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MULTIBEAM RADAR TECHNOLOGY APPLIED TO SPACE SURVEILLANCE IN THE LEO REGIME

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ABSTRACT

This paper illustrates the Italian BIstatic RAdar for LEo Survey (BIRALES) sensor for Space Surveillance and Tracking in the LEO regime. BIRALES is a bistatic radar whose receiving part has been refurbished to synthetize up to 32 simultaneous beams in the antenna field of view. The multibeam configuration offers the possibility of estimating the track of the detected objects inside the receiver field of view by analysing the beams illumination sequence. The estimated track is then coupled with the available Doppler shift and slant range measurements. The availability of such a plethora of information is then exploited to perform initial orbit determination with a single passage of a resident space object inside the sensor field of view. This work describes BIRALES sensor setup and operation, showing the performance of the sensor in terms of observation and tracking capabilities.

Keywords: Space Surveillance and Tracking, Radar sensor, Orbit Determination, Space Debris

1 INTRODUCTION

Over the last decades, space debris population has been exponentially growing and it is now recognized as one of the main threats for satellites orbiting around Earth. Therefore, monitoring the space debris environment has become a key issue in the context of all space activities. An international effort is being devoted to improving the performance of optical and radar sensors for space objects monitoring. Collision risk assessment is performed daily by satellite operators who are provided with conjunction data messages to support decisions on the execution of collision avoidance manoeuvres **Error! Reference source not found.**. In addition, re-entry predictions of objects are regularly produced to estimate on ground risks [2]. Both collision risk assessment and re-entry predictions rely on the accurate estimation and prediction of the state of the orbiting objects, which are derived from the tracking of the space objects using dedicated optical, radar and laser sensors.

(a) (b)

Figure 1: BIRALES sensor. (a): Medicina radio astronomical station located in Medicina (Italy); (b): Radio Frequency Transmitter (RFT) located at the Italian Joint Test Range of Salto di Quirra in Sardinia (Italy).

Within this context, this work presents an assessment of the results that can be achieved with the Italian BIstatic RAdar for LEo Survey (BIRALES) sensor [3] (see Figure 1). BIRALES is part of the Italian contribution to the European Space Surveillance and Tracking (SST) Support Framework. It is a bistatic radar composed by the Radio Frequency Transmitter (RFT) located at the Italian Joint Test Range of Salto di Quirra in Sardinia (Italy) and by part of the Northern Cross (NC) radiotelescope located in Medicina (Bologna, Italy) as multibeam receiver. The receiving part currently uses 16 antennas of the North-South arm of the NC radiotelescope (see Figure 2). Each antenna is equipped with four receivers, whose signals are processed electronically to synthetize up to 32 simultaneous beams.

The innovative multibeam configuration of the receiver offers the possibility of estimating the track of the detected objects in the receiver field of view by analysing the beams illumination sequence. This task is complicated by the peculiar geometrical configuration of the receiver and the complex gain pattern. More specifically, each beam features multiple gain peaks (main lobe, grating lobes, and side lobes). Therefore, when a beam is illuminated, the identification of the gain lobe responsible for the beam illumination is not straightforward. The ambiguities introduced by the presence of multiple gain lobes per beam are solved with a tailored track identification algorithm. The estimated track is then coupled with the available Doppler shift and slant range measurements. Such a plethora of information offers the possibility of performing initial orbit determination (IOD) with a single passage of a resident space object inside the sensor field of view (FoV).

This work describes BIRALES sensor and shows its performance in terms of observation and tracking capabilities. The first part of the paper is dedicated to the description of BIRALES sensor. Then, a detailed illustration of the IOD algorithm is offered, with the track reconstruction algorithm representing the core of the method. Finally, the performance of the sensor is presented as obtained with numerical simulations.

2 BIRALES SENSOR

BIRALES sensor uses a bistatic configuration. The Radio Frequency Transmitter (RFT) located at the Italian Joint Test Range of Salto di Quirra (PISQ) in Sardinia is used as transmitter, and part of the Northern Cross radio telescope of the radio astronomy station of Medicina as receiver. The RFT consists of an amplifier that supplies a maximum power of 10 kW in the bandwidth 410-415 MHz. It is a 7m-dish completely steerable at a maximum speed of 3 deg/s

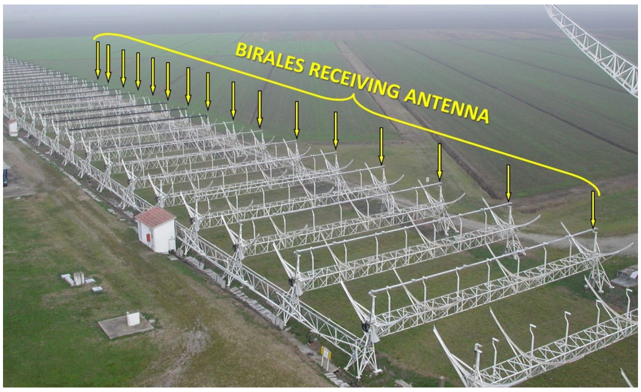

Figure 2: BIRALES receiving antenna.

with right-hand circular polarization. Its FoV matches almost perfectly the receiving antenna one, with a beam width of 6 deg. The receiving antenna is a portion of the Northern Cross Radio Telescope, which is currently one of the largest UHF-capable antennas in the world, being located at the Medicina Radio Astronomical Station, near Bologna, in Northern Italy [4]. It is owned by the University of Bologna but managed and operated by the Institute of Radio astronomy at the Italian National Institute of Astrophysics (INAF-IRA). It consists of two perpendicular branches: the East-West (E/W) arm is 564 m long and consists of a single cylindrical antenna with a width of 35 m, whereas the North-South (N/S) branch is made of 64 parallel antennas with a length of 23.5 m and width of 7.5 m each.

The portion dedicated to BIRALES receiving antenna is currently composed of 16 parabolic cylindrical antennas of the N/S branch. The total collecting area is about 2800 m^2 and it allows the detection of small objects with sub-metric Radar Cross Section (RCS) at 1000 km of altitude. The peculiarity of the receiver is represented by the possibility of detecting meridian passages only, as it can be moved in elevation only. BIRALES works in survey mode and exploits an innovative concept based on multibeam technique. Due to the large numbers of receivers installed on the Northern Cross (4 receivers in each N/S antenna for a total of 64 receivers), the FoV can be populated with many independent beams. When an object transits inside the antenna FoV, the beams are illuminated by the reflected radio waves. Thus, by looking at the beam illumination sequence, it is possible to estimate the ground track of the transiting objects, with a higher level of detail with respect to a single-beam system.

The system architecture is shown in Figure 3. Using the RFT it is possible to transmit a CW signal able to illuminate the target in LEO. The echo radio reflected by the orbital object is received by the Northern Cross and the acquired analog signal is sent to the pre-processing room by an optical fiber link. The digitized data are processed by means of a data acquisition system based on FPGA boards and CPUs, which digitally assembles measured radar echoes using an FFT in spatial domain in order to evaluate the signal detected in each beam. Therefore, Doppler shift, illumination time, antenna pointing angles and measured power intensity associated to each beam are available as well and they are sent to the Italian SST Operation Centre (ISOC) to estimate the orbit of the object detected in a classified environment.

The sensor has been recently upgraded in order to provide also range measurements. Radar ranging works by transmitting, along with the carrier wave, a chirp of known period and span. The Doppler shift can be estimated by the carrier reflection, and the knowledge of this correction for the underlying chirp and of the transmission epoch provides a time of flight.

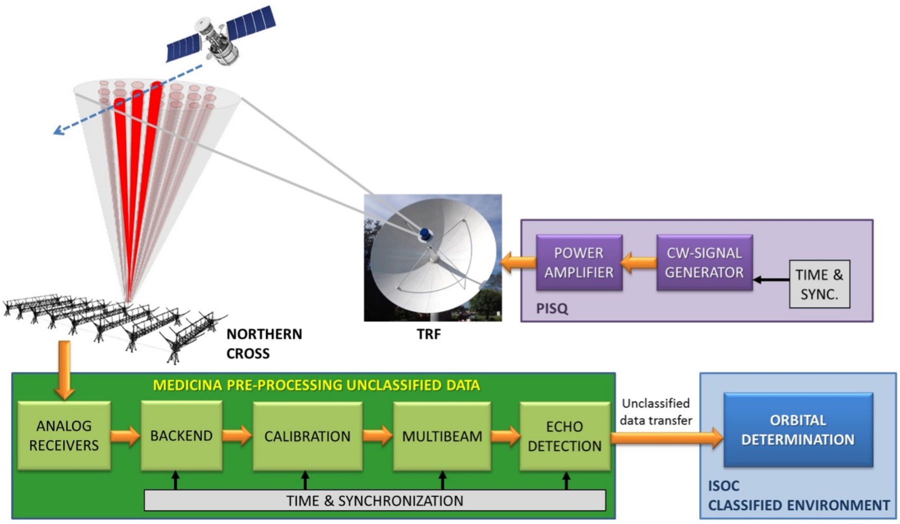

Figure 3: BIRALES system architecture.

BIRALES is endowed with a back end system that acquires 64 analog signals coming from 64 antenna receivers and digitized them with 64 Analog to Digital converters (ADCs). The analog band at the ADCs inputs is 16 MHz centred at 30 MHz (down converted frequency). The data sampled are sent to a first FFT block in order to generate channels with a sample resolution of 78 KHz, that is the maximum space debris Doppler shift.

The BIRALES system requires a real-time processing back end that can perform fine channelization of the incoming antenna voltages, pixelate the FoV with multiple coherent beams and process each of these beams for detection of debris echoes. Accurate beam pointing requires the calibration of the array of antennas. Additionally, the system must store and visualize the results, as well as transmit them to the orbit determination system. In order to accommodate all these processing stages whilst enabling the addition of new stages with ease, a framework for generating processing pipelines was developed for BIRALES.

The pipelining framework makes up the real-time software back end. This framework allows for the chaining of different software modules into pipelines, the main ones being:

- The *calibration pipeline*, which receives data from the digital back end and correlates the antenna signals together to generate correlation matrices. These are then used by the calibration routine to generate calibration coefficients to compensate for instrumental phase and gain errors.
- The *real-time processing pipeline*, which receives data from the digital back end, performs beamforming and channelization and either writes the resulting data to file or forwards it to the online detection modules for debris detection.

3 INITIAL ORBIT DETERMINATION

The starting point for the IOD algorithm implemented for BIRALES sensor is represented by a measurement text file including, for all the beams illuminated during the object passage, the epoch and the recorded slant range, Doppler shift and SNR measurements. Then, the algorithm is divided in two parts:

- *Track reconstruction*: this part is dedicated to the estimation of the track of the object inside the receiver FoV starting from the available SNR and slant range measurements.

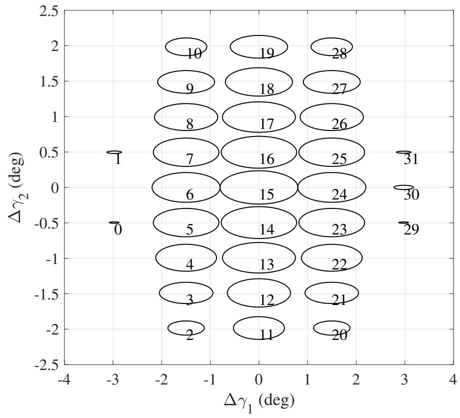

Figure 4: BIRALES receiver beam pattern in terms of angular deviations $\Delta\gamma_1$ and $\Delta\gamma_2$.

- *State estimation*: the state of the object is estimated on the basis of the available slant range and Doppler shift measurements, and the estimated track.

In the following sections, both phases are described in detail. The analyses are performed considering the current configuration (32 beams) and slant range measurements available.

3.1 Track reconstruction

The peculiarity of BIRALES sensor is the possibility of populating its receiver FoV with 32 beams. Figure 4 shows the distribution of the 32 beams within the receiver FoV. The angles $\Delta\gamma_1$ and $\Delta\gamma_2$ are the angular deviations with respect to the receiver nominal pointing. Each beam typically has a main lobe, some side lobes and may show the so-called *grating lobes*, which are generated by the geometry of the array itself. The gain of these grating lobes may be more or less significant according to the investigated beam. The gain pattern of each single beam mainly depends on its position inside the receiver FoV. Beams located close to the line of sight of the sensor typically show only a main lobe and side lobes, whose gain is much lower than the one of the main lobe. An example is given in Figure 5a for beam 24, with one main gain peak and other secondary, much weaker, side lobes. These beams will be defined throughout the paper as *dominant beams*. On the contrary, beams located at the boundaries of the FoV typically have the main lobe and one grating lobe, whose gain is comparable with the one of the main lobe. Figure 5b shows the gain pattern of beam 30: besides the gain peak associated to the main lobe, the pattern shows another gain peak, whose gain is comparable with the one of the main lobe.

The peculiarity of the receiver gain pattern affects the approach to be followed in the definition of the object track inside the receiver FoV. The idea at the basis of the approach is to reconstruct the track of the object by looking at the sequence of illumination of the beams. This, in turn, essentially consists in matching the measured SNR profile with the one obtained by the estimated track. The algorithm can be divided in two phases:

- a first *phase S1*, in which a first estimate for the object track is obtained by looking at the recorded SNR peaks
- a second *phase S2*, in which the obtained track is used as a first guess for a least-squares fit aimed at minimizing the residuals with respect to the whole SNR profile of all the illuminated beams.

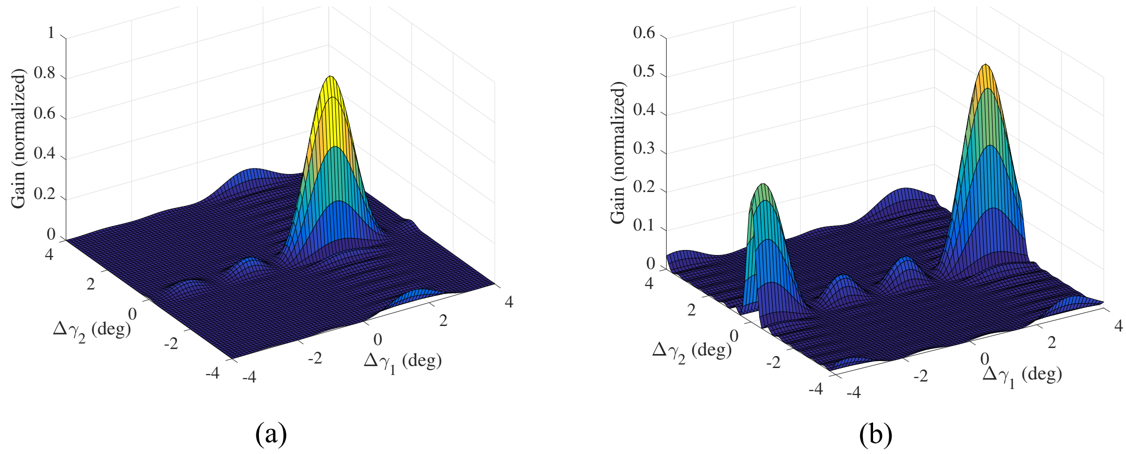

Figure 5: Example of gain patterns for single beams. (a): beam 24, with one main lobe and several minor side lobes; (b): beam 30, with one main lobe, one grating lobe and minor side lobes.

The first estimate in phase S1 is obtained by looking at all the SNR peaks recorded during the passage of the object and associating each *signal peak* to a given *gain peak* of a specific beam. This probably represents the most challenging aspect of the track definition algorithm, given the presence of multiple gain peaks per beam. When one beam is illuminated, indeed, it is not straightforward to understand which gain peak is responsible for the beam illumination. It is therefore necessary to identify some SNR peaks that are likely to be associated to specific gain peaks. The idea behind the implemented approach consists in starting the process by considering the largest SNR peak recorded by each dominant beam. When one of these beams is illuminated, its maximum signal peak is automatically associated to the main lobe of the beam in terms of angular deviation. By assuming a linear trend in time of the angular deviation profiles $\Delta\gamma_1$ and $\Delta\gamma_2$ and performing a first polynomial fit, this allows us to obtain a first estimate of the track of the object inside the receiver FoV. Once this track is defined, all SNR peaks can be considered, including the ones of beams with multiple comparable gain peaks. Each signal peak can then be associated to a specific gain peak by identifying the lobe with minimum deviation with respect to the previously estimated track at the epoch the SNR peak was detected. This procedure provides us with a full list including, for each recorded signal peak, the corresponding time epoch and angular deviations of the associated gain peaks. These data are processed with a new linear fit, and a refined first guess for the object track is obtained.

The described approach allows us to maximize the information extracted from the beam illumination sequence by simply looking at the recorded SNR peaks and exploiting the gain pattern. This procedure does not require any other measurement apart from the SNR. If slant range measurements are also available, then a further step can be performed. Starting from the estimated object track, and assuming a polynomial trend of the angular deviations with time, by knowing the slant range measurements at each observation instant, it is possible to perform a least-squares fit aimed at minimizing the residuals with respect to the whole SNR profile of all the beams. This second step, referred to as S2, grants better accuracy to the estimate and concludes the track definition phase.

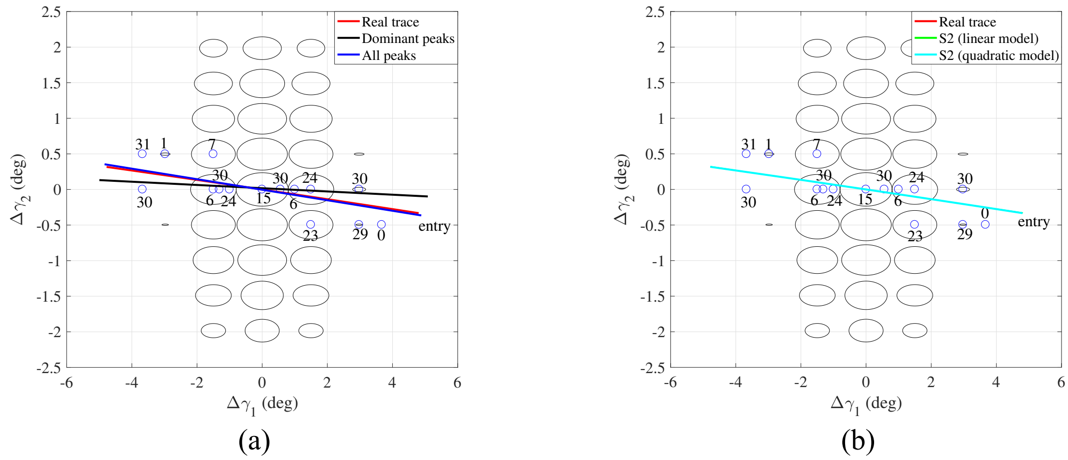

Figure 6: Trace definition for object NORAD ID 41765, passage April 20, 2018. (a): step S1, track definition based on SNR peaks; (b): step S2, nonlinear least-squares on the whole SNR profiles.

3.2 State estimation

The output of the track definition phase is a value of $\Delta\gamma_1$ and $\Delta\gamma_2$ for each observation instant. These two estimates, along with the Doppler shift and slant range measurements, are used to estimate the state and covariance of the object at the epoch of the first observation. The estimation is done with a Levenberg-Marquardt least-squares batch algorithm and requires an accurate model for the object dynamics. The considered high-fidelity propagator, called AIDA (Accurate Integrator for Debris Analysis), includes the gravitational model EGM2008 up to order 10, the atmospheric drag with the atmosphere model NRLMSISE-00, third body perturbations, and solar radiation pressure with a dual-cone model for Earth shadow for objects whose geometrical parameters are known. For unknown objects, only gravitational and third-body effects are considered.

4 PERFORMANCE ASSESSMENT

This section is devoted to assessing the performance of BIRALES with numerical test cases carried out with a dedicated software simulator. Given a catalogue of space objects, the simulator identifies the passages of all the objects and generates the simulated measurements in terms of slant range, Doppler shift and SNR (see [5] for further details). The simulated measurements are provided as input to the orbit determination module.

The analysis is performed assuming the following levels of measurement noise: 3 m of standard deviation for the slant range (SR), 9 Hz of discretization for the Doppler shift (DS), and a white Gaussian noise for the SNR, assuming a ratio of 30 dB between the nominal signal and the added white noise.

4.1 Initial Orbit Determination of object NORAD ID 41765

A first example of the performance of the IOD algorithm is offered in this section. Figure 6 shows the results of the trace definition phase for object NORAD ID 41765, April 20, 2018, 12:41:38.36 UTC. The real track of the object is shown in red. Figure 6a shows the results of step S1. The estimated track obtained considering the largest SNR peaks of the dominant beams only (beams 6, 7, 15 and 24) is shown in black. The final result of step S1 is shown in blue: as can be seen, by considering all the SNR peaks, the accuracy of the estimate significantly

Noise	# of objects	ε_p (km)	ε_v (km/s)	σ_p (km)	σ_v (km/s)
-	29	1.29e-3	2.07e-4	4.84e-4	3.50e-5
DS and SR	30	7.87e-3	2.91e-3	6.78e-2	5.38e-3
DS, SR and SNR	27	5.39e-2	1.32e-2	7.47e-2	4.38e-3

Table 1: BIRALES IOD statistical performance.

increases. Figure 6b shows the estimated track obtained with step S2, considering a linear (green) and quadratic (cyan) trend in time of the angular deviations: the availability of the slant range allows us to obtain a further improvement in the definition of the trace, getting to an estimate almost overlapping the real track.

The estimated angular deviations $\Delta\gamma_1$ and $\Delta\gamma_2$ are then coupled with the already available Doppler shift and slant range measurements to obtain an estimate of the state of the object at the epoch of the first measurement. As described in Section 3.2, a batch algorithm is used. For the case under study, an error of 23.97 m in position and 1.20 m/s in velocity is obtained.

4.2 Statistical performance on a catalogue of objects

The accuracy of BIRALES is here assessed on a catalogue of space objects. An observation window of two days is considered, covering the range 5-6 September 2018, with 2490 objects from the NORAD catalogue with at least one passage in the sensor field of view. For all objects, only the first passage is exploited to perform IOD (i.e. the objects are assumed to be unknown). The performance is assessed in terms of mean position and velocity errors (ε_p and ε_v, respectively), and the associated mean standard deviations σ_p and σ_v.

The results are reported in Table 1. The overall number of observable objects is quite low. This is partly due to our decision of selecting the first passage only, and partly to the peculiarity of the sensor of detecting meridian passages only with a narrow field of view. Let us now focus on the IOD performance. As can be seen, if no measurement noise is added to the simulated measurements, the accuracy granted is relatively high, with a mean position error of the order of 1 m. If measurement noise is considered, the performance decreases, with an average decrease in accuracy of around one order of magnitude in position and two orders of magnitude in velocity. Still, the average position error is lower than 100 m.

5 CONCLUDING REMARKS

This paper illustrated the system architecture of the innovative BIRALES sensor, as well as the tailored initial orbit determination algorithm. The performance of the sensor in terms of achievable accuracy of the orbital estimation process has been assessed with numerical simulations. The results show that the data provided by the sensor can be processed to estimate the orbital states with reasonable accuracy with just a single passage of the object inside the field of view of the sensor. Future developments will include experimental testing with slant range measurements, and the possible coupling with other Italian and European sensors.

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