Operational application of an adaptive beamforming approach for angular track estimation in survey radars

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Abstract

In the last years many space surveillance initiatives started to deal with the resident space objects overpopulation, by relying on the use of on-ground sensors. In particular, survey radars allow to first characterize the target orbit from a single transit, through measurements which are Doppler shift, slant range and angular profile. In this framework, the Music Approach for Track Estimate and Refinement (MATER) algorithm was developed to compute the angular track in survey radars provided with an array receiver, such as BIRALES sensor, which represents the baseline of the work.

The paper presents MATER algorithm and its extension to derive the angular track when multiple sources are simultaneously detected. This is fundamental in survey applications, fragments cloud observations and proximity operations monitoring. Real BIRALES observations are finally discussed.

1 Introduction

In the last decades, in orbit population has become one of the main problems for space agencies and institutions all around the world. Among orbiting satellites, only a minor fraction can be classified as cooperative, whereas the majority constitutes space debris. This category includes inactive satellites, rocket bodies and fragments of all sizes [1]. The so-called space debris pose threats to human space activities, and so different strategies are being implemented to guarantee safe operations. The Inter-Agency Space Debris Coordination Committee (IADC) is in charge of coordinating the Space Surveillance and Tracking (SST) international activities related to the issues of man-made and natural debris in space. Europe deals with this topic through two programs: the European Space Agency (ESA) Space Situational Awareness (SSA) program [2] and the European Space Surveillance and Tracking (EUSST) framework [3]. The latter groups European national agencies and institutions from 15 member states and is in charge of carrying out the following services: collision avoidance [4], fragmentation analysis [5][6] and re-entry prediction [7]. These services exploit measurements obtained through ground-based sensors, both optical, laser and radars [3], which are then used to conduct orbit determination procedures [8]. The last ones are commonly used to track debris flying in Low Earth Orbit (LEO), and can be distinguished in tracking radars, such as TIRA and MFDR, and survey radars, like GRAVES, S3TSR and BIRALES.

This work presents the new data processing chain used by BIRALES to compute the angular track in the receiver array through an algorithm embedding an adaptive beamforming technique. This approach takes in input the signal Correlation Matrix (CM) resulting from a channelization strategy.

The paper is organized as follows. First, the new algorithm is presented and its application to SST services is discussed based on simulations. Then, the new architecture based on the channelization strategy is outlined. Finally, the performance of the approach is assessed based on real data applications.

2 BIRALES

BIRALES stands for Bistatic Radar for LEO Survey, and it is an Italian radar sensor operating in a bistatic configuration, with a baseline of 580 km [8][10][11]. 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 a portion of the Norther Cross of Medicina Radiotelescope, located in Medicina (near Bologna). The TX (Figure 1) is a single parabolic antenna able to transmit a theoretical 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.

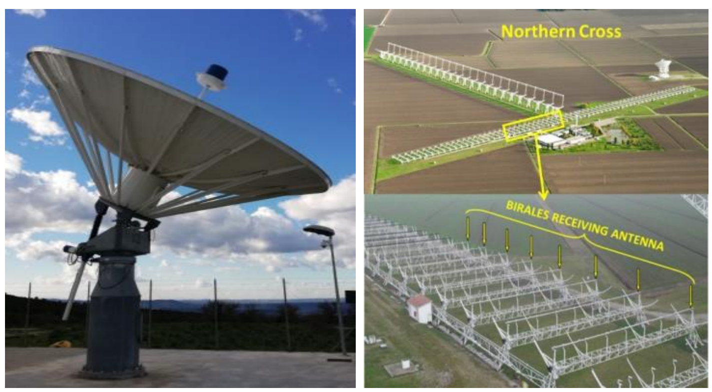

Figure 1. BIRALES TX (left) and RX (right).

The Northern Cross Radio Telescope is a T-shaped radar array, and its cylinders can be pointed in elevation only. In particular, the section currently dedicated to BIRALES operations includes 8 out of 64 cylinders (Figure 1). Each cylinder contains 4 sensors arranged along the focal line, with a spacing of 5.67 m along E-W direction. Hence, the BIRALES receiver consists of a planar array of 32 elements with a half-power beamwidth of 6.6 X 5.7 deg.

BIRALES owns two different systems: an umodulated continuous wave (CW) at 410.085 MHz, used to measure Doppler shift (DS), and a compressed chirp, centered at 412.5 MHz and with a bandwidth of 4 MHz, for slant range (SR) measurements. Operationally, the CW is also used to generate angular track measurements according to a static beamforming technique [12].

The system is undergoing an upgrade process, with the construction of a new transmitting station and the inclusion of the entire North-South branch of the Northern Cross (64 cylinders in total). This will result in a detection sensibility improvement and in a larger field of view (FoV) of both the transmitter and the receiver [13]. Overall, this will allow to improve the cataloguing performance, both in terms of number of transits detected and in the minimum detectable size. Besides this, in recent years a new approach has been developed to generate the angular track through an adaptive beamforming technique [14], which allows a more robust measurement accuracy with respect to the current methodology mentioned above. The new approach for the angular track measurement is the topic of the current paper and is better discussed in the next sections.

3 Music Approach for Track Estimate and Refinement

To reconstruct the angular track measurements in BIRALES receiver FoV, the Music Approach for Track Estimate and Refinement (MATER) algorithm has been developed [14]. It first estimates the signal Directions of Arrival (DOAs) through MUSIC algorithm [16], and then clusters them to compute the angular profile, by possibly solving the ambiguity problem in the uncatalogued scenario, as further discussed below.

3.1 MATER algorithm

The received signal at each antenna can be written as [15]:

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

In Eq. 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 receiver 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 CM at a specific epoch as:

$$\boldsymbol{R_{xx}}(t) = E\{\boldsymbol{x}\boldsymbol{x}^{\boldsymbol{H}}\} \tag{2}$$

From the signal CM $\boldsymbol{R_{xx}}$, it is possible to estimate its 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 [15]. In this work, the Multiple Signal Classification (MUSIC) algorithm [16] is used, which first decomposes the CM in the signal and the noise subspaces. Known the number of sources N_s, the signal subspace $\boldsymbol{U_s}$ 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:

$$\boldsymbol{R_{xx}} = \boldsymbol{U\Lambda U^H} \quad , \quad \boldsymbol{U} = [\,\boldsymbol{U_s} \quad \boldsymbol{U_n}\,] \tag{3}$$

The estimate of the location of the i-th source, related to the eigenvector $\boldsymbol{U_{s_i}}$, in the FoV is then computed by solving the maximization of the function:

$$J(\Delta\gamma_1, \Delta\gamma_2) = \left[\boldsymbol{a}(\Delta\gamma_1, \Delta\gamma_2)^{\boldsymbol{H}} \left[\boldsymbol{I} - \boldsymbol{U_{s_i}}\boldsymbol{U_{s_i}^H}\right] \boldsymbol{a}(\Delta\gamma_1, \Delta\gamma_2)\right]^{-1} \tag{4}$$

which represents the array response to the impinging signal.

By this way it is theoretically possible to estimate the DOA at each observation epoch, and then cluster them to retrieve the angular track in the receiver FoV.

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:

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

Where d_x and d_y are the distances between receivers, measured in wavelengths, while i and j are integer indexes indicating the i-th and j-th grating lobe, in East-West and North-South directions, respectively. These peaks all correspond to possible solutions. An example of MUSIC patterns for one single and two detected sources is represented in Figure 2.

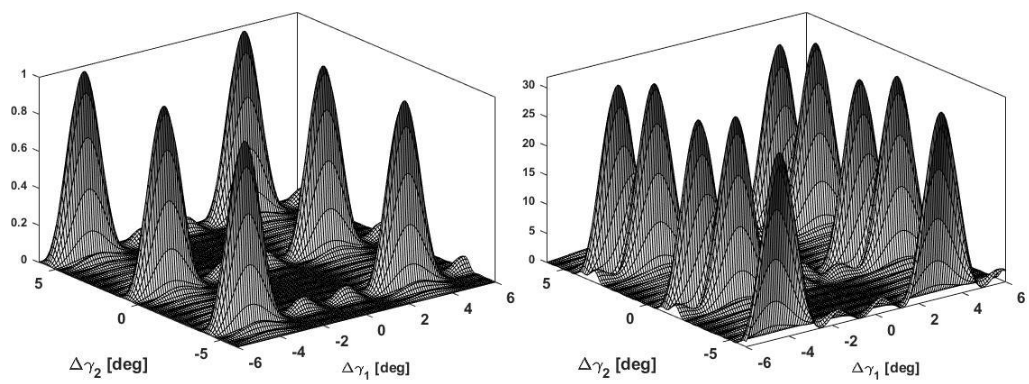

Figure 2. MUSIC array response for one single (left) and two (right) detected sources.

In the catalogued case, a transit prediction is available, and it can be used to solve the ambiguity. Then, a quadratic regression in time, for the two angular coordinates separately, provides the angular track profile (as represented in Figure 3 for a simulated single source scenario). In the uncatalogued case instead all the solutions must be kept, and clustering the estimated DOAs results in multiple track candidates for each source detected (as represented in Figure 4 for the same simulated single source scenario as in Figure 3).

Most populated cluster criterion

The first criterion is based on the assumption that the detected source spends a remarkable portion of the transit in a central region of the receiver FoV. Given that, for each source, at each epoch the most central DOA estimation is kept. At the end, the solutions are clustered, and the cluster presenting most estimations is considered as correct.

This method provides a straightforward way to solve the ambiguity problem. However, it turns out to be not fully reliable for transits which do not cross the centre of the receiver FoV, given its assumption.

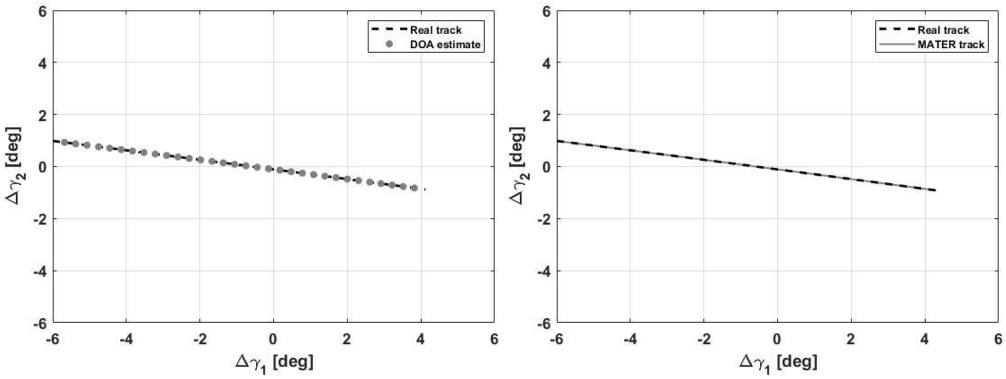

Figure 3. DOAs estimations (left) and track reconstruction (right) in the catalogued case.

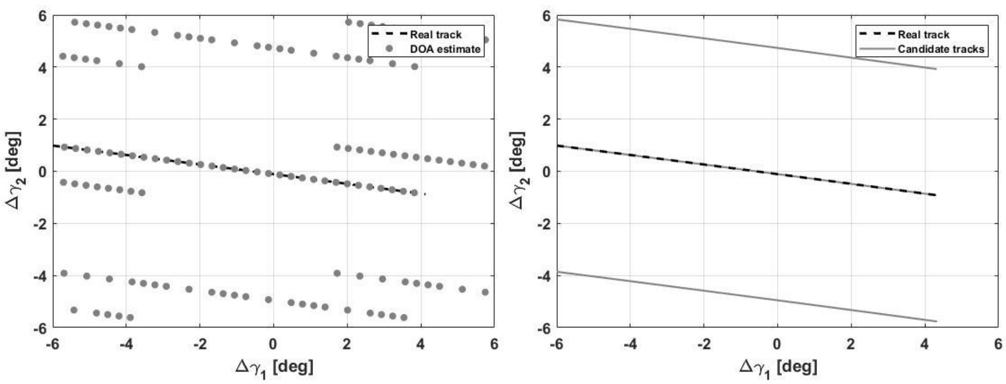

Figure 4. DOAs estimations and angular track candidates in the uncatalogued case.

To identify the correct angular track candidate, different criteria have been developed and presented in [14][17], and are recapped as follows.

Delta-k technique based criterion

From Eq. 5 it is clear that two signals at different frequencies experience different shifts of the ambiguous estimation with respect to the correct solution. Based on this, the *delta-k* based criterion compare, at each time and for each $\boldsymbol{U}_{s_i}$ eigenvector, two sets of DOAs computed from two different CMs, each one related to a specific frequency. Then, the criterion selects the estimation presenting the smallest angular deviation. The correct estimation, theoretically no-shifting from a set to the other, presents an angular difference because of the noise effect. This procedure is repeated for all the detection epochs, and the solutions are clustered. At the end, for each source, the cluster presenting the most DOAs is selected.

Such an approach allows to compute the angular track in a straightforward way. However, it needs the possibility to compute the signal CMs at two different frequencies, which is not the current case for BIRALES, as the CMs are created on one single CW signal.

Orbit determination criterion

For each angular track candidate, an Initial Orbit Determination (IOD) is conducted. To this end, the algorithm presented in [18] is exploited, by using either the measured SR, if available, or the SR reconstructed from angles and DS. In the latter situation, the approach illustrated in [19] is exploited. Then, for each IOD solution the correlation with respect to the measurements used to generate them is computed, and the one featuring the best correlation index is considered as correct, together with the related angular track.

While the SR is not always available, DS is measured each time the angular track candidates are present, as it is derived from the same processed signal. Thus, this method can always be applied. However, the SR estimation from DS and angles can result unreliable because of the measurements noise.

SNR criterion

For each IOD result computed from the track candidates, a synthetic Signal to Noise Ratio (SNR) along the transit can be computed and compared to the one actually recorded. Then, the SNR trend best matching the real profile is selected, and the angular track candidate connected to it is returned. In [14] this criterion is assessed as the most robust. However, in operational application, besides the drawbacks also affecting the orbit determination criterion, it needs the detected power information to compute the real SNR, which is not always available.

3.2 MATER in multiple sources scenario

MATER allows to reconstruct the angular tracks of multiple sources simultaneously detected. This typically occurs during survey applications, fragmentations cloud and proximity operations monitoring [20][21]. In this scenario, the same process as described in Sec. 3.1 can be used after having identified the number of detected sources at each time instant.

Figure 5 and Figure 6 show the MATER phases, for the catalogued and the uncatalogued case respectively, for a scenario in which the detections of 4 sources overlap in time. For the uncatalogued case, the ambiguity is solved through the *delta-k* technique-based criterion.

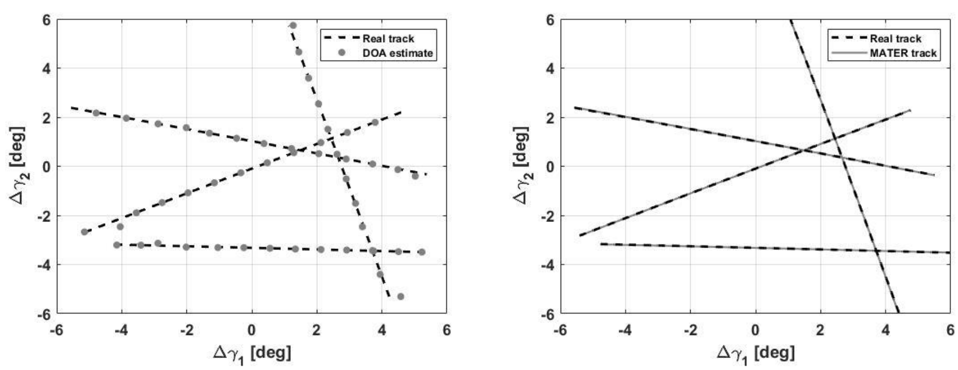

Figure 5. DOAs estimations (left) and track reconstruction (right) in the catalogued case for the multiple sources scenario.

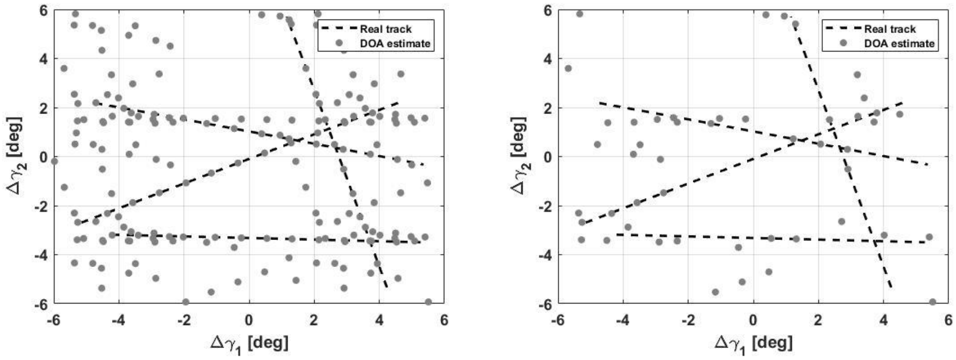

Figure 6. DOAs estimations and angular track candidates in the uncatalogued case for the multiple sources scenario.

4 Channelization strategy

To improve MATER performance from the CM, the signal shall be properly pre-processed. To this end, a channelization strategy has been designed to reduce the receiver bandwidth from 85.5 kHz to 10.43 Hz. In the channel related to the signal frequencies, this action increases the signal power used to create CM, which has two main effects:

1. Increase the number of detectable objects.
2. Retrieve a more accurate angular track in MATER algorithm.

It is worth to point out that, when two targets are simultaneously detected, their signal power can be detected from the same channel only if they have similar relative velocities with respect to the sensor, and this can occur during fragments cloud and proximity operations monitoring. However, these relative velocities are generally different, and so, at a specific epoch, different channels detect the signal coming from different sources. Thus, a specific CM history is computed for each source, reducing the multiple sources scenario to a single one.

The final operational workflow is designed in two steps:

1. The detection block acquires the detected signal frequencies based on the 85.5 kHz bandwidth, providing the DS trend for a detected source transit.
2. At each transit epoch, the channel related to the frequencies detected at each epoch is used to create the CM related to that instant. This operation can be done with a margin, that is creating a set of CMs for the channels around the identified one, and then retaining the CM featuring the maximum CM eigenvalue.
3. Calibrate the signal CM, both instrumentally and geometrically.

At this point, MATER algorithm is run as described in Sec. 3.

5 Operational applications

The current section illustrates the operational application of MATER for BIRALES data.

5.1 Single sources

The new approach has been validated on a data set of 46 LEO satellites whose ephemerides are accurately known. Results are reported in Table 1, where it is possible to observe that both catalogued and uncatalogued scenarios feature similar performance, and the latter (applied in this case through the maximum occurrence criterion) always grants convergence to the correct solution. However, these transits have been observed such that they cross the central region of the receiver FoV, and this makes the uncatalogued case easily solvable through the above-mentioned criterion.

	$\Delta\gamma_1$	$\Delta\gamma_2$
Catalogued	9.6e-02°	1.5e-01°
Uncatalogued	9.8e-02°	1.5e-01°

Table 1. Results of real data validation of MATER algorithm.

The process has been used also to monitor the re-entry of Aeolus satellite of the European Space Agency, whose on-ground re-entry occurred on July 28th, 2023. Figure 7 shows the angular track computed for the observation on July, 27th. In this case, the measurement was computed adopting the uncatalogued case approach as the target was being maneuvered during the observation. It can be noticed that the estimated track, which was in advance with respect to the prediction, is aligned towards the reference one.

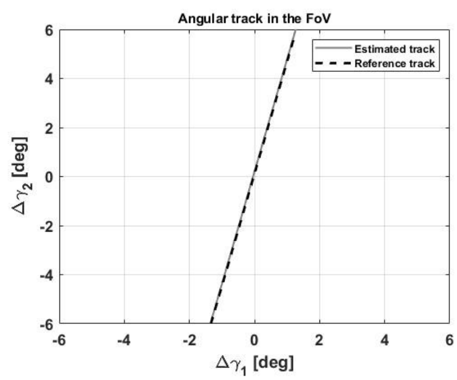

Figure 7 Aeolus satellite re-entry : angular track computed from an observation on July 27th, 2023.

5.2 Multiple sources

The approach was applied on December 2nd, 2022, to observe SARAL satellite. During the acquisition, the satellite was detected, but an interference occurred, whose signal was stronger than the one reflected by the target. MATER algorithm was run in the multiple sources scenario, searching for 2 sources. Figure 8 shows the DOA estimated by the process: it is possible to notice the estimations related to the target which align towards the reference track, as well as some DOAs forming four clusters with circular shape, which are related to the interference signal. Based on this result, it was possible to understand that the interference signal was stayed quite fixed during the acquisition and additional studies identified that it was coming from Cassiopea-A, the most effective radiosource which can be detected by Medicina radiotelescope.

The channelization strategy described in Sec. 4 partially mitigates this problem, as it increases the signal for a specific target detected.

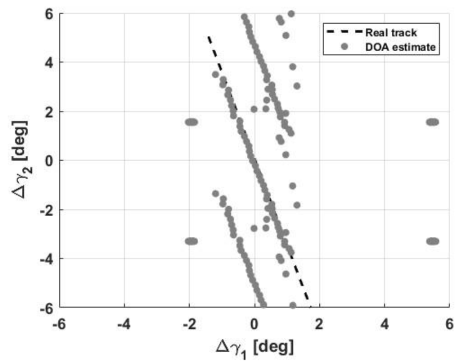

Figure 8 SARAL satellite observation: signal DOAs estimated considering 2 sources.

6 Conclusions

The work illustrated the operational application of MATER algorithm, which is devoted to reconstruct the angular track measurement in survey radars provided with an array receiver. This new approach is based on an adaptive beamforming technique, which also allows to compute the angular track when multiple objects are simultaneously detected. A channelization strategy allows to enhance the measurements quality. The validation on real data acquired by BIRALES is also reported.

In the future, this new approach will be operationally implemented in BIRALES receiver back-end. Also, the pipeline will be extended to include the additional receiver elements which will be added to the array portion involved in the upgrade of the receiver station.

7 Acknowledgement

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