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Exploration of an innovative ranging method for bi-static radar, applied in LEO Space Debris surveying and tracking

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Abstract

Space Situational Awareness (SSA) is referred as one of the capacitive areas of strategic interest to be developed/completed in the future in the short and medium term, for any nation with the target of the access to the space. One of the fundamental components is the Space Surveillance and Tracking (SST) program, considered as the capability to build a spatial mapping of the objects in orbit, their classification and the exact identification of their orbital characteristics. For this reason, radar measurements are relevant, in particular to observe objects in Low Earth Orbit. The Italian National Institute of Astrophysics together with Vitrociset company and Politecnico di Milano, studied and developed a new and innovative method for the range measure applied to bi-static radars to support the European Union Space Surveillance and Tracking (EUSST) program. Several tests have been carried out using the BIRALES and BIRALET sensors for survey and tracking observations respectively. Finally, the results obtained from observations have been compared with the real positions of the targets in order to validate the system. The ranging method relies on the synchronization of the transmitting and receiving antennas and on the correlation of the echo received from the scattering of the orbiting object. To do that, the transmitting antenna emits simultaneously two different signals: a Chirp signal for range measurement and a second "Continuous Wave" (CW) for Doppler shift measurement and object track reconstruction. Overall, we simultaneously obtain time profiles for range, angular position (azimuth and elevation), and Doppler during the passage of the objects inside the sensor Field of View. By virtue of the above plethora of measurements, this method guarantees also the possibility to produce an Initial Orbital Determination (IOD) for unknown objects.

Keywords: range, bi-static, radar, BIRALES, multibeam, EUSST.

1. Introduction

The number of manmade objects orbiting the Earth has dramatically increased during the last years, posing a serious risk for space based activities [1]. Most of the objects currently orbiting the Earth are classified as space debris and include inactive satellites, discarded launch stages, and fragments originated from satellite breakups and collisions. Mitigation guidelines have been published by various organisations such as the Inter-Agency Space Debris Coordination (IADC) committee and the United Nations (UN). In parallel specific space programs were started to build the expertise required to manage the challenges posed by the space traffic control problem. Collision risk assessment is performed daily by satellite operators and conjunction summary messages are provided to satellite operators by the United States Strategic Command (USSTRATCOM) to support decisions on the execution of collision avoidance manoeuvres [2]. In addition, re-entry predictions of objects are regularly produced to estimate on ground risks [3].

Survey and tracking of objects in Earth orbit is one of the main areas where the European Space Surveillance and Tracking (SST) Support Framework and the ESA Space Situational Awareness (SSA) programmes are active [4], with the aim of implementing a European network of sensors for surveillance and tracking of objects in Earth's orbit.

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(EUSST) program, considered as the capability to build a spatial mapping of the objects in orbit, their classification and the exact identification of their orbital characteristics. Typically, with the aim to prevent collisions, space-based and ground-based systems have been used to monitor the space debris situation at various altitudes [5]. Ground-based measurements are carried out by means of state-of-the-art sensors, both radar and optical. Within this topic, the Italian Northern Cross radio telescope array has been upgraded to serve the European SST Framework as a component of the Italian contribution to the European network for SST in the frame of the BIstatic RAdar for LEo Survey (BIRALES) sensor [6].

2. BIRALES system architecture

BIRALES is a bistatic radar [7] composed of two distinct antennas (see figure 1), with a baseline of about 580 km.

Fig. 1. BIRALES Tx and Rx location.

The transmitting antenna is the Radio Frequency Transmitter (TRF) of the Italian Joint Test Range of Salto di Quirra (PISQ) in Sardinia, Italy (see figure 2). It consists of a powerful amplifier able to supply a maximum power of 10kW in the bandwidth 410-415MHz. It is a 7m dish completely steerable at a maximum speed of 3deg/sec and with right hand circular polarization. It is available for operation 24h/day. Its field of view (FoV) matches almost perfectly the receiving antenna, with a beam of 7.5deg.

The receiving antenna is a portion of the Northern Cross Radio Telescope (see figure 3), which is currently one of the largest UHF-capable antenna in the world, being located at the Medicina Radio Astronomical Station, near Bologna, in Northern Italy. It is owned by the University of Bologna but managed and operated by the National Institute for Astrophysics - Institute of Radio Astronomy (INAF-IRA).

The portion dedicated to the BIRALES receiver is actually composed of 8 parabolic cylindrical antennas of the North-South (N-S) arm, with a total collecting area of about 1400 square meters; it allows to detect small objects with a size of 10cm at 1000km.

The Field of View (FoV) is 5.7° x 6.6° and this is a first prototype on which new radar technologies and orbital determination algorithms are being tested. In the coming years, an extension of the field of view up to 95deg in the north-south direction is planned, to obtain an effective radar for surveillance. In order to to achieve the new configuration, additional antennas of the Northern Cross will be used and an array of new emitters will be placed closer to the receiving part.

Fig. 2 BIRALES transmitting antenna (TRF).

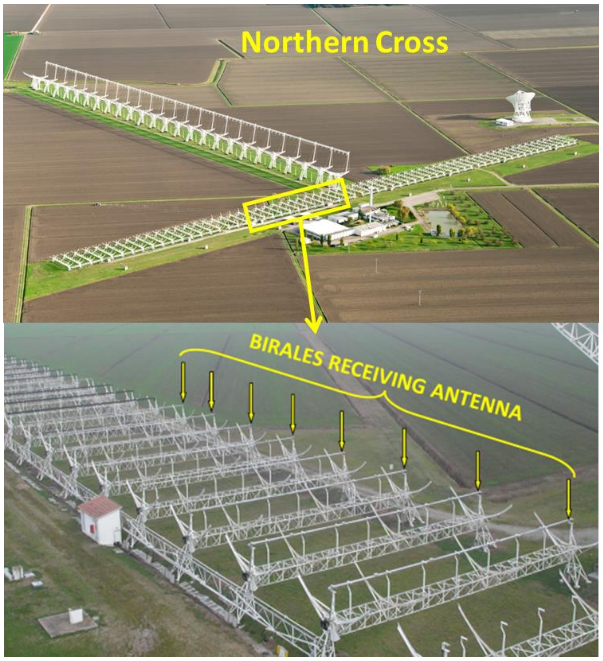

Fig. 3. BIRALES receiving antenna (Northern Cross telescope).

Each cylinder has 4 receivers installed in the focal line, for a total of 32 receivers (figure 4). Due to the large number of receivers installed on the Northern Cross, BIRALES FoV can be populated with many independent beams (figure 5). 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 angular path of the transiting object, with a higher level of details with respect to a single-beam system. The information about the sequence of illuminated beams allows to discern the trajectory of the object.

In addition another beam is generated for the range measure (the red one in figure 5). Unfortunately in this prototyping phase, the beam generated for the range measure is not the same of the antenna FoV, so now we can measure only the range on a piece of the orbing track.

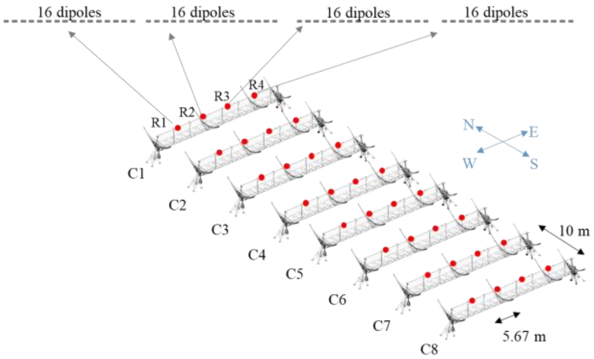

Fig. 4. Receivers (red dots) installed in the antenna focal line. Each receiver grouped 16 dipoles.

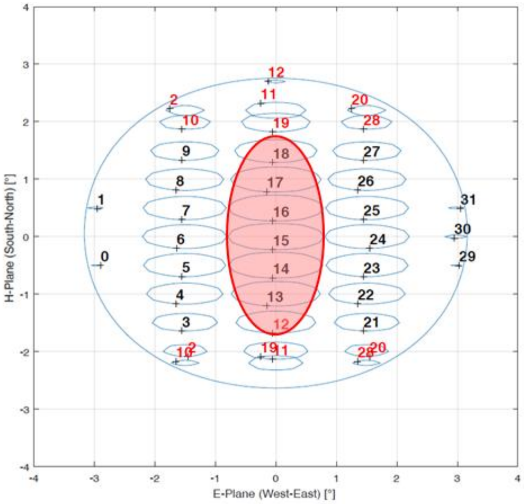

Fig. 5. Distribution of the beams in the BIRALES FoV. Blue beams are generated by the multiebeam, the red one is the beam actually used for the range measure.

3. Range measurement system

BIRALES exploits an innovative concept based on two different systems, working at the same time:

- Multibeam CW system
- Single beam pulse compression radar

In practical the sensor couples two radar systems. Transmitting antenna emits simultaneously two different signals: a Chirp signal for range measurement and a second “Continuous Wave” for Doppler shift measurement and object track reconstruction (figure 6). Overall, we simultaneously obtain time profiles for range, angular position (azimuth and elevation) and Doppler during the passage of the objects inside the sensor field of view. This method guarantees also the possibility to produce an Initial Orbital Determination (IOD) for unknown objects. Details of the schematic blocks are in [8].

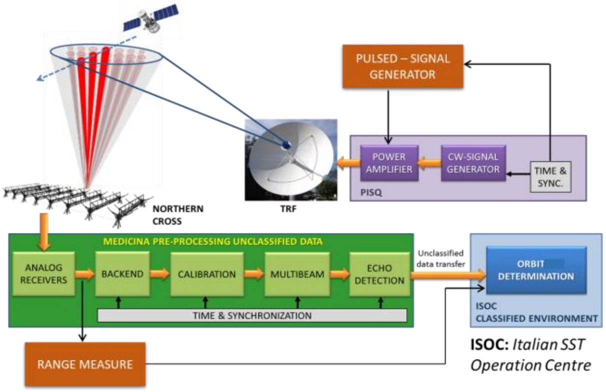

Fig. 6. BIRALES schematic block.

BIRALES is completely autonomous: the received echoes are immediately processed and the orbital parameters obtained are compared against the parameters of catalogued objects (through a correlator) in order to check whether the observed object is catalogued or not. If the observed object is not classified, the measured orbital parameters are uploaded into the European database and used, together with the other sensors data, for collision avoidance, fragmentation or re-entry services.

4. Validation campaign results

A validation campaign is currently underway aiming at assessing its performances. Targeted observations are performed by pointing the system towards calibration objects. 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. Since more than one object may cross the field of view during the observation time window, each detected passage and the associated measurements undergo a correlation process against the whole TLE catalog. If a univocal match with a known object is identified, the measurement is associated to it and considered valid. Specifically, this is done by propagating the TLEs up to the observation epoch and checking that the Doppler shift and its time derivative have a mean error below a selectable threshold. It is also enforced that the predicted position of the object is compatible with the pointing of the receiving antenna.

The next step of the validation procedure concerns the slant range. Orbital propagation of the TLEs based on the Simplified General Perturbation Model SGP4 is not suitable for this purpose due to the possible inaccuracies of the predictions. Therefore, the campaign is focused on objects monitored by the International Laser Ranging Service (ILRS), which provides the positional state of the satellites with an accuracy of the order of the centimeter.

Currently, around 80% of the detected passages are successfully correlated on a daily basis to objects in the public TLE database. The analysis has shown that the slant range value obtained by the system was constantly shifted with respect to the ILRS predictions: this is apparent in figure 7, which refers to a passage of satellite Jason-3 (SCN: 41240) on Sept. 27, 2019.

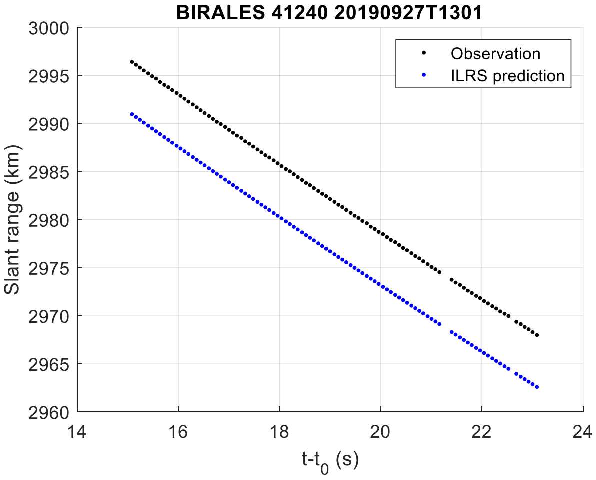

Fig. 7. Observed vs. predicted slant range during passage of sat. Jason-3 on 2019/09/27, no correction applied.

The results of the observation campaign, conducted on the passages of the objects from the ILRS catalogue reported in Table 1, were used to analyze and estimate this bias, which turned out to have a mean value of 5,45613 km. This value was verified to be correlated with time delays in the measurement chain.

Table 1. Observed passages of objects from the ILRS catalogue.

Sat. name	SCN	Epoch [UTC]	RCS [m^2]	Slant range [km]
Explorer-27	1328	2019/09/25 11:11	2.16	2024
Explorer-27	1328	2019/09/26 12:20	2.16	2250
Explorer-27	1328	2019/09/27 09:42	2.16	2100
Explorer-27	1328	2019/09/27 11:36	2.16	2134
Jason-3	41240	2019/09/27 13:02	2.89	2976
TechnoSat	42829	2019/09/30 08:58	0.39	1341
Explorer-27	1328	2019/09/30 09:23	2.16	2137
Explorer-27	1328	2019/10/07 06:06	2.16	2420
Explorer-27	1328	2019/10/07 08:00	2.16	2360

The system has been consequently calibrated. By correcting the slant range measurements by the estimated bias, the accuracy of the measurements is improved accordingly. This is shown in figure 8, which reports the slant range of the satellite Explorer 27 (SCN: 1328) on Sept. 30, 2019. With the correction applied, the RMSE between the observed and the predicted slant ranges for this passage turns out to be 80m.

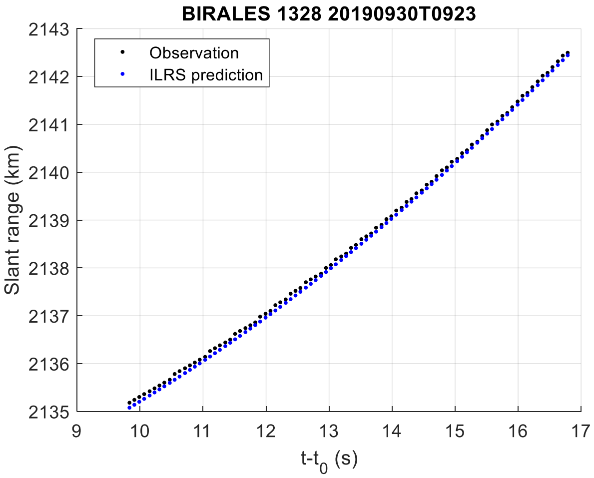

Fig. 8. Observed vs. predicted slant range during the passage of sat. Explorer-27 on 2019/09/30 after bias correction.

The calibration campaign is still ongoing, in order to confirm that the deviation of the measured slant range is compatible with the requirements of the EU-SST program. Afterwards, the calibration campaigns will be repeated periodically as requested by the EUSST program.

5. Application in a real case of re-entry

BIRALES was included in the list of sensors to be tasked to monitor the reentry of a stage of the Chinese CZ-5B launcher (NORAD ID 45601). The CZ-5B was launched on the May 5, 2020 and its stage was expected to reenter uncontrolled in the subsequent days. BIRALES was able to track the target by acquiring data from three observations (see table 2).

Figures 9-11 report the data gathered during the third observation on May 11, 2020. More specifically, figure 9 illustrates the beams illuminated during the passage of the target in the sensor FoV. The ellipses represent the receiving beams, whereas the intensity of the measured signal is shown by the green background. As can be deduced from the figure, beams are illuminated due to the passage of the target either in the main or in the grating lobes. The red line is the track as predicted form the last TLE available right before the observation. The slant range and Doppler shift of the received signal are reported in figures 10 and 11 respectively.

The data (measured SNR per beam, slant range and Doppler shift) have been used to perform an orbit determination refinement process. By relying on the available TLE as initial guess, the measured SNR and the slant range are used to refine the track of the target in the sensor FoV (green line in figure 9). Then, the obtained angular profiles are merged with the measured slant range and Doppler shift to obtain the estimated target state in terms of mean state and covariance matrix. The result of the process for the data of May 11, 2020 is reported in Table 3.

Table 2. BIRALES observation epochs and slant range intervals during the reentry campaign of the stage of the Chinese CZ-5B launcher (NORAD ID 45601).

Observation epoch (UTC)	Slant range interval
2020-05-09 10:30	780 ÷ 800 km
2020-05-10 10:05	758 ÷ 772 km
2020-05-11 09:31	710 ÷ 731 km

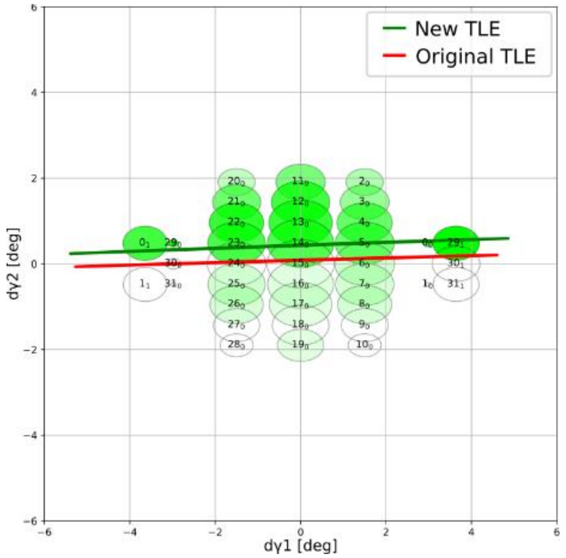

Fig. 9. Illumination of BIRALES beams during the passage of the stage of the Chinese CZ-5B launcher (NORAD ID 45601) on May 11, 2020. Red line: predicted track from last available TLE; green line: track corrected using the observation data.

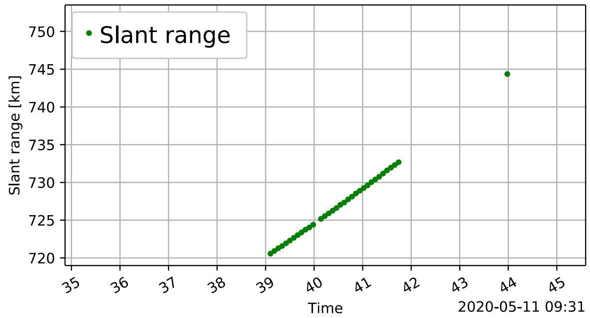

Fig. 10. Measured slant range during the passage of the stage of the Chinese CZ-5B launcher (NORAD ID 45601) on May 11, 2020.

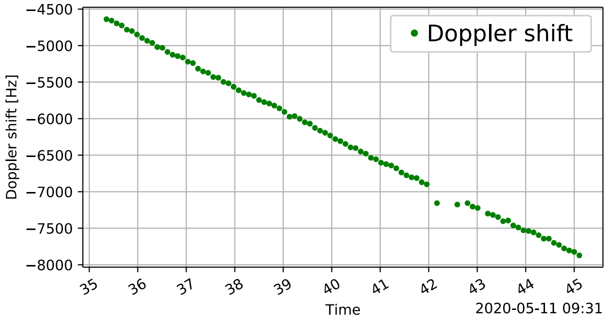

Fig. 11. Measured Doppler shift during the passage of the stage of the Chinese CZ-5B launcher (NORAD ID 45601) on May 11, 2020.

Table 3. Estimated state of the stage of the Chinese CZ-5B launcher (NORAD ID 45601) using the data obtained on May 11, 2020. Reference epoch: 2020-05-11T09:31:35.3568 UTC. Standard deviation computed from the diagonal of the covariance matrix.

Est. ECEF state	**Position [km]**		
Mean state	4796.503	967.657	4346.483
Standard deviation (σ)	1.348	0.262	0.470

Est. ECEF state	**Velocity [km/s]**		
Mean state	-0.6775	7.1625	-0.6531
Standard deviation (σ)	0.0365	0.0113	0.0298

6. Conclusions

The results show that the data provided by BIRALES 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. The preliminary results confirm that the measurements collected by the BIRALES system, after calibration and bias correction, are very promising and comply with the design and simulations. The application on a real case (re-entry of the Chinese CZ-5B launcher) demonstrated the effectiveness of the method, with good estimates of the re-entry epoch. Using last TLE generated by BIRALES, the italian operating center (ISOC), that is in charge for the re-entry service, estimated a re-entry epoch very close to the real one, with only 6 minute of difference.

This method guarantees also the possibility to produce an IOD for unknown objects.

Future works are needed to increase the accuracy of measurements, to better support the EUSST consortium, to build a spatial mapping of the objects in orbit, their classification and the exact identification of their orbital characteristics.

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The Northern Cross Radio Telescope is a facility of the University of Bologna operated under agreement by the National Institute for Astrophysics - Institute of Radio Astronomy (INAF-IRA).

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