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

Introduction

Current in-orbit overcrowding [1]

- 8800 satellites still functioning
- 35340 tracked space debris
- >130 millions estimated space debris

On-ground means to maintain space objects catalogue, with tracking and survey sensors

Fragmentations

CZ-6A RB and H-2A DEB fragmentations:
- CZ-6A RB explosion: November 12°, 2022
- H-2A DEB: November 17°, 2022
- Evidence of mutual implication [2]

[1] ESA website, Space debris by the numbers, Access 21/11/2023
[2] M.F. Montaruli et al., Assessment of the CZ-6A RB and the H-2A DEB fragmentation events, EUCASS 2023
OUTLINE

01 BIRALES data processing
02 MATER - Catalogued object
03 MATER - Uncatalogued object
04 Operations – Real observations
05 Conclusions
01 BIRALES
DATA PROCESSING
Blisatic Radar for Leo Survey (BIRALES)
Static beamforming \([3]\)

**Disadvantage:** both main lobes and grating lobes appear in sensor FoV

BIRALES: multibeam approach

Static beamforming \(^3\)

Disadvantage: both main lobes and grating lobes appear in sensor FoV

**BIRALES: multibeam approach**

**Static beamforming**\(^3\)

**Disadvantage**: both main lobes and grating lobes appear in sensor FoV

BIRALES: adaptive beamforming approach

Static beamforming \cite{3}

Adaptive beamforming

Medicina (Bologna)  
Salto di Quirra (Sardinia)
BIRALES: adaptive beamforming approach

**MUSIC** - **MUltilple Signal Classification** \(^{[4]}\)

Raw signal

\[\text{Covariance matrix} \rightarrow \text{MUSIC}^{[2]} \rightarrow \text{DOA estimation}\]

BIRALES: adaptive beamforming approach

MUSIC - MUltiple SIgnal Classification [4]

Direction of Arrival (DOA)

Raw signal

Angular track

Covariance matrix → MUSIC [2] → DOA estimation

DOA ambiguity problem

DOA solution is unique if distance between antennas is less than $\lambda/2$

- Presence of multiple DOA estimates
- Ambiguity solving criteria needed

Signal DOA
MATER
CATALOGUED OBJECT

POLITECNICO MILANO 1863
Music Approach for Track Estimate and Refinement (MATER)

Music Approach for Track Estimate and Refinement (MATER)

Catalogued case

Signal covariance matrix → Estimate DOAs for each epoch → State prediction

Music Approach for Track Estimate and Refinement (MATER)

Catalogued case

Signal covariance matrix → Estimate DOAs for each epoch → State prediction → Regression → Final track

Music Approach for Track Estimate and Refinement (MATER)

Catalogued case

Signal covariance matrix → Estimate DOAs for each epoch → Regression → State prediction → Final track

Numerical Validation
- 899 NORAD LEO passages
- Entire FoV involved
- Accuracy: 1e-03 – 1e-02 deg

MATER
UNCATALOGUED OBJECT
Music Approach for Track Estimate and Refinement (MATER)

**Uncatalogued case**

- Signal covariance matrix
- Estimate DOAs for each epoch
- State prediction

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case

Signal covariance matrix

Estimate DOAs for each epoch

Clustering based on RANSAC

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case

- Signal covariance matrix
- Estimate DOAs for each epoch
- Clustering based on RANSAC
- Ambiguity solving criterion

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case

Signal covariance matrix

Estimate DOAs for each epoch

Clustering based on RANSAC

Ambiguity solving criterion

- Exploit additional data
  - DS and/or SR to run a IOD for each candidate track
  - Compare the predicted and real SNR
- Statistical approach
- Signal processing approach

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case
- Signal covariance matrix
- Estimate DOAs for each epoch
- Clustering based on RANSAC
- Ambiguity solving criterion

Exploit additional data
Statistical approach
Signal processing approach

Music Approach for Track Estimate and Refinement (MATER)

- Uncatalogued case
  - Signal covariance matrix
  - Estimate DOAs for each epoch
  - Clustering based on RANSAC
  - Ambiguity solving criterion

- Exploit additional data
- Statistical approach
- Signal processing approach

\[ \delta^n > \delta_{\lambda 2} - \delta_{\lambda 1} \]
Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case

- Signal covariance matrix
- Estimate DOAs for each epoch
- Clustering based on RANSAC
- Ambiguity solving criterion

- Exploit additional data
- Statistical approach
- Signal processing approach

Numerical Validation
- Entire FoV involved
- Nominal and sensitivity analysis
- Accuracy: 1e-03 – 1e-02 deg

04 OPERATIONS
REAL OBSERVATIONS
Operations

ISS transit

Previous signal processing chain:
- Still designed for static beamforming
- Very noisy covariance matrices

Only large objects with small SR

- April 28°, 2021
- Accuracy: 1e-02 - 1e-01 deg

Array response

Operations

3rd Long March re-entry

- From October 31st to November 4th, 2022
- First operational involvement in SST services

November 1\textsuperscript{st}, 2022
h. 08:40 UTC

November 2\textsuperscript{nd}, 2022
h. 08:24 UTC

November 4\textsuperscript{th}, 2022
h. 07:29 UTC
Operations

SARAL transit

- December 2°, 2022
- Target: SARAL (norad ID 39086)
- Radiosource: Cassiopea-A
Operations – new processing pipeline

- Split the receiver bandwidth in multiple channels
- Signal power increase enhances the detection rate and the angular track accuracy
- Multiple sources simultaneously detected are processed separately

8192 channels → Detection block → Channel selected → Correlate

$BW_{RX} \sim 85000 \, Hz$

$BW_{RX} \sim 10 \, Hz$

$SNR \propto \frac{1}{BW_{RX}}$

Angular track accuracy
Operations – new processing pipeline

Aeolus re-entry campaign

- July 24°-28°, 2023
- The target was maneuvering during the observation
- Uncatalogued case
Operations – validation

Calibrator

- ILRS and DORIS catalogue
- 46 observations of LEO satellites

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<tr>
<th></th>
<th>$\Delta \gamma_1$</th>
<th>$\Delta \gamma_2$</th>
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<tbody>
<tr>
<td>Catalogued</td>
<td>9.6e-02°</td>
<td>1.5e-01°</td>
</tr>
<tr>
<td>Uncatalogued</td>
<td>9.8e-02°</td>
<td>1.5e-01°</td>
</tr>
</tbody>
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Error will be reduced by compensating the elevation-depending distortion (ongoing activity)
Conclusions

To recap:

- Architecture defined
- Validation campaign
- First operational involvements in SST services
- Multiple sources simultaneously detected (fragmentations, proximity operations)

Next steps:

- Compensation of the elevation-depending distortion
- Operational architecture implementation
- RSO characterization
- Admissible Regions approach to solve ambiguity in DOA estimation
MATER – Admissible Region Approach

- Optical AR\cite{6} for each candidate
- Conversion to bistatic plane (Virtual Debris)
- Cross check with DS and SR

\cite{6} G. Tommei et al., Orbit determination of space debris: admissible regions, Celestial Mechanics and Dynamical Astronomy, 2007.
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THANK YOU FOR THE ATTENTION!
ANY QUESTION?

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