function of double circular polarization.

Mobile User Objective System (MUOS) developed by the U.S. military is an important part of the new generation of military communication network of the U.S. Navy. The first three satellites of this series were launched in 2012, 2013 and 2015 [3].
installs a 12m deployable mesh reflector. The 3TOB (Three Terminals On Boundary) algorithm is used to calculate the beam pointing and its coverage. It can form 16 point beams, each of which multiplexes 4 4MHz WCDMA RF carriers. As shown in Fig. 4, it consists of four satellites (and another standby satellite) which cover the global information network. Each satellite is a follow-up satellite of the UFO (UHF Follow On) constellation, providing low-speed, time-to-time mobile communication services for the U.S. Army and the Allied Forces.

Fig. 3. Feed array of Alphasat-I-XL (Size 2.5m x 2.5m x 0.6m).

Other large-aperture multi-beam antennas, such as DBSD-G1 launched by the United States in 2008, adopt S-band feed and have a reflector aperture of 15.8m, which can form 250 common variable beams [4]. TeereStar-1/-2, launched in 2009 and 2013 respectively, is the first satellite in the world that can communicate directly with ground handheld terminals. The satellite uses a super-large S-band metal mesh reflector antenna with a diameter of 18 m, which has the ability to generate 500 variable beams [5]. Thuraya-3, developed by the United States for the United Arab Emirates in 2008, uses L-band feed and 12.25m receiving and transmitting common antenna to form 250-300 variable beams [6]. SkyTerra-1/-2 was launched in 2010 and 2013 respectively. The L-band feed array was also used. The reflector aperture of SkyTerra-1/-2 is 22m, and it has the ability to generate 500 variable beams [7]. In addition, the InmmaSat-4/-5 and MEXSAT-1/-2/-3 communication satellites launched in recent years also use super-large reflector multi-beam antennas. Fig. 5 illustrates the beam condition of some typical satellite systems. Fig. 6 shows the InmmaSat-4 and Teerestar-2 satellites.
3. Ku/Ka-Band Reflector Multi-beam Antennas

In recent years, the international demand for high-throughput satellites has become extremely urgent. For this reason, the world’s major space powers have begun to focus on Ku/Ka band, which usually uses multiple small-aperture solid surface launchers for GEO satellite antennas. Especially in the area of high rainfall, broadband communication and communication with mobile platforms such as ships and aircraft, Ku band is mostly used. In Ku band, the wavelength is relatively short, and the point beam with high directivity can usually be obtained by using fixed reflector technology.

CIEL2 communication satellite antenna, which has been in orbit since 2008, uses Ku-band SFPB (single feed per beam) beamforming mode, and is illuminated on three reflectors by three groups of feeders (18-19 horns per group), which can provide 54 point beams for user links and one tracking link beam at the same time. The antenna uses the ultra-light reflector provided by Astrium Company to obtain the pointing accuracy of 0.03 degree. In order to improve the C/I value and reduce the attenuation of the antenna, the company has also carried out the shaping design of the three reflectors [8].

Fig. 7 shows a Ku band feed designed to cover North, Central and South America. In the antenna structure part, four 1.2m parabolic reflectors are installed on two pallets in pairs. Based on performance, quality and cost considerations, the single feed per beam (SFPB) scheme has been adopted to form 35 beams. In addition to 16 transmit/receive beams over North America, the antenna generates 19 beams of different sizes in South and Central America. The peak gain of the transmitted beam is between 38.4-41.7 dB and that of the received beam is between 41.2-42.3 dB. The C/I values are greater than 18 dBi [2].
The Canadian Anik-F2 satellite launched in July 2004 was the world's largest communications satellite at the time, as shown in Fig. 8, which was manufactured by Boeing Satellite Systems. Four 1.4-meter reflectors and four 0.9-meter reflectors are mounted on the east and west panels for Ka-band transmission and reception, producing 51 beams covering the US and Canada [9].

KA-SAT, launched at the end of 2010, is the first full Ka band high-throughput communication satellite in Europe, with an upstream frequency of 29.5-30.0 GHz and a downstream frequency of 19.7-20.2 GHz. Four reflectors are used to realize four-color multiplexing. 82 beams can be generated at the same time, and the frequency multiplexing can be up to 20 times. The beam coverage area includes Europe, the Mediterranean and parts of Central Asia [10]. The communication capacity exceeds 70 Gbit/s. The application of Ka band not only greatly improves the antenna gain and communication capacity, but also effectively improves the C/I value. Its excellent performance makes researchers all over the world more confident about the application of Ka band.

The MEDUSA project of Deutsches Zentrum für Luft- und Raumfahrt (DLR) is a successful example of satellite-borne MFPB (multiple feeds per beam) antenna [11]. In the design, the beam forming scheme with seven feeds per beam is adopted. The distance between the centers of two feeding groups of adjacent beams is twice the distance between the centers of feeding units, and the peripheral feed unit used to form overlapping beams is multiplexed twice, as shown in Fig. 9. Its beamforming network uses a large number of phase shifters and four-port waveguide branch couplers, and distributes phase and energy in a periodic topology. Both transmit and receive antennas adopt four-color multiplexing scheme with dual-frequency and dual-circular polarization. 18 user beams with a width of 0.8° are radiated by 74 horn units to cover parts of the Arabian Peninsula, Egypt and Libya. The coverage is shown in Fig. 10.
For the constellation satellites on MEO, the reflector scheme is also adopted. For example, O3b constellation satellites launched successively in Britain from 2013 to 2015, each satellite uses 12 pairs of Ka-band forward-fed controllable reflector antennas. The antenna structure is shown in Fig. 11, which can form 12 point beams. In addition, the ICO constellation satellite in this orbit can form 163 point beams by using two pairs of reflector antennas.

In addition, many countries in the world launched a large number of large-capacity synchronous orbit communication satellites equipped with multi-aperture multi-beam antennas in the early years. For example, Express AM4 in Russia in 2011, ViaSat-1 in Ka band in USA, YahSat-1B in UAE in 2012 and JCSAT-13 in Japan. Express AM5 launched in 2013, Amos-4 launched in Israel, DirectCTV-14 launched in the United States at the end of 2014, EutelSat-3B launched in Europe, Assat-3A and EutelSat 115 West B
launched in 2015, etc. Fig. 12 shows images of Amos-4 and EutelSat-3B satellites.

Fig. 12. Amos-4 and EutelSat-3B.

4. Some Multi-beam Antenna with High-Throughput Satellite Scheme

Airbus also uses a SFPB antenna with a large reflector on the E300 platform [12]. It integrates a non-collapsible 5-meter diameter reflector on the Eurostar NEO platform as shown in Fig. 13. The antenna operates in Ka band and is applied to the high-throughput satellite scheme. In terms of beam coverage, the European region has a beam width of 0.3°, while the African region has a beam width of 0.8°. The three-color coverage scheme is adopted, as shown in Fig. 14.

Fig. 13. Eurostar NEO near-earth object platform.

Fig. 14. Eurostar NEO beam coverage scheme.
In 2017, Yves Demers proposed a beam coverage scheme for high-throughput GEO satellites and gave a possible example of VHTS(very high-throughput satellite) coverage [13]. The coverage includes a regular hexagonal mesh consisting of 0.3° elements, and the interval between the center and the center is 0.26°. The use of architectures such as frequency hopping can increase the number of beams and thus expand the coverage. As shown in Fig. 15, this may result in beam scanning covering more than 1,000 beams and over 20 beam widths.

Fig. 15. VHTS coverage of 1587 beams with a beam diameter of 0.3°.

5. Development of Some Other Multi-beam Reflector Antennas

(a) Ka-band 3.5-metre mirror
(b) Placing an experimental 5 m diameter Labm reflector into a large space simulator of ESA
(c) CAD of Katrema reflector
(d) 5-metre retractable mesh reflector assembly

Fig. 16. Several new types of large-aperture reflectors.

Future communication payloads will provide greater capacity, depending mainly on antenna fields with a large number of beams, possibly more than 1,000 beams. This requires dynamic resource allocation based on time multiplexing methods(such as beam hopping) [14]. In the THD-SAT project funded by CNES, a
3.5-metre solid-state migration reflector EQM (see Fig. 16 (a)) for Ka-band transverse antennas was designed and manufactured. The antenna can generate small beams between 0.21 degree (national coverage) and 0.35 degree (continental coverage), so that the system performance can be optimized. It has recently been successfully validated [15]. Other new reflective surfaces are shown in Fig. 16 (b), 16 (c) and 16 (d).

More compact reflector design can also be applied to LEO/MEO satellites. While maintaining a very simple mechanical design, special attention is paid to quasi-optical beamforming that can achieve multi-beam operation [16]. A beamformer providing a multi-beam line source may be combined with a cylindrical parabolic reflector for point beam operation [17], as shown in Fig. 17.

Fig. 17. Cylindrical parabolic reflector.

6. Development Trend of Spaceborne Multi-beam Antennas

From the development trend of satellite antenna technology, with the rapid development of high-throughput satellite system, multi-beam antenna technology has become the key technology direction to achieve multiple frequency and polarization multiplexing, thus doubling the capacity of satellite. The multi-beam antenna has strong application potential in space-based/ground-based beamforming, beam reconstruction, beam scanning and beam hopping. It has obvious advantages in coverage of irregular areas, making it the key to promote the flexibility of beam coverage in future communication satellite systems.

Over the past decade, the international demand for Ka-band high-throughput satellites has been very urgent. At present, Ku band technology has been very mature, Ka band is becoming a hot topic in the international research, and sub-millimeter band is the direction of further research of satellite-borne multi-beam antenna. With the further improvement of research frequency band, more and more attention has been paid to the study of lensed waveguide arrays and quasi-optical beamforming networks.

In the aspect of reflector antenna, for Ka-band communication satellite, its reflector will be expanded from the current single solid structure to the deployable reticulated reflector. In the L/S band, in order to meet the requirements of the antenna gain of GEO mobile communication satellite, a large deployable reflector antenna of more than 10 meters is usually used on the satellite, while the aperture of the antenna on the fourth generation and subsequent similar satellites will be larger.

In beamforming and signal processing, in order to meet the development requirements of future large-capacity GEO communication satellites, the digital beamforming technology adopted by space-borne multi-beam antenna will replace the analog beamforming technology to a greater extent. For mobile communication satellites, in order to reduce the complexity of satellite load and improve the stability and reliability of beamforming system, ground-based beamforming (GBBF) technology has to be considered. As one of the core technologies of the new generation mobile communication satellites, GBBF is regarded as an
important symbol to distinguish the third generation from the fourth generation mobile communication satellites. It will be combined with Ancillary Terrestrial Component (ATC) technology to construct satellite-ground mobile communication system. It can be seen that GBBF technology has become an inevitable choice for multi-beam antenna of new generation mobile communication satellite in beamforming.

References


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