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THE ITALIAN BIRALET RADAR SYSTEM TO PERFORM RANGE AND RANGE RATE MEASUREMENTS IN THE EUSST EUROPEAN SPACE SURVEILLANCE AND TRACKING PROGRAM

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Abstract

Space debris is a term for all human-made objects orbiting the Earth reentering the atmosphere. These objects have variable sizes and shapes and they can include non-functional satellites and spacecraft, abandoned launch vehicle stages and fragmentation debris. The population of space debris is continuously growing and it represents a potential issue for active satellites and spacecraft. New collisions and fragmentation could exponentially increase the amount of debris and so the level of risk represented by these objects. The monitoring of space environment is necessary to prevent new collisions and consequently to offer collision avoidance services. For this reason, radar measurements are relevant, in particular to observe objects in Low Earth Orbit, between 200 and 2000 km of altitude, the most crowded orbit with more than 24,000 trackable objects with sizes greater than 10 cm.

In this paper, we present the design of the Italian BIRALET system, an acronym which stands for BIstatic RAdar for LEo Tracking. It is a bi-static radar used for space debris detection and tracking in Low Earth Orbit. The transmitter is the so called Radio Frequency Transmitter (TRF), a fully steerable parabolic antenna with a 7 m diameter dish, with a primary focus configuration, located inside the Military Italian Joint Test Range in the region of "Salto di Quirra" (Cagliari, Sardinia, Italy). The TRF has a set of powerful amplifiers able to supply a transmitting RMS power between 1 and 10 kW in the bandwidth of 410-415 MHz. The receiver system of the BIRALET is the Sardinia Radio Telescope (SRT), located in San Basilio, around 35 km from Cagliari (Sardinia, Italy), and with a baseline from the TRF of about 20 km. It is a flexible instrument designed for radio astronomy studies and space science, which recently was also utilized for space debris monitoring. The antenna is a multi-reflector system with a quasi-Gregorian configuration, with a 64-meter parabolic primary mirror and a 7.9-meter elliptical secondary mirror. The telescope has three other mirrors (two with a diameter of 2.9 m and one with a diameter of 3.9 m), which provide the Beam Wave-Guide (BWG) system. The telescope is able to host up to 20 remotely controllable receivers and to observe the sky with high efficiency in the frequency range between 0.3–116 GHz. The front-end used for space debris monitoring is the P-band receiver of the SRT, which is installed in the primary focus of the telescope. In fact, the receiver is a cryogenically cooled dual-band coaxial feed that simultaneously covers the L-band (1300 – 1800 MHz) and the P band (305 - 418 MHz) frequency range.

The back-end of the BIRALET system, funded and developed under the European Space Surveillance and Tracking program, is based on the National Instrument USRP-2954R board. The electronic board in the TRF is configured to transmit a mixed signal composed from a chirp plus a continuous wave tone, with an overall bandwidth of 5 MHz. In this way, it is possible to perform range, with a spatial resolution of few tens of meters, and range rate measurements, with a bandwidth resolution of about 10 Hz. The overall performances of the radar are also determined by the synchronization accuracy between the TRF and the SRT. The receiver and the transmitter are synchronized in time and frequency using the GPS 1PPS (pulse per second) and the 10 MHz reference signals. An integrated GPS receiver in the USRP-2954R guarantees a maximum error of 10^{-7} seconds. In this paper, we present a preliminary measurement campaign of detection of known objects, for which it is possible to estimate range rate and range, in order to establish the performance of the system and in particular of the dedicated back-end. Thanks to range and range rate data collected by the BIRALET system in the measurement campaign (using a dedicated orbit determination software), it is possible to improve the knowledge of the orbit of the observed space debris and consequently to update our database of known objects.

Keywords: Space Debris, Sardinia Radio Telescope, BIRALET, bi-static radar, radio astronomy.

Nomenclature

BI-static RAdar for LEo Tracking (BIRALET),
BI-static RAdar for LEo Survey (BIRALES),
Radio Frequency Transmitter (TRF),
Sardinia Radio Telescope (SRT),
Beam Wave Guide (BWG)
Phased Array Feed (PAF)

1. Introduction

Since 1957, with the rapid advancement of space adventure, rockets and satellites have been sent to space on several missions. A lot of these objects have lost their original activity over time, move out of control and orbit the Earth as space debris and, in many cases, reentering the atmosphere. In case of new collisions, they can damage other in-orbit objects and consequently create new debris [1]. This triggers the exponential increasing population of space debris and it raises the level of risk represented by these objects for active satellites and spacecraft. The monitoring of space environment is necessary to prevent new collisions and consequently to offer services of collision avoidance. In fact, collision avoidance procedures represent an important space debris mitigation measure but they require an accurate knowledge of the state of the orbiting objects [2-4]. Within this framework, a network of dedicated sensors (radars, telescopes and lasers) is necessary for the surveillance and tracking of space debris. Concerning radar measurements, they are particularly relevant for the observation of the objects in Low Earth Orbit (LEO), between 200 and 2000 km of altitude, the most crowded orbit. In this orbit, the largest database of catalogued objects, which is composed by more than 24,000 debris of assorted sizes larger than 1 centimeter, is maintained by the United States Strategic Command (USSTRATCOM) [5], which features the Space Surveillance Network (SSN), an extensive network of optical, lasers and various types of radar sensors (such as phased arrays, reflector antennas and multi-static fences) [6-7]. The large amount of data coming from the SSN is elaborated by the US Joint Space Operations Center (JSpOC), that performs orbit determination with its own software and processes the data in order to provide the orbital parameters in the universal format named two-line element set (TLE) [8].

In 2014, also the European Commission started a dedicated framework for Space Surveillance and Tracking (SST), with the implementation of a European network of sensors, i.e. radars, telescopes and lasers [9-14].

Regarding the Italian contribution to European SST project, in addition to military sensors, there are two bi-static radars which work in survey and tracking mode, respectively: BIRALES and BIRALET. 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), and they have a radio telescope as a receiver. The BIRALES radar, which uses the Northern Cross radio telescope as a receiver, can generate a set of data for every observed space debris, i.e. range, range rate, illumination time and measured power intensity [15]. Instead, the Sardinia Radio Telescope (SRT) is the receiver of the BIRALET system [3]. It performs range, range rate measurements and receives power intensity in tracking mode, using the mono-beam P-band receiver. Compared to the early years when SRT was used for space debris measurement campaign [3], the system was first upgraded with a dedicated channel for space debris monitoring, that consists of a dedicated backend based on the Red Pitaya board, which permits only Doppler shift measurement [16-19]. Recently, the system has been improved with the development of a new dedicated backend based on the National Instrument USRP-2954R board [20], that performs range and range rate measurements. In this paper, we present the main features of the BIRALET radar system, including frontend and backend details. A measurement campaign for system testing and preliminary results are presented.

2. The Sardinia Radio Telescope as a receiver of the P-band BIRALET radar

The Italian BIRALET system, is a bi-static radar used for space debris detection and tracking. As mentioned in the introduction, the transmitter is the TRF, a fully steerable parabolic antenna with a 7-meter diameter dish, with a primary focus configuration, located in the Italian Joint Test Range in the region “Salto di Quirra” (Cagliari, Sardinia, Italy). The TRF system has a set of powerful amplifiers able to transmit an RMS power between 1 and 10 kW in the bandwidth of 410-415 MHz [16]. The receiver system of BIRALET is the SRT antenna, located in San Basilio, around 35 km from Cagliari (Sardinia, Italy). The baseline between SRT and TRF is about 20 km [16-18]. The BIRALET system is shown in Figure 1.

SRT is a flexible instrument, designed for radio astronomy studies and space science, which is also utilized for space debris monitoring from 2014 [3]. The antenna is a multi-reflector system with a quasi-Gregorian configuration, with a parabolic primary mirror, 64-meters in diameter and a 7.9-meter elliptical secondary mirror. SRT has three other mirrors (two with a diameter of 2.9 m and one with a diameter of 3.9 m), which form the Beam Wave-Guide (BWG) system. SRT is able to host up to 20 remotely controllable receivers and to observe the sky with high efficiency in the frequency range between 0.3–116 GHz [17].

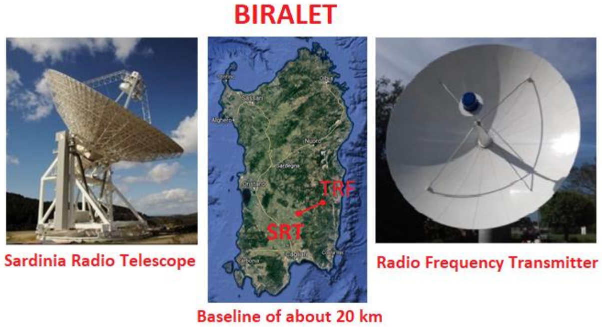

Figure 1: The BIRALET radar composed of SRT and TRF, with a baseline of about 20 km.

The front-end used for space debris monitoring is the P-band receiver of the SRT, which is installed in the primary focus of the telescope. In fact, the receiver is a cryogenically cooled dual-band and dual-polarization coaxial feed that can simultaneously observe the L-band and the P-band. Regarding space debris observations, we installed a band pass filter in both polarizations of the P-band receiver. The filter centered at 410 MHz, with 16 MHz bandwidth and 1.1 dB of insertion loss, , was installed in order to reduce the observation frequency band to 402-418 MHz [16]. The SRT, with its LP-band receiver and its frequency response (S-parameters) are shown in Figure 2.

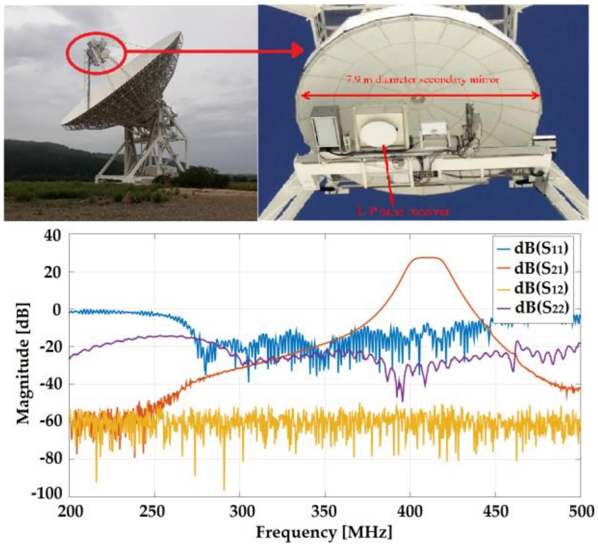

Figure 2: The Sardinia Radio Telescope, its LP-band receiver and its S-parameters [16].

From the S21 red curve of Figure 2, it is possible to appreciate the contribution of the band pass filter at 410 MHz that confines the signal in the 3-dB bandwidth 402-418 MHz. The S21 curve shows a maximum gain of about 27 dB, which matches, apart from some losses attributed to the coaxial cables used during the measurement, with the overall gain of the P-band receiver [16].

The main characteristics of the BIRALET system, such as antennas gain and half power beam widths (HPBWs), are summarized in Table 1.

Table 1: Main features of the BIRALET system.

Antenna name	SRT	TRF
Frequency	402-418 MHz	404-415 MHz
Antenna gain	46.6 dBi	26.0 dBi
HPBW	0.8 deg	7.5 deg
Azimuth speed	0.85 deg/sec	3 deg/sec
Elevation speed	0.5 deg/sec	3 deg/sec
Polarization	Circular	Circular and linear
Sidelobes	<-20 dB	<-20 dB
Noise Temp.	NA	20 K

The signal acquisition chain, from the P-band receiver to the dedicated back-end, is shown in Figure 3. After the P-band receiver block, before the signal reaches the dedicated back-end based on USRP-2954 board, it goes through the Focus Selector. This system permits the selection of the SRT focus, depending on the type of observation, and it is characterized by an overall gain of about 20 dB. Finally, an optical link is used, in order to connect the Focus Selector to the shielded room of the SRT radio astronomy station, where all the back-ends are installed. The distance covered by the optical link is of about 500 meters, composed of the initial RF-optical transducer, the optical fiber and the final RF-optical transducer, with a negligible total loss.

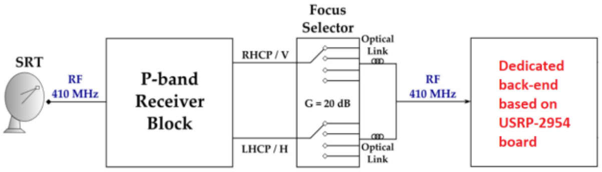

Figure 2: Space debris dedicated acquisition chain.

3. The BIRALET dedicated back-end for space debris range and range rate measurements

The back-end of the BIRALET system, funded and developed under the European Space Surveillance and Tracking program (EUSST), is based on a National Instrument USRP-2954 board [20]. The board installed on the TRF is configured to transmit a mixed signal composed of a chirp plus a continuous wave tone, that is described in detail in the following. The chirp plus the continuous wave tone, permits range and range rate measurements. In detail, the USRP-2954 board is used to generate the I/Q samples of the transmitted waveform. The I/Q samples are then converted into an analogue signal by two 16-bit DACs and up-converted by the I/Q up-converter chip. Finally, this signal is amplified thanks to the 10 kW power amplifier of the TRF and it is transmitted towards the expected target position (predicted using the TLE [8]). The transmitter architecture is shown in Figure 4.

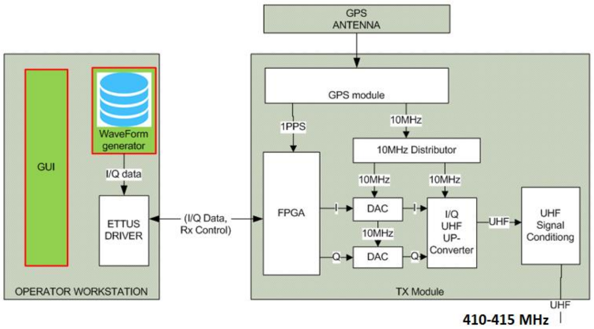

Figure 4: Transmitter architecture of the TRF antenna based on the USRP-2954 board.

The UHF signal at 410-415 MHz, received by SRT, is directly processed by the USRP-2954 board. This signal is then down converted to the board baseband by an I/Q down converter chip and finally digitalized by two ADCs. I/Q signals are then sent to the operator workstation for processing. The processing can be done both in real-time mode or in offline mode, by using the real time stored I/Q samples. This feature is extremely useful for testing purposes and for analyzing further improvements of the radar processing chain. The receiver architecture is shown in Figure 5.

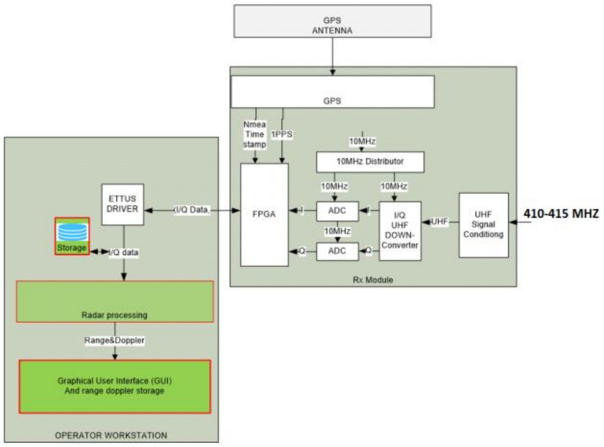

Figure 5: Receiver architecture of the SRT dedicated back-end based on the USRP-2954 board.

The overall performances of the radar are also determined by the synchronization accuracy between the TRF and the SRT. The receiver and the transmitter are synchronized in time and frequency using the GPS 1PPS (pulse per second) and the 10 MHz reference signals. In particular, the 10 MHz signal is used as reference for all down-conversions and sampling frequency generation (ensuring no drift between transmitter and receiver); the 1 PPS signal is used to simultaneously start the acquisition/generation between receiver/transmitter. An integrated GPS receiver in the USRP-2954 guarantees a maximum error of 10^{-7} seconds.

The aim of the system is to detect debris at a range equal to 3000 km with a measurement accuracy of about 30 meters and to perform also range rate measurements. For this reason, we have chosen, as waveform transmitted by TRF, a mixed signal composed of a frequency modulation continuous wave (FMCW) signal, known as chirp, plus a continuous wave (CW) tone, with an overall bandwidth of 5 MHz, as shown in Figure 6.

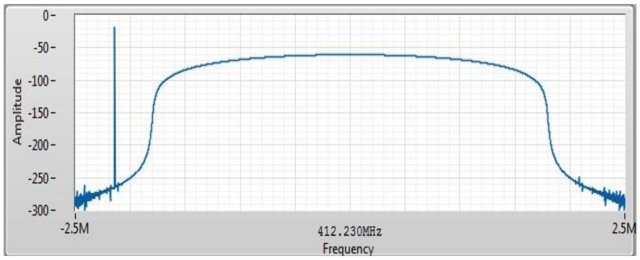

Figure 6: Transmitted signal composed of FMCW chirp plus a CW tone.

In particular, the transmitted signal is set to a central frequency of 412.23MHz, with the CW tone generated with an offset frequency of -2.145 MHz from the central one. Regarding the chirp, it is a down-chirp in the range of 3.6 MHz, with a pulse repetition interval (PRI) of 20 ms and a pulse repetition frequency (PRF) of 50 Hz. This guarantees a range measurement of objects at distances up to 3000 km, as shown by the following formula [21]:

$$PRF = c/2d \cong 50\ Hz \qquad (1)$$

where c is the speed of light and d is the maximum range, in this case equal to 3000 km. This value of PRF prevents the possibility of Doppler measurements using only a pulsed signal, because typical space debris Doppler shift values in LEO are in the range of a few kilohertz (in P-band), values greater than our PRF. For this reason, we have designed a system that transmits a chirp plus a CW tone, in order to work as a pulsed radar (for range measurements) and as a CW radar (for Doppler measurements).

The sampling frequency is 5 MS/s and the maximum transmitted power is 10 KW, with a 100% duty cycle. Using a 100% duty cycle allows us to use all the energy from the transmitter (there is no coupling between transmitter and receiver) and the 50 Hz PRF allows us to measure the range without ambiguities (the Doppler information, to compensate the range error, is extracted from the tone). Using a chirp of 3.6 MHz allows us to exploit all the usable bandwidth, maximizing the range resolution and leaving a small portion of the spectrum for the tone used for Doppler extraction. This permits a Doppler shift of more than 100kHz, more than sufficient, considering the expected target speed with the used carrier.

In order to maximize the signal to noise ratio for the range extraction, we used a matched filter to perform a pulse compression. The interpulse integration is also used by the addition of four chirps (see Figure 7). This means that we have a measurement of the target range and Doppler, every 80 ms (the step between each measure is four pulses: 20 ms * 4= 80 ms).

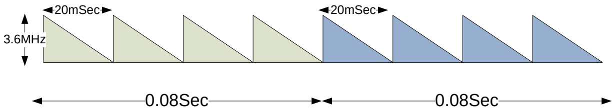

Figure 7: FMCW pulse train.

Finally, both range and Doppler shift measurements are time stamped with a millisecond accuracy, allowing precise target trajectory prediction.

4. Measurement campaign for system testing and preliminary results

A validation campaign of the new ranging system is currently underway, aiming at assessing the BIRALET radar performances. Target observations are performed by pointing the system towards calibration objects from the International Laser Ranging Service (ILRS) database, which provides the positional state of the satellites with an accuracy of around a centimeter. The resulting measurements are compared against the associated accurate ephemerides. First, the observable passages of the objects are predicted, then the transmitter and the receiver are pointed accordingly, in order to observe them.

The BIRALET system was employed in beam-parking mode, for a preliminary measurement campaign, in order to validate the integration of the new ranging system. A calibration measurement of the receiver chain was performed with the objective of investigating the received signal delay. In this way, we compensated the time error, and consequently the range error, caused by the receiver chain from the SRT P-band receiver to the dedicated backend based on USRP-2954 board. After this important calibration, a set of ILRS objects were detected on the 13th of December 2019, to compare measured Doppler and range with the data available from the associated accurate ephemerides. In Table 2, the slant-range and Doppler errors, obtained as the difference between measured and predicted values, are reported for the ILRS objects (SCNs 36508 and 41335, for which accurate ephemerides were available) and other targets (for which TLEs were adopted).

Table 2: Preliminary results of the testing measurement campaign.

SCN	Epoch	Slant-range error [m]	Doppler error [Hz]
16791	2019/12/13 9:07:54	-4	-3
36508	2019/12/13 9:53:25	67	-5
41335	2019/12/13 10:05:06	-69	-32
40697	2019/12/13 10:30:38	-35	-51
37387	2019/12/13 10:47:54	-84	-28
40894	2019/12/13 10:59:38	0	-38
5395	2019/12/13 11:15:16	75	10
11962	2019/12/13 11:26:58	-31	-3
38338	2019/12/13 11:54:33	40	11

The analysis of the data from Table 2, collected by the BIRALET system, shows that we have a slant-range and Doppler error compatible with the requirements requested by the EUSST program. However, the calibration measurement campaign must be repeated periodically in order to update these results and maintain the high performance of the system.

5. Conclusions and future works

The preliminary results confirm that the measurements collected by the BIRALET radar, after calibration and bias correction, are accurate and comply with the design and simulations. There are different parameters in the processing chain that can be tuned in order to improve the quality and sensitivity of the measurement. For example, if the Doppler of the object is known, the signal to noise ratio can be improved by 3 dB sending all the available transmitting power in the chirp. Another improvement can be done by increasing the integration time (increasing the number of integrated pulses of Figure 7) or changing the transmitted waveform. Many tests can be done by tuning the system parameters, and by processing the real time stored I/Q samples offline. Further measurements and processing refinements will be made in the next few months, in order to evaluate the performance of the system. The evaluation will be tested on coverage and accuracy, using several targets with different radar cross sections and orbiting at several altitudes.

One of the physical limitations of the current BIRALET system could be the relatively low pointing speed of the SRT (0.85 deg/sec in azimuth, 0.5 deg/sec in elevation) and the availability of only one beam, resulting in a limited field of view (HPBW of 0.8 degrees, as reported in Table 1). Space debris with angular speed greater than the maximum antenna angular movement, cannot be tracked because the antenna tracking capability is too slow to follow their apparent motion in the sky [18]. On the other hand, it cannot measure the trajectory direction of the object with only one beam. Imaging the sky with a multi-beam receiver would increase the telescope field of view and survey speed, allowing the coverage of a greater portion of the sky in less time, [18]. One way to do it, as a future project, would be to develop a Phased Array Feed (PAF) as a receiver for the primary focus of SRT [18, 22-25]**Errore. L'origine riferimento non è stata trovata.**. A PAF consists of closely packed antenna elements that, by spatially sampling the focal plane, can synthesize multiple independent beams. Beam shapes and directions are controlled electronically by weighting the amplitudes and phases of the signals applied to the individual antennas by a beam-former [22-25]. Consequently, through the beam-forming process, PAFs are able to synthesize multiple beams and optimize each of them, enhancing aperture efficiency as well as effective field-of-view. The beam shapes and side lobes can be modified in real time and be set to minimize their response, in relation to undesired radio frequency interferences.

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