A SATELLITE MULTIBEAM ANTENNA FOR HIGH-RATE DATA RELAYS

ESA/ESTEC, NOORDWIJK, THE NETHERLANDS
5 – 8 OCTOBER 2010

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ABSTRACT

This paper presents recent progress on a novel multibeam antenna that is designed to serve as a key component for multiple transparent real-time capable data relays linking several LEO satellites to a single earth station via a GEO satellite. High data rates up to several hundreds of Mbit/s can be achieved. The proposed antenna operates at about 26 GHz and can track LEO satellites by switching between different beams and applying digital beamforming to each beam.

1. INTRODUCTION

In recent years, the amount of data acquired by single low-earth-orbit (LEO) earth observation satellites has grown tremendously. Therefore, the relatively short span of time (typically ~10 min), during which a given earth station can maintain contact to a passing LEO satellite to download all its gathered data, represents an increasingly serious bottleneck.

An elegant way to circumvent this bottleneck is the utilization of a geosynchronous-earth-orbit (GEO) satellite to redirect high data rate LEO signals to an earth station (Fig. 1). Thus, long contact times to LEO satellites based on only one ground station can be obtained, since the majority of LEO satellites will be visible for the GEO satellite for at least 50% of their orbital period.

For typical LEO earth observation satellites moving on polar orbits, GEO data relays offer up to a factor of 15 higher access times than a direct link to a given single ground station could provide. That gain in contact time can be utilized to increase the transmitted data volume and/or to reduce the data rate requirements depending on the mission specific needs. For several smaller state-of-the-art earth observation satellites, a data rate of some tens of Mbit/s would already result in a sufficient data download capacity, if a GEO data relay is being employed instead of a direct link to a single ground station.

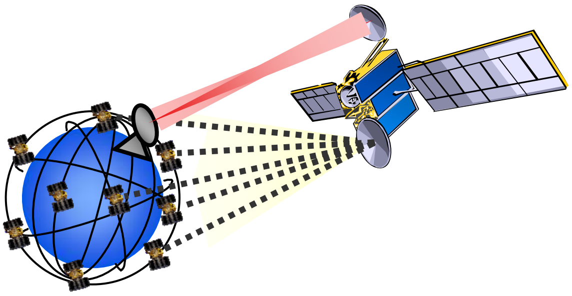

Figure 1. Concept of the high-rate data relay between a GEO satellite and several LEO satellites

In order to exploit the potential of GEO data relays more efficiently and to make them suitable for the increasing complexity of present and future earth observation applications, we envisage exemplarily a data rate of 200 Mbit/s as a target requirement for the further discussion of our GEO data relay antenna approach presented in this paper.

Another advantage of the concept described here is that even simultaneous data link communication from multiple LEO satellites to one GEO satellite becomes feasible, if a suited multibeam antenna is used on the GEO satellite for receiving the inter-satellite link (ISL) signals.

Therefore, to demonstrate and utilize the advantageous potential of GEO data relays, we propose a novel Ka-band multibeam receiving antenna as payload component for GEO satellites, which is capable of serving as the key element of multiple high bit rate GEO data relays.

2. MULTIBEAM ANTENNA CONCEPT

For high data rate communication from a LEO to a GEO satellite, antennas with high gain are required. Instead of equipping many LEO satellites with large Tx antennas, it is advantageous to have an Rx antenna with higher gain on the GEO side.

Based on an exemplary bit rate requirement of 200 Mbit/s, we have performed link budget calculations for a carrier frequency of 26 GHz to check the proposed concept for consistency and feasibility. Our investigation shows that in particular for the ISL, which is typically more critical than the GEO feeder downlink, a closed link budget is obtained with quadrature phase shift key (QPSK) modulation at a code rate of 0.75 assuming a LEO Tx antenna EIRP of about 59 dBW and a GEO Rx antenna gain of about 42 dBi (G/T 14.6 dBi/K). On the LEO side, this EIRP can be achieved with an antenna comprising a mechanically steered reflector of 60 cm diameter and providing a Tx power of 50 W at the antenna flange. The link budget can of course be scaled to the user's needs. If e.g. only a bit rate of 100 Mbit/s is required, a LEO Tx reflector diameter of 40 cm would be sufficient.

To obtain multibeam capability and the required gain on the GEO side, an electronically steerable antenna is very attractive.

Generally, two basic architectures of electronically steerable antennas with multibeam capability can be distinguished: A direct radiating array (DRA) and an array of feeds positioned near the focal plane of a reflector. Obtaining the desired high gain with the DRA approach would afford a very high number of radiating elements resulting in a too high complexity of the corresponding control logic. There are examples of simplified solutions to utilize DRA for satellite communications in the literature [1]. However, they are limited to a very low scan volume and to a few beams only. The second solution is more suitable to fulfil our requirements, since the high gain is obtained through the aperture of a reflector. This allows to use an array of feeds having considerably fewer elements than a DRA would require.

There are various types of curved reflector antennas: centred and offset, single- or multi-reflector. For the application proposed here, a concept with a centred front-fed curved reflector would lead to a configuration, in which the array of feeds would be located outside the GEO satellite, being heavily exposed to high temperature differences that might range from about -170°C to +120°C. To at least partially protect the array of feeds from the harsh environment either a centred dual reflector (e.g. Cassegrain) or offset reflector antennas can be used.

Fig. 2 shows an offset single reflector arrangement that allows to attach the array of feeds to the satellite surface. While the top layer of the array is aligned with the satellite surface, the underlying layers with the active components are accessible from inside the satellite allowing the stabilization of their temperature.

As depicted in Fig. 2, the output signals of each patch of the multifeed array pass first an LNA amplification stage integrated into the multifeed array (not explicitly shown here). The outputs of the LNAs are directed to a switch matrix via a wiring harness. The reconfigurable switch matrix, which connects the subset of patches receiving an ISL signal to the transponder frontends and signal processing electronics, will be implemented in RF Micro-Electro-Mechanical Systems (MEMS) technology [2], which is very advantageous due to its low losses and its inherent low power consumption.

The multibeam antenna concept presented here is based on imaging signals transmitted from LEO satellites under certain angles into the direction of the GEO satellite onto different locations on the array of feeds depending on the angle of incidence with respect to the symmetry axis of the main reflector. A similar antenna concept was already proposed recently [3] employing exclusively an electronic switching technique to track the movement of a given LEO signal across the array of feeds, as the LEO satellite proceeds along its orbit. As will be discussed in more detail in the following section, in particular the uniformity and smoothness of the receiving gain of the multibeam antenna structure presented in [3] can still be further optimized, if the direction of each beam can be electronically steered to a sufficient extent. This can be accomplished by the additional use of a suited beamforming technique.

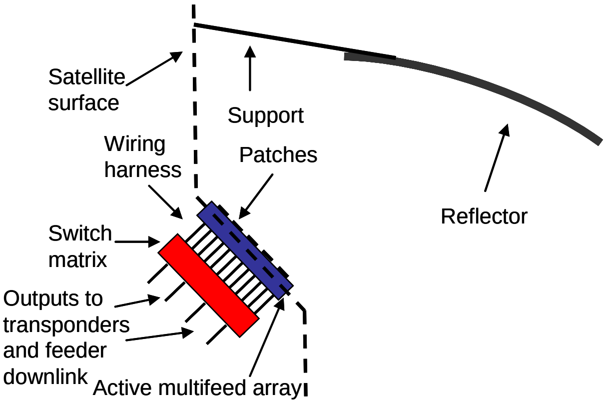

Figure 2. Schematic view of the multibeam antenna in offset single reflector configuration

3. BEAMFORMING

As already described in [3], LEO satellites can be tracked by switching between different beams. However, the antenna gain can vary significantly in such a case, as the tracked satellite moves from the tip of one beam to another. The amount of this gain variance depends on the beamwidth and the distance between the elements. Decreasing the distance between the multifeed array elements leads certainly to a rise of the gain minima at the transition point from one beam to another. However, it results also in a much higher number of feed elements and thus complexity of the whole antenna as well as in an increased mutual coupling between the elements. In the results presented in [3], which were not optimized yet, the gain difference between tips of two adjacent beams exceeds 10 dB for some steering directions.

To level these gain minima and therefore to raise the average gain of the antenna without decreasing the distance between the elements, we envisage to use digital beamforming [4] on the level of sub-arrays of the multifeed array. Fig. 3 shows a schematic view of the proposed beamforming concept.

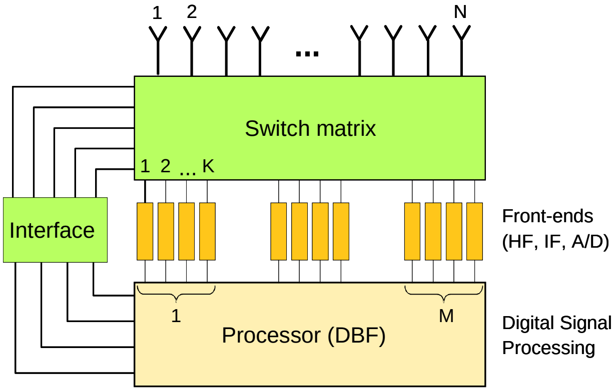

Figure 3. Beamforming concept

Out of N multifeed array elements, the switch matrix simultaneously transmits signals of M beams, where each beam is generated by K array elements. Accordingly, for each beam the computed beamforming coefficients are applied to K elements resulting in steering the beam towards the desired direction.

4. MULTIFEED ARRAY

The multifeed array will have a hexagonal or octagonal shape and will contain several hundreds of radiating elements (patches) arranged on square grids.

4.1. Single Radiator

To be capable to run several ISLs simultaneously in a frequency division multiple access scheme, each one operating at a data rate of 200 Mbit/s, the antenna needs to support an appropriately high bandwidth. According to basic physical considerations, the realization of an operating frequency band from 25.75 GHz to 26.25 GHz should be feasible by using configurations that offer broad bandwidth, good polarization purity and low sensitivity with respect to tolerances inherent to the fabrication process. To enhance the bandwidth and to minimize the influence of the feed network on the radiation pattern of the patch antenna, an aperture-coupled feeding scheme was chosen. Good polarization purity and robustness against tolerances can be achieved by exciting two orthogonal linearly polarized field components with two separate feeds. A 90° phase shift between them can be realized by using an integrated hybrid. Figure 4 shows schematically the top view of the chosen configuration for the patch antenna. A similar antenna is presented in [5] exhibiting good circular polarization purity as well as robustness against tolerances over the whole bandwidth. To increase the directivity of the chosen single radiator architecture, an additional patch of the same size was placed above the first one (stacked patch architecture).

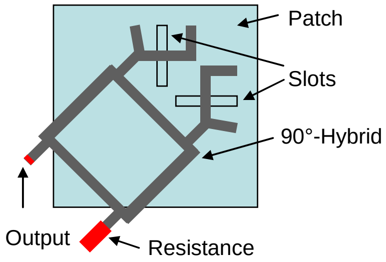

Figure 4. Top view of one element of the multifeed array

4.2. 2x2 Sub-Arrays

Signals from LEO satellites will be received by 2x2 sub-arrays (K = 4 in Fig. 3). The size of the sub-arrays was chosen as a compromise between the illumination of the reflector and the complexity of the beamforming unit. To improve the quality of circular polarization, sequential rotation of antenna elements will be used [6]. Fig. 5 shows a cut-out of a multifeed array with sequential rotation of array elements. Tracking of moving satellites will occur by switching between two adjacent 2x2 sub-arrays (e. g. S1 and S2 in Fig. 5) and utilizing digital beamforming when the beam from a satellite is within the coverage area of a single 2x2 sub-array. Since the maximum steering angle of the beams is determined by adjacent switched beam directions and thus very small, the distance between the antenna elements can exceed half the free space wavelength without generating grating lobes.

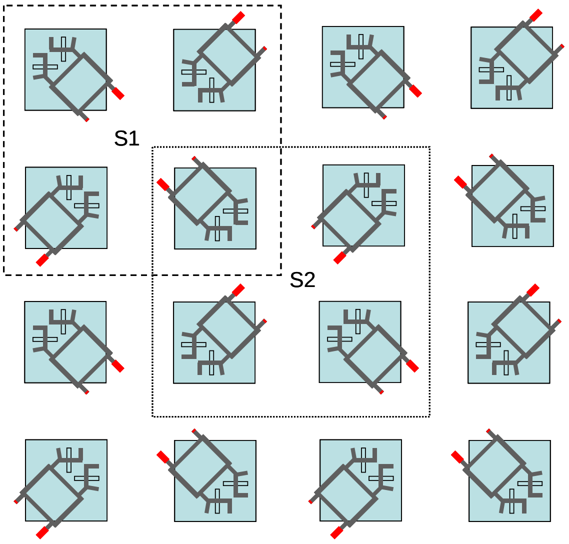

Figure 5. Cut-out of the multifeed array with two marked overlapping 2x2 sub-arrays

5. NUMERICAL RESULTS

In the following, preliminary numerical results of the multibeam antenna concept described above with the offset single reflector configuration (see Fig. 6) are shown.

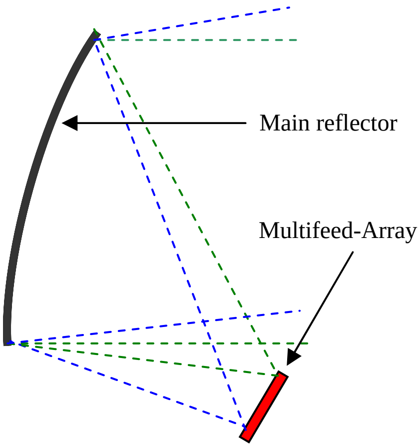

Figure 6. Schematic view of an offset single reflector antenna

The simulations were performed in *FEKO* [7] for a frequency of 26 GHz employing the physical optics (PO) method with full ray-tracing. The grid was composed of nearly 1.5 million triangles with edge sizes of the order of $\lambda/8$, where λ is the wavelength in free space. With the available computational resources, the complete feeder with over one thousand elements can not be modelled. Therefore, a 2x2 array composed of sequentially rotated circularly polarized patches with an interelement spacing of 0.7λ was simulated separately in *Ansoft Designer* [8]. The far-fields produced by this array were imported in *FEKO* and used as a field source to start the ray-tracing. That way mutual coupling between the elements of this 2x2 array has been taken into account.

Figs. 7 and 8 show the obtained scanning capabilities of the offset single reflector antenna depicted in Fig. 6. The reflector diameter is 1.2 m, F/D is 0.75, where F is the focal length and D is the diameter of the paraboloid, and the distance between the patch elements is 8 mm (0.7λ).

For illustration purposes, the results presented above show only curves with the spacing between the corresponding non-overlapping 2x2 arrays of 16 mm. However, due to the inherent overlapping capability (Fig. 5), twice as much curves can in principle be generated, improving the uniformity and smoothness of the receiving gain of the multibeam antenna. As described in sec. 3, even further improvement can be achieved by using digital beamforming.

Fig. 9 shows two adjacent curves close to the antenna boresight direction obtained without beamforming (solid lines) and a third curve (dashed line) that was generated by using digital beamforming shifting the main lobe of the beam about in the middle between the two main lobes without beamforming. As in this case the gain minimum in between the two curves obtained without beamforming is not significant, beamforming results here only in a moderate gain increase of about 0.5 dB. However, the situation is different for higher steering angles.

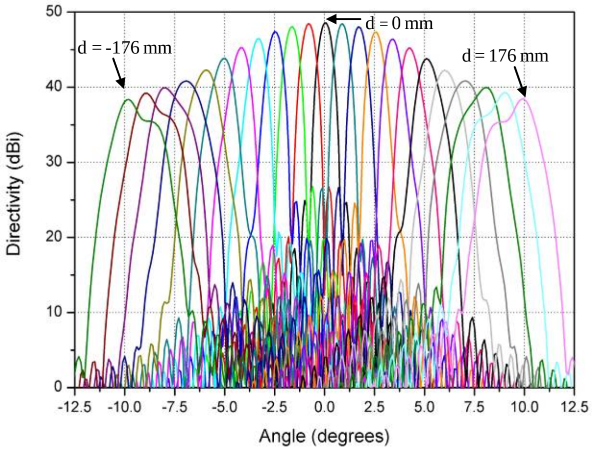

Figure 7. Scanning capabilities of the offset single reflector antenna in the symmetry plane

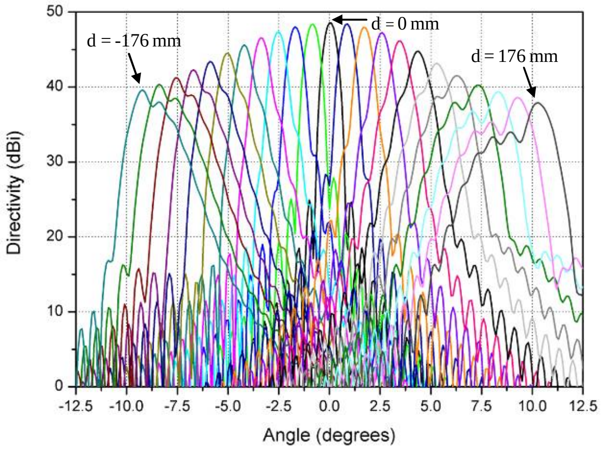

Figure 8. Scanning capabilities of the offset single reflector antenna in the asymmetry plane

Fig. 10 shows results obtained at the edge of the covering area of the antenna. The two curves with solid lines belong to adjacent gain profiles calculated without beamforming and the four curves with dashed lines are generated by steering the direction of the main beam of the 2x2 array in the range of 5° to 20°. In this case, at the edge of the covering area, a gain increase of more than 3 dB can be obtained using beamforming.

Thus, by using digital beamforming, both the uniformity and the smoothness of the gain profile of the antenna in the whole steering range can be improved.

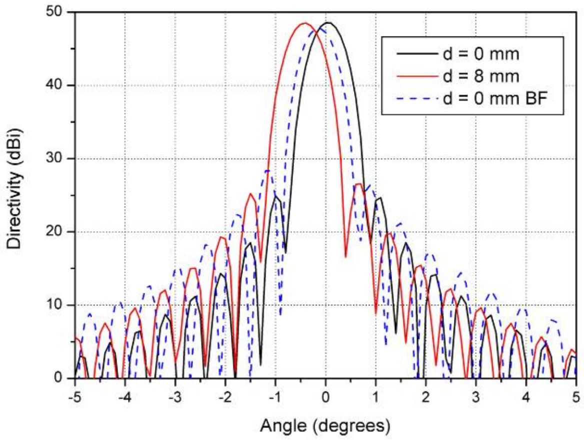

Figure 9. Scanning capabilities of the offset single-reflector antenna in the asymmetry plane

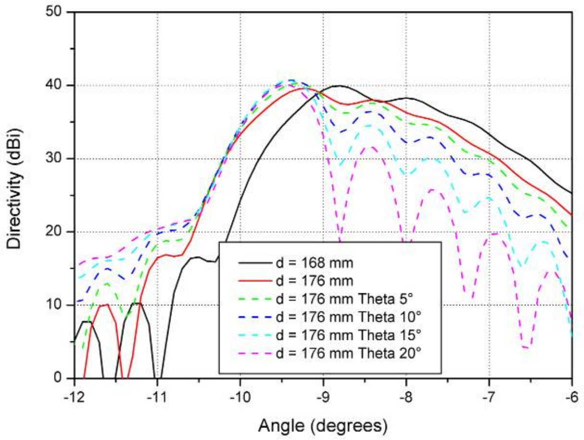

Figure 10. Scanning capabilities of the offset single-reflector antenna in the asymmetry plane

6. CONCLUSIONS

In this paper, first numerical results of a multibeam antenna for high-rate data relays between a geosynchronous satellite and several LEO satellites were presented. The investigated antenna architecture allows tracking of satellites both by switching between different beams and by using digital beamforming. The optimization of the antenna system is still ongoing, so that further improvements of the performance are still expected.

7. ACKNOWLEDGMENT

This work was funded by the Space Agency of the German Aerospace Center (DLR) through the “GEO data relays for low earth orbit satellites – GeReLEO” project under contract no. 50 YB 0907.

Further consortium partners associated are: EADS Innovation Works Germany, Fraunhofer Institute for Electronic Nanosystems (ENAS), SINTEC Microwave Systems GmbH, Steinbeis Innovationszentrum Raumfahrt, and Astrium GmbH as a subcontractor of the DLR Institute of Communications and Navigation.

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