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Comando & Controle e Defesa Cibernética: Sistemas Satelitais

Smallsat with Offset Reflector Antenna

Pequeno Satélite com Antena Refletora Offset

Márcio Martins da Silva Costa[1,2], Rafael Lemos Paes[2] e Angelo Passaro[2]
[1]Technological Institute of Aeronautics (ITA), São José dos Campos/SP, Brazil
[2] Institute for Advanced Studies (IEAv), São José dos Campos/SP, Brazil

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E-mail adresses:

marciocosta@ita.br (M.M.S.Costa),
rafael.paes.it@ieee.org (R.L.Paes),
angelopassaro@gmail.com (T. Autor).

Resumo

O emprego de pequenos satélites tem sido cada vez mais frequente nos últimos anos. Recursos como baixo custo, tecnologias mais acessíveis e a miniaturização de componentes de engenharia estão direcionando as tendências para plataformas menores. Seguindo esta tendência, novos sistemas de SAR (Radar de Abertura Sintética, do inglês, *Synthetic Aperture Radar*) empregados a partir do espaço foram adaptados para se adequarem às novas arquiteturas. Este artigo apresenta um novo projeto baseado no emprego de uma antena refletora *offset* desdobrável em malha associada à uma pequena plataforma espacial. Na análise são levadas em conta algumas considerações tais como a geometria, órbita e fixação ao satélite que reforçam as vantagens do uso de antenas refletoras de malha.

Abstract

The employment of smallsats have been increasingly in the last years. Features like low cost, more accessible technologies, and the miniaturization of engineering components are driving the trends to smaller platforms. Following this trend, new spaceborne SAR (Synthetic Aperture Radar) systems have been adapted to suit the new architectures. This paper presents a new design based on the employment of a mesh deployable offset reflector antenna in association with a small spacecraft. In the analysis are taken into account some considerations as geometry, orbit and attachment to the satellite which reinforce the advantages of using mesh offset reflector antennas.

I. INTRODUCTION

Over the years, SAR satellites have been highlighted in remote sensing activities due to their several advantages over optical sensors. While the second one has limitations such as a dependency of daylight, weather conditions, among others, SAR sensors can overcome them operating as an active sensor.

Spaceborne SAR systems follow different criteria from those observed by optical sensors launched into space. Depending on the mission objectives, several requirements must be followed [1]. Nevertheless, the first step is to analyze the radar equation

$$P_{Dr} = P_t G^2 \lambda^2 \sigma / (4\pi)^3 \, R^4 \text{,for } G = 4\pi A_e / \lambda^2 \qquad (1)$$

where P_{Dr} denotes the total power delivered to the radar signal processor; G is the antenna gain; P_t is the peak transmitted power; λ is the wavelength; σ is the target-specific parameter called Radar Cross Section (*RCS*); R is the distance from the satellite to the imaged area; and A_e the antenna effective aperture.

The expression (1) suggests that to double R, A_e must increase four times. The higher altitudes can provide a large coverage area on the Earth.

However, higher altitudes imply a more expensive satellite with a bigger solar array and a larger antenna.

For several years, this relationship was a challenge for engineering while the planar antennas were the main technology employed in the previous missions focused on Earth observation.

The offset architecture has several advantages over the planar antennas. The gain of the reflector antennas allows improving the signal-to-noise ratio, using a lower transmission power. If Digital Beamforming (*DBF*) array is implemented in association, the transmission of the path of feed elements generates a broad transmit beam able to illuminate a wide swath on the Earth. The echoes received from a given direction activate only one or a small number of elements, which means that a low number of signals will be processed. In other words, it reduces the necessity of processing on board capacity if compared with traditional planar antennas. This implies yet in a hardware reduction, reduction of energy, and increase of the lifetime of satellite [1], [2]. This feature reduces considerably the power requirement, usually between 3,000W and 5,000W for traditional planar systems, to levels about 1,000 W [2]–[9].

Considering the conditions about the length of A_e mentioned in (1), deployable structures are the only way to build a large and lightweight antenna able to be applied in a satellite.

Another advantage lies in the fact that these structures cab better withstand the efforts inside the launcher fairing. So, the deployable antenna is only subject to the orbital loads, which are considerably lower than loads during the launch.

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The disadvantage to employ deployable offset reflector antennas is the risk of the reconstruction in space. However, *e.g.*, SMAP mission shows that the opening of the structure can be performed successfully in space [10].

The future of the employment of mesh deployable offset reflector antenna is promising. The next mission to implement the same antenna concept will be NISAR (NISAR-ISRO Synthetic Aperture Radar). NISAR is a joint mission between the United States and India with the purpose to launch a satellite with L-band and S-band SAR systems into a 747 km polar orbit. Another mission to implement the same antenna concept is the Tandem-L, conducted by DLR. The relevant difference between SMAP and Tandem-L is the feed and the antenna architecture. While SMAP uses just one feed horn, Tandem-L incorporates the benefits of the innovative *DBF* techniques associated with a fixed offset reflector antenna to have a wide swath of about 350 km. The mission could be launched in 2023 [11]–[19].

Although previous proposals seem to suggest missions with larger platforms, the general trend is that the researchers will turn to small satellites. To strengthen this statement, it follows some considerations.

The ongoing technologies are driving to miniaturization of engineering components. In this case, the use of Micro-Electro-Mechanical Systems (*MEMS*), the Micro-Opto-Electro-Mechanical Systems (*MOEMS*), and micro photonic devices as the core of microwave-photonic outfit for telecommunications satellite payload have been a remarkable solution to reduce the mass and the power necessity of the platform [20].

Furthermore, small satellites can be developed using different approaches with a reduced budget, low experience, low technology, and reduced response time. These advantages allow to have more frequent missions with fast response for application data; the use of different kinds of missions for several potential users; the improvement of the knowledge; and the encouraging for local industry [13], [21]–[23].

Finally, this summary shows that there are no space missions, or not known, which employ mesh deployable offset reflector antenna associated with small satellite. Hence, the contribution of this work lies in the analysis of this innovative proposal space system.

This paper is organized into five sections. Section II presents the antenna design, Section III proposal a spaceborne SAR system design, and Section IV analyses the performance and results. At last, Section V presents final considerations.

II. ANTENNA DESIGN

Consider the geometry of an offset parabolic reflector antenna as illustrated in Fig. 1.

Point *O* is the focal point where the feed is positioned. The transmitted signal travels along $\overline{OP}$ at an angle ψ and it is reflected parallel to the *z*-axis towards the plane limited by $\overline{AB}$. ψ_0 is the angle formed by $\overline{OV}$ and the *z*-axis, where *V* is the center of the dish. The whole signals are projected $\overline{AB}$ to define the effective aperture of the antenna. *F* is the focal length, *R* is the length of $\overline{OP}$, *L* is the projection of $\overline{OP}$ on the *z*-axis and ρ is the projection of $\overline{OP}$ on the *y*-axis. *D* and *D'* are the aperture diameter and the clearance, respectively [24]–[27].

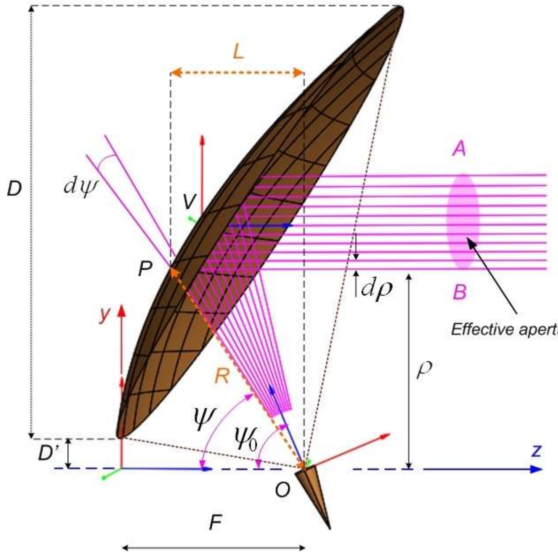


Fig. 1. Geometry of the Reflector Antenna.

Considering that the total optical path length is given by 2F, the relation between R and L can be expressed by

$$R + L = 2F, \forall\psi. \tag{2}$$

Fig.1 can provide another relations as:

$$\rho = R\sin\psi \text{ and } L = R\cos\psi. \tag{3}$$

After mathematic iterations between expressions (2) and (3), ρ can be expressed by

$$\rho = 2F\left(\frac{\sin\psi}{1+\cos\psi}\right) = 2F\tan\left(\frac{\psi}{2}\right). \tag{4}$$

Using again the expression (2)

$$F - L = F\tan^2\left(\frac{\psi}{2}\right). \tag{5}$$

So, L and ρ gives the know equation for a parabola

$$4F(F - L) = \rho^2. \tag{6}$$

Or, in terms of the *xyz*-coordinate system, where $\rho^2 = x^2 + y^2$ and $z = -L$,

$$4F(F + z) = x^2 + y^2. \tag{7}$$

If the proposal reflector antenna is a parabolic dish with a circular aperture, ψ_0 can be expressed by

$$\psi_0 = 2\arctan\left(\frac{D' + (D/2)}{2F}\right). \tag{8}$$

So, for a circular parabolic reflector with *D* diameter, the gain in relation to the isotropic antenna is given by

$$G = k\gamma\pi^2\left(\frac{D}{\lambda}\right). \tag{9}$$

where the product $k\gamma$ is the global efficiency of the assembly [26].

III. SPACEBORNE SAR SYSTEM DESIGN AND ANALYSIS

To analyze the employment of an offset reflector antenna in a small satellite, the Brazilian Multi-Mission Platform (MMP) is used as a reference of a spacecraft bus (Fig.2). The basic specifications are summarized in Table I.

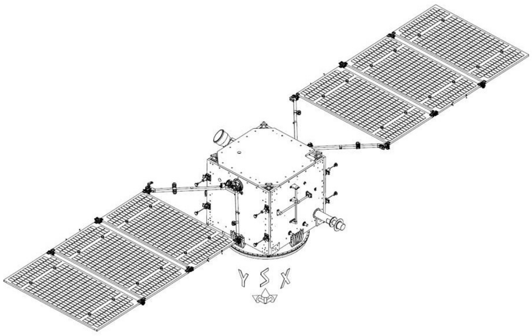


Fig. 2. Brazilian Multi-Mission Platform (MMP) in orbit configuration (Courtesy of National Institute for Space Research, INPE)

TABLE I. BRAZILIAN MULTI-MISSION PLATFORM (MMP) PARAMETERS

Parameter	Value
Dry Mass	*300 kg*
Total Mass	*345 kg*
Power (average)	*225 W*
Power (total)	*304 W*
MMP/Payload Mechanical Interface	*951.6x951.6 mm(xy-axis)*

The set of input parameters considered for reflector patterns is listed in Table II. The simulation of the antenna modeling was performed using TICRA-GRASP Student Edition® software, version 10.3.0. In all the cases studied, it was considered the right-circular transmit polarization (*Rhc*).

TABLE II. REFLECTOR ANTENNA DESIGN

Parameter	Symbol	Value
Frequency	f_s	*1.5GHz*
Wavelength	λ	*0.2 m*
Reflector Diameter	*D*	*7 m*
Reflector Offset	*D'*	*0.572 m*
Reflector Clearance Aperture Efficiency	*m*	*0.504 m*
Feed Element Spacing (for 2 channels)	Δy	*0.85 m*

A. Offset reflector antenna design

The first design example considered the reflector antenna fed by one channel as shown in Fig.1. The normalized antenna gain pattern is depicted in Fig. 4(a). where the black line shows the co-polar pattern and the red shows the cross-polar pattern. For $\phi = 0,$ the angle that the antenna points to the center of the paraboloid, the -3dB points are limited between -1º and 2º. This range in degrees shows that the *Rhc* transmit polarization shifts the main lobe slightly to the right. This narrow beam shape is generated by the mechanical molding of the reflector dish. In other words, the position of the feed will give the solid angle that will be illuminated.

The graph shows another feature of the use of reflector antennas. While the peak-to-sidelobe ratio varies about 10dB, the peak-to-mainlobe ratio varies about 35dB. This justifies peak gains of about 36dB in reflector antennas used in missions as SMAP[8], [25], [28].

However, spaceborne SAR systems with one channel have a limitation in their capabilities to provide large swath and high resolution at the same time. Despite the benefits of the reflector antennas, the *PRF* (Pulse Repetition Frequency) must be large to provide a broad beam to meet the Nyquist criteria. Unless such systems employ complex mechanical systems and dedicated algorithms as used in SMAP mission [28].

With the objective to overcome this restriction and provide a broad beam, the number of the feeders is increased in this approach to simulate an array of channels.

However, small satellites do not have adequate dimensions to install multiple horns, which are particularly large for *L*-band. Then, considering the MMP dimensions, the design was limited in the use of the two feeders in azimuth, as the concept of One-dimensionally Defocused Reflector Antennas, illustrated in Fig. 3 [27], [29], [30]. At the picture view, the two channels are set without space between then. The green narrows represent the coordinates of the elements willing along-track direction (or azimuth) where the satellite is moving.

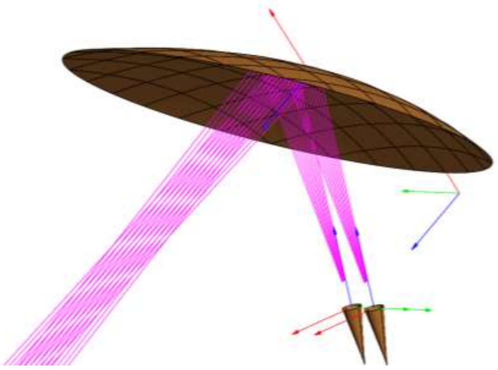
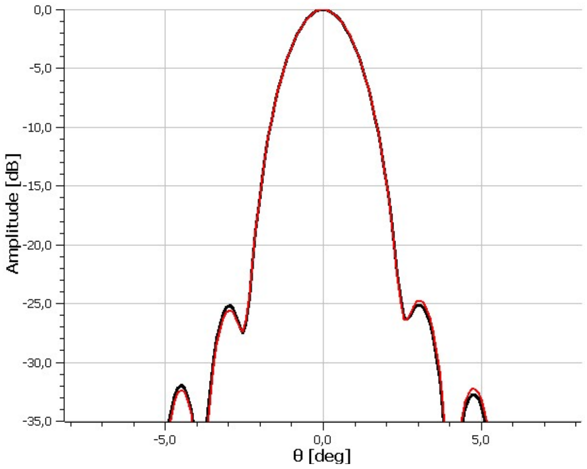


Fig. 3. Offset Reflector Antenna illuminated by two feeds.

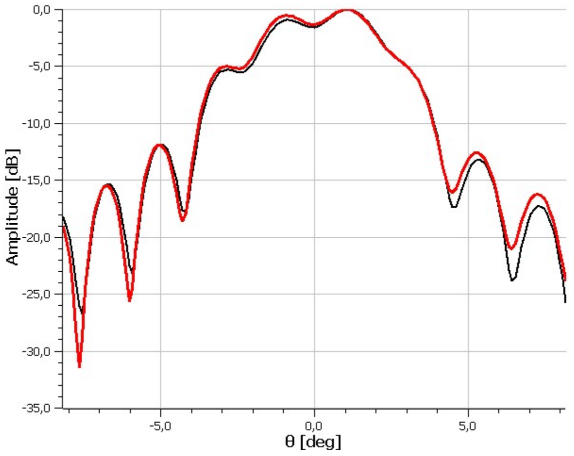
The normalized antenna gain pattern is depicted in Fig. 4(b). The -3dB points are away from each other from about 5º. Hence, the main lobe has not a narrow pattern as before. Nevertheless, the gain is reduced by about 5dB for the peak-to-sidelobe ratio and 18dB for the peak-to-mainlobe ratio.

If the channels are displaced by 0.85m, the bandwidth is increasing by 6º at the -3dB. Nevertheless, the peak gain decreases by about 12dB. The normalized antenna gain pattern is depicted in Fig. 4(c).

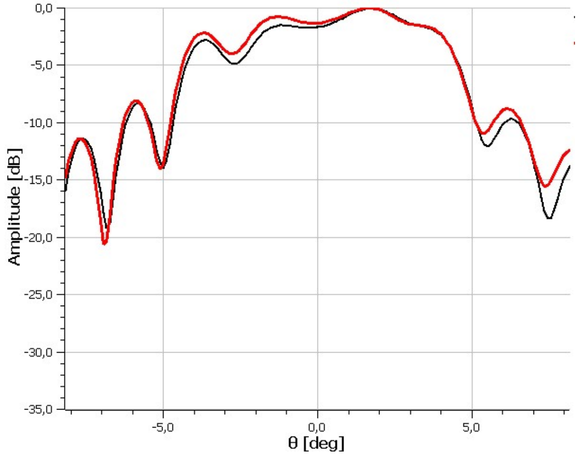
The analysis shows that the greater the displacement of the channels, the smaller will be the antenna gain *G*. In other words, if both feeds are activated together the peak transmitted P_t will be divided between the two channels. One of the causes is the contribution of the noise raised from both channels.



a) Reflector antenna illuminated by one feed (1 channel).



b) Reflector antenna illuminated by two feeds (1 channel).



c) Two channels displaced by 0.85 m.

Fig. 4. Antenna gain patterns

Still, this configuration seems interesting. The region located between the two main lobes tends to increase the gain. So, the result is a broad beam able to illuminate a large swath [25], [27].

B. Array processing design

The MMP can provide 225 W average power and 900 W peak power, during 10 minutes. So this work considers an array in azimuth with two channels, *Rhc* polarized, aligned along azimuth direction.

Three traveling wave tube amplifiers (TWTA) provide the power that is combined in the High Power Summation Assembly (HPSA) with its “4 out of 6” redundancy to provide 500W per channel (Fig.5).

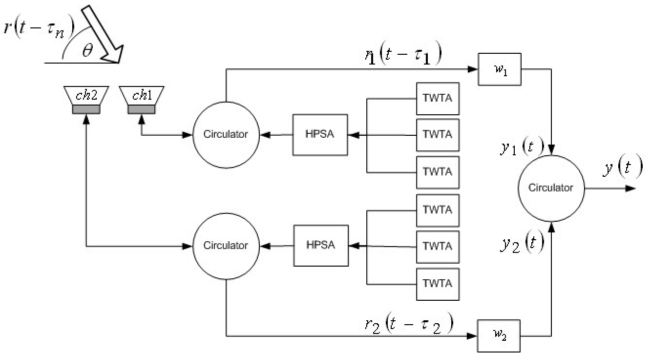


Fig. 5. Array with linear processing.

The echo signal $r(t)$ arrives at the channels (*ch1* and *ch2)* at θ angle is represented by

$$r(t,n) = \sqrt{2}\, Re\{\tilde{r}(t,n)\, exp[j\omega_c t]\}, n = 1,2, \tag{10}$$

where ω_c is the carrier frequency in radians.

The $r(t,n)$ is given by

$$r(t,n) = [r(t-\tau_1) r(t-\tau_1)]^T, \tag{11}$$

where $[*]^T$ indicates the transpose matrix.

For the plane wave represented in (11), (10) becomes

$$r(t,n) = \sqrt{2}\, Re\{\tilde{r}(t-\tau_n)\, exp[j\omega_c(t-\tau_n)]\}, n = 1,2 \tag{12}$$

where $\tilde{r}(t-\tau_n)$ is the complex envelope and τ_n is the signal delay for each channel.

Considering that the array is a system with an impulse response $h_n(\tau)$, each channel output is processed by a linear, time-invariant filter. The sum of the output gives the array output $y(t)$ and can be written in a vector notation as

$$y(t) = \int_{-\infty}^{\infty} h^T(t-\tau) r(\tau,n) d\tau, \tag{13}$$

where

$$h(\tau) = [h_1(\tau) h_2(\tau)]^T. \tag{14}$$

In the frequency domain, expression (13) turns to

$$Y(\omega) = H^T(\omega) R(\omega). \tag{15}$$

Defining the complex weight vector as

$$w^T = [w_1^* w_2^*]. \tag{16}$$

And defining the vector $v_k(k)$ as the *array manifold vector*, which is the vector that incorporates all of the spatial characteristics of the array, given by

$$v_k(k) = [exp(-jk^T n_1)\, exp(-jk^T n_2)]^T \tag{17}$$

where k represents the time that the signal was acquired. The expression (13) can be rewritten by

$$y(t,k) = w^T v_k(k)\, exp[j\omega t], \qquad (18)$$

for ω is the input frequency [31]. So

$$Y(\omega,k) = w^T v_k(k). \qquad (19)$$

Finally, considering that both channels have the same white noise power, the expression (9) can be changed to

$$G = \frac{\left|w^T v(k)\right|^2}{w^T w}. \qquad (20)$$

IV. FINAL CONSIDERATIONS

The future of the spaceborne SAR is promising. New technologies are emerging and bringing new possibilities.

Several researchers indicate that there is considerable interest in the development of offset reflector antennas, small satellites, and *DBF* techniques.

This research seeks to associate these new trends through the proposal of innovative architectures, able to contribute to remote sensing needs. In addition, this research seeks low-cost and complex solutions to meet emerging countries.

It is expected that this spaceborne SAR system research proposal, operating in low orbit, can provide a wide swath with the use of a small satellite. This research is named BR-SAR (Fig.6).

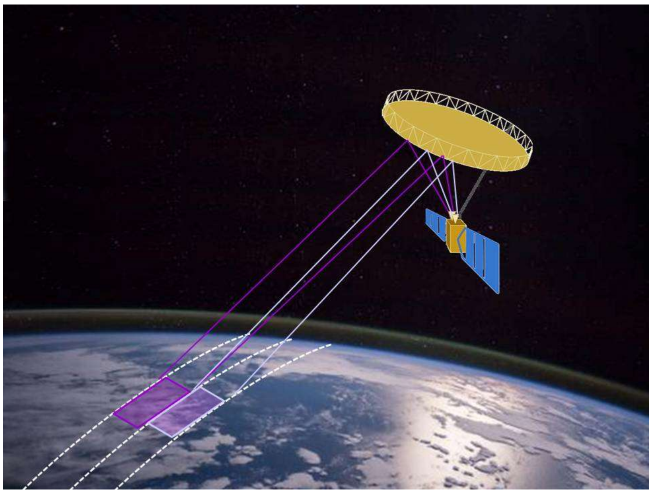


Fig. 6. Artistic conception of BR-SAR spacecraft, using Brazilian Multi-Mission Platform (MMP) associated with 7 m mesh deployable offset reflector antenna.

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