Wideband Low-Profile Circularly Polarized All-Metal Antenna for Triton Exploration

Laetitia Niyonzima*, Pauline Vryghem*, Modeste Bodehou*, Christophe Craeye* Sébastien Le Maistre†
*(ICTEAM): Université Catholique de Louvain, Louvain la Neuve, Belgium
†(ELI): Université Catholique de Louvain, Louvain la Neuve, Belgium

***Abstract*—A low-profile, broadband 2×2 planar array constructed only of metal is proposed for space applications. The single element of the array is capable of generating circular polarization with a non-symmetrical (with respect to broadside) radiation pattern. Sequential rotation is introduced at the array level to correct the asymmetry of the beam and for improving the polarization purity. The resulting antenna radiates at broadside with a 12.5 dBi gain and impedance bandwidth of 18.22 %. Its overall size is 1.42$\lambda\times$1.42$\lambda\times$0.2817λ. The total volume of the antenna is $1.0961 \times 10^{-5}\,\mathrm{m}^3$ and the total weight is estimated at 42 g. It has been shown that the product gain-bandwidth is competitive as compared to available solutions in the literature.**

***Index Terms*—All-metal antenna, planar array, circular polarization, sequential rotation, Gain-bandwidth product.**

I. INTRODUCTION

Since the Second World War, scientists around the world have always been interested in exploring space. For some missions, the link between the planet to be explored and the Earth is ensured by a direct link using a planetary lander [1], while other missions require the development of an orbiter around the planet to be explored. The orbiter acts as a relay between the lander and the Earth. In both cases, the system requires the development of antennas capable of providing the wireless link in the harsh space environment. The antenna must be able to operate at extreme temperatures and withstand high levels of radiation, so, it should preferably be made of metal only [1–4]. The antenna should have a small mass so that it can be integrated into small satellites [7]. Studies have been carried out to design antennas that are more or less compact while still delivering high performances [4], [9], [10]. The beam should be shaped so that the antenna can communicate when the orbiter is high or at grazing angles. The polarization must be circular to combat interference due to multipath or, in the X-band, to counter the Faraday Effect which can change the polarization [8]. The goal of this paper is to design an antenna positioned on a lander at the surface of Triton, and communicating with a Neptune orbiter. Triton is the biggest moon of Neptune. The antenna will serve to transmit signals containing useful information on Triton's rotation, on the tides, etc., through Doppler measurement. According to the data from the Ice Giants mission report [14], the antenna must meet the requirements summarized in TABLE I. In addition, the antenna array proposed in this paper should be used in the X-band around a resonance frequency of 8.45 GHz. The paper is organized as follows. Section II describes the single element used for the proposed antenna array. Section III provides the design of the proposed 2×2 planar antenna array and the technique used to arrange the antenna so as to make it compact. Conclusions are drawn in section IV.

TABLE I
ANTENNA REQUIREMENTS

Parameter	Equatorial orbit		Polar orbit	
Index	value	Unit	Value	Unit
Material	All-Metal	-	All-Metal	Unit
Maximun mass	126	g	126	g
Frequency	8.45	GHz	8.45	GHz
Bandwidth	295.02	KHz	145.34	KHz
Axial ratio	5	dB	5	dB
Azimuth range	90 or 270	[°]	[0, 360]	[°]
Max. elevation range	[73,90]	[°]	[61,89]	[°]

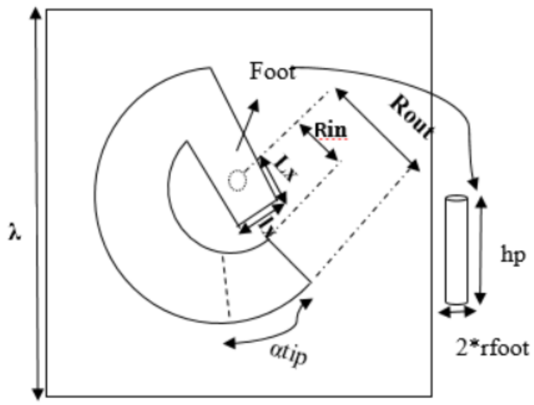

Fig. 1. Top view of the geometry of single element.

II. SINGLE ELEMENT ANTENNA DESIGN AND PERFORMANCE

The unit cell element is a grounded semi-circular monopole similar to the solutions proposed in [2], [11]. The structure is illustrated in Figs. 1 and 2. The semi-circular part of the monopole is aligned horizontally on the ground plane. The power supply is ensured by means of a delta gap placed at the level of the parallelepiped section (see Fig. 2). The other part is returned to the ground plane. The design proposed in [11] has been re-optimized in order to reduce the volume while maintaining its relative bandwidth. The proposed antenna can

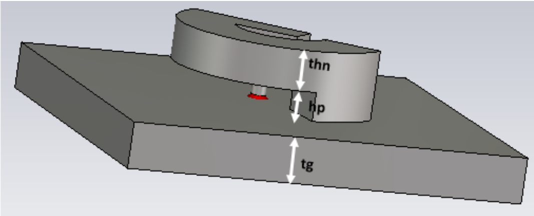

Fig. 2. Pespective view of the unit cell.

TABLE II
DIMENSIONS OF THE ANTENNA ELEMENT

Parameter	Rout	Rin	Lx	lx	tg
Dimensions[mm]	9.34	4.11	2.05	3.04	4
Parameter	α**tip**	**hp**	**thn**	**rfoot**	λ
Dimensions[mm]	45°	2.342	3.572	0.65	35.5

be made only of aluminum or copper. The asymmetric shape of the antenna results from a compromise between circular polarization purity and broadside gain. It is worth mentioning that, in practice, a standard SMA connector with extended central contact can replace the foot part. The dimensions of the unit cell are summarized in TABLE II. The single element radiation is analyzed with the CST commercial software and with an in-house MoM code (MoM3D). The simulated directivity and return loss (S11) is provided in Fig. 3. A good agreement is observed. An axial ratio (AR) of 1 dB is obtained, which confirms a good polarization purity. Residual differences between the two results may be due to the detailed meshing near the antenna feed. The maximum simulated directivity is equal to 7.69 dBi and is obtained at an elevation angle $\theta = 6°$ from broadside. Our application requires a beam pointing at broadside and symmetric with respect to broadside. The beam asymmetry with be corrected by introducing a sequential rotation of the elements in the array.

III. 2×2 ANTENNA ARRAY DESIGN

The elements in the proposed antenna array are arranged following a clockwise sequential rotation (see Fig. 4) similarly to what has been done in [12] , [13]. The rotation angle is Φ = 2pi/N , where N the number of elements of the array. The elements are arranged in 0°, 90°, 180° and 270° fashion. The sequential rotation allows one to improve the polarization purity, while ensuring maximum radiation at broadside. The position of the antenna on the ground plane has been optimized for better antenna performance in terms of compactness, gain and good circular polarization. Moreover, the array has been made as compact as possible while keeping good performance in terms of gain and polarization purity. The elements are separated by a distance equal to 0.357λ, with λ being the free-space wavelength. The antenna is also intended to be as space-saving as possible. ´The antenna is too large to compare its gain*bandwidth performance with the CHU limit defined in [15] and [16]. This is why, more simply, the

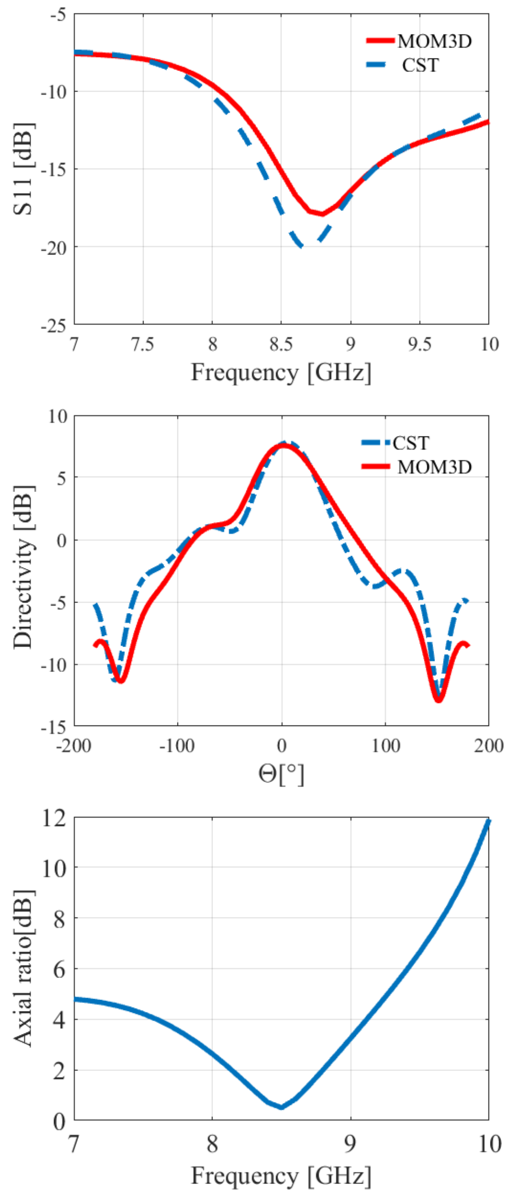

Fig. 3. Analysis of the single element. The results from an in-house MoM code (MoM3D) are compared with that from CST; the axial ratio bandwidth at θ=6° from broadside

gain-bandwidth product will be compared with the size of the antenna expressed in wavelengths. For large arrays the size will be given by kh [17] the electrical height at center frequency and for small arrays or single elements, the size will be given by ka.

From here, we defined normalized gain bandwidth products as:

$$NGBP1 = G * BWG * 1/ka \quad (1)$$

$$NGBP2 = G * BWI * 1/kh \quad (2)$$

where:

a, the radius of the smallest sphere that contains the antenna;

h, the height of the antenna element ;

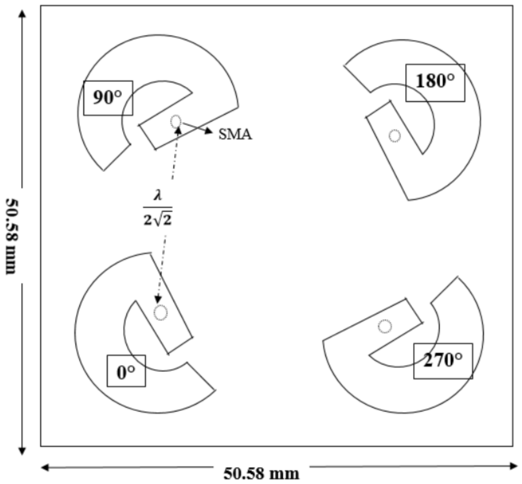

Fig. 4. Top view of geometry of the proposed 2x2 antenna array.

k, the free-space wavenumber at operating frequency;
BWG, 3-dB relative gain bandwidth;
G, the peak gain;
BWI, the relative impedance bandwidth.

Fig. 5a provides the active reflection coefficient analyzed with the CST commercial software. Results from the analysis of the standard planar array (without sequential rotation) are compared with that from the proposed antenna. While the proposed antenna presents a better matching at the central frequency, the S11 -10 dB bandwidth is lower (18.22% for the proposed antenna and 20.05% for the classical planar array). For some space applications, a relative bandwidth defined with -15 dB should be considered which correspond to the bandwidth of 6% for the proposed antenna. Nevertheless, this bandwidth is sufficient for space applications [1], [16]. Fig. 5a provides also the isolation from the other ports (S21, S31, S41 are displayed). Fig. 5b provides the simulated radiation patterns and axial ratios of the proposed antenna over different azimuthal angles. By considering the antenna requirements for Triton exploration where the elevation should be included in [73°,90°] for equatorial orbit and in [61°,90°] for polar orbit which correspond respectively to θ included in [0°,17°] and [0°,29°], the proposed antenna provides a maximun gain of 12.5 dBi for θ = 0°. The worst case when the equatorial orbit is used corresponds to θ = 17°, the maximun gain showed by the proposed antenna is around 10 dBi. The maximun gain decreases to 6 dBi at θ = 29° which corresponds to the worst case when polar orbit is used. To conclude with the antenna requirements, the proposed antenna promises a maximun gain of 12.5 dBi at θ = 0°, 10 dBi at θ = 17°and 6 dBi at θ = 29° .

Fig. 5c illustrates in the same figure the evolution of the broadside gain and the worst case of axial ratio versus frequency. Defining the radiation pattern bandwidth as the one corresponding to a 3 dB drop of the gain with respect to the operating frequency gain, a 42% pattern bandwidth is

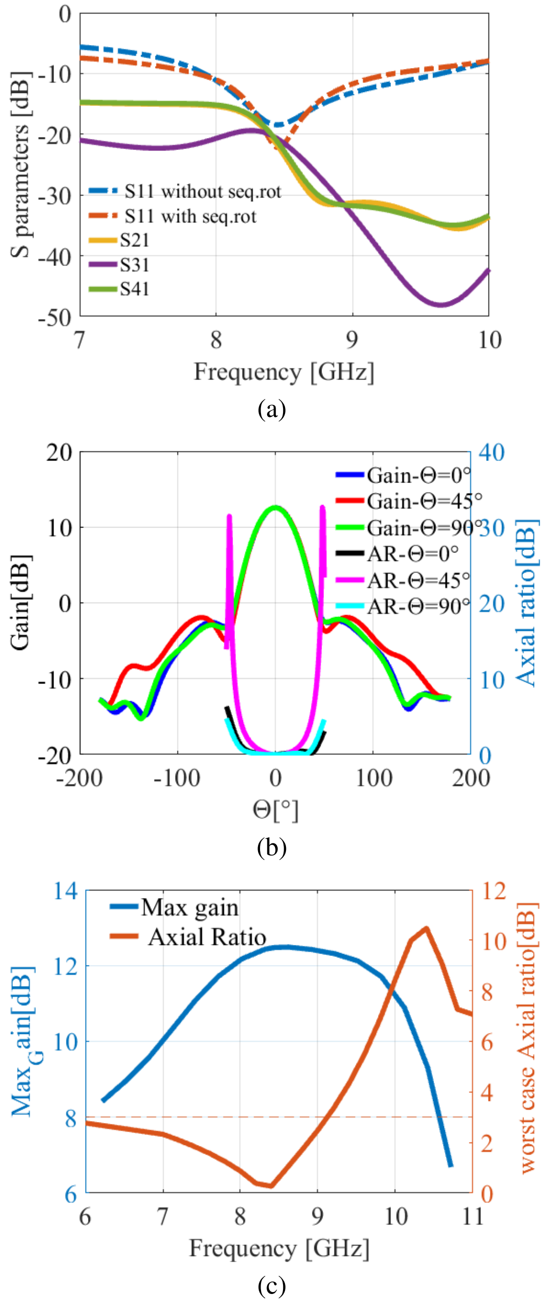

Fig. 5. (a) Reflexion coefficient of proposed antenna array by using sequential rotation or not and the isolation between ports, (b) Gain and axial Ratio for differents cuts (c) Maximun Gain and Axial ratio function of the frequency

obtained. This bandwidth is larger than the reflection coefficient bandwidth 18.22%. These two quantities are known to be independent when IEEE definitions are used. Therefore, we will consider the reflection coefficient bandwidth as the usefull antenna bandwidth.The worst 3-dB axial ratio bandwidth is around 9.42%. Fig. 6a compares the axial ratio of the proposed antenna with that that from the single element and the classical array (without sequential rotation). It can be concluded that the sequential rotation significantly improves the polarization

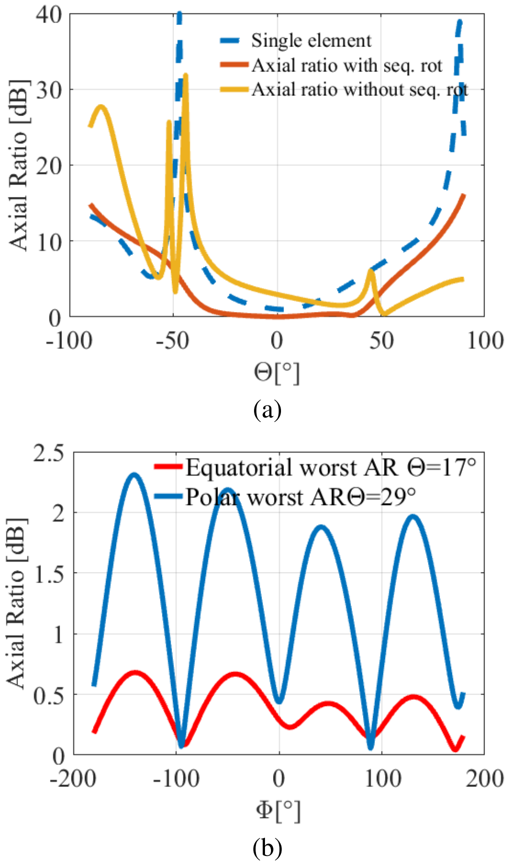

Fig. 6. (a)Axial ratio as a function of the elevation angle θ . Results from the proposed antenna are compared with that that from the single element and the classical antenna array. (b) The worst case axial ratio as a function of azimuthal angle ϕ

purity in the elevation range both for equatorial and polar orbits. Fig. 6b provides the worst case axial ratio. The worst case axial ratio means the largest value over all azimuthal angles for the angle θ of interest. One can conclude that the axial ratio is still less than 3 dB at $\theta = 29°$ which is the largest angle from broadside in the considered application.

Finally, Table III compares the proposed 2×2 planar antenna array with some recent compact all-metal designs. We defined a gain*bandwidth divided by kh for the large arrays and by ka for single elements or small arrays. The normalized gain-bandwidth product (NGBP) defined above is given in the last column of Table 3. This leads to the conclusion that the proposed antenna array has the advantage of being the least bulky for the given impedance bandwidth and gain, while maintaining a good bandwidth of axial ratio over the main beam.

IV. Conclusion

A compact circularly polarized array devoted to space exploration has been designed. It has been shown that the proposed antenna provides a competitive gain-bandwidth product as compared to results of recent all-metal antennas from the literature. Simulation results meet the antenna requirements,

TABLE III
COMPACT ALL-ANTENNAS COMPARISON WITH RECENT PUBLISHED DESIGNS

Ref.	**Size**	**N**	**Peak Gain [dB]**	**Cent. Freq [GHz]**	**10-dB band. [%]**	**kh/** ka	**GBP**
(2)	5.8λ× 5.8λ× 0.845λ	8*8	25.3	8.425	23.67	1.04	5.78
(3)	2λ× 2λ× 0.6λ	1	14.2	8.2	5	3.14	0.23
(8)	6.8λ× 3.32λ× 0.093λ	8*12	5	10	51	0.58	4.44
(9)	3.4λ× 1.13λ× 0.43λ	1 (5*)	13.37	8.5	7.72	0.36	2.66
(10)	0.46λ× 0.36λ× 4λ	1*4	12.1	10	14.74	1.89	0.99
This work	**1.42λ× 1.42λ× 0.2817λ**	**2*2**	**12.5**	**8.45**	**18.22**	**1.05**	**5.23**

(*) slots

which means that the proposed antenna is a good candidate for Triton exploration.

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