Advantages of Using a C-band Phased Array Feed as a Receiver in the Sardinia Radio Telescope for Space Debris Monitoring

Luca Schirru
National Institute for Astrophysics
Astronomical Observatory of Cagliari
(INAF – OAC)
Department of Electrical and Electronic Engineering,
University of Cagliari
Cagliari, Italy
luca.schirru@inaf.it

Tonino Pisanu
National Institute for Astrophysics
Astronomical Observatory of Cagliari
(INAF – OAC)
Selargius (Cagliari), Italy
tonino.pisanu@inaf.it

Alessandro Navarrini
National Institute for Astrophysics
Astronomical Observatory of Cagliari
(INAF – OAC)
Selargius (Cagliari), Italy
alessandro.navarrini@inaf.it

Enrico Urru
National Institute for Astrophysics
Astronomical Observatory of Cagliari (INAF – OAC)
Selargius (Cagliari), Italy

Francesco Gaudiomonte
National Institute for Astrophysics
Astronomical Observatory of Cagliari (INAF – OAC)
Selargius (Cagliari), Italy

Pierluigi Ortu
National Institute for Astrophysics
Astronomical Observatory of Cagliari (INAF – OAC)
Selargius (Cagliari), Italy

Giorgio Montisci
Department of Electrical and Electronic Engineering,
University of Cagliari
Cagliari, Italy
gmontisc@unica.it

***Abstract*—The population of space debris is continuously growing and it represents a potential problem for satellites and spacecraft. In fact, new collisions could exponentially rise the number of debris and so the level of threat represented by these objects. To prevent new collisions, the monitoring of space environment is necessary. For this reason, radar measurements are relevant, in particular to observe Space Debris in Low Earth Orbit. In recent years, the Sardinia Radio Telescope, a fully steerable wheel-and-track 64-m antenna, located in Sardinia (Italy), has been used as a receiver in a P-band bi-static radar for space debris monitoring purposes. In this paper the authors investigate the advantages of using a Phased Array Feed in C-band for space debris monitoring (e.g. improved sensitivity and gain, detection of the object trajectory allowed by multiple beams, improvement of the orbit determination of known and unknown debris), as a receiver of the Sardinia Radio Telescope compared to the already used mono-beam P-band receiver.**

Keywords – Space Debris, Phased Array Feed, C-band, Sardinia Radio Telescope, bi-static radar

I. Introduction

Space debris consist of manmade objects, with variable sizes and shapes, that have stopped their originally functions and which continue to orbit around the Earth. The presence of this kind of objects represents an obstacle for every manned and unmanned spacecraft maneuvers, and it increases the risk of possible new collisions, as described by the Kessler syndrome [1].

In order to prevent the space debris problem, in 2015 the European Commission started a dedicated framework for Space Surveillance and Tracking (SST). Within this framework, a network of dedicated sensors (radars, telescopes and lasers) for the surveillance and the tracking of objects has been implemented. Focusing on radar sensors, they are relevant to observe space debris that orbiting in Low Earth Orbit (LEO), between 200 and 2000 km of altitude. Regarding the Italian contribution, there are two radars based on two different radio telescopes as a receiver: the Bi-static Radar for Leo Survey (BIRALES) system and the Bi-static Radar for Leo Tracking (BIRALET) system. Each of these systems uses the same transmitter, named Radio Frequency Transmitter (TRF), located in Sardinia, which operates in Continuous Wave (CW) mode at 410 MHz (P-band). The BIRALES system, which employs the Northern Cross radio telescope as a receiver, has been chosen to monitor the space environment in survey mode and it can generate a set of data for every observed space debris, i.e. Doppler shift, illumination time and measured power intensity [2]. Instead, the BIRALET system employs the Sardinia Radio Telescope (SRT) as a receiver and it performs Doppler shift measurements and received power intensity in tracking mode, using the mono-beam P-band receiver [3]. Compared to the early years when the SRT was used for space debris measurement campaign, the system has recently been upgraded with a dedicated channel for space debris monitoring that comprises a dedicated backend with its acquisition chain [4]. One of the limitations of the current BIRALET system is the relatively low pointing speed of SRT (0.5 deg/sec in azimuth, 0.85 deg/sec in elevation) and the availability of only one beam, resulting in a limited Field of View (FoV). Space debris with angular speed (as seen from the SRT site) greater than the maximum antenna angular movement cannot be tracked as the antenna would be too slow to follow their apparent motion in the sky. Imaging the sky with a multi-beam array receiver installed at the primary focus of the SRT would increase the telescope FoV and the survey speed (how quickly we can image a given area of sky to a given sensitivity level), assuming that the receiver sensitivity in not compromised with respect to that of a single-pixel feed. This allows to have a good spatial resolution and an increased FoV which permits to cover a greater portion of the sky in less time with respect to mono-beam observations, such as the case of the P-band BIRALET system.

As a matter of fact, one of the open-ended frontiers of the instrumentation for radio telescopes is the increase of the FoV. This could be obtained using a Phased Array Feed (PAF), also known as a Focal Plane Array (FPA), onto the primary focus of a radio telescope [5]. Through the beam-forming process, PAFs are able to synthesize multiple beams and optimize each of them. The beam shapes and side lobes can be modified in real time and be set to minimize their response towards undesired Radio Frequency Interferences (RFI). Some radio astronomy phased arrays have been developed for astronomical research, such as the Low Frequency Array (LOFAR) and its expansion LOFAR2.0, a phased array radio telescope based in The Netherlands with extensions throughout Europe [6]; the Murchison Widefield Array (MWA) telescope, located in the remote Murchison region of Western Australia [7] and the Australian SKA Pathfinder (ASKAP), a world-class high-dynamic range wide-field-of-view survey instrument [8]. ASKAP utilizes a PAF at the focus of each of its antennas, while LOFAR and MWA are phased array operating in aperture array mode. The technologies adopted in these radio telescopes contribute to develop the Square Kilometer Array (SKA) [9].

In this paper, we analyze the performances of the P-band BIRALET system and investigate the advantages and improvements of using a PAF in C-band for space debris monitoring, in particular improved antenna gain, detection of the object trajectory due to multiple beams and improvement of the orbit determination of known and unknown debris.

II. A TYPICAL MEASUREMENT CAMPAIGN PERFORMED BY THE P-BAND BIRALET SYSTEM

The BIRALET system (see. Fig. 1) is a bi-static radar composed by the TRF as a transmitter and the SRT as a receiver, with a baseline of about 20 km. In particular, the TRF is located in Italian Joint Test Range in the region “Salto di Quirra” (Cagliari, Sardinia, Italy). It is a fully steerable wheel-and-track 7-m diameter parabolic dish configuration with a maximum angular speed of 3 deg/sec. Fundamentally, the system is composed by a set of powerful amplifiers capable of supplying a power between 1 and 10 kW in the bandwidth 410-415 MHz [2]. The receiving antenna, the SRT, is a fully steerable wheel-and-track 64-m dish located near San Basilio (Cagliari, Sardinia, Italy). The front-end used for space debris monitoring is the L-P receiver, a cryogenically cooled coaxial receiver with two channels, one for the P band (305-410 MHz) and the other one for the L band (1300 – 1800 MHz) [4].

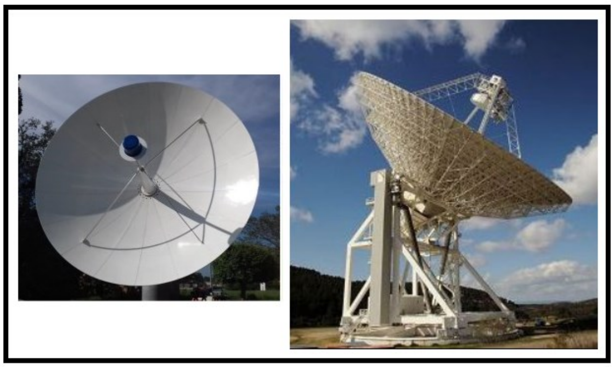

Fig. 1. The P-band BIRALET system. In particular, on left the TRF, on right the SRT.

The BIRALET system, as mentioned above, works in P-band. Its main characteristics are summarized in Table I:

TABLE I. CHARACTERISTICS OF THE P-BAND BIRALET SYSTEM.

Antenna name	SRT	TRF
Frequency	410 MHz	410 MHz
Antenna gain	46.6 dBi	27.3 dBi
Half Power Beam Width (HPBW)	0.8 deg	7.3 deg
Azimuth speed	0.85 deg/sec	3 deg/sec
Elevation speed	0.5 deg/sec	3 deg/sec

The typical scenario of observation is similar to operations for sky imaging with a single antenna as a receiver in a standard radio telescope. Imaging a large angular area of the sky with a single beam it requires to point that beam to a specific direction of the sky, then steering the antenna to different positions in order to cover the desired sky area. For each of the pointing, the antenna will be sensitive to signals from an angular area (FoV) depending on the HPBW (Half Power Beam Width), approximately equal to λ/D (with D is the telescope diameter). Different observing techniques are available to map a given area of the sky with a single-pixel feed (raster scan, on-the-flight mapping, etc.). If the beam shape is known, it is possible to mosaic over a given field with near-uniform sensitivity. This kind of pointing is the same used for space debris tracking observations with the BIRALET system. In fact, a generic known object can be tracked pointing the antenna beam in direction of the predicted object orbit. Moreover, this observation mode, based on various pointing for one sky map, could be used for tracking of unknown objects considering the covariance matrix associated to the object state. In other words, it is possible to track the object with a set of telescope pointing around the space debris predicted orbit through the covariance matrix related to the object state. The covariance matrix with the object state, in particular for unknown object, should be defined in a first measurement campaign using data performed by a survey radar, such as the BIRALES system. In this way, it is possible to observe unknown space debris with a multi-static radar composed by the BIRALES for survey mode and the BIRALET for tracking mode.

It is important to highlight that, for every measurement campaign, the pointing coordinates of the SRT must be predicted with high accuracy, since the HPBW of the system in P-band is 0.8 degree (Table I). One of the last measurement campaigns was performed on December 13, 2018 and was focused on observations of known objects. A set of measurements were performed to test the system with different known object at different distances from the TRF, which transmitted a signal with 5 kW power. The BIRALET system was used in beam-parking mode, requiring one pointing for each of the space-debris to be detected. The results are shown in Table II.

TABLE II. MEASUREMENT CAMPAIGN ON DECEMBER 13, 2018.

Object ID	RCS [m^2]	Estimated Slant range [km]	Time (UTC)	Measured Doppler [kHz]	Estimated Doppler [kHz]
#25415	0.55	1853.70	13:05:05.11	No detection	-6.276
#6350	1.73	1694.08	13:28:25.90	2.070	2.660
#1328	2.16	1901.43	13:48:19.51	-3.300	-4.036
#22824	0.16	2838.18	14:08:51.25	No detection	-14.257
#26222	4.99	1571.69	14:30:57.87	-3.486	-3.635
#25482	1.06	1732.62	15:00:36.67	-6.480	-6.313
#30774	3.64	1526.68	15:57:26.28	-2.110	-1.591

Fig. 2 shows the data acquisition at the centre of the visibility time interval for the object #1328, of order 1 sec. The plot shows the spectrum of the signals received from the SRT, including the carrier of the TRF at frequency 410.084205 MHz as well as the echo signal from the space debris at frequency 410.080905 MHz. The signal from the carrier is received from the SRT antenna side lobes due to the high power of the transmitter located at a short distance (baseline 20 km). This aspect occurs for every observation scenario, with any transmitted power in the 1 kW to 10 kW range.

The Doppler shift was calculated by taking the difference between the debris peak frequency and the carrier peak frequency, as shown in Fig. 2. In this particular case (object #1328), the measured Doppler shift was equal to -3.3 kHz.

The analysis of the results, obtained from the measurement campaign on December 13, 2018 (Table II) shows that two debris, the #25415 and the #22824, were not detected. In particular, these debris have a radar cross section (RCS) of 0.55 and 0.16 squared meters respectively, which are smaller than the others debris. The non-detection can be traced back to the following:

- An error in the computation of the pointing coordinates. The computation of new coordinates and a new measurement campaign for these debris should be carried to verify this hypothesis.
- A really low received peak power, which could be lost in the noise floor of the receiver chain. This situation arises in case of echo signals from space debris resulting in low Signal-to-Noise Ratios (SNRs). To minimize this problem and increase SNR at least two options are possible: 1) the transmitter power is increased; 2) the BIRALET system is upgraded for operation to higher frequencies, in order to improve antenna gain (at equivalent transmitted power).

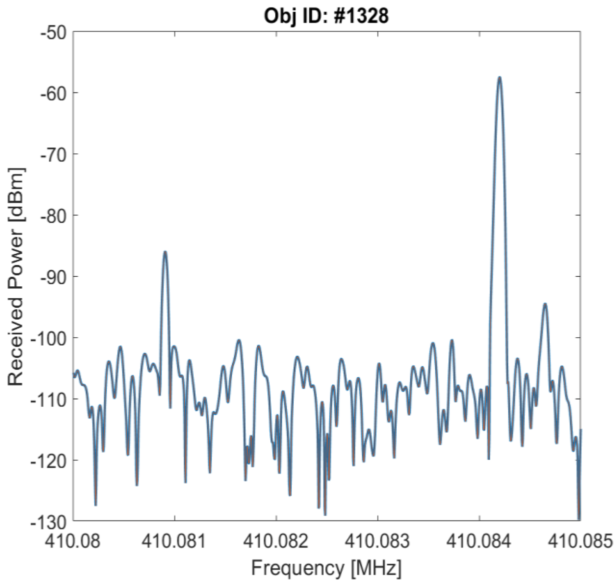

Fig. 2. Object #1328 detection at 13:48:19.51 UTC. The Doppler measurement has been obtained with the subtraction between the carrier frequency and the debris frequency.

III. Improvement of the SRT performances using a C-band PAF as a receiver for Space Debris monitoring

As previously described, a multi-beam receiver installed at the focal plane of a telescope increases its FoV and a greater portion of the sky can be covered in less time with respect to a mono-beam observation. We point out that the development of a multi-beam system requires to carry out a dedicated feasibility study, followed by a long process of simulations, prototyping, verification, production, assembly and final characterization. A PAF is an array of closely packed antenna elements placed at the focal plane of a large dish. The PAF array is set to Nyquist sample the electromagnetic field in the focal plane. Beams can be formed by analog methods, for example by introducing delays between elements and by managing the electrical lengths of the transmission lines, and by proper weighting in phase and amplitude the signals from the different PAF elements. This approach tends to be simple and cost effective, but restrictive. A better option is to form the beams digitally using signal processors. This method is highly flexible because any weights can be update in real time to form arbitrary beams. A disadvantage of the digital beam-former is the computational process, which is very intensive. Either way, it is necessary to include a beam-former in the signal path, adding complexity to the telescope system.

A. The SRT as a tracking Multi-beam system

The data obtained from the measurement campaigns are used in input at orbit determination algorithms. The observational data will usually consist of such measurements as range, Doppler shift, azimuth and elevation pointing, or other observable quantities. However, for the space debris orbit determination problem, the minimal set of necessary parameters are the position and velocity vectors at some given epoch. Therefore, the state variables (position, velocity, unknown model parameters, etc.) will not be observed, but rather the observable will usually be some nonlinear function of the state variables [10]. After an estimate of the apparent space debris trajectory on the sky from the SRT site has been obtained, the subsequent motion and other values can be predicted for the observations. These predicted values will differ from the true values because of inaccuracies in the estimated state vector (i.e., position and velocity vector) caused by errors in the orbit determination process, such as approximations involved in the method of orbit improvement and in the mathematical model, errors in the observations, errors in the computational procedure used in the solution process. Consequently, the process of observation and estimation must be repeated continuously as the space debris motion evolves [10]. Thus, for each space debris observation it would be advantageous to have a multi-beam systems multiple information are obtained in a unique antenna pointing with respect to a mono-beam system. In the case of a mono-beam system, for each mechanical antenna pointing, there is a unique reference point for the measured data (Doppler and/or range measurement, received SNR) of each observed debris. Instead, when a multi-beam system is employed the number of reference points matches the number of beams. When an object transits inside the antenna FoV, beams are illuminated by the reflected radio waves. By looking at the beam illumination sequence, it is possible to estimate the ground track of the transiting object, with a higher level of detail with respect to a single-beam system [11].

B. The advantages using C-band respect to P-band

Another important aspect regards the observing frequency of the BIRALET system. As shown in Table I, in P-band (at 410 MHz), the gains of the SRT and of the TRF are equal to 46.6 dBi and 27.3 dBi, respectively. As shown in Table II, two objects could not be detected in the measurement campaign of December 13, 2018. If the BIRALET system were upgraded for operation to higher frequencies, in particular to C-band at 6 GHz the received SNR from the debris and the chances of detection would considerably increase. Table III lists the estimated SNR at 410 MHz and at 6 GHz, for the two debris that were not detected in the previous campaign. The estimated values are obtained with the radar equation [12] and considering an ideal noise floor in a noise bandwidth of 30 Hz.

TABLE III. RECEIVED SNR: P-BAND VS C-BAND.

Object ID	Slant range [km]	RCS [m^2]	Received SNR at 410 MHz [dB]	Received SNR at 6 GHz [dB]
#25415	1853.70	0.55	33.8	57.1
#22824	2838.18	0.16	21.1	44.4

The analysis of the results of Table III, we can conclude that space debris with RCS lower than 0.5 m^2 and for slant ranges greater than 1800/2000 km, the P-band BIRALET system is to the edge of its capabilities in terms of detection sensitivity. We point out that these SNRs are estimated by assuming an ideal noise floor. In the real case, the noise floor is higher and the SNR lower. Upgrading the BIRALET from 410 MHz to 6 GHz would increase the SRT and the TRF's antenna gains by about 23 dB as reported in Table IV, thus improving the expected SNR:

TABLE IV. CHARACTERISTICS OF THE C-BAND BIRALET SYSTEM.

Antenna name	SRT	TRF
Frequency	6 GHz	6 GHz
Antenna gain	69.9 dBi	50.6 dBi
Half Power Beam Width (HPBW)	0.05 deg	0.5 deg
Azimuth speed	0.85 deg/sec	3 deg/sec
Elevation speed	0.5 deg/sec	3 deg/sec

The HPBW in Table IV refers to one antenna beam in C-band. The HPBW scales approximately inversely to frequency (at C-band the HPBW are smaller than at 410 MHz). The reduction of FoV due to operation at higher frequency can be (partially) compensated by a PAF, generating multiple independent beams.

Therefore, a C-band PAF installed in the SRT can improve the system performances in terms of minimum sizes of the observed objects.

IV. CONSLUSION

In this paper, we described the characteristics of the P-band BIRALET system. In a recent measurement campaign of space debris monitoring the detection at long slant-range of two objects with low RCS was not achieved. We presented considerations for the possible implementation of a new C-band radar based on a PAF as a receiver for the SRT that would permit multi-beaming and improvement of data for the orbit determination algorithms. Using the C-band for the new radar, the performances of the BIRALET system would considerably improve. In particular, the received SNR for the objects that in a previous measurement campaign in P-band were not detected, would be incremented by more than 23 dB. Furthermore, the new multi-beam system permits to increase the number of reference point for each space debris observation.

ACKNOWLEDGMENT

The authors would like to thank the Italian SST Operation Center (ISOC) and the research group from Department of Aerospace Science and Technology (Politecnico di Milano) for providing the list of the debris to be detected.

This work was supported in part by the European Commission Framework Programme H2020 and Copernicus, "SST – Space Surveillance and Tracking" under grants 785257-2-3SST2016 and 237/G/GRO/COPE/16/8935-1SST2016.

REFERENCES

[1] G. Muntoni, L. Schirru, T. Pisanu, G. Montisci, G. Valente, F. Gaudiomonte, G. Serra, E. Urru, P. Ortu, A. Fanti, "Space debris detection in Low Earth Orbit with the Sardinia Radio Telescope", Electronics, vol. 6, no 3, pp. 1-16, August 2017.

[2] T. Pisanu, L. Schirru, E. Urru, F. Gaudiomonte, P. Ortu, G. Bianchi, C. Bortolotti, M. Roma, G. Muntoni, G. Montisci, F. Protopapa, A. Podda, A. Sulis, G. Valente, "Upgrading the Italian BIRALES System to a Pulse Compression Radar for Space Debris Range Measurements", IEEE 22nd International Microwave and Radar Conference (MIKON), Poznan, Poland, 15-17 May 2018.

[3] G. Valente, T. Pisanu, P. Bolli, S. Mariotti, P. Marongiu, A. Navarrini, R. Nesti, A. Orfei, J. Roda, "The Dual Band L-P Feed System for the Sardinia Radio Telescope prime focus", In Proceedings of the Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V, San Diego, CA, USA, 27 June 2010.

[4] L. Schirru, G. Muntoni, T. Pisanu, E. Urru, G. Valente, F. Gaudiomonte, P. Ortu, A. Melis, R. Concu, G. Bianchi, G. Montisci, "Upgrading the Sardinia Radio Telescope to a Bistatic Tracking Radar for Space Debris", 1st IAA Conference on Space Situational Awareness (ICSSA), Orlando, FL, USA, 13-15 November 2017.

[5] D. C. Chang, C. N. Hu, C. I. Hung, K. T. Ho, "Pattern synthesis of the offset reflector antenna system with less complicated phased array feed", IEEE Transactions on Antennas and Propagation, vol. 42, no 2, pp. 240-245, 1994.

[6] S. J. Wijnholds, W. A. van Cappellen, "In Situ Antenna Performance Evaluation of the LOFAR Phased Array Radio Telescope", IEEE Transactions on Antennas and Propagation, vol. 59, no 6, pp. 1981-1989, 2011.

[7] R. Wayth, T. Colegate, M. Sokolowski, A. Sutinjo, D. Ung, "Advanced, efficient primary beam modeling for the Murchison Widefield Array radio telescope", 2016 International Conference on Electromagnetics in Advanced Applications (ICEAA), Cairns, Australia, 19-23 September 2016.

[8] D. R. DeBoer, R. G. Gough, J. D. Bunton, T. J. Cornwell, R. J. Beresford, S. Johnston, I. J. Feain, A. E. Schinckel, C. A. Jackson, M. J. Kesteven, A. Chippendale, G. A. Hampson, J. D. O'Sullivan, S. G. Hay, C. E. Jacka, T. W. Sweetnam, M. C. Storey, L. Ball, B. J. Boyle, "Australian SKA Pathfinder: A High-Dynamic Range Wide-Field of View Survey Telescope", Proceedings of the IEEE, vol. 97, no 8, pp. 1507-1521, 2009.

[9] A. van Ardenne, J.D. Bregman, W.A. van Cappellen, G.W. Kant, J.G. Bij de Vaate, "Extending the Field of View with Phased Array Techniques: Results of European SKA Research.", Proceedings of the IEEE 2009, 97, 1531–1542.

[10] B. D. Tapley, B. E. Schutz, G. H. Born, “Statistical Orbit Determination”, Elsevier Academic Press, California, USA, 2004.

[11] A. Morselli, P. Di Lizia, G. Bianchi, C. Bortolotti, S. Montebugnoli, G. Naldi, F. Perini, G. Pupillo, M. Roma, M. Schiaffino, A. Mattana, E. Salerno, A. Magro, K. Z. Adami, R. Armellin, A. Lazzareschi Sergiusti, W. Villadei, F. Dolce, M. Reali, J. Paoli, "A new high sensitivity radar sensor for space debris detection and accurate orbit determination", In Proceedings of the 2015 IEEE Metrology for Aerospace (MetroAeroSpace), Benevento, Italy, 4–5 June 2015, pp. 562–567.

[12] M. I. Skolnik, “Radar Handbook”, McGraw-Hill, Boston, Massachusetts, 1990.