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Resident space object orbit determination using a multireceiver radar system

M.F. Montaruli [a]*, L. Facchini[a], P. Di Lizia[a], M. Massari[a], G. Pupillo[b], G. Naldi[b], G. Bianchi[b]

[a] *Department of Aerospace Science and Technology, Politecnico di Milano, Via G. La Masa 34, 20156 Milano, Italy marcofelice.montaruli@polimi.it*
[b] *Istituto Nazionale di Astrofisica-Istituto di Radioastronomia (INAF – IRA), Via P. Gobetti 101, 40129 Bologna,*
* Corresponding Author

Abstract

The increasing in-orbit population of resident objects is currently fostering many Space Surveillance and Tracking (SST) initiatives. Italy contributes to the EUSST (European SST) initiative with the BIstatic RAdar for LEo Survey (BIRALES), whose transmitter is the Radio Frequency Transmitter, located at the Italian Joint Test Range of Salto di Quirra in Sardinia, and whose receiver is a portion of the Northern Cross Radio Telescope, located at the Medicina Radio Astronomical Station, near Bologna.

In order to perform orbit determination (OD) from BIRALES observations, the receiver raw data shall be properly processed, such that angular profiles are correctly reconstructed. In this framework, this work proposes the Music Approach for Track Estimate and Refinement (MATER) algorithm. First, the signal direction of arrival (DOA) is estimated with the MUltiple SIgnal Classification (MUSIC) technique, which exploits the signal covariance matrix.

For catalogued objects, the available ephemerides can be exploited in the DOA estimation process to save computational time and to avoid ambiguity in the solution. For uncatalogued objects, multiple track candidates occur due to the intrinsic array ambiguity. In order to solve such an ambiguity, all candidates enter an initial OD process. Consequently, multiple orbits are reconstructed, and their probabilistic correlation indexes are computed. The correct track is selected as the one corresponding to the orbit featuring the best index.

MATER is first tested on a synthetic dataset of 899 LEO passages. The algorithm converges to the correct solution in 100% both for catalogued and uncatalogued objects. The obtained angular accuracy is in the order of 1e-4 deg. In addition, the performance of MATER on a challenging real scenario is presented.

Keywords: space debris, EUSST, BIRALES, MUSIC, orbit determination, radar

Acronyms/Abbreviations

- Bistatic Radar for Leo Survey (BIRALES)
- Covariance Matrix (CM)
- Direction of Arrival (DOA)
- Doppler Shift (DS)
- East-West (E-W)
- European Space Agency (ESA)
- European Space Surveillance and Tracking (EUSST)
- Field of View (FoV)
- Geostationary Orbit (GEO)
- Line of Sight (LoS)
- Low Earth Orbit (LEO)
- Multibeam Orbit Determination Algorithm (MODA)
- Multiple Signal Classification (MUSIC)
- Music Approach for Track Estimate and Refinement (MATER)
- North-South (N-S)
- Orbit Determination (OD)
- Radar Cross Section (RCS)
- Radio Frequency Transmitter (TRF)
- Random Samples Consensus (RANSAC)
- Receiver (RX)
- Root Mean Square Error (RMSE).
- Signal to Noise Ratio (SNR)
- Slant Range (SR)
- Space Situational Awareness (SSA)
- Space Surveillance and Tracking (SST)
- Transmitter (TX)
- Two-Line Element (TLE)

1. Introduction

In the last decades, in orbit population has become a problem of outmost importance for space agencies and institutions all around the world. The two most populated regions are Low Earth Orbit (LEO) and Geostationary Orbit (GEO). Among orbiting satellites, just a small fraction is represented by co-operative satellites and the main part is represented by space debris, which include inactive satellites, rocket bodies, and fragments of all sizes [1]. Space debris represent a threat for space activities (in orbit collision risk, for instance) and so different strategies have been implemented in order to guarantee safe operations. For this purpose, an international commitment is currently taking place in

Space Surveillance and Tracking (SST) field. Europe deals with this topic through two programmes: the European Space Agency (ESA) Space Situational Awareness (SSA) programme [2] and the European Space Surveillance and Tracking (EUSST) framework [3]. The latter groups European national agencies and institutions and is in charge of carrying out the following services: conjunction analysis, collision risk assessment, fragmentation analysis and re-entry prediction. These services exploit measurements obtained through ground-based sensors. Radars are commonly used to track debris flying in LEO environment. Some examples of European radars used for SST are TIRA, GESTRA, GRAVES, SATAM, S3TSR and MFDR [4].

In Italy there is an on-going effort to contribute to the EUSST network with the Bistatic Radar for Leo Survey (BIRALES) sensor [5]. It owns an array receiver which introduces an ambiguity in the track reconstruction. To overcome this task, a tailored algorithm was developed in the past based on a multibeam concept.

This paper presents an innovative method for the reconstruction of the angular profiles by relying on alternative signal processing techniques and orbit determination (OD) algorithms. The paper is organized as follows: first BIRALES characteristics are listed and the multibeam based algorithm is presented, together with its limitations. Then, the new method is described and the process is tested both on a synthetic dataset of 899 LEO passages from the NORAD catalogue and on a real case passage.

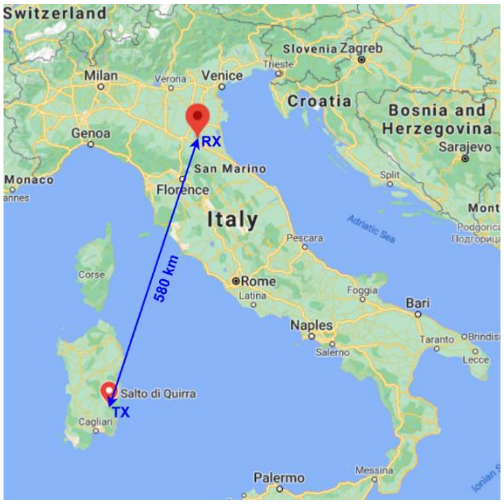

Fig. 1. BIRALES baseline

2. BIRALES

BIRALES is a radar sensor operating in a bistatic configuration, with a baseline of 580 km. The transmitter (TX) is the Radio Frequency Transmitter (TRF), located at the Italian Joint Test Range of Salto di Quirra (Sardinia). Instead, the receiver (RX) is located at the Medicina Radio Astronomical Station (near Bologna), as shown in Fig. 1. The TX (Fig. 2) is a single parabolic antenna able to transmit a peak power of 10 kW in the frequency range 410-415 MHz and it has a beamwidth of 7 deg. The dish can be steered in both azimuth and elevation.

Fig. 2. BIRALES TX

The RX is a portion of the Northern Cross Radio Telescope. As it can be seen in Fig. 3, the Northern Cross is T-shaped: one arm is arranged along the North-South (N-S) direction, the other is the East-West (E-W) one. Both arms can be mechanically pointed only in elevation, either in North pointing or South pointing configuration. BIRALES receiver is a section of the N-S arm that, at the present, includes 8 cylinders, but an extension is planned. Each cylinder contains 4 sensors arranged along the focal line, with a spacing of 5.67 m along E-W direction. Hence, the BIRALES RX consists of a planar array of 32 elements with a half-power beamwidth of 6.6 X 5.7 deg.

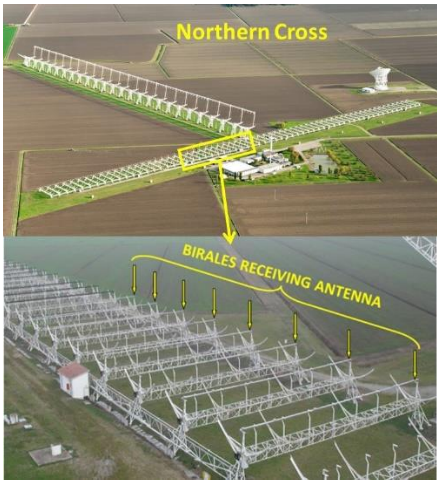

Fig. 3. BIRALES RX

BIRALES operates in survey mode; thus, once the pointing strategy has been decided, the orientation of both TX and RX is kept fixed throughout the observation and the tracking of the object is done electronically inside the Field of View (FoV).

BIRALES owns two different systems. On one hand, in order to obtain Doppler Shift (DS) and signal to noise ratio profiles (SNR), the TX radiates an umodulated continuous wave at 410.085 MHz. On the other hand, Slant Range (SR) is measured thanks to a pulse compressed chirp, centered at 412.5 MHz and with a bandwidth of 4 MHz, transmitted by the TRF.

Based on the array configuration of the receiver, in the past its FoV was populated with multiple narrow independent beams. This is achieved by means of digital beamforming in the receiver back-end. The number and location of the beams is up to the user, but it is usually set to 32. An example of the resulting multibeam configuration is shown in Fig. 4, where contours define the -3 dB beamwidth of each beam main lobe with respect to the RX main lobe maximum gain. The blue ellipse represents the single analogue beam used for slant range measurements.

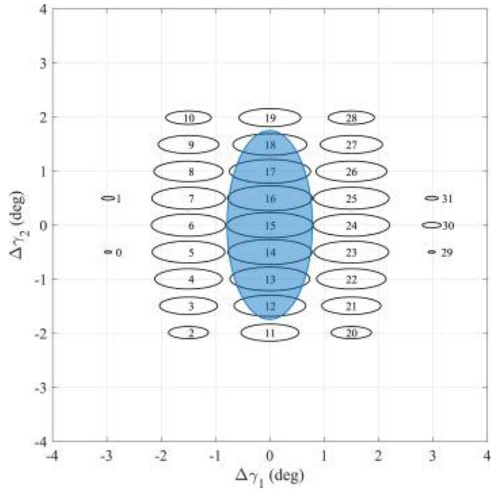

Fig. 4. Multibeam configuration of BIRALES receiver.

Based on the illuminated beams sequence, it is theoretically possible to determine the trace of the transiting object in the FoV. However, the mutual spacing among array elements is longer than half wavelength in both E-W and N-S directions and this introduces a sampling ambiguity, which results in multiple grating lobes for any beam. At this point it is difficult to determine whether the illumination has to be linked to the main or to a grating lobe.

The Multibeam Orbit Determination Algorithm (MODA) [6] deals with such an issue and aims at reconstructing the track in three phases. First, a filtering action is carried out and the process identifies the best candidate which covers a certain region of the FoV. Then, a refinement phase is performed, which provides a rough estimate of the angular track thanks to an optimization process in a least square sense, where the measured SNRs are matched against the predicted ones (computed thanks to SR measurements). Finally, a second optimization is conducted, in order to fit the orbital mean state, and possibly the Radar Cross Section (RCS), with the angular profile given at the end of the refinement phase and with the SR and DS measurements. The final angular trace and the orbital state (in terms of mean state and covariance) are returned as output.

In synthetic data analysis, this approach is successful in about 95% of the cases, but in real scenarios the procedure turns out to be strongly affected by the signal quality and the process can either converge to a wrong solution or not converge at all. Furthermore, MODA algorithm needs the simultaneous presence of SR and DS information, which are not always available measurements. For this reason, the present work deals with BIRALES track estimation problem in an alternative way.

3. Track reconstruction method for BIRALES

In order to deal with BIRALES track reconstruction problem by overcoming MODA limitations, the present work deepens modern signal processing techniques. The received signal at each antenna can be written as:

$$\boldsymbol{x}(t) = \boldsymbol{a}(\Delta\gamma_1, \Delta\gamma_2)\boldsymbol{s}(t) + \boldsymbol{n}(t) \qquad (1)$$

$\boldsymbol{a}(\Delta\gamma_1, \Delta\gamma_2)$ stands for the steering vector of the source in receiver FoV, where $\Delta\gamma_1$ and $\Delta\gamma_2$ are the angular deviations (azimuth and elevation) with respect to the RX Line of Sight (LoS). $\boldsymbol{s}(t)$ is the temporal envelop of the signal and $\boldsymbol{n}$ is a complex noise. It is possible to compute the signal covariance matrix (CM) at a specific epoch, as:

$$\boldsymbol{R_{xx}}(t) = E\{\boldsymbol{x}\boldsymbol{x}^*\} \qquad (2)$$

The angles, which are time-varying during the total path, are assumed to remain approximately constant during the time interval in which the signal is collected. This assumption is reasonable if the integration time is short enough.

Either from the signal $\boldsymbol{x}$, or from its covariance matrix $\boldsymbol{R_{xx}}$, it is possible to estimate the Direction of Arrival (DOA) $[\Delta\gamma_1, \Delta\gamma_2]$. For this purpose, different approaches exist, such as beamforming-based methods, maximum likelihood and subspace methods. The objective functions of these estimators differ from each other according to hypothesis of the model and the assumptions made on the covariance matrix structure. Consequently, each technique results in a different accuracy and computational burden [7].

To perform OD, track reconstruction shall be as accurate as possible; thus, a super-resolution technique is selected. Similar methods are usually not employed in DOA tracking, as the real-time implementation turns out to be complicated. This is not a drawback for BIRALES, since the whole data can be analyzed in post-processing and no real-time implementation is needed. Particularly, Multiple Signal Classification (MUSIC) algorithm [8] is chosen because it presents a lower complexity than other methods with comparable accuracy. Furthermore, the assumptions the method is based on are generally valid (i.e., knowing the number of objects that are passing through the FoV, and that the sources are uncorrelated). In addition, it is particularly suited to be implemented as an optimization procedure, which is useful if a coarse estimation of the location is known in advance (when the satellite passage prediction is known).

The method exploits the spectral decomposition of the covariance matrix. First, its eigenvectors are ordered according to the related eigenvalue, in descendent order. Known the number of sources N_s, the signal subspace U_s is the one composed by the first N_s eigenvectors and the noise subspace the one composed by the remaining ones. This is formulated in eq. (3):

$$\boldsymbol{R_{xx}} = \boldsymbol{U\Lambda U}^* \quad , \quad \boldsymbol{U} = [\,\boldsymbol{U_s} \quad \boldsymbol{U_n}\,] \quad (3)$$

The present work addresses the scenario in which a single source is observed; therefore, $N_s = 1$ and the signal subspace turns out to be composed of the eigenvector corresponding to the maximum eigenvalue.

The estimate of the location of source in the FoV is then computed by solving the maximization of the function:

$$J(\Delta\gamma_1, \Delta\gamma_2) = \frac{1}{\boldsymbol{a}(\Delta\gamma_1, \Delta\gamma_2)^* \boldsymbol{U_n} \boldsymbol{U_n}^* \boldsymbol{a}(\Delta\gamma_1, \Delta\gamma_2)} \quad (4)$$

which represents the array response to the impinging signal.

By this way it is theoretically possible to estimate the DOA at each observation epoch. However, a unique solution is provided only if the mutual distance among array receivers is smaller than half-wavelength. BIRALES array receivers do not respect such a rule and the sampling ambiguity results in multiple spurious peaks, with mutual spacing equal to:

$$\begin{aligned} \Delta\gamma_1 &\simeq \sin^{-1}\left(\frac{i}{d_x}\right) \\ \Delta\gamma_2 &= \sin^{-1}\left(\frac{j}{d_y}\right) \end{aligned} \quad (5)$$

Where d_x and d_y are the distances between receivers, measured in number of wavelengths, while i and j are integer indexes. These peaks all correspond to possible solutions. An example of MUSIC pattern in is shown in Fig.5.

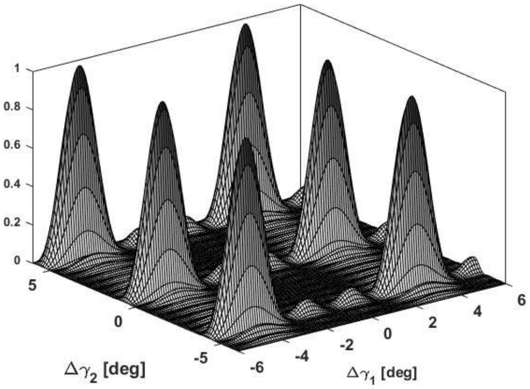

Fig. 5. MUSIC array response.

Proper strategies are to be planned in order to solve such a problem.

4. Music Approach for Track Estimate and Refinement

In order to reconstruct the correct track by solving the estimation ambiguity described above, the Music Approach for Track Estimate and Refinement (MATER) algorithm has been developed. The procedure depends on whether the observed object is catalogued, or it is not.

4.1 Catalogued case

If the transiting object is known, for instance through a Two-Line Element (TLE), a prediction of the orbit is available. Thus, the predicted DOA of the passage during the transit can be exploited as first guess in the maximization of Eq. 4. So, no ambiguity problems arise and the procedure turns out to be as follows:

1. At each observation epoch, find the local maximum of Eq. 4, using the initial $\boldsymbol{\Delta\gamma^0}$ from the prediction. The result is represented in Fig. 6, which shows the estimated DOAs compared to the real track.
2. Perform a fit of the angular profile assuming a quadratic trend in time, t_0 being the first epoch of observation:

$$\begin{aligned} \widehat{\Delta\gamma_1}(t) &= a_2(t - t_0)^2 + a_1(t - t_0) + a_0 \\ \widehat{\Delta\gamma_2}(t) &= b_2(t - t_0)^2 + b_1(t - t_0) + b_0 \end{aligned} \quad (6)$$

At this point the angular track is obtained (Fig. 7) and it can be directly used to perform OD.

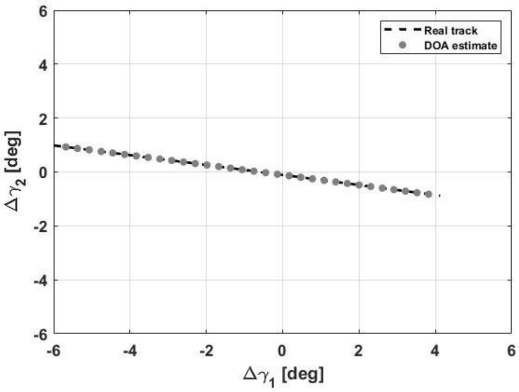

Fig. 6. DOAs estimations in the catalogued case.

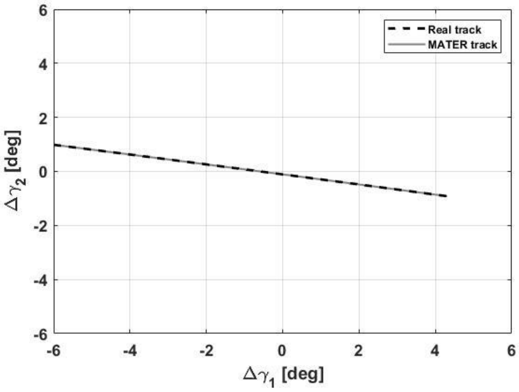

Fig. 7. Track reconstruction in the catalogued case.

4.2 Uncatalogued case

If the passage prediction is not available, the process is less straightforward. Indeed, for the uncatalogued objects CM is the only input, as no passage prediction is available. Thus, it cannot be taken as sure that the maximization of Eq. 4 converges to the correct solution (that is, the correct DOA), as multiple peaks are present. Past work [9] presented a procedure to solve this ambiguity, by assuming that the source is expected to spend remarkable time in the central region of the FoV: hence, it retains the most central solution time by time and, then, it considers the track which groups most DOAs estimations as the correct one. By this way, ambiguity is generally solved, but in those passages which spend most time in FoV side regions. In order to enhance algorithm performances, the present work describes a more robust and consistent procedure.

First, Eq. 4 is computed on a grid of angular coordinates and N_p peaks, with a mutual distance according to Eq. 5, are identified. N_p is a parameter up to the user and in this work it is set equal to 9. The peaks related to a region outside of the FoV are discarded, while the others represent the first guesses in the maximization of Eq. 4. By this way, multiple DOAs are identified at each epoch, as represented in Fig. 8.

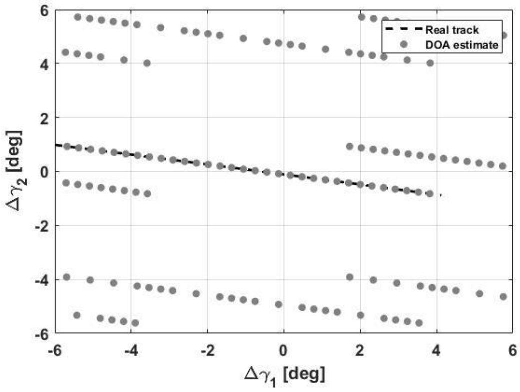

Fig. 8. DOAs estimations in the uncatalogued case.

A clustering process based on Random Samples Consensus (RANSAC) groups the DOAs in parallel tracks and, for each one, a second order regression in time is performed, similarly to Eq. 6. Then, those tracks which cross regions out of the FoV (hence unfeasible solutions) are rejected. At this point, multiple candidates may be still present, like in Fig. 9. It can be noticed that the tracks related to marginal DOAs are not represented, as, after the time regression, turned out to cross regions out of the FoV.

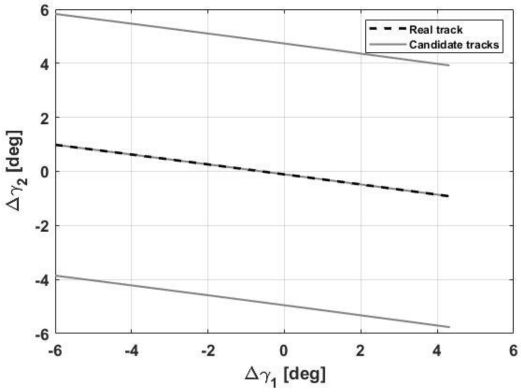

Fig. 9. Track candidates in the uncatalogued case.

In order to identify the correct solution, an OD criterion is here presented. First, OD is performed, according to the radar procedure proposed in [10], for each track candidate. Then, the algorithm computes Mahalanobis distance between the measured quantities and the determined orbital state projected onto the measurement space. The mean among all the Mahalanobis distances of the transit is taken as a correlation index and the correct track is identified as the candidate featuring the best one, that is the lowest one. Under a logical point of view, the correct solution is selected as the one most consistent with the measurements.

5. Analysis and results

5.1 Numerical simulations

In order to validate the approach, MATER algorithm is tested on a synthetic dataset composed of 899 LEO passages, whose projections onto the measurement space are spread on the entire FoV. The pointing directions of transmitter and receiver are selected in order to observe as most objects as possible [6]. Both SR and DS measurements are Gaussianly distributed, with mean equal to the prediction according to the TLE, and standard deviation coherent with sensor accuracy. CM is generated for each passage instant, according to Eq. 1 and Eq. 2. Referred to Eq. 1, the signal $\boldsymbol{s}(t)$ is generated from SNR, which is simulated based on orbit geometry and considering a 1 m2 RCS (with an associated Gaussianly distributed noise, such that both RCS fluctuations and satellite tumbling are simulated). CM noise $\boldsymbol{n}(t)$ is modelled through a Gaussian distribution with zero mean.

Starting from these data, MATER algorithm is run and performances are assessed in terms of convergence rate, mean OD correlation index ζ and mean values of root mean square error (RMSE) $\varepsilon_{\Delta\gamma_1}$ and $\varepsilon_{\Delta\gamma_2}$, for the two angular coordinates. Results for catalogued and uncatalogued cases are reported in Tab. 1. It is possible to appreciate both 100% convergence rate and high-level accuracy, both in terms of mean correlation indexes and RMSEs.

Table 1. Numerical tests result

	Success	ζ	$\varepsilon_{\Delta\gamma_1}$	$\varepsilon_{\Delta\gamma_2}$
Cat.	100 %	6.7e-02	5.3e-04°	4.2e-04°
Uncat.	100 %	6.8e-02	5.1e-04°	4.2e-04°

5.2 Real observation

MATER algorithm was applied during the re-entry campaign of the Chinese launcher CZ-5B R/B (more known as Long March) occurred in May 2021. European SST monitored such an event and BIRALES was the most contributing sensor. During the campaign, the closest the satellite to the re-entry epoch, the less reliable passage prediction (provided by TLE) was and a procedure suitable for uncatalogued object was to be exploited. The last transit observable from the receiver station occurred on 9th of May, at 00:33:43 (less than 2 hours before satellite decay) and it was monitored through the approach described in this work.

Fig. 10 reports the DOAs estimated along the passage. The estimations are few, to two reasons: on one hand, the signal was very weak, as the transit was low on the horizon (so large SR); on the other hand, BIRALES processing chain is currently designed with a multibeam logics, which is not optimal to run MATER approach.

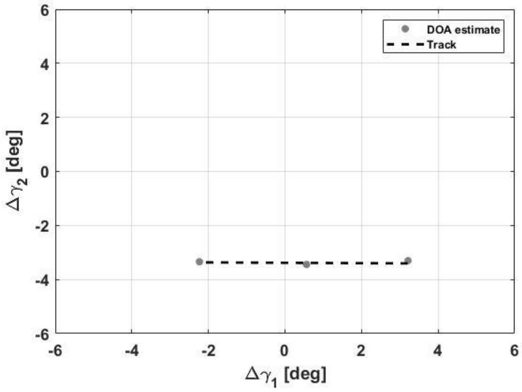

Fig. 10. DOAs estimations of Long March last transit on BIRALES.

For this real case scenario, it is not possible to evaluate track reconstruction accuracy in terms of RMSE, as the passage prediction is not reliable, due to the high-level orbital perturbation the satellite experiences in the last phase of re-entry. The dashed line represents the predicted track which is slightly modified (according to reasonable assumptions), in order to evaluate if DOAs are correctly estimated. It is possible to state that the estimations are noisy, but consistent.

6. Discussion

MATER shows appreciable performances in numerical tests, both in catalogued and uncatalogued case. Also, the angular RMSE is a bit lower along $\Delta\gamma_2$ than along $\Delta\gamma_1$ and this can be linked to the larger number of array elements in the former direction, which grants higher resolution.

As stated above, in the real case scenario the reconstructed track is consistent with the expected orbital trajectory, but it is difficult to evaluate the accuracy. Anyways, it can be appreciated that the approach presented in this paper can work in very challenging scenarios, by also remedying multibeam approach limitations in re-entry campaign, in which satellite dynamics is very perturbed and predictions turn out to be unreliable. The estimations are noisy, but consistent and performances are expected to improve, by modifying the way in which BIRALES processes signal.

7. Conclusions

During space objects observation campaign, track reconstruction is of utmost importance for accurate OD. This activity is particularly problematic for BIRALES sensor because of the intrinsic ambiguity of the receiver array. This paper presented a new processing scheme of the system which relies on modern estimation techniques. The performances were assessed through numerical simulations, starting from a synthetic dataset of LEO passages that are observable considering the bistatic geometry and interest the entire receiver FoV. The analysis highlighted that the track of all objects can be estimated correctly with high-level accuracy. Then, the approach demonstrated its potential in Long March re-entry campaign, which represents a very challenging scenario, both for signal quality during the transit and for passage prediction unreliability.

In future, BIRALES process chain will be properly modified to improve MATER approach performances. Furthermore, detection of multiple objects which are simultaneously present in receiver FoV will be addressed.

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