A Preliminary Design for Lessonia-1 Spaceborne SAR Mission Employing Offset Reflector Antenna and Compact Polarimetry Features

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***Abstract* — Lessonia-1 is a spaceborne Synthetic Aperture Radar (SAR) mission that belongs to Brazilian Strategic Space Systems Program (PESE - acronym in Portuguese), which comprises a part of the Brazilian Space Program. Lessonia is expected to be launched in 2026, according to the roadmap of PESE. This program has dual purpose, meeting civilian and defense requirements. In this letter, a proposed design for Lessonia spaceborne SAR mission is presented employing an Offset Reflector Antenna associated with Compact Polarimetry (CP) technique, based on the Multi-Mission Platform (MMP - a bus developed by National Institute for Space Research - INPE, Brazil). This preliminary approach represents one of the possibilities of payload for Lessonia SAR mission. This paper aims to present technical concepts proposed for this mission and that have already been explored by respected space agencies in the last years.**

***Keywords* — Spaceborne SAR, Offset Reflector Antenna, Compact Polarimetry.**

I. INTRODUCTION

LESSONIA constellation mission or LESSONIA is proposed as a spaceborne Synthetic Aperture Radar (SAR) mission belonging to the Strategic Space Systems Program (PESE - acronym in Portuguese), which comprises a part of Brazilian Space Program including the defense requirements for the space area [1] .

A country with biodiversity and several natural resources distributed along with immense territory and maritime area such as Brazil cannot do without the ability to monitor large areas with high-resolution images, independent of daylight, vegetal and cloud coverage, smoke, and weather conditions. This attributes provided by spaceborne SAR sensors are the motivation to conduct the Lessonia-1 Project that intends to be the first Brazilian SAR satellite expected to be launched in 2026, according to the roadmap of PESE.

The Lessonia-1 products are not limited to being used only for defense. One of the basic guidelines of the Project is that it meets both civilian and defense requirements.

In this case, the Project foresees applications in deforestation, forest biomass change, forest height, vertical forest structure, tailings dams monitoring, soil moisture, flooding, ocean currents, water level change, landslides, precision agriculture, Amazon forest monitoring, among others [2]–[4].

There are also several possibilities of application for defense, having as examples the operational environment awareness, monitoring of borders, surveillance of ship traffic, detection and surveillance of targets, among others [3]–[6].

The preliminary architecture of Lessonia-1 is based on the MAPSAR mission, which was a result of a joint-phase A study conducted by National Institute for Space Research (INPE, Brazil) and DLR (Germany Space Center) between 2001 and 2007 [7], [8]. The key features of this new approach of the L-Band project are the use of a Mesh Deployable Offset Reflector Antenna associated with new Compact Polarimetry (CP) algorithms designed to overcome the equatorial anomalies present in the extensive areas of Brazil ionosphere.

The use of an Offset architecture has several advantages over the Cassegrain configuration studied in the original MAPSAR Project [7]. In this approach, the concept is to overcome the technical constraint of association large swath widths and high resolution using an array in azimuth with two channels, pointing to different sessions of the antenna dish. The received signals are amplified, digitized and processed by dedicated algorithms to allow the reconstruction of the high-resolution image with large swath. It should be noted that the expression *large swath* is used in this work to represent values about 60 km. It's not exactly a broad swath. However, compared to the initial project, it means doubling the average values of 30 km in high-resolution mode [7].

CP technique is a general term used to describe a number of techniques based on coherent dual-polarized SAR, all of them involving the use of a transmit polarization other than the linear horizontal H or vertical V. The basic idea is to transmit a circularly polarized wave, or a linear wave oriented at 45 degrees, in order to gain increased polarimetric information over horizontal/vertical dual-pol transmissions, without the swath width reduction of Full Polarimetry (Full-POL). As an additional bonus, such option allows reducing mass and complexity of the system. In this work, the hybrid polarization mode (Hybrid Polarimetric or Hybrid-POL), which represents a circularly polarized wave on transmission

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(would be right or left) followed by dual linear reception is considered in order to minimizes the Faraday Rotation Effect when the radar wave propagation traverse ionospheric irregularities [9], [10].

This paper aims to present these two technical concepts proposed for Lessonia-1 Project: the Offset Reflector Antenna and the Compact Polarimetry.

II. Offset Reflector Antenna

Reflector Antennas are not a new technology. Since 1983 missions as Venera 15/16, Cassini, and Magellan, launched in deep space, have used reflector Antenna resources [11] .

Years later, in 1988, Kare [12] introduced an Offset architecture during the joint studies conducted by NASA /JPL and DLR for Tandem-L project.

The heritage of the successful employment of reflector antennas over the years enhances the trend to implement new designs in modern SAR systems [13].

In 2015 NASA/JPL launched the Soil Moisture Active Passive (SMAP) mission, an L-band SAR satellite outfitted with a 6 m mesh deployable Offset Reflector Antenna able to provide high spatial resolution with a 1000 km swath [14].

The next scheduled SAR mission using Offset Reflector Antenna will be the NISAR mission and the Tandem-L mission. The first one is the joint NASA-ISRO (Indian Space Research Organization) Earth-observing mission to make global measurements of the causes and consequences of land surface changes, beyond other applications as ecosystem disturbances, ice sheet collapse and evaluation of natural hazards. The NISAR is being designed to be the first SAR satellite to use two different radar frequencies (*S* and *L* band). In this case, the mechanical characteristic of the Offset Reflector Antenna is being associated with Digital beamforming techniques in order to implement the SweepSAR mode. This mode consists in a one-dimensional phased array feed that illuminates a narrow segment of the 12 m antenna's reflecting surface on the transmission, enabling to cover 242 km wide swaths on the ground. NISAR is planned to be launch in December 2021 (Fig. 1) [15], [16].

Fig. 1. Artistic conception of the deployed NASA–ISRO NISAR where it can be identified the Offset Reflector Antenna (up), the boom assembly (middle), and the spacecraft bus (down).
(image credit: NASA/JPL-Caltech, available in [15]).

The second one, Tandem-L mission, foresees the employment of two formation-flying SAR satellites to monitor the dynamic process on the Earth's surface. The Tandem-L concept associates a mesh deployable Offset Reflector Antenna with a Digital beamforming technique, in order to provide a 350 Km wide swath with azimuthal resolution of 7m [15].

Both missions have some advantages over conventional SAR. Comparing with the traditional technologies, they require less power to transmit, are relatively immune to range ambiguities, are simpler to implement, are better suited for longer wavelength systems, such as L Band, and they do not require extremely high data transmission rates. Additionally, the realization of a Hybrid-Polarity system is easier than with an active Planar Antenna, and the beam shape is generated according to the mechanical molding of the reflector dish. In this case, each feeder illuminates a segment of the antenna dish that reflects to certain range of the target. The processing of the echo signals from each feeder allows to build a mosaicking of sub-swaths. This is the method to generate a large swath. [2], [7], [17].

Following this concept, a preliminary design for Lessonia-1 mission considered the employment of an Offset Reflector Antenna. Additionally, in order to mobilize the national industry and research institutions, the Brazilian Multi-Mission Platform (PMM - acronym in Portuguese) is used as a baseline for the spacecraft bus (Fig. 2).

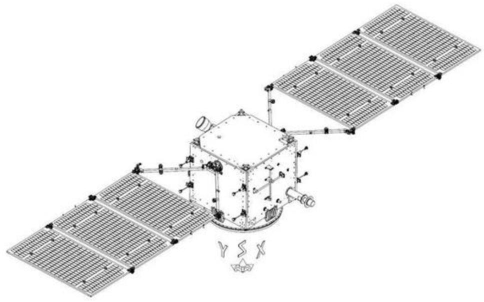

Fig 2. Brazilian Multi-Mission Platform (MMP) in orbit configuration (Courtesy of National Institute for Space Research, INPE)

Planar Antennas would also be an option for the Lessonia-1 mission. However, considering the previously established requirements for MAPSAR, which foresaw a maximum incident angle of 45 degrees, and an antenna aperture of at least $27m^2$, implying an orbit 600 km height, the required size for the phased array would exceed the weight capabilities supported by PMM. The alternative was disregarded.

PMM is based on a modular concept. Its first application is in Amazonia-1, a Brazilian Earth observation mission using an optical sensor. The launch of Amazonia-1 is foreseen for June 2020[18].

Considering the PMM dimensions, it is possible to use two feeders in azimuth, following the concept of One-dimensionally Defocused Reflector Antenna (Fig. 3) [19], where the *y*-axis (green arrows) represents the coordinates of the elements willing along-track direction along which the satellite is moving.

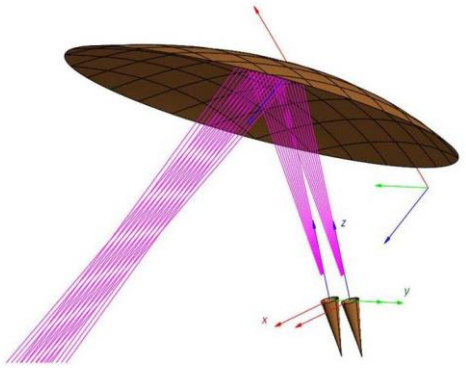

Fig 3. Offset Reflector Antenna illuminated by two feeders.

The set of preliminary input parameters considered for the Reflector Antenna patterns are presented in Table I.

The PMM can provide 225 W average power and 900 W peak power for 10 min. Considering these characteristics, we have adopted two operational modes. In Mode 1, a single channel is fed, using 225W, and in Mode 2 both channels are fed with 900 W.

TABLE I
OFFSET REFLECTOR ANTENNA DESIGN

Parameter	Symbol	Value
Sampling Frequency	f_s	1.5GHz
Wavelength	f_s	0.2 m
Reflector Diameter	D	7 m
Reflector Offset	D'	0.572 m
Reflector Clearence Aperture Efficiency	m	0.504 m

In both Modes, the echo signals received by each channel are amplified, digitized and processed by dedicated algorithms to allow the reconstruction of the high resolution image with the mosaic of sub-swaths.

For Mode 1, the antenna gain pattern can reach values about 35 dB with the swath about 30 km, as suggested in MAPSAR high resolution mode.

For mode 2, the power rate is divided between the two channels. The antenna gain pattern reduces to about 14dB, but the bandwidth increases from 6º (at mode 1) to 8º. In this mode, the mechanical molding of the reflector dish allows illuminating a swath about 60 km.

Considering the dimensions of the PMM, it is also possible to separate the two channels by 0.85m. In this way, the bandwidth increases almost to 10º. However, the antenna gain pattern significantly reduces to about 8 dB. Therefore, the proposed configuration assumes the two channels adjoined.

Fig. 4 exhibits an artistic conception of Lessonia-1 spacecraft, using PMM bus associated with a 7 m mesh deployable Offset Reflector Antenna. The two swaths projected on the Earth represent the second mode mentioned before. A larger swath width can be produced after processing a mosaicking of these two sub-swaths.

III. Compact Polarimetry

In 2005, Souyris introduced the CP concept. The objective was to reduce the cost and the complexity of the space segment that employed Full-Pol in their systems.

The original model of Souyris foresaw a transmission using a polarization different from the usual horizontal and vertical, taking as an example an oriented wave of $\pi/4$ [11]. Two years later, Stacy and Preiss proposed the so-called Dual-Circular mode in which the wave would be transmitted and received using circular polarization [20]. In 2009, Raney proposed the Hybrid-POL in which the transmission is realized with the use of the circular transmission to the right or the left, with the signal received by linear polarization, horizontal and vertical [21], [22].

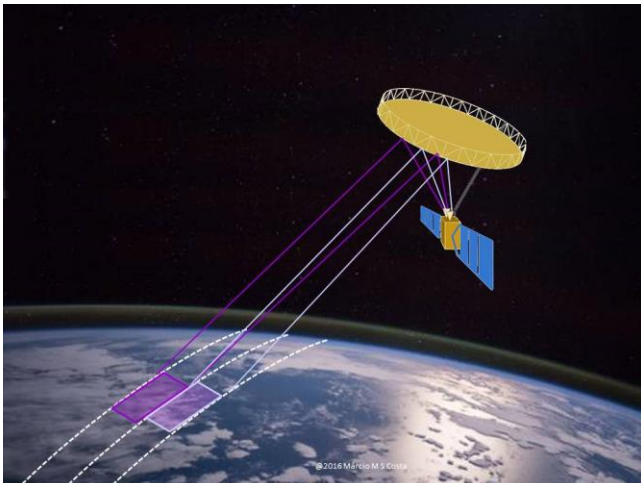

Fig 4. Artistic conception of BR-SAR spacecraft, using Brazilian Multi-Mission Platform (MMP) associated with a 7 m mesh deployable offset Reflector Antenna.

Currently, RISAT-1 missions (Radar Imaging Satellite-1), ALOS-2 (Advanced Land Observing Satellite-2), and RADARSAT Constellation Mission (RCM) are the missions that have incorporated CP modes in their payloads.

RISAT-1 is a C-Band SAR remote-sensing mission launched in April 26th, 2012 from the Indian Space Research Organization - ISRO, assuming 536 Km heliosynchronous orbit. It has been the first space system to operate the Hybrid-POL CP mode. Due to its features, RISAT-1 can provide high-resolution images (around 1 m) with 100 km swath. The mission has been supporting the worldwide community of remote sensing with SAR data. It is expected that the mission will continue through the RISAT-1A mission, which can be launched in November 2019 [23].

Another current orbital SAR system that employs CP is the ALOS-2 (Advanced Land Observing Satellite-2). The mission was launched on May 24, 2014, by the Japan Aerospace Exploration Agency (JAXA) from the Yoshinobu Launch Complex located at Tanegashima Space Center in Japan. The SAR Radar system named Phased Array type L-band Synthetic Aperture Radar-2 (PALSAR) was included in

ALOS-2 to monitor Earth's dynamic processes, such as earthquakes, volcanoes, biomass changes, among others. In this mission, the PC mode intends to be evaluated experimentally [15].

RCM is a set of three identical small satellites launched on Jun 12th, 2019. It will allow accessing 90% of Earth surface with a high spatial resolution (<1.3m in spot mode) and high temporal resolution, i.e., up to four times a day. Each satellite will have a small planar antenna which restricts the swath to about 30 to 40 km in stripmap mode. However, it is expected that the constellation will reach 100 km swath by the image composition from the three satellites [15]. It will be the first spaceborne SAR to employ Hybrid-POL mode in the world.

In the scope of Lessonia-1 mission, it was considered the Right Circular Polarization on transmission (*Rhc*) and linear polarization on receive (Hybrid-POL) as RCM. The researchers have in mind that the circular polarization reduce, but not remove entirely, the effects of Ionosphere over wave propagation [24].

In order to understand the concept of CP, consider a wave transmitted circularly to the right, the reception of the echo signal made simultaneously by antennas with horizontal and vertical polarization, the Jones vector for the right circular polarization, and assuming the Theorem of Reciprocity, the Scattering vector $\vec{k}_{Rhc}$ is defined as

$$\vec{k}_{Rhc} = \frac{1}{\sqrt{2}}\begin{bmatrix} S_{HH} & S_{HV} \\ S_{HV} & S_{VV} \end{bmatrix}\begin{bmatrix} 1 \\ -j \end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix} S_{RH} \\ S_{RV} \end{bmatrix}, \tag{1}$$

with

$$\begin{aligned} S_{RH} &= S_{HH} - jS_{HV}, \\ S_{RV} &= S_{HV} - jS_{VV}, \end{aligned} \tag{2}$$

where S_{RH} represents the right circular transmission and linear horizontal reception and S_{RV} represents the right circular transmission and linear vertical reception [24].

The Covariance matrix relative to the Scattering vector $\vec{k}_{Rhc}$ is:

$$C_{Rhc} = \begin{bmatrix} \langle |S_{RH}|^2 \rangle & \langle S_{RH}S_{RV}^* \rangle \\ \langle S_{RV}S_{RH}^* \rangle & \langle |S_{RV}|^2 \rangle \end{bmatrix}. \tag{3}$$

This resulting matrix can be rearranged into a sum of three matrices. The first one encompasses only the co-polarized terms (HH and VV); in the second, only the terms with cross-polarization (HV and VH) are included. The last one contains residual terms [25], as follows:

$$C_{Rhc} = C_{co-POL} + C_{cr-POL} + C_{res} \tag{4}$$

$$C_{co-POL} = \frac{1}{2}\begin{bmatrix} \langle |S_{HH}|^2 \rangle & \langle jS_{HH}S_{VV}^* \rangle \\ \langle -jS_{VV}S_{HH}^* \rangle & \langle |S_{VV}|^2 \rangle \end{bmatrix} \tag{5}$$

$$C_{cr-POL} = \frac{1}{2}\begin{bmatrix} \langle |S_{HV}|^2 \rangle & -\langle j|S_{HV}|^2 \rangle \\ \langle j|S_{HV}|^2 \rangle & \langle |S_{HV}|^2 \rangle \end{bmatrix} \tag{6}$$

$$C_{res} = \frac{1}{2}\begin{bmatrix} \langle -2\Im(S_{HH}S_{HV}^*) \rangle & \langle S_{HH}S_{HV}^* + S_{HV}S_{VV}^* \rangle \\ \langle S_{HV}S_{HH}^* + S_{VV}S_{HV}^* \rangle & \langle 2\Im(S_{VV}S_{HV}^*) \rangle \end{bmatrix} \tag{7}$$

where $\Im(\cdot)$ represents the imaginary part.

Taking into account that with the use of Compact Polarization only the components S_{RH} and S_{RH} are measurable and that the components S_{HH}, S_{HV} and S_{VV} are unknown, in the expressions from (5) to (7) there are three unknown real terms:

$$\langle |S_{HH}|^2 \rangle, \langle |S_{HV}|^2 \rangle \text{and } \langle |S_{VV}|^2 \rangle. \tag{8}$$

and six unknown complex terms:

$$\begin{aligned} &\langle S_{HH}S_{VV}^* \rangle, \langle S_{VV}S_{HH}^* \rangle, \langle S_{HH}S_{HV}^* \rangle, \\ &\langle S_{HV}S_{VV}^* \rangle, \langle S_{HV}S_{HH}^* \rangle \text{ and } \langle S_{VV}S_{HV}^* \rangle. \end{aligned} \tag{9}$$

The partial reconstruction model of the Covariance matrix from Full-POL SAR system proposed by Souyris considers the case which the illuminated scenario has Reflection Symmetry with relation to the incident plane [26], [27]. This model is suitable for regions where there is volumetric scattering, such as sea surfaces, forest canopy, among others [25]. In this case, the Reflection Symmetry Hypothesis, there is a complete uncorrelation between the co-polarized and polarized cross-polarization scattering coefficients, which implies [27]

$$\begin{aligned} \langle S_{HH}S_{HV}^* \rangle &= \langle S_{HV}S_{HH}^* \rangle = 0 \\ \langle S_{VV}S_{VH}^* \rangle &= \langle S_{VH}S_{VV}^* \rangle = 0 \\ \langle S_{HH}S_{VH}^* \rangle &= \langle S_{VH}S_{HH}^* \rangle = 0 \\ \langle S_{VV}S_{HV}^* \rangle &= \langle S_{HV}S_{VV}^* \rangle = 0. \end{aligned} \tag{10}$$

In this way, the residual matrix (7) cancels out and the indeterminations presented in (8) and (9) are reduced to the four terms $\langle |S_{HH}|^2 \rangle, \langle |S_{VV}|^2 \rangle, \langle S_{HH}S_{VV}^* \rangle$ and $\langle |S_{HV}|^2 \rangle$

$$C_{Rhc} = \frac{1}{2}\left\langle \begin{bmatrix} \langle |S_{HH}|^2 \rangle & j\langle S_{HH}S_{VV}^* \rangle \\ -j\langle S_{VV}S_{HH}^* \rangle & \langle |S_{VV}|^2 \rangle \end{bmatrix} + \langle |S_{HV}|^2 \rangle \begin{bmatrix} 1 & -j \\ j & 1 \end{bmatrix} \right\rangle. \quad (11)$$

In order to reduce the indeterminations presented in (11), Souyris proposed a method of interpolation of the state of polarization of the electromagnetic waves, assuming that this proposal can be extended to any state of polarization [26].

In this process, a relationship between S_{HH}, S_{HV} and S_{VV} is established based on the scattering of fully polarized waves and completely depolarized waves.

In the first case, the scattering of the cross polarized energy is very small, while the co-polarized components are almost perfectly correlated

$$\langle |S_{HV}|^2 \rangle \approx 0 \quad (12)$$

$$\rho_{HH-VV} = \frac{\langle S_{HH}S_{VV}^* \rangle}{\sqrt{\langle S_{HH}S_{HH}^* \rangle \langle S_{VV}S_{VV}^* \rangle}} \approx 1, \quad (13)$$

where ρ_{HH-VV} is the complex correlation or degree / magnitude of coherence between S_{HH} and S_{VV} [28].

For completely depolarized waves, the average power arriving at the radar receiver does not depend on the state of polarization. In this situation, the correlation between the co-polarized channels practically cancels out and the scattered energy intensity is practically the same between S_{HH}, $\sqrt{2}S_{HV}$ and S_{VV}. So

$$\langle |S_{HH}|^2 \rangle \approx \langle |S_{VV}|^2 \rangle \approx 2\langle |S_{HV}|^2 \rangle \quad (14)$$

$$\rho_{HH-VV} = \frac{\langle S_{HH}S_{VV}^* \rangle}{\sqrt{\langle S_{HH}S_{HH}^* \rangle \langle S_{VV}S_{VV}^* \rangle}} \approx 0, \quad (15)$$

where the expression (14) can be rewrite as

$$\langle |S_{HV}|^2 \rangle \cong \frac{\langle |S_{HH}|^2 \rangle + \langle |S_{VV}|^2 \rangle}{4}. \quad (16)$$

Considering these two cases considered limits of the physical interpretation of the scattering mechanism, Souyris proposed an interpolation of the state of polarization, as shown in Fig. 5.

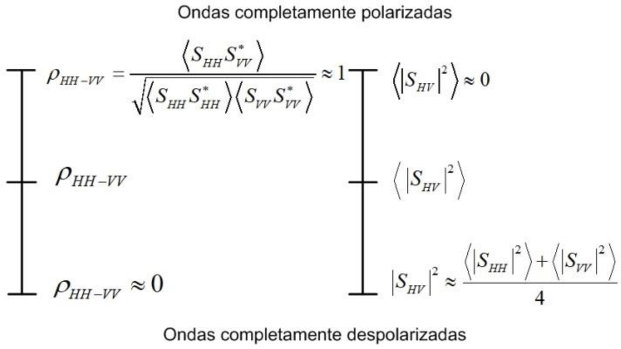

Fig 5. Linear interpolation of the state of polarization (Reflection Symmetry).

Comparing these two states, it is possible to stablish the following relation

$$\frac{\langle |S_{HV}|^2 \rangle}{\langle |S_{HH}|^2 \rangle + \langle |S_{VV}|^2 \rangle} = \frac{(1-\rho_{HH-VV})}{4}. \quad (17)$$

The expression (17) is the second hypothesis assumed by Souyris. The first being the Symmetry of Reflection presented in (10).

By combining (10), (11) and (17), a linear system of four equations, with four unknown elements, was solved numerically by means of an interactive process, where the cross-polarized term is set to 0 at the initial step as follow.

Step 1 – Initialization

$$X = 0$$
$$\rho_{HH-VV}^{(0)} = \frac{jC_{12}}{\sqrt{C_{11}C_{22}}}, \quad (18)$$

Step 2 – Iteration

$$X^{(n)} = \frac{(C_{11}+C_{22})}{2}\frac{|(1-\rho_{HH-VV})|}{|(3-\rho_{HH-VV})|} \quad (19)$$

$$\rho_{HH-VV}^{(n)} = \frac{j(C_{12}-X)}{\sqrt{(C_{11}-X)\cdot(C_{22}-X)}}, \quad (20)$$

where the value at (20) update the value of X and n is the number of interactions.

Step 3 - Reconstruction

$$\begin{aligned} C_{11} &= \langle |S_{HH}|^2 \rangle + \langle |S_{HV}|^2 \rangle \\ &\Rightarrow \langle |S_{HH}|^2 \rangle = C_{11} - X \\ C_{12} &= j\langle S_{HH}S_{VV}^* \rangle + \langle |S_{HV}|^2 \rangle \\ &\Rightarrow j\langle S_{HH}S_{VV}^* \rangle = jC_{12} - X \end{aligned} \quad (21)$$

$$C_{22} = \left\langle |S_{VV}|^2 \right\rangle + \left\langle |S_{HV}|^2 \right\rangle$$
$$\Rightarrow \left\langle |S_{VV}|^2 \right\rangle = C_{22} - X$$

Observing the hypothesis of Reflection Symmetry presented in (10), the Covariance matrix of the Full-POL mode (3) is rewritten in order to make a pseudo reconstruction, which means the approximation of Full-POL parameters using this CP algorithm.

$$C^{Full-POL(3\times3)} = \left\langle \begin{bmatrix} \left\langle |S_{HH}|^2 \right\rangle & 0 & \left\langle S_{HH} S_{VV}^* \right\rangle \\ 0 & 2\left\langle |S_{HV}|^2 \right\rangle & 0 \\ \left\langle S_{VV} S_{HH}^* \right\rangle & 0 & \left\langle |S_{VV}|^2 \right\rangle \end{bmatrix} \right\rangle \quad (22)$$

IV. Final Considerations

In this paper, the basic technical concepts studied for Lessonia-1 mission are presented. The advantages of the Offset reflector Antenna and some preliminary parameters for Lessonia-1 were presented. The concept of CP was presented without considering the ionospheric irregularities.

Finally, the authors highlighted that this work is a preliminarily approach representing one of the possibilities of payload for Lessonia SAR mission. The Commission for Coordination and Implementation of Space Systems (CCISE), a Brazilian Air Force organization responsible for establishing the strategies of implantation of PESE, in partnership with the Brazilian Space Agency (AEB), has been following the steps foreseeing for the mission analysis and design in order to launch Lessonia-1 mission in 2026. The Pre-Phase A report is about to be elaborated.

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