A REVIEW: PERFORMANCE OF MULTIBEAM DUAL PARABOLIC CYLINDRICAL REFLECTOR ANTENNAS IN LEO SATELLITES

Mohamed Sanad[1*] and Noha Hassan[1]
[1]Faculty of Engineering, Cairo University, Egypt
[*] He is now with the Elect & Biomedical Eng Dept, Univ of Nevada, Reno, USA

***Abstract** – The characteristics of multibeam dual parabolic cylindrical reflector antennas are summarized in this article. They can generate an arbitrary number of beams with arbitrary tilt angles for each beam. They can be remotely controlled to cover any arbitrary area, of any shape and size, even if the antenna was mounted on a quasi-stationary platform. Their performance in Low-Earth Orbit (LEO) satellites and ground stations (terminals) have been presented. A simple beam tracking technique was developed. For any specific satellite orbit, the orientation of the ground-station antenna could be adjusted such that its beams are parallel to the satellite's beams and directed toward them. The ground-station antenna can simultaneously communicate with multiple satellites in different orbits. A single antenna can cover the whole mm-band (17.8-30 GHz), which is one of the most widely used bands in LEO satellites. The overall size of a mm-wave antenna, generating 20-24 dB gain, is 14.8x10.4x3.7 cm³ and its weight is 0.37 kg.*

Keywords – Cylindrical reflector antennas, dual parabolic, ground station antennas, multibeam LEO satellite antennas, multiple LEO ground stations, simple LEO satellite beam steering and tracking

1. INTRODUCTION

Low Earth Orbit (LEO) satellites are typically organized as satellite constellations [1]-[4]. The satellite number of a LEO satellite constellation would be tens of thousands to realize fully global coverage [5]-[8]. Many mega-constellations are already operating, such as Starlink from SpaceX, Kuiper from Amazon, One WEB, and CubeSat [9]-[10]. This imposes a big challenge on terminals and ground stations for satellite management.

Switched-beam smart antennas are considered as one of the candidates for LEO satellites and ground stations (terminals). They can produce multiple beams to simultaneously support different satellites. Multibeam antennas create narrow beams limited to a fixed number of scan directions that the system switches back and forth from [11]-[13]. A single multi-column array may be driven by a feed network to produce multiple beams from a single aperture. Complicated antennas have been developed using multibeam forming networks driving planar arrays of radiating elements, such as the Butler matrix [14]-[16]. Efforts have been made to make amplitude distribution in antenna array depending on frequency either by using filters or frequency-dependent power dividers. However, they add complexity, and they significantly reduce the bandwidth. Some special passive beam scanning techniques are used such as frequency-beam scanning [17]. Also, some massive access frameworks for LEO multibeam satellite IoT networks were designed [18]. They all have narrow bandwidths.

Other classes of multibeam antennas based on a classic Luneburg cylindrical lens have been tried [19]-[20]. The Luneburg lenses are composed of layered structures of dielectric concentric shells, each of a different refractive index. The cost of the classic Luneburg lens is high. It is heavy and its production process is complicated. Moreover, these antenna systems have narrow frequency bandwidths.

On the other hand, the currently used multi-beam technologies do not provide a clear way of adding massive MIMO configurations. In the currently available multibeam antennas, all beams are either not tilted in the vertical plane, or they are all tilted by the same vertical tilt angle.

In this paper, a foldable / deployable switched-beam antenna has been applied to LEO satellites and LEO ground stations. The used antenna consists of two parabolic cylindrical reflectors and a set of small size broadband resonant feeds, as shown in Fig. 1. The authors of this paper originally invented the basic concept of dual parabolic cylindrical reflector antennas and their broadband resonant feeds [21]-[28]. To significantly reduce the weight and the wind load of the proposed reflectors, several holes can be punched in their surfaces, as shown in the figure. Moreover, the gridded (punched) reflectors of the developed antenna can be remotely folded and deployed, as shown in the figure. All that makes this multibeam antenna advantageous in several applications such as satellites, earth stations and space shuttles.

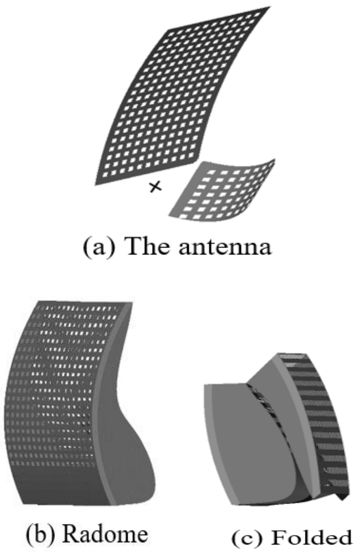

Fig. 1 – A dual parabolic cylindrical reflector antenna with a single feed

2. GENERATING AN ARBITRARY NUMBER OF BEAMS WITH ARBITRARY BEAM-TILTS AND WIDTHS

The proposed antenna can generate an arbitrary number of beams with arbitrary electric beam-tilt and beamwidth for each beam. Multibeam technology can be easily applied to the dual parabolic cylindrical reflector antenna by adding multi-feeds as shown in Fig. 2. Shifting the location of any feed away from the focus of the sub-reflector results in tilting the beam that is generated by this feed. Thus, each beam can be easily tilted vertically, and/or horizontally, by remotely shifting its feed. For example, Fig. 2 shows a penta-beam antenna using five feeds. It should be noted that the feeds do not have to be of the same vertical height. Fig. 3 shows a penta-beam antenna with five feeds at different heights. This configuration generates five beams with five different vertical tilt angles as shown in the figure. These tilt angles can be remotely controlled. On the other hand, the horizontal and vertical beamwidths of the beams and the isolation between them can be controlled by adjusting the design parameters of the antenna. Furthermore, to significantly increase the vertical beamwidth of the beams, the upper and lower edges of the main reflector can be rolled, as shown in Fig. 4. To increase the horizontal beamwidth of the beams, the surface of the main reflector can be bent horizontally to the back, as was shown in [28]. The exact effect of these techniques on the horizontal and vertical beamwidths of the beams should be tried numerically.

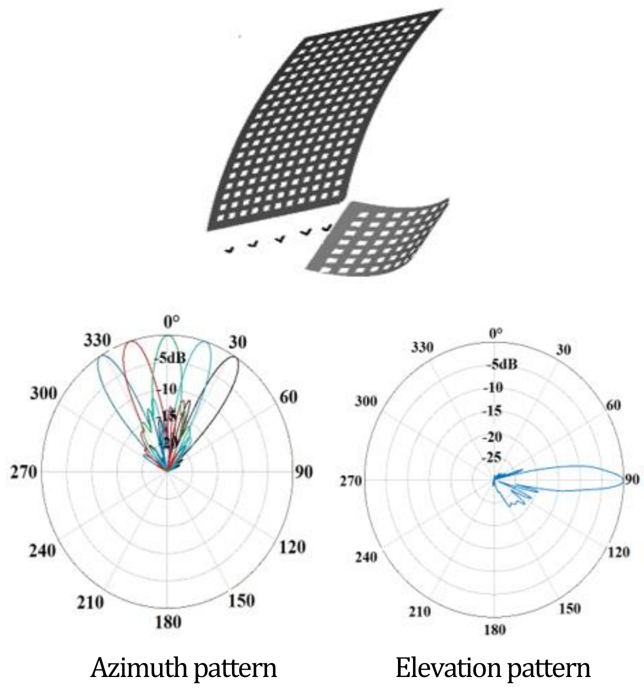

Fig. 2 – A penta-beam antenna covering 90° with an array of five feeds

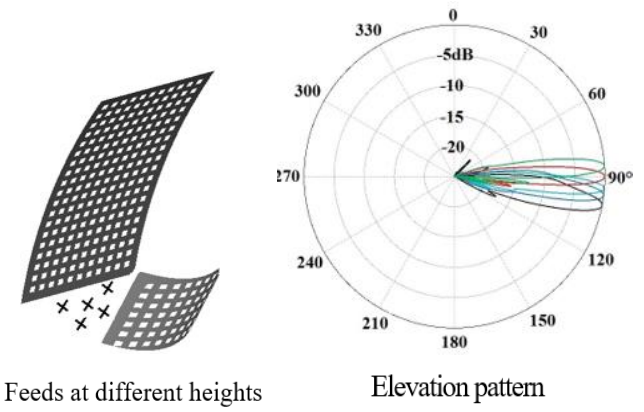

Fig. 3 – A penta-beam antenna with five different vertical tilt angles (five feeds at different heights)

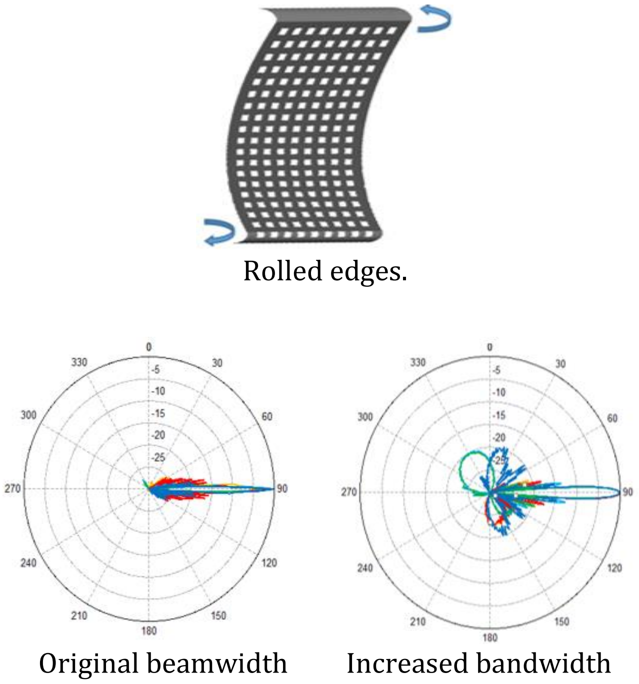

Fig. 4 – Rolling the edges of the main reflector

To double the number of horizontally sectored beams, the developed antenna can generate multiple beams with simultaneous vertical and horizontal sectorization. Simultaneous vertical and horizontal sectorization can be achieved by using two or more rows of feeds at the same time, as shown in Fig. 5. It shows the radiation patterns of two sets of penta-beams in two different vertical groups using two rows of feeds. This adds more freedom to generate multibeam in different forms. The horizontal feed locations in the two rows are adjusted such that the peaks of the upper group of beams are above the nulls of the lower group of beams and vice versa. Hence, every user will always be close to the peak of a beam.

Four of these penta-beam units can be used together to cover 360° with forty beams, as shown in Fig. 6. On the other hand, to cover a wider area around the orbit of the satellite, the number of vertical sets of beams can be increased to three sets (instead of two), or even more. For example, Fig. 7 shows an antenna with three rows of feeds generating sixty beams in three vertical sets covering 360°. It should be noted that the antenna does not have to use the same number of feeds in all rows.

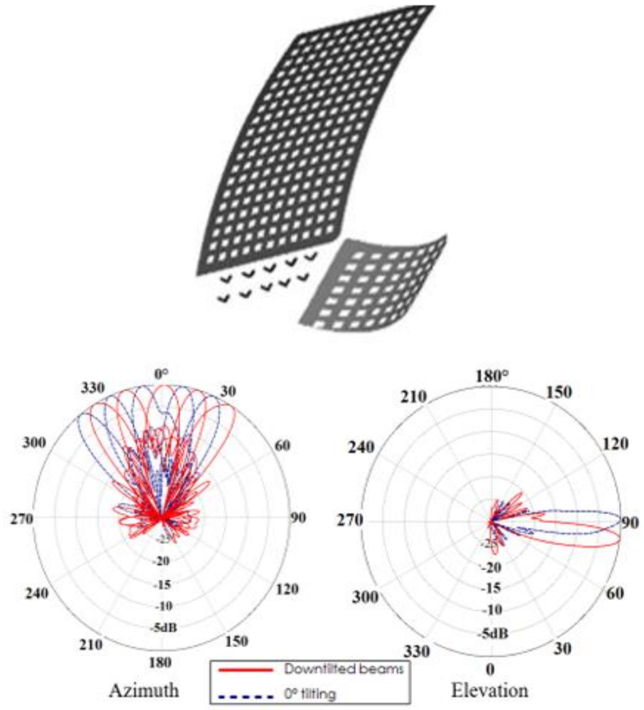

Fig. 5 – A penta-beam antenna generates ten beams in two vertical sets

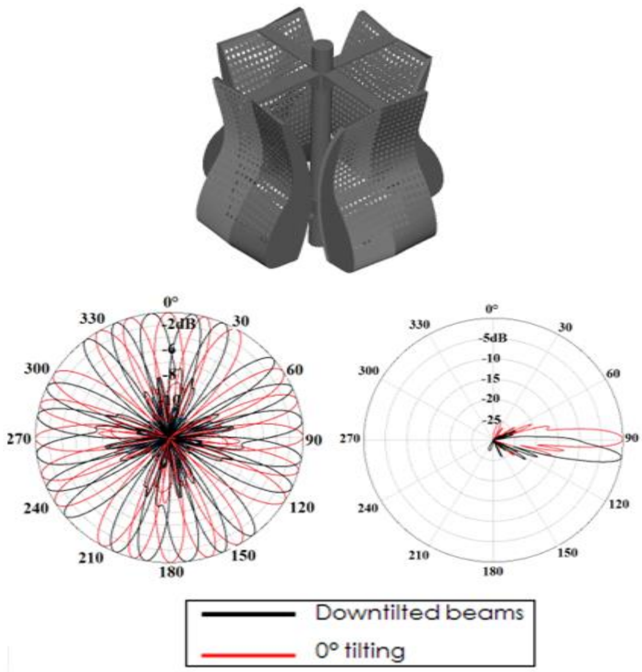

Fig. 6 – Four penta-beam units covering 360o with forty beams

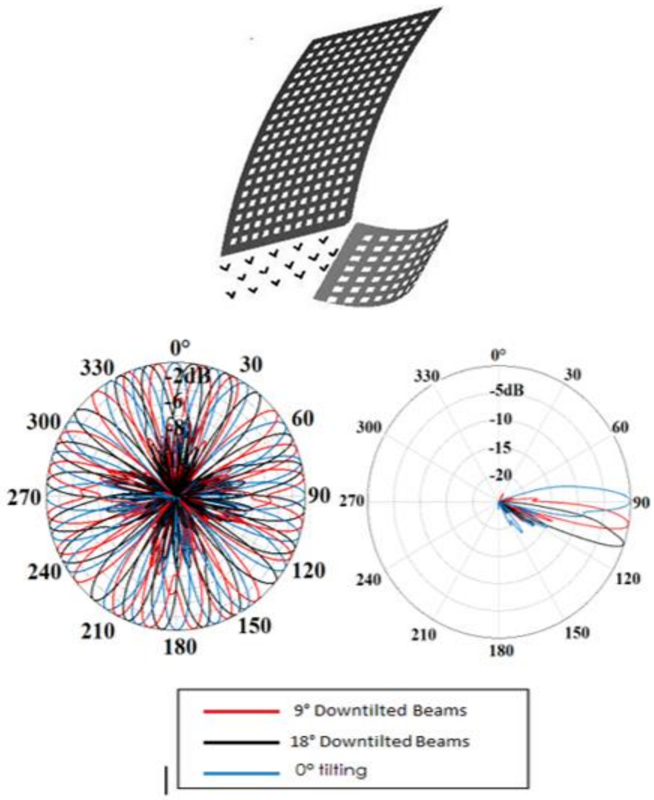

Fig. 7 – Three rows of feeds generating 60 beams in 3 vertical sets covering 360°

3. COVERING A SET OF REMOTELY CONTROLLED SECTORS OF ARBITRARY SHAPES

If all beams of the above multibeam antenna are adjusted to have equal vertical tilt angles, they will cover a circular area around the antenna (360°), as shown in Fig. 6 and Fig. 7. The radius of this covered circle depends on the height of the antenna and the vertical tilt angles of the beams. The radius of the covered area increases by decreasing the vertical tilt angles of the beams and vice versa. To significantly increase the radius of the covered circle, more vertical arrays of beams can be used with simultaneous vertical and horizontal sectorization. Instead of covering a circle, the antenna can also cover any area of an arbitrary shape and size by controlling the vertical beam tilt of each beam individually [23]. Each beam can be individually tilted with an arbitrary remote electric vertical beam tilt. This means that the vertical beam tilt of all beams (up to 60 beams) can be different from each other, if needed. Furthermore, the beams can be divided into different groups of beams to cover different areas of arbitrary shapes and sizes (a circle, square, rectangle, triangle, half a circle, ellipse, etc.). The relationship between the vertical beam tilt angles and the shape and size of the covered area can be estimated and programmed to be controlled remotely and automatically in order to cover any specific zone.

On the other hand, sometimes, the antenna is required to cover fixed areas while it is mounted on a quasi-stationary platform (e.g., aircraft) with movement in all directions, as shown in Fig. 8. Again, this can be achieved by controlling the vertical beam tilt angle of each beam. If the height of the aircraft changes, the antenna can keep covering the same area by automatically and remotely controlling the vertical tilt angles of all the beams. The exact relationship between the height and the vertical beam tilt angles can be accurately estimated and programmed to be modified remotely and automatically to cover a fixed area. If the height of the aircraft increases, the beams must be rotated upwards and if the height decreases, the beams must be rotated downwards to keep the covered area constant.

Fig. 8 – The antenna on a quasi-stationary aircraft

4. MULTI BEAM ANTENNAS ON LEO SATELLITES AND GROUND STATIONS

As explained above, the switched-beam technology increases the number of beams covering the same main sector and, thus, reduces the beamwidths. Hence, every user will always be near to the peak of a beam. In this developed technology, this can be achieved in different forms depending on the required overall number of beams, their vertical/horizontal tilting angles, and their required beamwidths. For example, one, two, or more of these antenna units can be used on the LEO satellite and on the LEO ground station (terminal), as shown in Fig. 9 [21]. Each of these antennas can be designed to generate an arbitrary number of beams to cover any arbitrary area of any size and any shape.

The antennas on the satellite are fixed such that their generated beams are all perpendicular to the orbit of the satellite (i.e., perpendicular to the movement direction of the satellite). The vertical slope of these beams can be remotely controlled and adjusted for the best coverage of any specific area on the ground having any arbitrary shape and size. For any specific satellite orbit, the horizontal orientation, and the vertical slope of the ground station (terminal) antennas will always be automatically adjusted such that their beams are parallel to the beams of the satellite antennas and directed toward them, as shown in Fig. 9. This automatic orientation process completely depends on the location, the orientation, and the elevation of the ground station (terminal) antenna with no need for any of the complicated adaptive steering and tracking techniques that must interact with the LEO satellite and without any adaptive beam shaping [21]. This automatic orientation process can achieve beam alignment, without the need for any complex steering and tracking mechanisms.

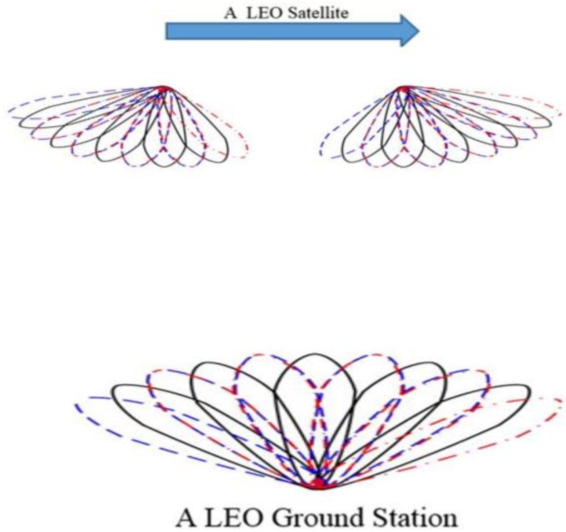

Fig. 9 – Multibeam antennas on an LEO satellite and an LEO ground station

5. A GROUND STATION ANTENNA CONNECTED TO MULTIPLE SATELLITES IN DIFFERENT ORBITS

In some cases, the ground station (terminal) antenna is required to, simultaneously, communicate with multiple satellites in different orbits. This can be easily achieved using the same concept of the developed multibeam antennas. For example, Fig. 10 shows a multibeam antenna, simultaneously communicating with five satellites in five different orbits. Each satellite has one of these antennas covering 90^{o}. However, two of these antennas can be used on each satellite to cover 180^{o}.

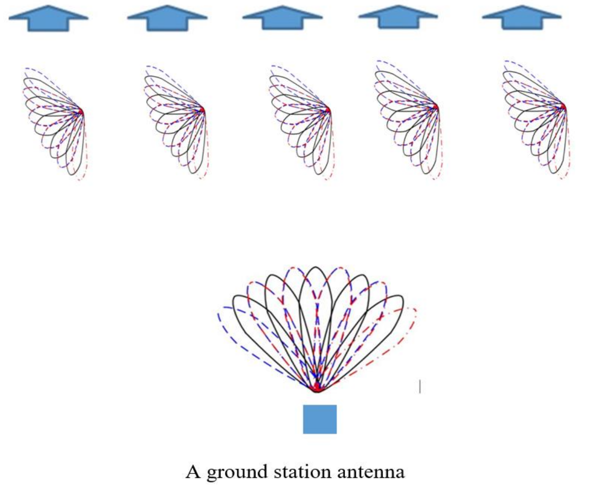

Fig. 10 – A ground station antenna connected to five satellites in five different orbits

The antennas on the satellites are fixed such that the beams of each satellite are perpendicular to its orbit. For any specific group of satellite orbits, the horizontal orientation, and the vertical slope of the beams of the ground station (terminal antenna) will always be automatically adjusted such that each beam of the terminal antenna is parallel to the beams of one of these satellite antennas and directed toward them. Again, this automatic orientation process, completely depends on the location, the orientation, and the elevation of the terminal antenna with no need for any of the complicated adaptive steering and tracking techniques that must interact with the LEO satellite and without any adaptive beam shaping.

6. SPECIFICATIONS OF THE USED LEO SATELLITE AND GROUND STATION ANTENNAS

Dual parabolic cylindrical reflector antennas have many design parameters that can be optimized together to provide any required specs, no matter how challenging they are. For example, a sub-6GHz (3.3-6.0 GHz) penta-beam antenna unit was manufactured by a 3D printer and then the reflecting portions/faces were covered by a very thin layer of aluminum foil/tape. The length/width of the main reflector are 80/56 cm. The length/width of the sub-reflector are 17/56 cm. The vertical and horizontal beamwidths of the generated beams can be controlled separately, by adjusting the dimensions of the antenna. Several holes were punched in the antenna and the radome to reduce their weight and the wind-load. The overall size of the antenna with a radome is 80 x 56 x 20 cm^{3}, while its overall weight is around 2 kg.

A GTD software code was written, especially, for dual parabolic cylindrical reflectors and its accuracy was verified experimentally several times with different configurations and applications [24]. The radiation patterns with two and three rows of feeds are those that were shown in Fig. 6 and Fig. 7, respectively, at a sample frequency 4 GHz. In all configurations, the gain is ranging from 20 to 24dBi. The first upper side lobe suppression is 15 dB and the isolation between polarizations is ≥ 20dB. The isolation between beams is ≥ 21dB. Each beam can be electrically tilted by an arbitrary tilt angle. It should be noted that the antenna does not have to use the same number of feeds in all rows. For example, the patterns in Fig. 9 and Fig. 10 are generated using five feeds in one row and six feeds in the other row.

The above calculated results were verified experimentally, on the roof of a building, using a basic set with a vector network analyzer and two calibrated reference feed horn antennas, as shown in Fig. 11 [24]. It was difficult to build an automated measurement setup for such a multibeam antenna that can handle a very large number of beams, which can reach 60 beams with 120 ports. So, instead, the calculated results were verified experimentally, for each beam, at several frequencies and several angles.

The dimensions of the above 5G sub-6GHz penta-beam antenna can be scaled down such that it resonates at the mm-wave frequency range (17.8-30 GHz), which is one of the most widely used bands in LEO satellite communications. The overall antenna size of the mm wave antenna with a radome is 14.8 x 10.4 x 3.7 cm^3 and its weight is 0.37 kg. The return loss of the scaled mm-wave feed antenna is shown in Fig 12 and its efficiency is shown in Fig. 13. The radiation patterns of the mm wave antenna are close to the above patterns of the sub-6GHz antenna.

The developed antenna can even work, simultaneously, at multi wide frequency bands such as 5G-sub-6GHz band (3.3-6.0 GHz) and mm band (17.8-30 GHz), by adding two sets of feeds, where each set operates at one of these frequency bands. On the other hand, generating many beams may result in using a very large number of ports, which may be difficult to deal with. To simplify the developed antenna configuration, and reduce the need for MIMO, single port orthogonally polarized feeds can be used with the new multibeam antenna [25].

Fig. 11 – Testing the 5G multibeam antenna

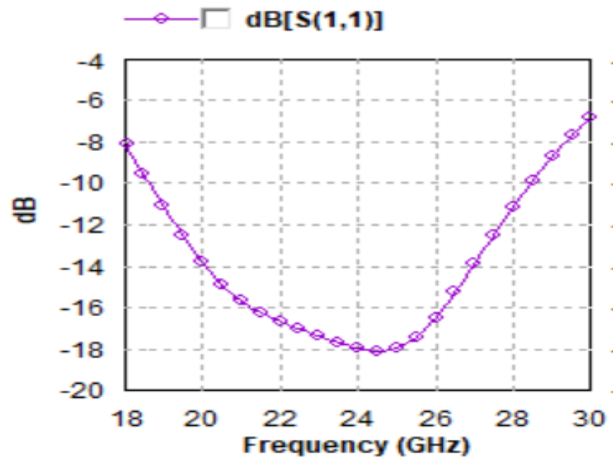

Fig. 12 – Return loss of the mm wave feed

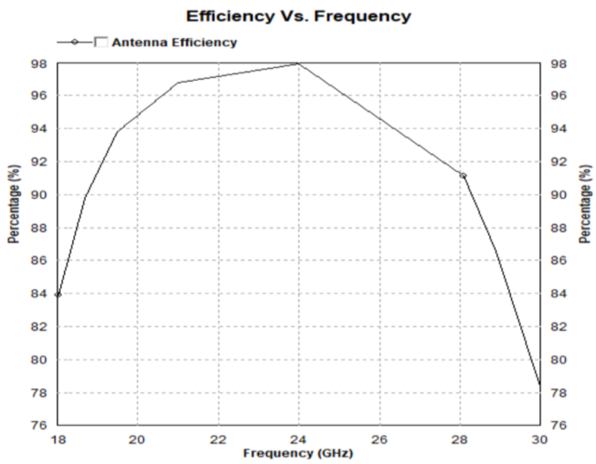

Fig. 13 – Efficiency of the mm wave feed

7. CONCLUSION

The characteristics of multibeam dual parabolic cylindrical reflector antennas were summarized. Its unique advantages in different applications were briefed. It was easy to manufacture and was very lightweight and low cost. It was gridded with punched holes in its body and in the radome, which made it lighter in weight and significantly reduced its wind-load. The antenna did not use any active components. So, it had a wide frequency bandwidth, which increased the capacity and the applications. It could cover the whole mm frequency band (17.8-30 GHz), which is one of the most widely used bands in LEO satellite communications. The overall size of a mm wave antenna generating 20-24 dB gain was 14.8 x 10.4 x 3.7 cm^3 and its weight was 0.37 kg. The developed antenna could even work simultaneously at different wide frequency bands such as 5G-sub-6GHz band (3.3-6.0 GHz) and mm band (17.8-30 GHz), by adding two sets of feeds, where each set operates at one of these bands. The antenna was foldable, deployable, and transparent. It could generate an arbitrary number of beams with arbitrary beam overlapping. This significantly increased the capacity and reduced the need for complicated MIMO techniques. Each beam could be individually tilted with an arbitrary remote electric vertical beam tilt. The beams could be tilted such that their vertical tilt angles were all different from each other, if required. It could have simultaneous vertical and horizontal sectorization.

The antenna could cover a circle of an arbitrary diameter. It could also cover any area of an arbitrary shape and size by controlling the vertical beam tilt of each beam, individually. Furthermore, it could be remotely controlled to cover any set of areas with any specific shape, with any required size (e.g., a circle, quasi-ellipse, quasi square, quasi-rectangle, quasi triangle, half a circle, etc.). The antenna could also cover fixed areas while it was mounted on a quasi-stationary platform (aircraft) with movement in all directions. As the aircraft moves in any direction, a fixed area could always be covered by automatically and remotely changing the vertical tilt angle of each beam according to an accurately estimated value.

The multibeam dual parabolic cylindrical reflector antenna was applied to LEO satellites and LEO ground stations (terminals). For any specific satellite orbit, a quite simple beam tracking technique was developed without using any adaptive technology. The orientation of each ground station (terminal) antenna was automatically controlled such that its beams were parallel to the beams of the satellite antennas and directed toward them. This automatic orientation process completely depended on the location, the orientation, and the elevation of the ground station (terminal) antenna with no need for any adaptive steering/tracking techniques or any adaptive beam shaping.

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AUTHORS

Mohamed Sanad is a professor emeritus at the Faculty of Engineering, Cairo University. He founded an antenna R&D company, “Amant Antennas”. He has been granted several US patents and published many antenna papers. He was awarded some international innovation prizes, such as the “Innovation Prize of Africa - IPA”. He directed and achieved several research projects for some of the largest telecommunication companies in the USA and the world. Dr. Sanad was the first one to embed the antenna inside cellular phones. He developed new antenna technologies for different applications such as handsets, base stations, LEO/GEO satellites, wireless battery charging for biomedical applications and RF hyperthermia cancer treatment. He got his Ph.D. from the University of Manitoba, Canada. Dr. Sanad is now a research professor at the Department of Biomedical and Electrical Engineering, University of Nevada, Reno, USA.

Noha Hassan is an associate professor at the Department of Biomedical Engineering, Cairo University. Her research interests are focused on the interaction between electromagnetic waves and the human body, as well as therapeutic applications of electromagnetic fields (EMFs). She has published several papers about the interaction between antennas and the human body, antenna shielding techniques and antenna applications in biomedical instruments. Dr. Hassan got her Ph.D. degree from the Department of Biomedical Engineering, University of Nevada, Reno, USA. Her Ph.D. thesis was on the interaction of electromagnetic fields with biological cells, as well as modeling the interaction with cell aggregates.