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Pointing enhancement techniques for deep-space antennas

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The present paper presents a very efficient technique for enhancing the pointing accuracy in beam-waveguide (BWG) antennas and its application to the deep space antenna DSA2 of the European Space Agency. The proposed technique permits to achieve a twofold result: on the one hand, it provides a solution to the beam aberration issue, arising when the antenna simultaneously receives from and transmits to a spacecraft moving in the transversal direction. On the other hand, it allows to perform a fast conical scan to enhance the pointing accuracy of the antenna. Both results are achieved by simple linear displacements of feeds and mirrors located in the lower part of the BWG, with a very limited deterioration of the antenna gain. The required displacements of feeds and mirrors are determined through a fast optimization algorithm, based on a top-down approach, which requires repeated physical–optics analyses of the lower part of the beam waveguide only, with a significant reduction in the computing time.

Keywords: Beam aberration, Beam waveguides, Cassegrain antennas, Radio astronomy, Reflector antennas

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I. INTRODUCTION

Deep-space missions for interplanetary exploration are typically supported from Earth by large reflector antennas [1]. These antennas operate in different frequency bands (e.g. S, X, and Ka band) in order to simultaneously perform several tasks, such as telecommand, telemetry, tracking, and data relaying. Most of these antennas are based on a beam-waveguide (BWG) feed system, where signals generated by different feeds are combined, separated, and focused by means of solid and dichroic mirrors (Fig. 1). Moreover, the BWG system allows for decoupling the feed system from the antenna elevation and azimuth movements.

These antennas, typically named deep-space antennas (DSAs), need to rotate in azimuth and elevation in order to track the space probes. To this aim, they can be operated in various operational modes, including program track, autotrack, and conical scan.

Program track is the simplest, yet most common tracking method used in ground station antennas. It consists in moving the antenna azimuth and elevation drives according to a data file, which accounts for Earth's rotation and for the satellite trajectory, and reports the antenna position required at any given instant, as a function of time. The pointing accuracy, therefore, depends both on the accuracy of the computation of satellite relative position and on the accuracy of the antenna pointing, which can be affected by gravity, wind, and thermal distortions of the main and subreflector. As a consequence, if the mentioned effects are not accounted for, the antenna may suffer a depointing gain loss. Since the system operates as an open-loop, it does not foresee a real-time computation and correction of the pointing error between the actual satellite position and the ground station beam direction. For this reason, program tracking is typically used when the ground station has a beam broad enough for minimizing the unavoidable depointing losses. This usually happens in S and X band, but not at higher frequencies. This error can be limited by adopting a pointing and calibration system, which consists in scanning the sky (when the antenna is not tracking) to determine the actual pointing direction of a set of radio star sources, used as calibration targets.

Conical scan represents a direct evolution of the program tracking method. In this case the antenna does not blindly follow the estimated satellite trajectory, but it implements a closed-loop automatic tracking algorithm that allows for minimizing the average antenna depointing. As shown in Fig. 2(a), the ground station beam rotates continuously about an axis initially defined by the program tracking estimated satellite trajectory. If the satellite moves on a path that differs from the one predicted, the received signal is modulated in amplitude by the ground station rotation and by the angular separation between the actual and estimated satellite directions. The closed-loop system then corrects the antenna movement, in order to minimize the modulation of the received signal. When this reaches zero, the ground station antenna is drawing in the sky a cone around the direction connecting it to the satellite. It is noted that the pointing error sensitivity increases with the selected cone semi-angle, but wide angles determine larger gain loss and longer conical scan time.

Autotrack (also known as monopulse tracking) is probably the most advanced and complex closed-loop tracking system employed in ground station antennas. This approach makes use of a particular class of higher-order modes in the excitation of the antenna feeds: these modes (usually TM_{01}, TE_{21}, and TE_{01} in circular waveguides) present radiation

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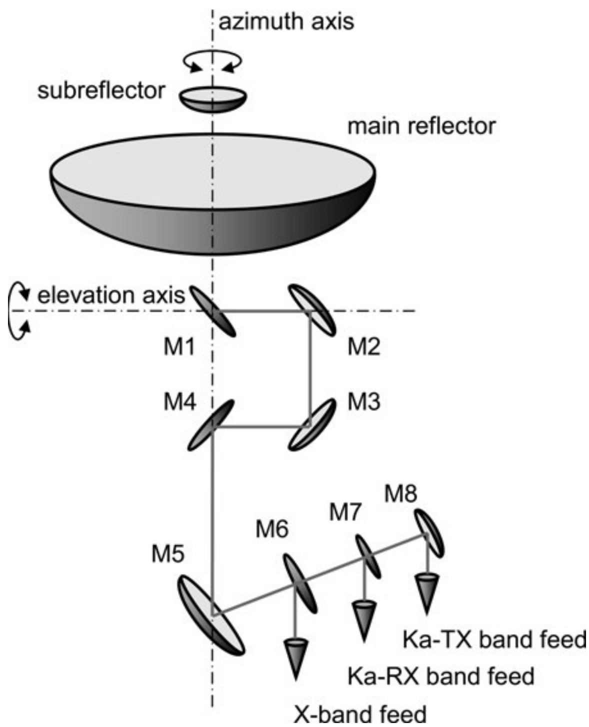

Fig. 1. Schematic of the beam waveguide of deep-space antenna DSA2 of European Space Agency.

patterns exhibiting a null in the axial direction, as opposed to the fundamental mode, which exhibits its maximum in the axial direction. Figure 2(b) depicts the operation principle of the autotracking mode. Ideally the null of the higher-order mode (also known as delta mode) coincides with the peak of the fundamental mode (also known as sum mode). As a consequence, if the ground station antenna is perfectly aligned with the satellite, the delta channel receives a null signal. If the alignment is not perfect, some higher-order modes are extracted by the tracking coupler and by comparing the delta mode to the sum mode, the depointing angle is calculated. These data are used to control the azimuth and elevation servo systems, in order to realign the antenna. The accuracy of the autotracking system depends on the characteristics of the tracking receiver and on the accuracy and speed of the servo systems. In particular, it is important that the delta mode null coincides with the sum mode peak, because the antenna is aligned according to the null direction. Moreover, a steep and deep null increases the sensitivity of the system, thus allowing for correcting a smaller depointing. Finally, a slow tracking receiver may cause a significant delay in the antenna pointing correction, thus reducing its effectiveness.

The operational modes described above (program track, conical scan, and autotrack) require the variation of the pointing direction and, as a consequence, the movement of the antenna. This is traditionally achieved by using a servo layer to rotate the main and subreflector. However, the speed of this movement is limited by the huge size of the antenna reflectors, and this reduces the efficiency of autotrack and conical scan systems. To overcome this limitation and to obtain a fast tracking system, a novel approach is presented in this paper, based on the implementation of a second servo layer, which permits the movement of the lower beam waveguide. Since the size of the components of the lower beam waveguide (feeds, solid mirrors, and dichroic mirrors) is much smaller, a fast tracking system can be implemented, thus leading to a reduction of the antenna pointing loss.

Moreover, the current trend to increase the operation frequency (from S and X bands to K and Ka bands) leads to new issues, related to the narrow beam of the radiation pattern. In particular, when the antenna operates in full-duplex (transmitting and receiving simultaneously) at high frequencies, another mechanism could cause depointing loss, due to the so-called beam aberration phenomenon. In fact, when targeted spacecrafts are not only moving along the antenna boresight but also in the transversal direction, the ground-station antenna receives and transmits in slightly different directions, with an angular separation up to 30–40 mdeg for current and planned missions. In X band, where the beam is relatively broad, the pointing loss is typically very low: for instance, in a 35-m antenna, the 3-dB beamwidth is approximately 60 mdeg, thus leading to a maximum pointing loss around 1 dB.

Conversely, in Ka band, the 3-dB beamwidth is much narrower (e.g. approximately 15 mdeg in a 35-m antenna), even smaller than the separation between transmission and reception directions. Therefore, typical values of the angular beam separation lead to unacceptable pointing loss. For

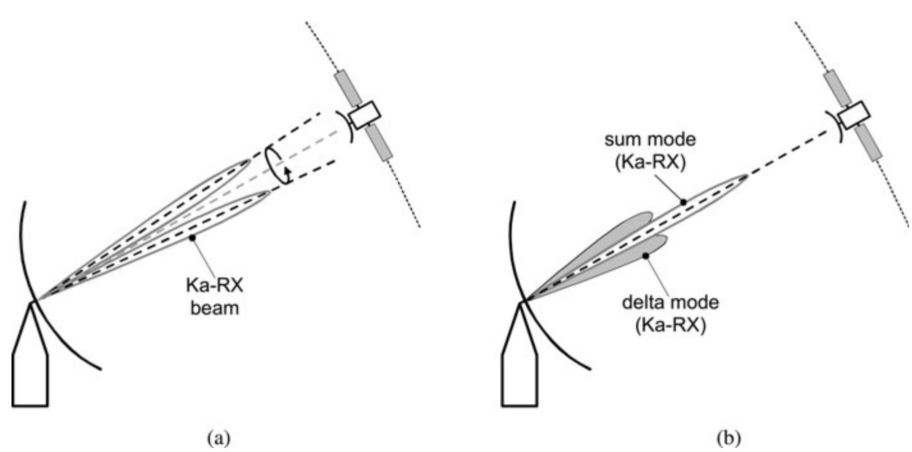

Fig. 2. Operational modes of deep-space antennas: (a) conical scan and (b) autotracking.

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simultaneous downlink and uplink in Ka-band, reception (RX) and transmission (TX) beams have to be pointed with a specific angular separation in order to receive from the position where the spacecraft was half signal round trip (SRT) in the past, and transmit where it will be half SRT in the future (Fig. 3). Since SRT is time varying, a system allowing for independent Ka-band RX and TX beam steering is required. This cannot be achieved by moving the main reflector of the antenna, but only by adjusting the feeds alignment, and/or the position of the lower BWG mirrors.

ESA is currently studying the possibility to implement in Deep-Space Antenna 2 (DSA2) two separate mirror/feed positioners, in order to concurrently correct the beam aberration by moving the Ka-band TX beam, and to realize a second-layer tracking mode superimposed to that of the main antenna drive system, by moving the Ka-band RX beam (for performing conical scan and/or autotracking).

The present paper presents a technique for solving the beam aberration issue and for performing fast conical scan and autotracking in DSAs, and its application to the case of ESA DSA2. After discussing the antenna structure (Section II), the adopted analysis and optimization technique is described (Section III), and the major results in the beam-aberration correction and conical scan are reported (Sections IV and V, respectively).

II. ESA DSA2

ESA DSA2 is a BWG antenna, based on a Cassegrain configuration, with a 35 m main reflector. The beam waveguide comprises eight mirrors (namely M1–M8; Fig. 1) and is equipped with three corrugated feed-horns operating respectively in X band (7.145–7.235 GHz for uplink and 8.4–8.5 GHz for downlink), Ka-band downlink (also denoted Ka-RX feed, 31.8–32.3 GHz), and Ka-band uplink (also denoted Ka-TX feed, 34.2–34.7 GHz). In particular, M1 and M4 are flat solid mirrors, M2 and M3 are offset paraboloids, M5 and M8 are offset ellipsoidal reflectors, and M6 and M7 are flat dichroic mirrors. More in detail, M6 reflects the X-band and is transparent in both Ka-bands, whereas M7 reflects the Ka-band downlink and is transparent in the Ka-band uplink.

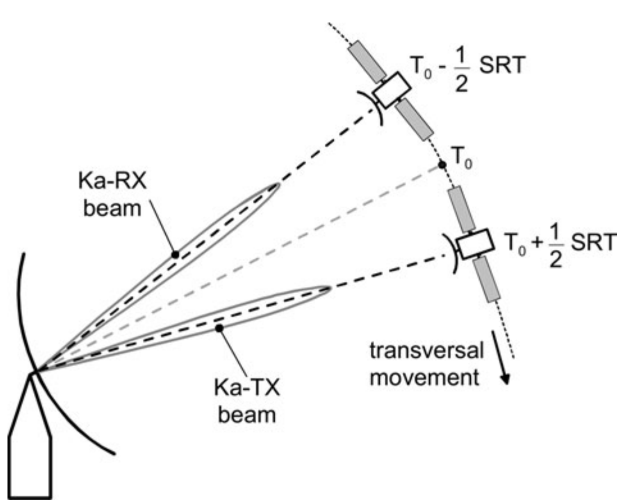

Fig. 3. Beam aberration phenomenon: the ground-station antenna receives and transmits simultaneously in slightly different directions.

To solve the beam aberration issue in Ka band, an angular separation between the Ka-RX and Ka-TX beams is needed. The required angular separation can be achieved by dynamically adjusting the position of the Ka-band feeds and of mirrors M7 and M8. Movements of other components of the beam waveguide would result in a supplementary squint of the X-band beam. Different techniques for the separation of RX and TX beam directions in ESA DSA2 are investigated. It was finally decided to point the antenna according to the RX direction and to squint the Ka-TX beam. This choice limits the possible movements only to the displacement of mirror M8 and of the Ka-TX feed.

Conversely, the conical scan and the autotracking are performed by squinting the Ka-RX beam. Similarly to the previous case, the possible movements are limited to the last elements of the BWG chain. In this case, the required beam squint can be achieved by displacing mirror M7 and the Ka-RX feed.

III. ANALYSIS AND DESIGN TECHNIQUES

The determination of the movements providing a given beam squint requires a tool for the accurate analysis of the beam waveguide antenna and an optimization procedure, which repeatedly modifies the configuration of the lower beam waveguide, to achieve the required beam squint with minimum gain degradation.

The analysis of the beam waveguide has been based on the commercial software GRASP by Ticra, which implements the physical optics (PO) [2]. GRASP is used in combination with a code based on the MoM/BI-RME method, which performs the modeling of the dichroic mirrors [3]. Even though both codes are very efficient, the simulation of a complete antenna configuration typically requires some hours on a standard computer, essentially due to the large size of the main reflector.

The optimization procedure could be based on a standard approach, which consists in iteratively moving part of the lower beam waveguide (e.g. Ka-TX feed and M8, or Ka-RX feed and M7), and in evaluating the overall antenna performance at each position. This procedure stops when a movement providing the required beam squint together with the lowest gain degradation is retrieved. The optimization based on the standard approach requires a large number of time-consuming iterations, thus leading to a prohibitively long computing time.

To overcome this drawback, we adopted a different and more effective optimization procedure, based on a top-down approach. If a given beam squint is required at a certain frequency, a plane wave impinging on the antenna at the desired direction is considered as a source, and the field generated on a mirror located in the lower BWG (e.g. M5) is calculated. It is noted that this analysis requires the modeling by PO of the upper beam waveguide, including the main reflector, and therefore it is very time consuming. As a second step, the feed horn operating in the considered frequency band is used as a source, and the field generated on the same mirror (e.g. M5) is calculated. This second analysis is by far much faster, since it only includes few elements of the lower BWG (e.g. from the feed to M5). Subsequently, the positions of a feed and a mirror (namely, Ka-TX feed and M8 when working in Ka-band uplink or Ka-RX feed and M7

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when working in Ka-band downlink) are iteratively modified, in order to match the two field patterns on mirror M5. Therefore, each optimization requires one time-consuming analysis of the upper beam waveguide and several fast simulations of the lower beam waveguide. Finally, an overall antenna simulation is performed when a good matching is achieved, with the sole scope of assessing the retrieved movement.

The main advantage of the top-down approach is a significant reduction in computing time with respect to the standard optimization. While the standard optimization approach requires tens of time-consuming analyses (each of them requiring some hours), the top-down approach is based on one single time-consuming analysis and tens of fast analyses of the lower BWG (each of them requiring few minutes). Therefore, a time reduction of several orders of magnitude can be achieved. Moreover, this technique provides a physical insight of the antenna performance. In fact, it has been observed that amplitude matching and phase matching separately impact on gain degradation and beam squint. In particular, a configuration of the lower beam waveguide yielding a matching of the normalized phase pattern generates a beam directed exactly in the direction of the considered plane wave. If this configuration also exhibits a good matching of the normalized amplitude pattern, a position generating minimum gain degradation has been found. On the contrary, a configuration with good phase matching and poor amplitude matching provides the required beam squint but a significant gain degradation. This crucial feature allows to easily drive the top-down method, thus providing a significant advantage with respect to the blind standard optimization.

IV. BEAM ABERRATION CORRECTION

The investigation of a technique for solving the beam aberration issue is described in Section IV. As previously discussed, the possible movements are limited to displacement of the solid ellipsoidal mirror M8 and of the Ka-TX feed. In all cases, PO simulations of the BWG antenna have been performed at the central frequency of the Ka-TX band (namely, at 34.45 GHz).

Preliminarily, two techniques already presented in the literature have been applied, as described in [4]. The first technique consists in translating the Ka-TX feed on the horizontal plane (Fig. 4(a)). This approach has already been implemented by NASA in DSS-13 and DSS-25 [5]. In our case, however, this technique did not provide satisfactory results, with a gain degradation of 3 dB in the case of beam squints of only 6 mdeg (Fig. 5(a)). As the requirement is to achieve 40 mdeg beam separation, this approach is not suitable for ESA DSA2.

The second technique consists in performing a rotation of mirror M8 around a pivot point (Fig. 4(b)) [6]. It resulted that a beam squint of 17 mdeg can be achieved with gain degradations of 3 dB (Fig. 5(b)), which is better than the previous technique but still not satisfactory.

Since classical techniques did not provide satisfactory results, the top-down optimization algorithm was applied to investigate new movement strategies of the lower beam waveguide.

The best performance has been achieved with linear shifts of mirror M8 and of the Ka-TX feed. In particular, the beam squint in the plane $\varphi = 0^\circ$ (x–z plane; Fig. 4(c)) is obtained by translating mirror M8 along the x and z axes. Figure 6(a) shows the gain degradation and the value of the x and z mirror displacements versus the beam squint (markers refer to calculated values, and lines are obtained by a best fitting procedure). It results that there is a linear relation between the beam squint and the displacements, and that a beam squint of 40 mdeg leads to a gain degradation of 2.1 dB. It is noted that the required beam squint is achieved with a significant shift of the mirror in the z direction and an additional small correction along the x axis. In order to simplify the implementation of movement servo mechanisms, it would be possible to neglect the x correction, at the cost of an additional performance deterioration (gain degradation of 4 dB with a beam squint of 40 mdeg).

Conversely, the beam squint in the plane $\varphi = 90^\circ$ (y–z plane; Fig. 4(c)) is obtained by independently translating both M8 and the Ka-TX feed along the y axis. Figure 6(b) shows the gain degradation and the y displacements of mirror and feed versus the beam squint. It results that, also in this case, there is a linear relation between the beam squint and the displacements, and that a beam squint of 40 mdeg determines a gain degradation of 1.5 dB. It is noted that the displacement of mirror and feed are almost identical in this case, and therefore the servo mechanisms could be simplified by moving them of the same quantity, at the cost of a gain loss of 4 dB with a beam squint of 40 mdeg.

It is finally remarked that, being the movements fully decoupled, it is possible to squint the beam in any direction, by combining the two displacements.

In order to have a physical insight of the top-down optimization approach, it is useful to examine the electric field patterns in the central portion of mirror M5 for some significant configurations.

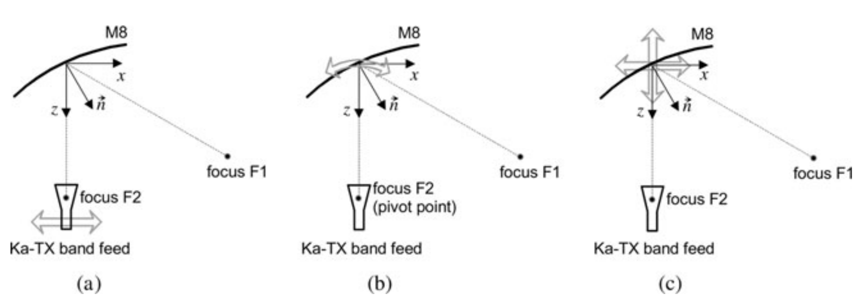

Fig. 4. Techniques to determine the beam squint in Ka-TX band: (a) translation of the Ka-TX feed; (b) rotation of mirror M8; and (c) translation of both mirror M8 and Ka-TX feed.

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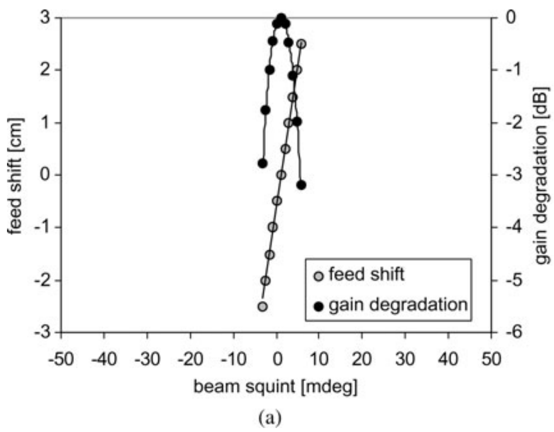

Fig. 5. Beam aberration correction based on classical techniques: (a) gain degradation versus beam squint, when translating the Ka-TX feed on the horizontal plane (Fig. 4(a)); and (b) gain degradation versus beam squint, when rotating mirror M8 around a pivot point (Fig. 4(b)).

Figure 7(a) shows the normalized patterns of amplitude and phase of the electric fields produced by a plane wave impinging with an angle $\theta = 20$ mdeg, $\varphi = 0$ (dashed lines), and by the Ka-TX feed, located in a position which produces a beam squint of 20 mdeg (color scale). It clearly appears that there is a good matching of both amplitude and phase. This case corresponds to a configuration which produces the desired beam squint of 20 mdeg with minimum gain degradation (about 1 dB).

As a second example, Fig. 7(b) shows the normalized patterns of amplitude and phase of the electric fields produced by the same plane wave (impinging with $\theta = 20$ mdeg, $\varphi = 0$, dashed lines) and by the Ka-TX feed, located in another position which produces the same beam squint of 20 mdeg (color scale). In this case, there is a good matching of the phase pattern (and this explains why the feed located in this position provides the required beam squint), but there is a poor matching of the amplitude, and therefore the gain degradation is more severe than in the previous case (about 6 dB).

In the last example, shown in Fig. 7(c), the normalized pattern of amplitude and phase of the electric fields produced by the same plane wave (impinging with $\theta = 20$ mdeg, $=0$, dashed lines) is compared with the one generated by the Ka-TX feed, located in position which produces a beam squint of 40 mdeg (color scale). It is evident in this case that there is no matching of the phase pattern, and therefore the feed located in that position does not yield the required beam squint.

V. CONICAL SCAN

The investigation of a technique to perform the conical scan by moving the lower beam waveguide is discussed in Section V. In particular, the conical scan can be performed by moving the dichroic mirror M7 and the Ka-RX feed. In all cases, PO simulations of the complete BWG antenna have been performed at the central frequency of the Ka-RX band (namely, at 32.05 GHz).

In this case, the maximum required beam squint is up to 10 mdeg. Several movements have been investigated, including the tilt and the shift of M7. The rotation of M7 around the y axis (Fig. 8(a)) allows for the beam squint in the plane $\varphi = 0^\circ$, whereas the rotation around the x axis allows for the beam squint in the plane $\varphi = 90^\circ$. This technique yields good results in terms of gain degradation: a beam squint up to 10 mdeg can be achieved with less than 0.3 dB gain reduction. However, this movement modifies the angle of incidence of the Ka-TX beam passing through the dichroic mirror M7, with a detrimental effect on the Ka-TX gain and radiation pattern.

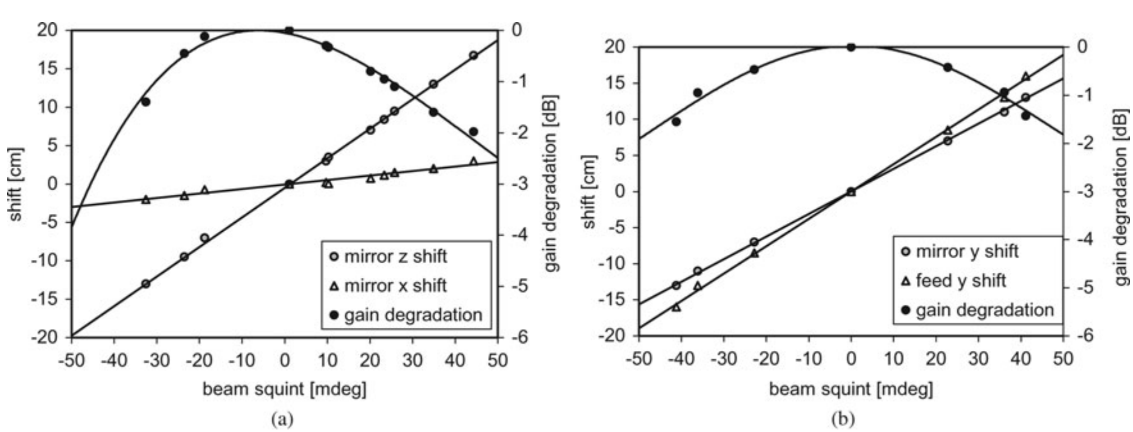

Fig. 6. Beam aberration correction based on the translation of mirror M8 and Ka-TX feed: (a) gain degradation and mirror shifts versus beam squint (plane $\varphi = 0^\circ$); and (b) gain degradation and mirror/feed shifts versus beam squint (plane $\varphi = 90^\circ$).

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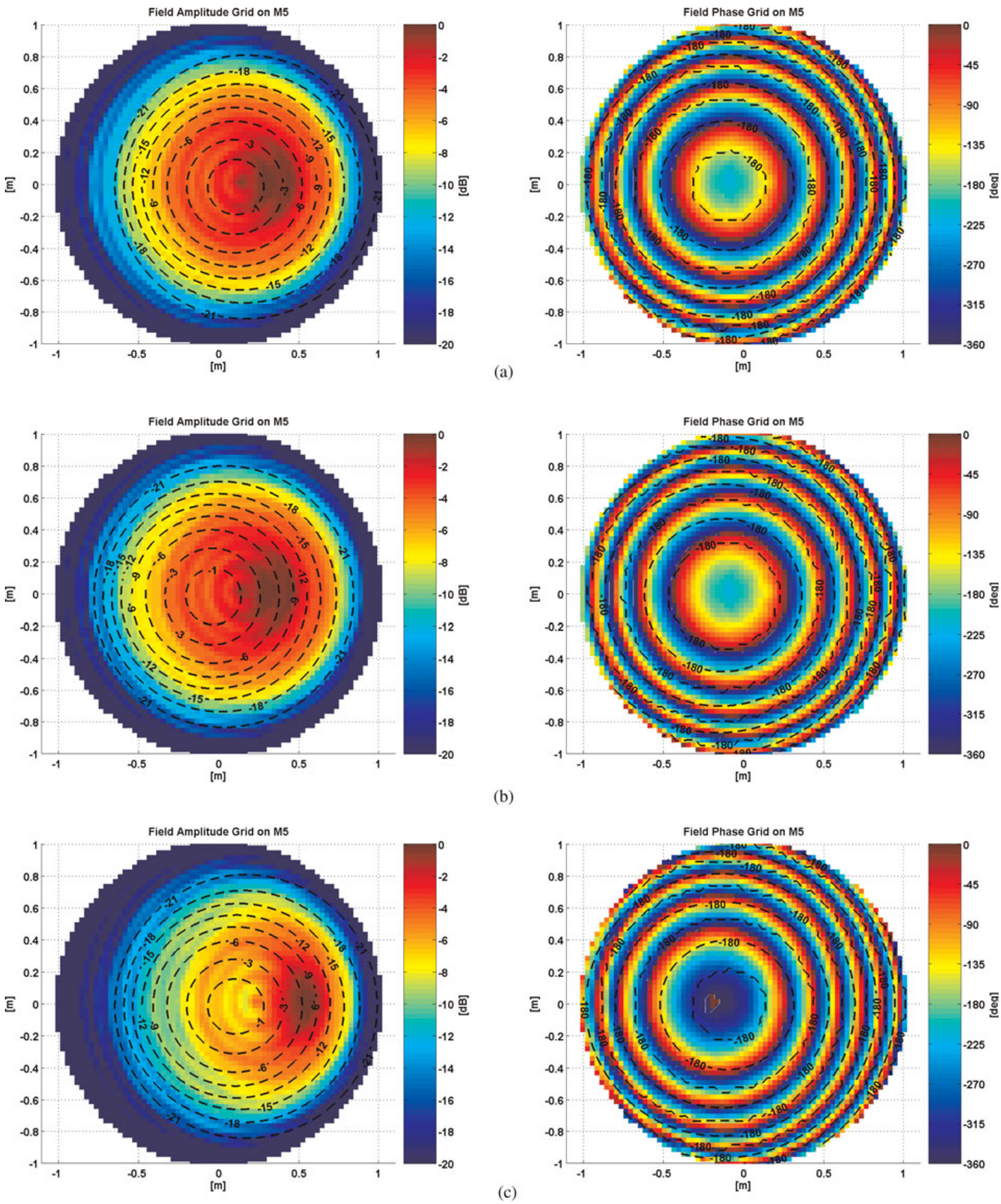

Fig. 7. Normalized patterns of amplitude and phase of the electric field on mirror M5, generated by a incident plane wave (dashed lines) and by the Ka-TX feed (color scale): (a) good matching of both amplitude and phase (good overall performance); (b) good matching of the phase, but not of the amplitude (significant gain degradation); and (c) bad matching of the phase (wrong beam squint).

For this reason, we adopted the top-down optimization algorithm to investigate different solutions. It resulted that the most effective technique is based on the shift of mirror M7 in the z direction to achieve the beam squint in the plane $\varphi = 0^\circ$, whereas the shift of the Ka-RX feed along the y axis allows for the beam squint in the plane $\varphi = 90^\circ$. The z translation applied to M7 yields a maximum gain degradation of 0.5 dB in case of a beam squint of 10 mdeg, as shown in Fig. 8(b). It is worth noting that this movement does not modify the incidence angle of the Ka-TX beam on the M7 dichroic mirror, thus completely decoupling the beam aberration correction and the conical scan. The y translation of the Ka-RX feed provides a beam squint of 10 mdeg with a gain degradation limited to 0.2 dB, as shown in

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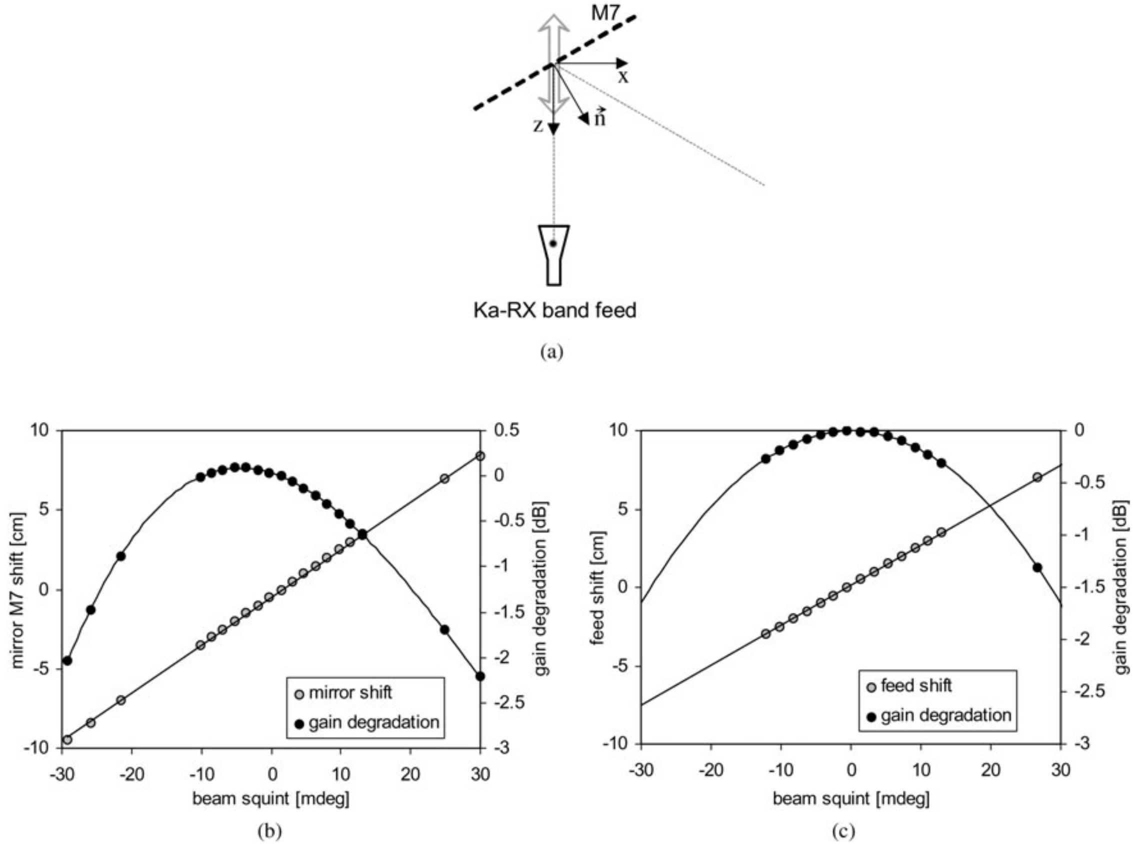

Fig. 8. Conical scan based on the translation of mirror M7 and Ka-RX feed: (a) movement of the mirror and of the feed; (b) gain degradation and mirror shifts versus beam squint (plane $\varphi = 0^{\circ}$); and (c) gain degradation and feed shift versus beam squint (plane $\varphi = 90^{\circ}$).

Fig. 8(c). Also in this case, since the position of mirror M7 is unchanged, there is no effect on the Ka-TX beam.

VI. CONCLUSIONS

The present paper has presented an efficient technique for the pointing enhancement in BWG antennas used to support deep-space missions. In particular, the issues related to beam aberration and fast conical scan in deep space antenna 2 of ESA have been addressed.

In the case of the beam aberration, where a squint of the Ka-band transmission beam is needed, the proposed approach consists in linear movements of the ellipsoidal mirror M8 and of the Ka-band transmission feed. PO simulations have shown that a beam squint of 40 mdeg can be achieved with a gain degradation of 2.1 dB.

In the case of the conical scan, where a squint of the Ka-band receiving beam is needed, the proposed approach consists in the linear translation of the dichroic mirror M7 and of the Ka-band receiving feed. In this case, a beam squint of 10 mdeg is achieved with a gain degradation of 0.5 dB. The main advantage of this approach is that this movement does not modify the incidence angle of the Ka-band transmission beam on the dichroic mirror M7, thus completely decoupling the beam aberration correction and the conical scan movements.

Finally, it is worth noting that the results mentioned above have been obtained by using a top-down optimization algorithm, which permits a substantial reduction in computing time and allows for a physical insight of the antenna behavior.

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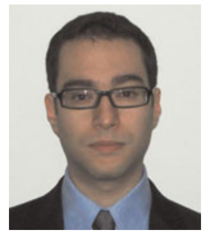
Piermario Besso was born in Chivasso, Italy, in 1963. He received the "Laurea" degree in Electronic Engineering from the Polytechnic of Turin, Italy, in 1988. In 1990, he joined CSELT (now Telecom Italia Lab, TILAB), where he was involved in the design of LOAD10 Inflatable Reflector (CONTRAVES-ESA), frequency selective surfaces for satellite application, mm-wave microstrip arrays for point-to-point communication systems, active microstrip antennas, and shaped reflector antennas for point-to-multipoint communication systems. He was also responsible for the design of an active receive-only microstrip antenna for the TV distribution at mm-waves and the design of frequency selective surfaces and complete feed systems for ground station antennas such as the 32-m Cassegrain antennas in Medicina, Bologna, Italy and Noto, Siracusa, Italy. Presently, he is Head of the Antenna and Infrastructure Section in the Ground Station Systems Division of ESOC/ESA. He is responsible for the front-end upgrades of the ESA ESTRACK network, for the development of the new DS3 ground station antenna in Malargue (Argentina) and of surveillance radar systems for the ESA Space Situational Awareness program.

Maurizio Bozzi was born in Voghera, Italy, in 1971. He received the "Laurea" degree in Electronic Engineering and the Ph.D. in Electronics and Computer Science from the University of Pavia, Italy, in 1996 and 2000, respectively. Since 2002, he has been an Assistant Professor in electromagnetics at the Department of Electronics of the University of Pavia, where he teaches the course of Numerical Techniques for Electromagnetics. He held research positions in various universities and research centers in Europe and North America, including the Technische Universitaet Darmstadt, Germany, the Universitat de Valencia, Spain, the École Polytechnique de Montréal, Québec, Canada, and the Centre Tecnologic de Telecomunicacions de Catalunya (CTTC), Barcelona, Spain. His research activities concern the development of numerical methods for the electromagnetic modeling of microwave and millimeter-wave components. Dr. Bozzi received the Best Young Scientist Paper Award at the XXVII General Assembly of URSI in 2002, and the MECSA Prize for the best paper presented by a young researcher at the Italian Conference on Electromagnetics in 2000.



Marco Formaggi was born in Novara, Italy, in 1978. He received his M.S. and Ph.D. degrees at Università degli Studi di Pavia, Italy, respectively, in 2003 and 2007. From April 2003 to October 2004 he was employed by Callisto Ltd as a contractor of ESA/ESOC, where he spent the whole period in the Ground Segment Section. His main task was the design and simulation of beam-waveguide ground station antennas in ideal conditions and affected by load cases such as gravity, wind, and thermal gradient. During his Ph.D. he has been devoted to the analysis and design of periodic structures for antenna applications and participated to two ESA founded studies concerning the introduction of the 26 GHz band in ESA ground stations and the development of a two-layer servo concept with movable beam-waveguide mirrors for deep-space antennas. Presently he is working for Cobham Technical Services in Leatherhead, UK. There he is involved in the design, analysis, and measurement of various antenna types and components, including corrugated horns, shaped reflectors, splash plate antennas, low profile arrays, dichroic mirrors, and waveguide components.

Luca Perregrini was born in Sondrio, Italy, in 1964. He received the "Laurea" degree in Electronic Engineering and the Ph.D. in Electronics and Computer Science from the University of Pavia, Pavia, Italy, in 1989 and 1993, respectively. In 1992, he joined the Department of Electronics of the University of Pavia, where he is now an Associate Professor in electromagnetics. His main research interests are in numerical methods for the analysis and optimization of waveguide circuits, frequency selective surfaces, reflectarrays, and printed microwave circuits. He co-authored the textbook Fondamenti di Onde Elettromagnetiche (Milano, Italy, McGraw-Hill Italia, 2003). Prof. Perregrini was an Invited Professor at the Polytechnical University of Montreal, Montreal, Quebec, Canada in 2001, 2002, and 2004. He was a consultant of the European Space Agency and of some European telecommunication companies. He serves as an Associate Editor for the IEEE Microwave and Wireless Components Letters and a Member of the Editorial Board of the International Journal of Microwave and Wireless Technologies.

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