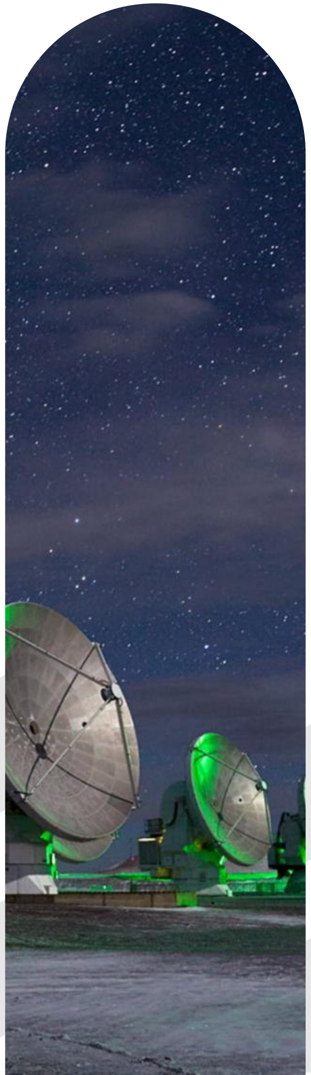
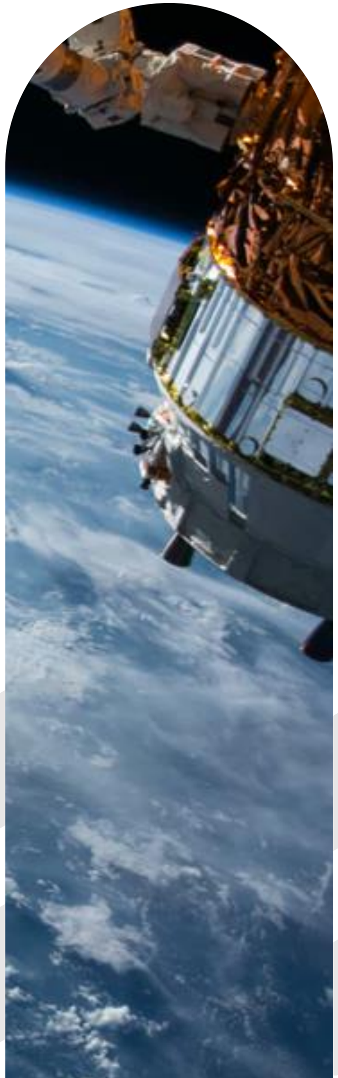
Operational application of an adaptive beamforming approach for angular track estimation in survey radars

M.F. Montaruli, M.A. De Luca,
P. Di Lizia, M. Massari, S. Tebaldini,
G. Bianchi, G. Pupillo, G. Naldi,
D. Cutajar, A. Magro, K. Zarb Adami





Introduction

Current in-orbit overcrowding [1]

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

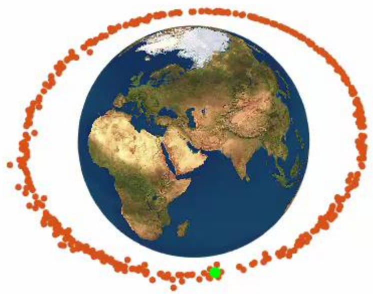
SST services

⇨ On-ground means to mantain 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]

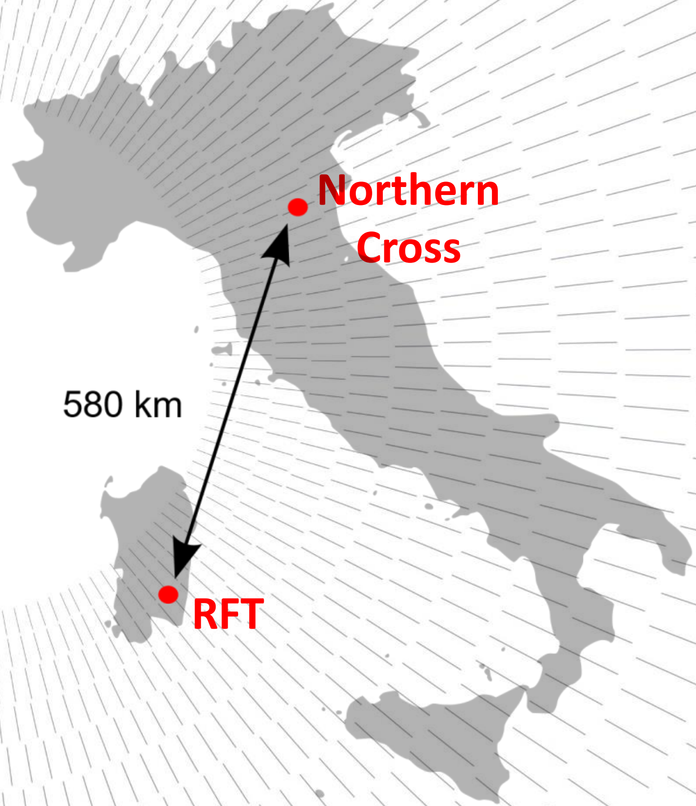


[1] *ESA website, Space debris by the numbers, Access 21/11/2023*
[2] *M.F. Montaruli et al., Assessment of the CZ-6A RB and the H-2A DEB fragmentation events, EUCASS 2023*

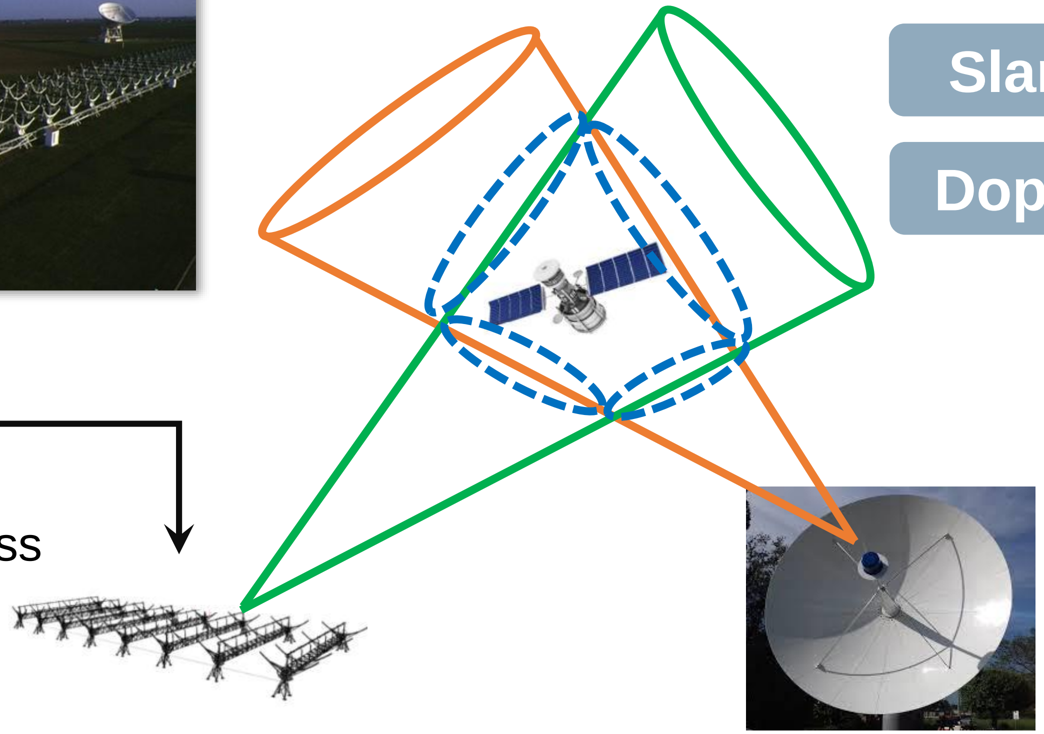
OUTLINE

01 BIRALES
DATA PROCESSING

BIstatic Radar for Leo Survey (BIRALES)



Northern Cross
(Bologna)



RFT
(Sardinia)

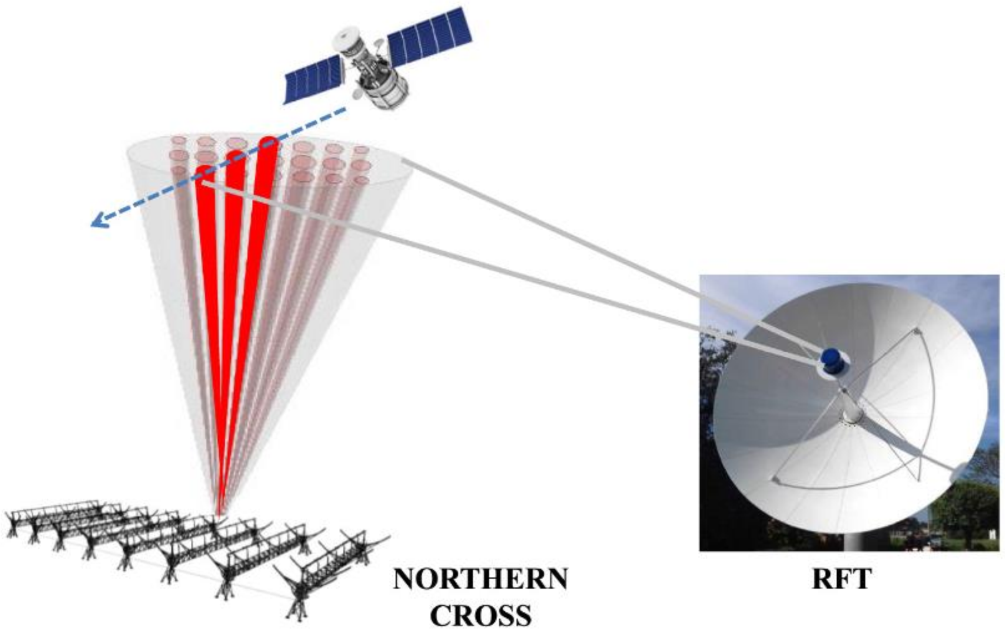
Angular profile

Slant Range

Doppler Shift

BIRALES: multibeam approach

Static beamforming [3]

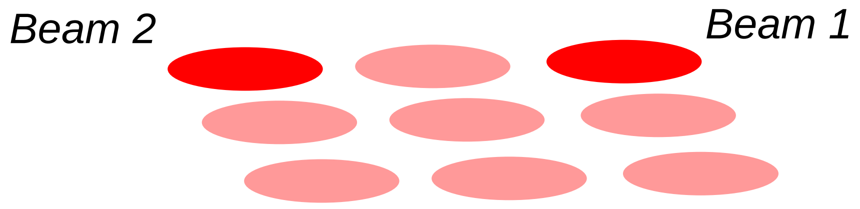


Medicina (Bologna)

Salto di Quirra (Sardinia)

Angular profile

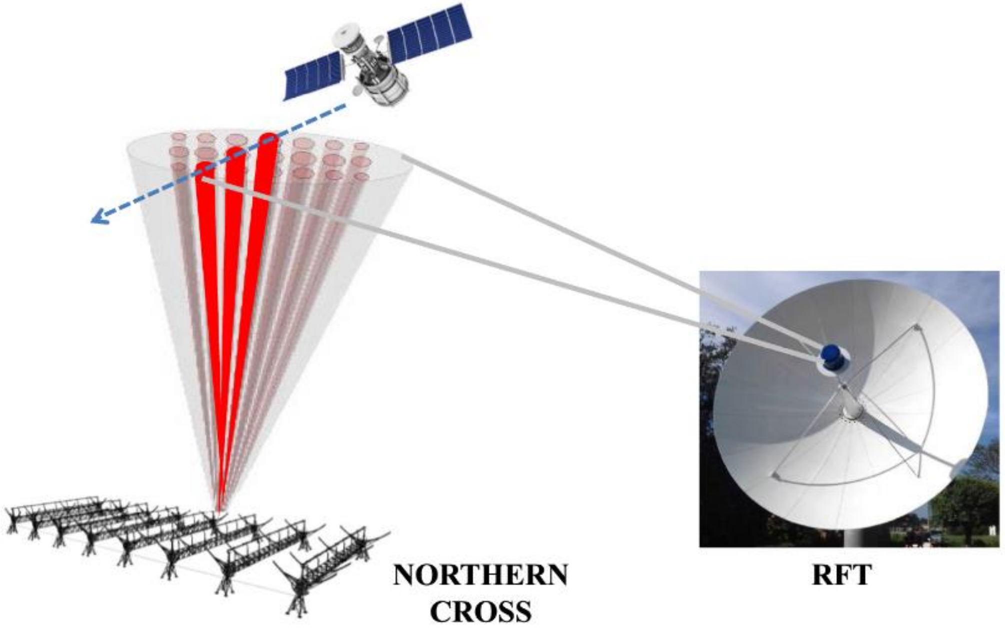
Disadvantage: both main lobes and grating lobes appear in sensor FoV



[3] *M. Losacco et al., Initial orbit determination with the multibeam radar sensor BIRALES, Acta Astronautica, 2020*

BIRALES: multibeam approach

Static beamforming [3]

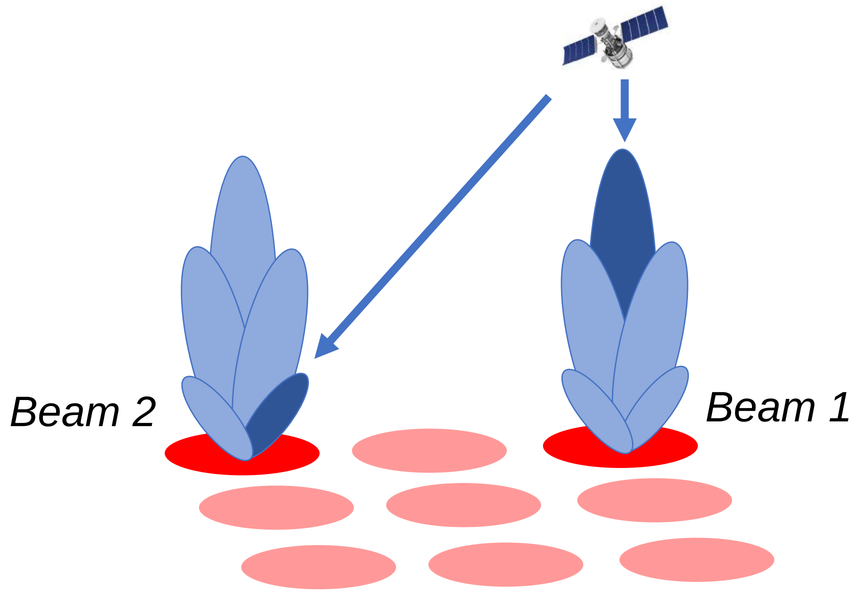


Medicina (Bologna)

Salto di Quirra (Sardinia)

Angular profile

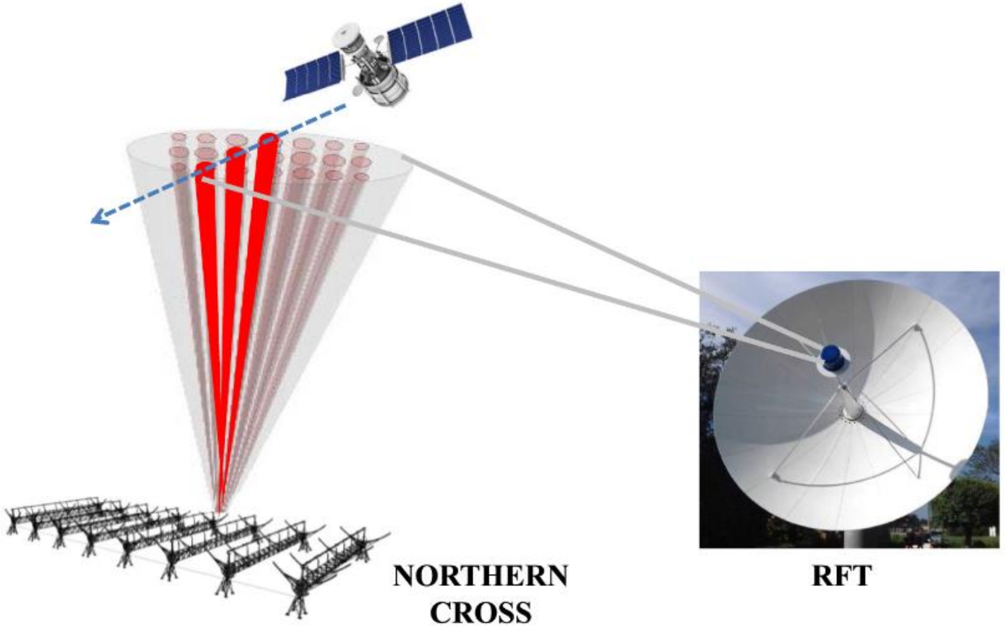
Disadvantage: both main lobes and grating lobes appear in sensor FoV



[3] *M. Losacco et al., Initial orbit determination with the multibeam radar sensor BIRALES, Acta Astronautica, 2020*

BIRALES: multibeam approach

Static beamforming [3]

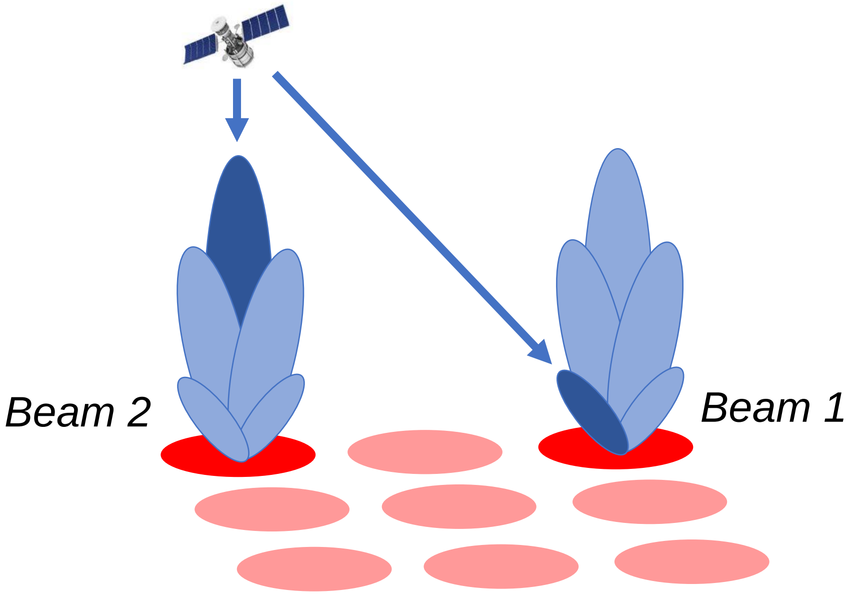


Medicina (Bologna)

Salto di Quirra (Sardinia)

Angular profile

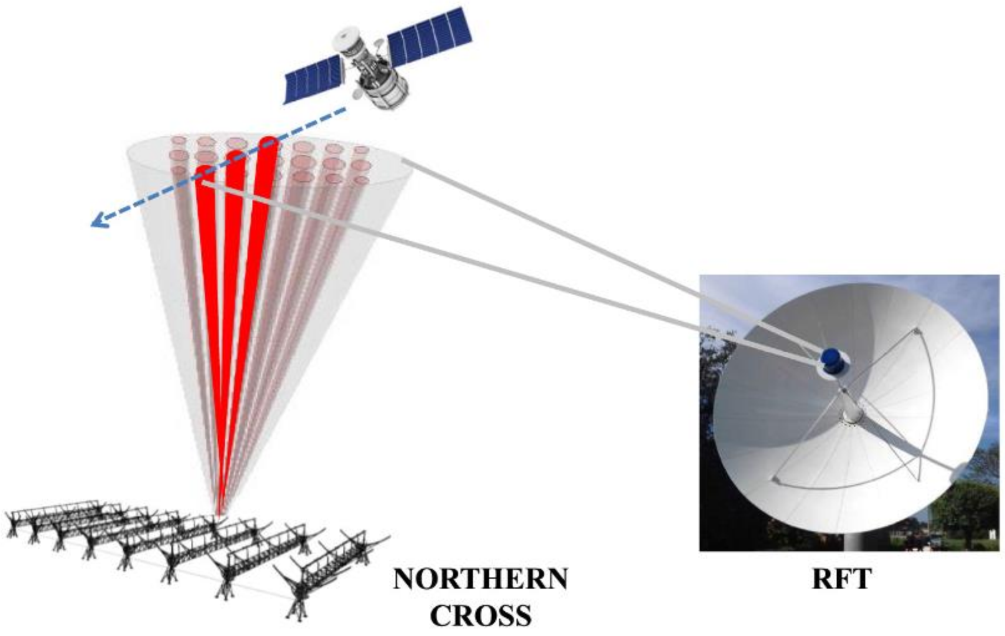
Disadvantage: both main lobes and grating lobes appear in sensor FoV



[3] *M. Losacco et al., Initial orbit determination with the multibeam radar sensor BIRALES, Acta Astronautica, 2020*

BIRALES: adaptive beamforming approach

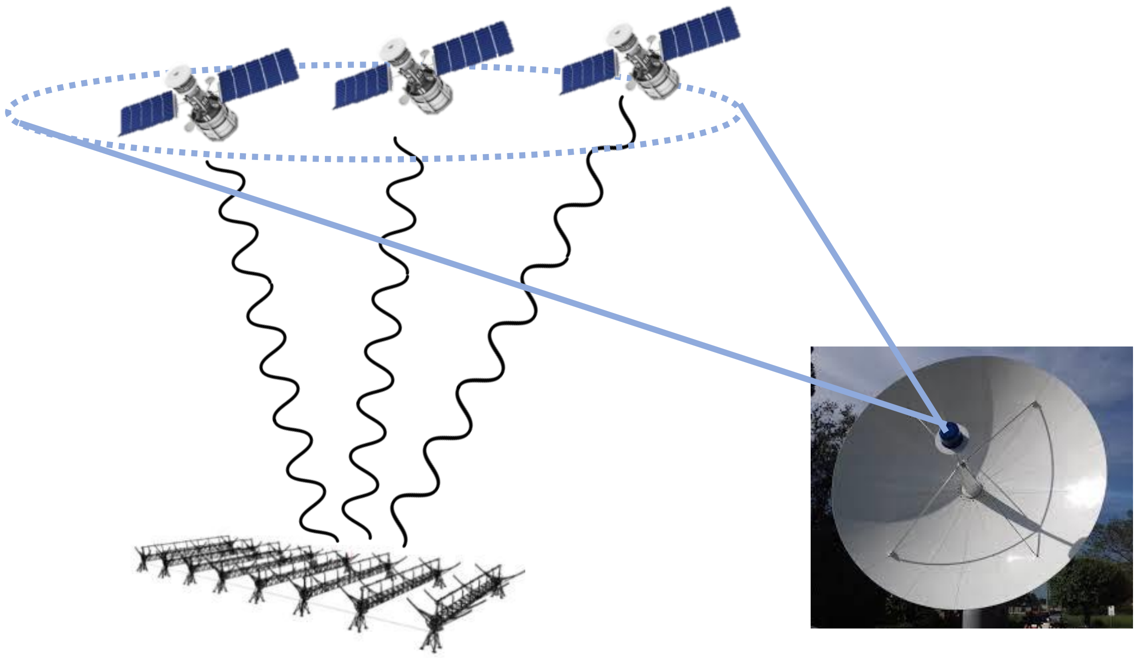
Static beamforming [3]



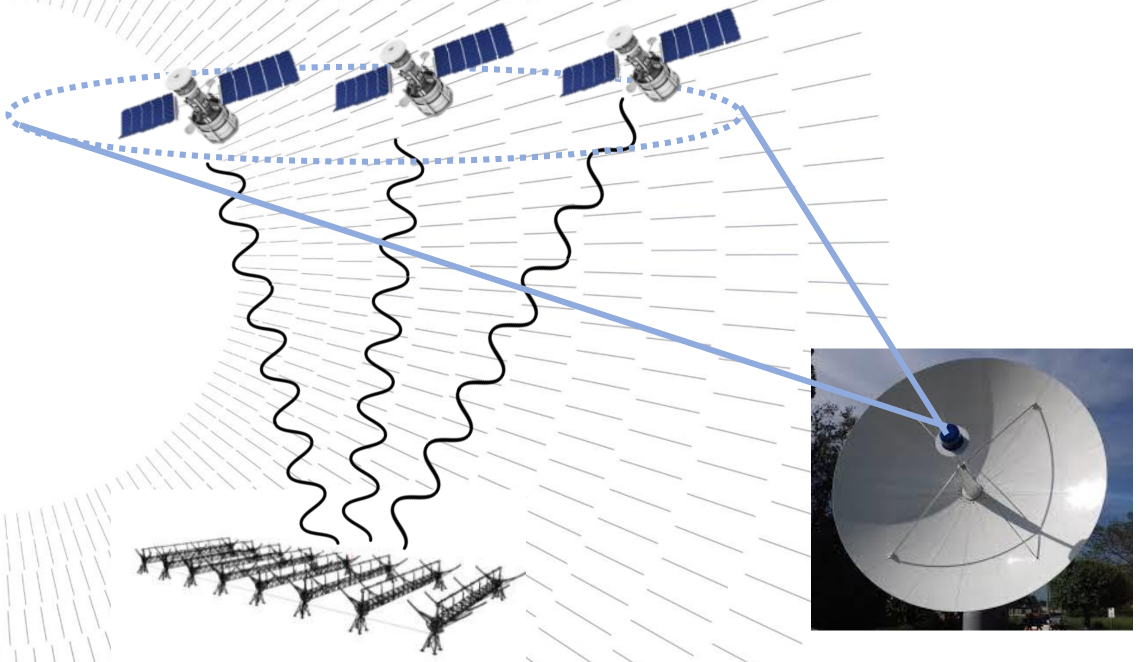
Medicina
(Bologna)

Salto di Quirra
(Sardinia)

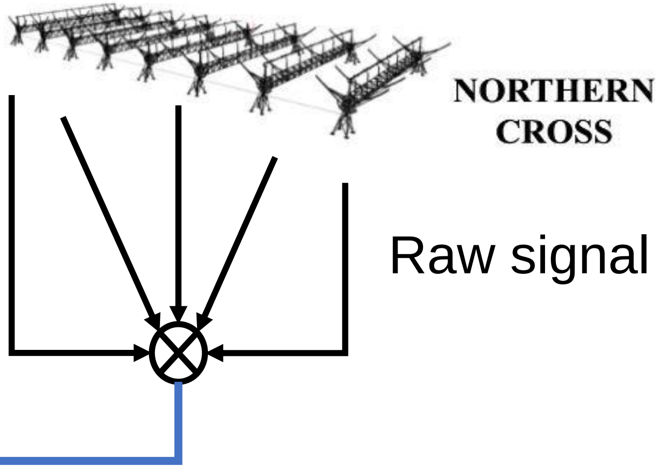
Adaptive beamforming



BIRALES: adaptive beamforming approach



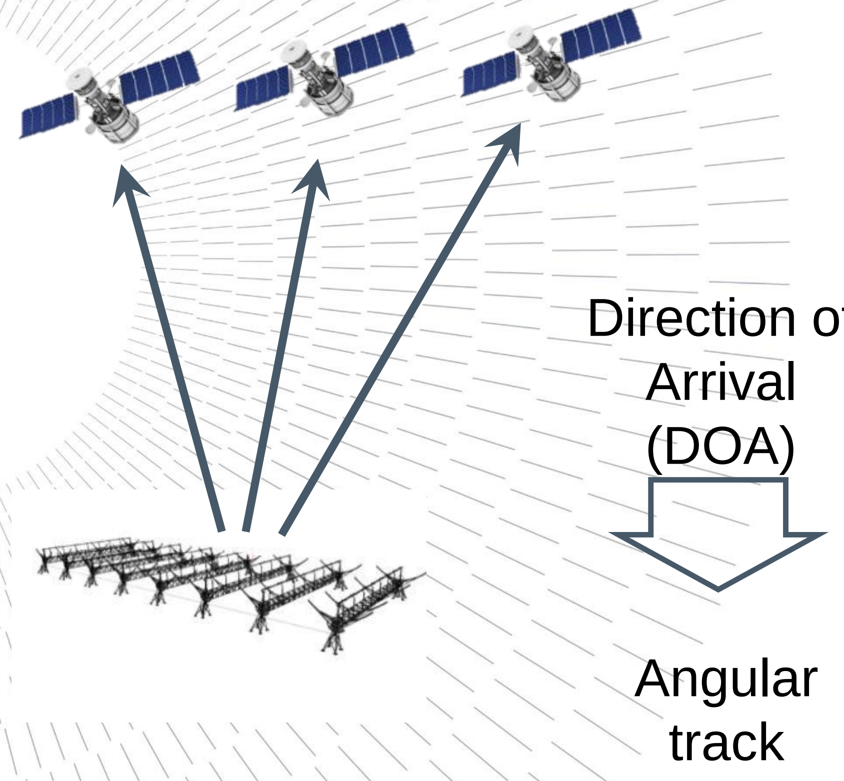
MUSIC - MUltiple SIgnal Classification [4]



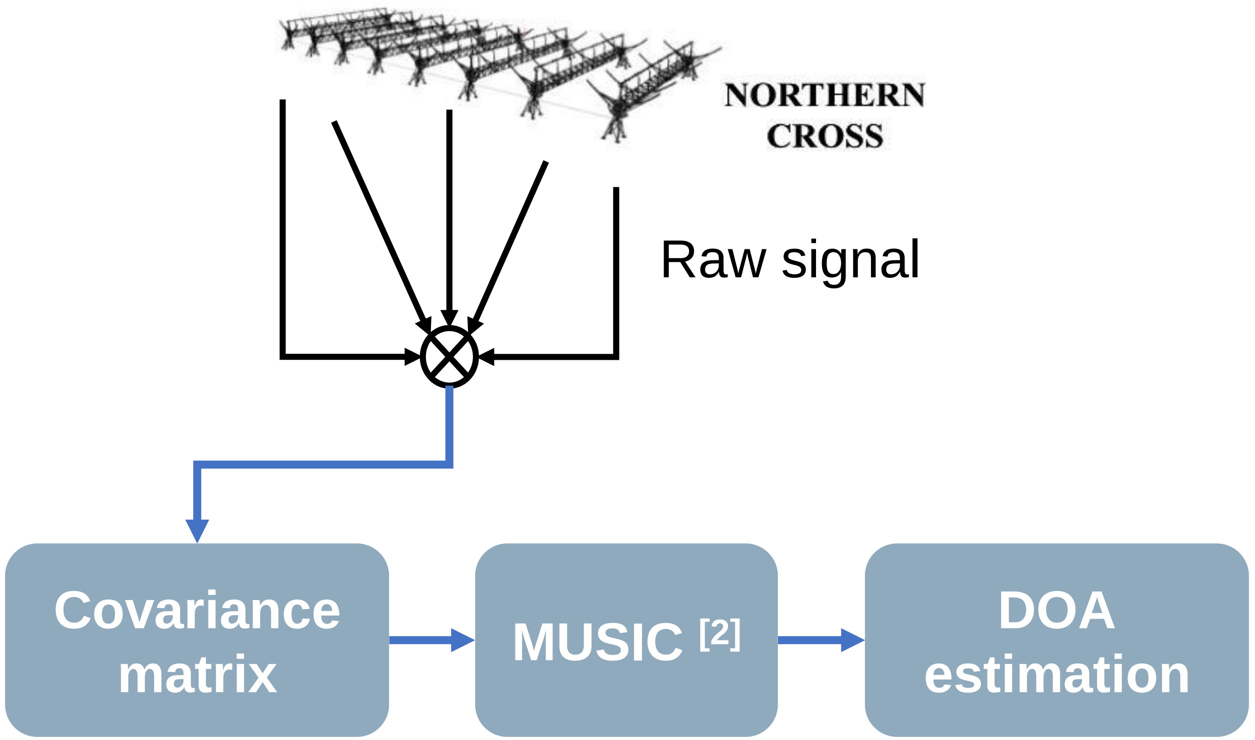
Covariance matrix → MUSIC [2] → DOA estimation

[4] *R. Schmidt, Multiple emitter location and signal parameter estimation, IEEE Transactions on Antennas and Propagation, 1982*

BIRALES: adaptive beamforming approach

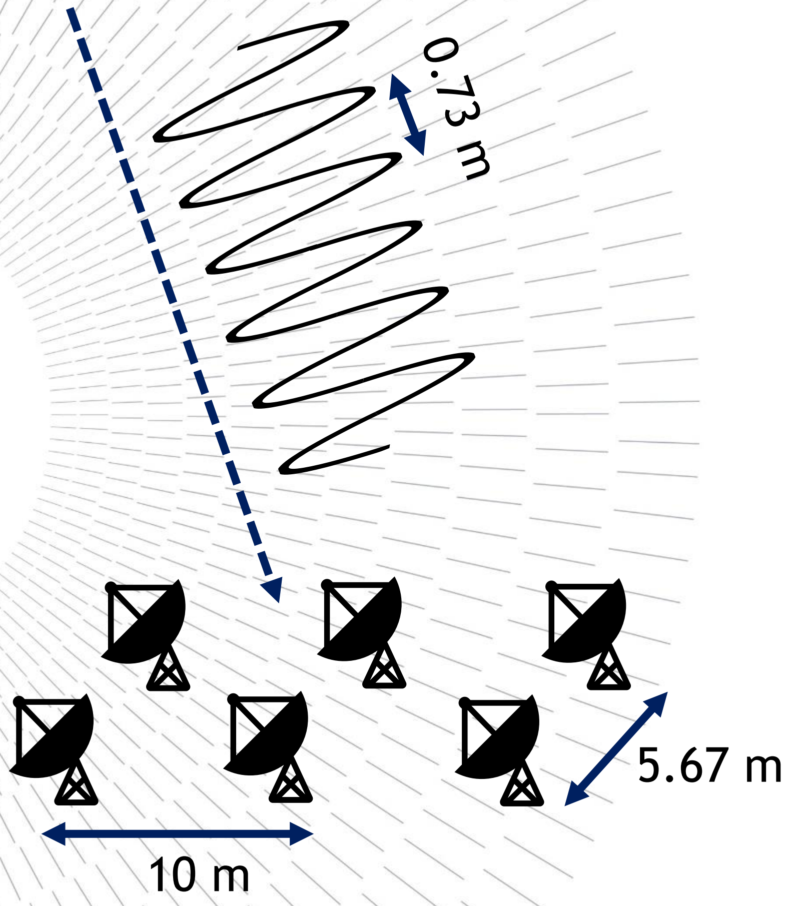


MUSIC *- MUltiple SIgnal Classification [4]*



[4] *R. Schmidt, Multiple emitter location and signal parameter estimation, IEEE Transactions on Antennas and Propagation, 1982*

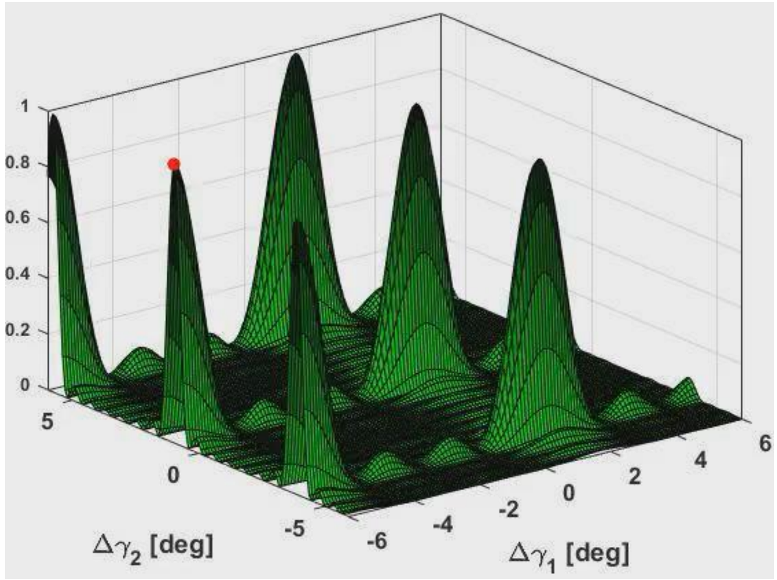
DOA ambiguity problem



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

⇨ Presence of multiple DOA estimates

⇨ Ambiguity solving criteria needed



● Signal DOA

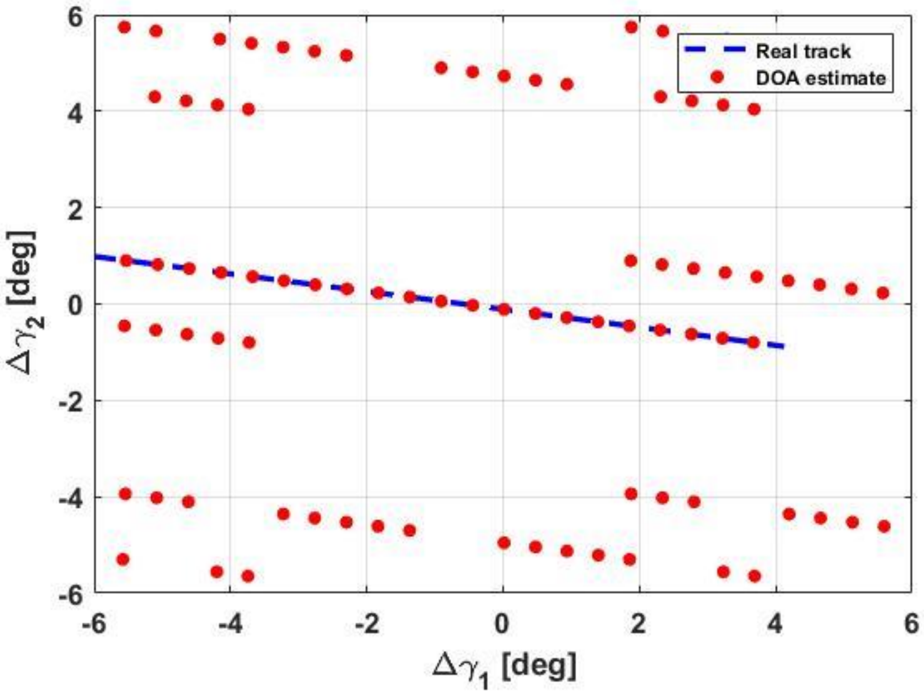
02 MATER

CATALOGUED OBJECT

Music Approach for Track Estimate and Refinement (MATER)

Catalogued case

Signal covariance matrix → Estimate DOAs for each epoch

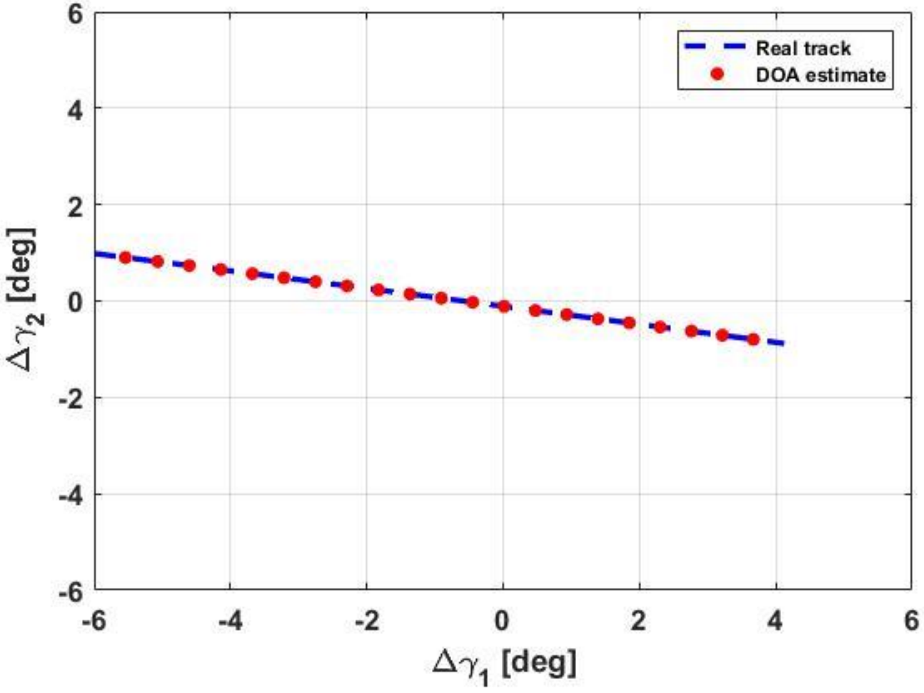


[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

Music Approach for Track Estimate and Refinement (MATER)

Catalogued case

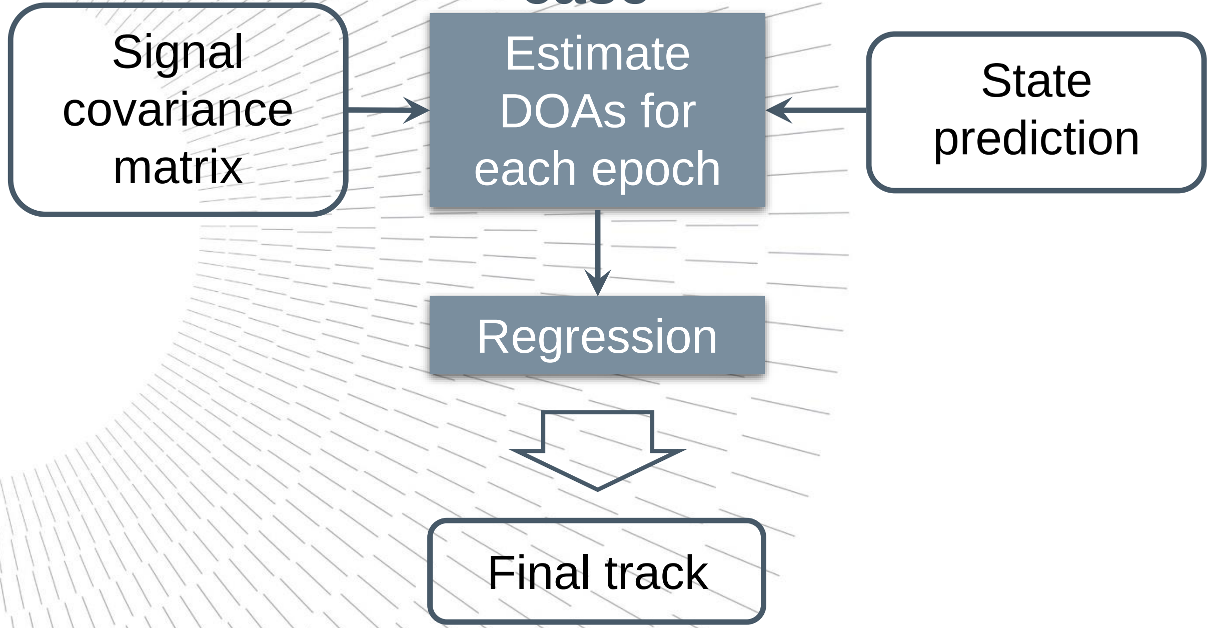
Signal covariance matrix → Estimate DOAs for each epoch ← State prediction

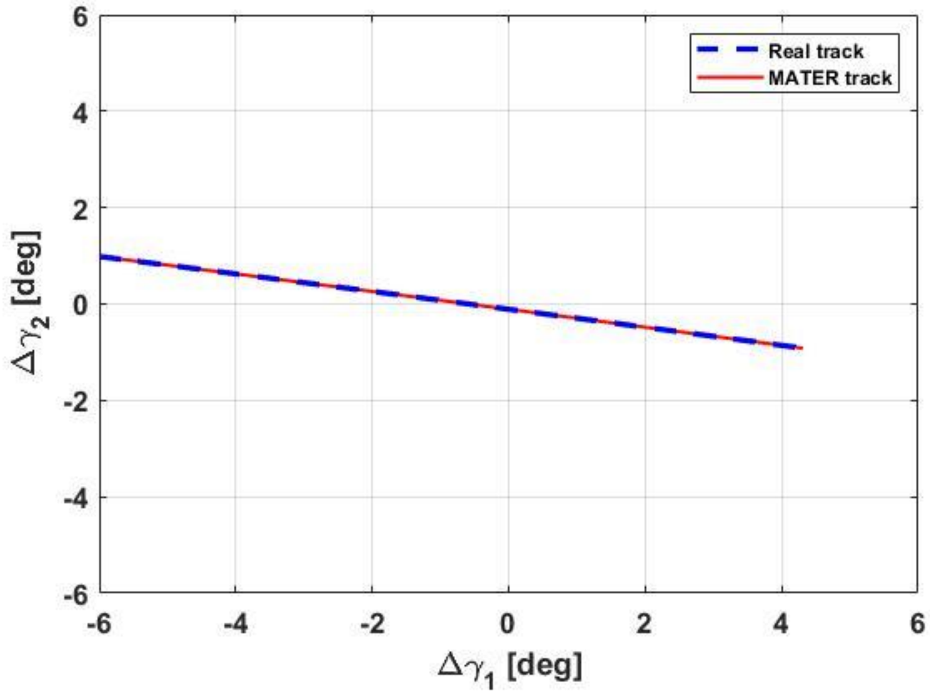


[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

Music Approach for Track Estimate and Refinement (MATER)

Catalogued case

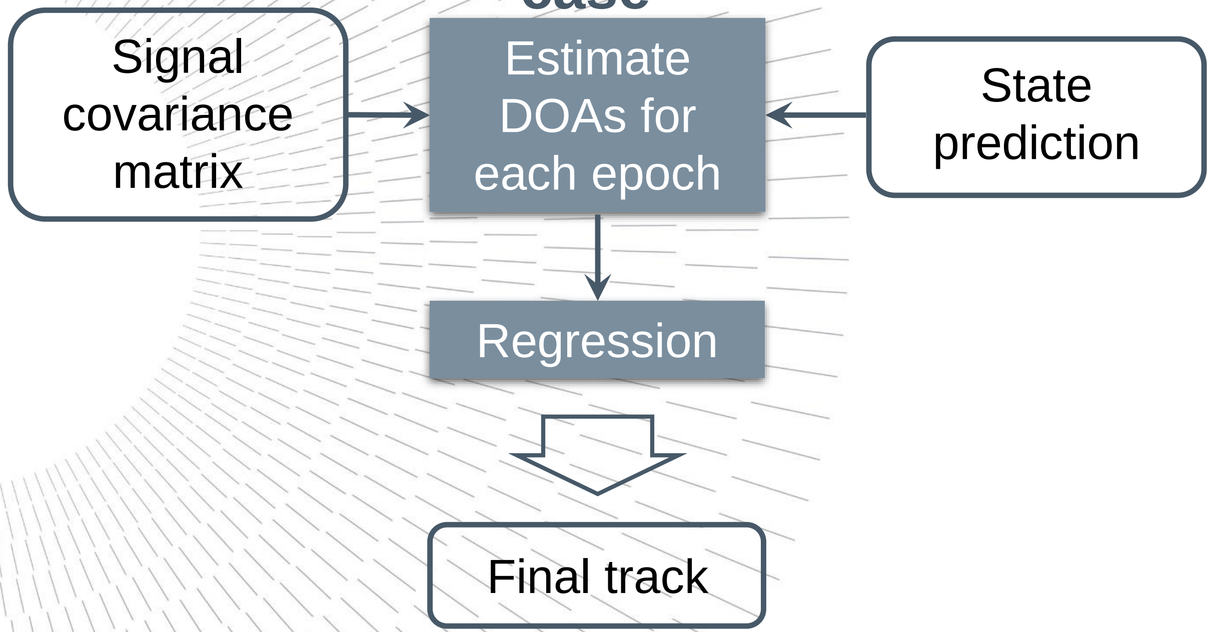




[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

Music Approach for Track Estimate and Refinement (MATER)

Catalogued case



Numerical Validation

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

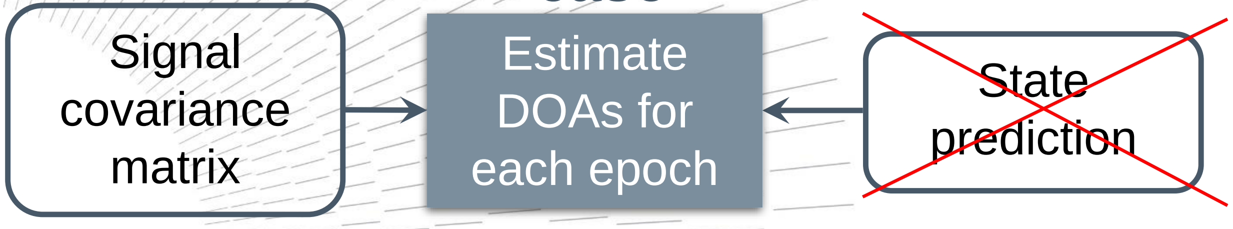
[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

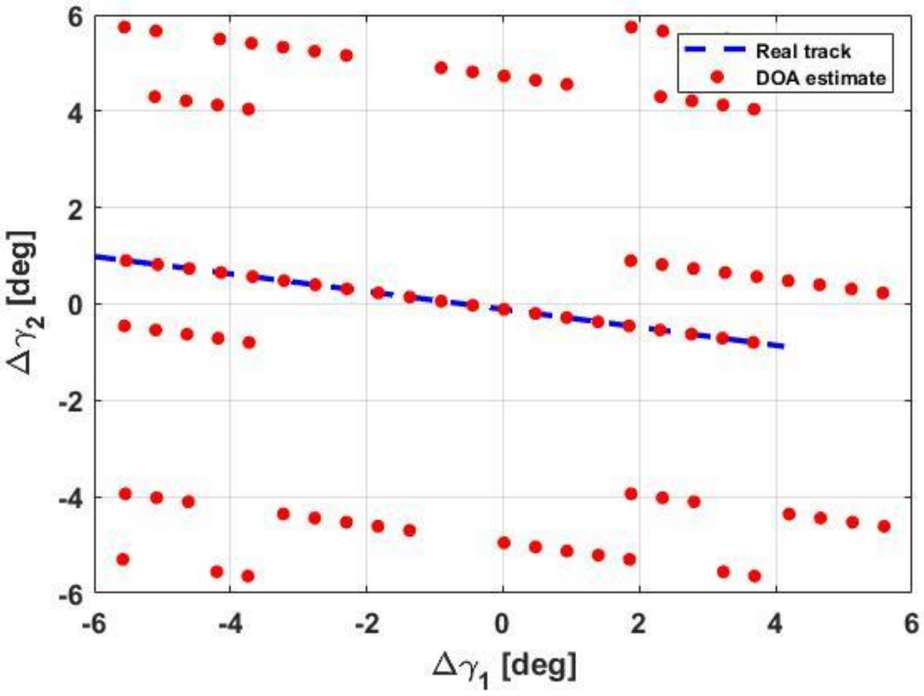
03 MATER

UNCATALOGUED OBJECT

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case

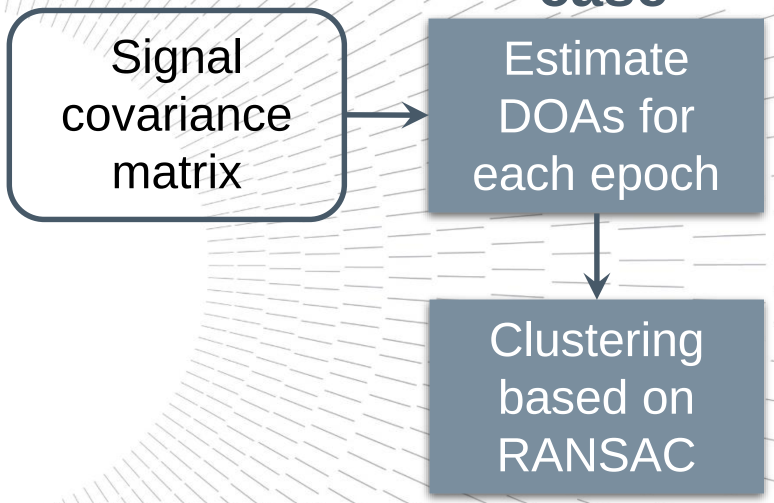


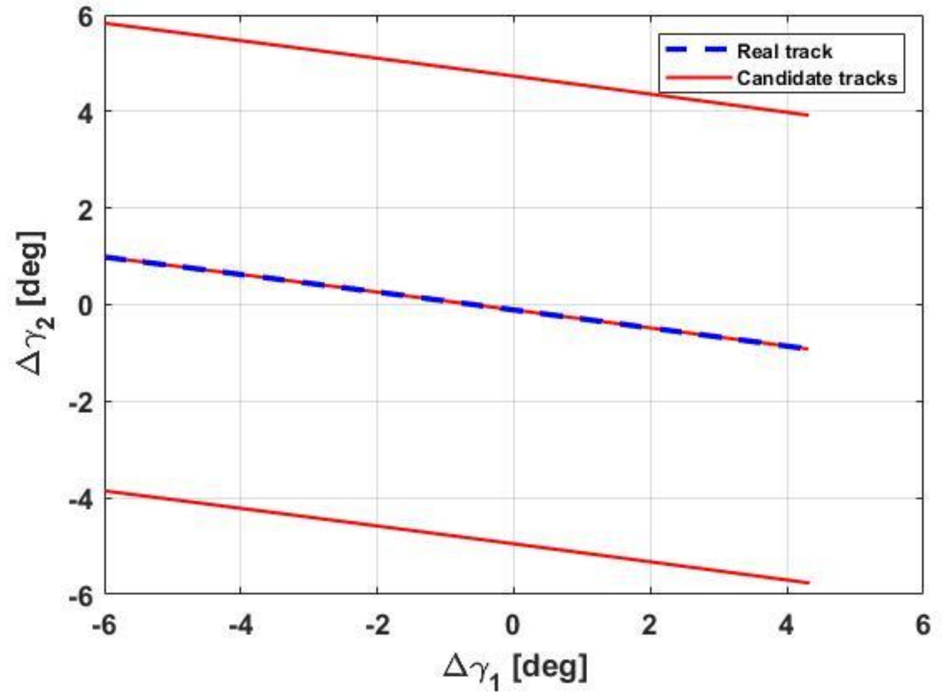


[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case

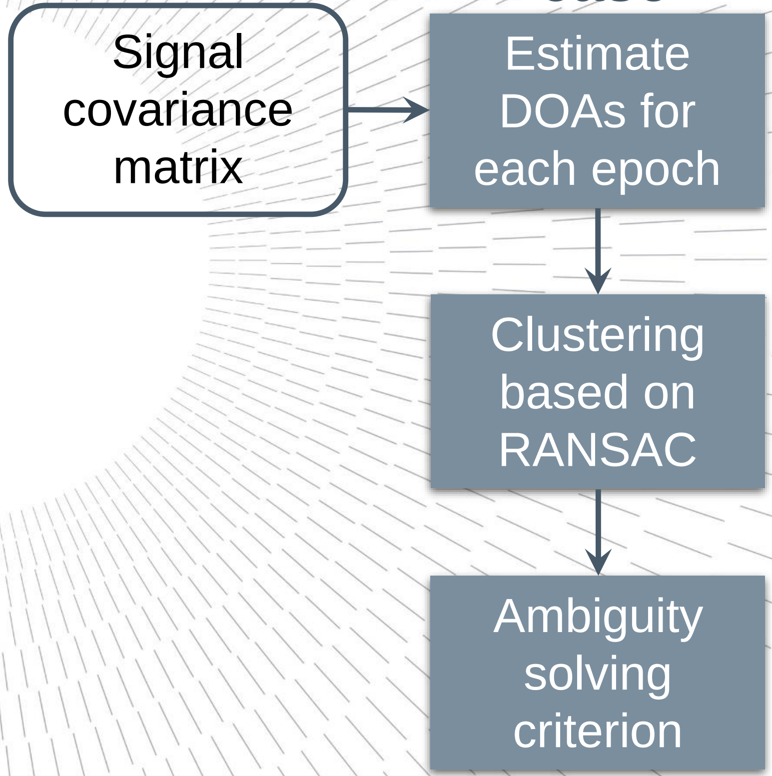


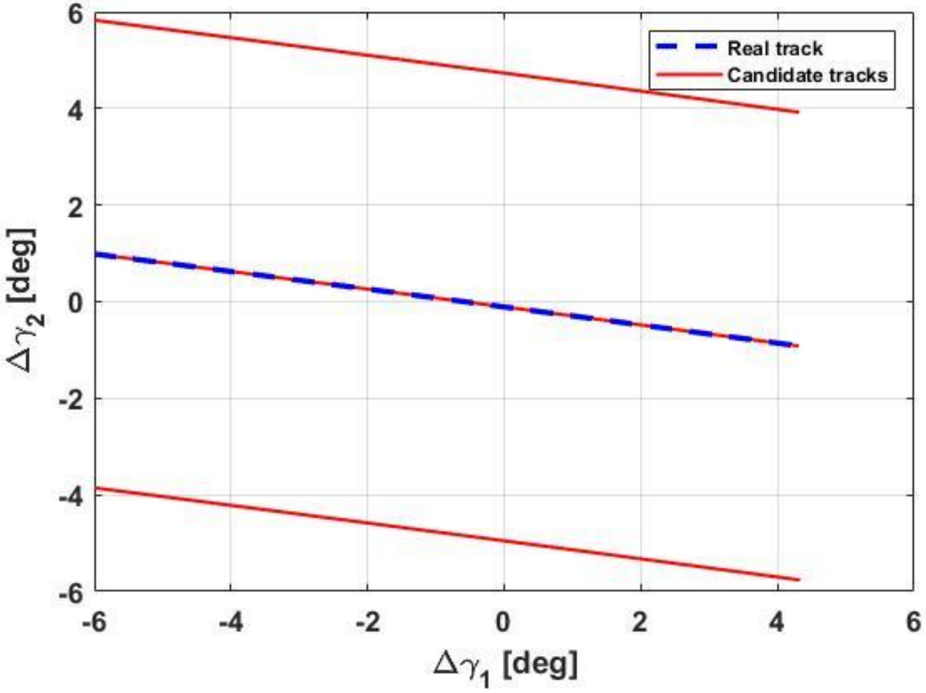


[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case

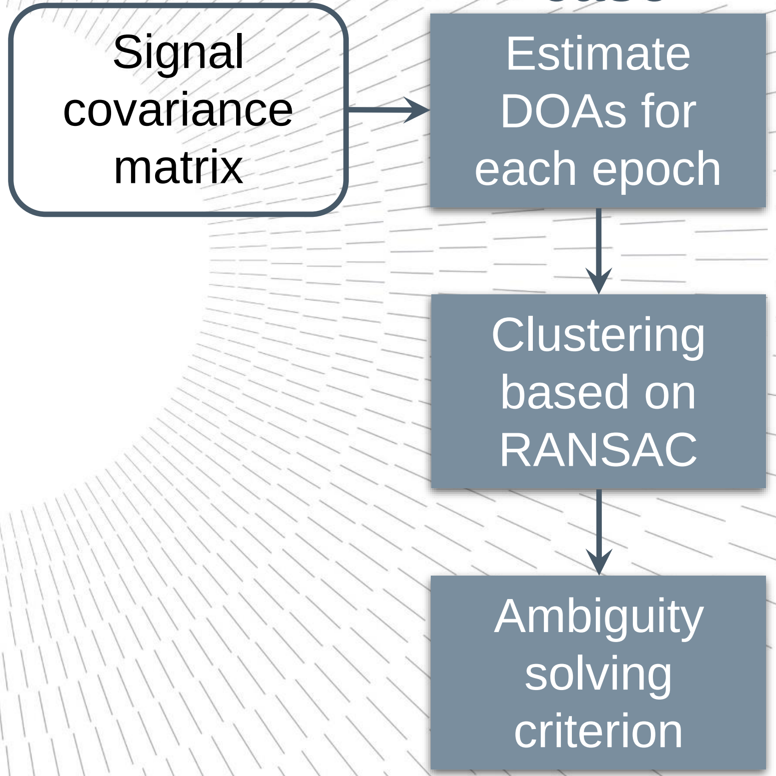




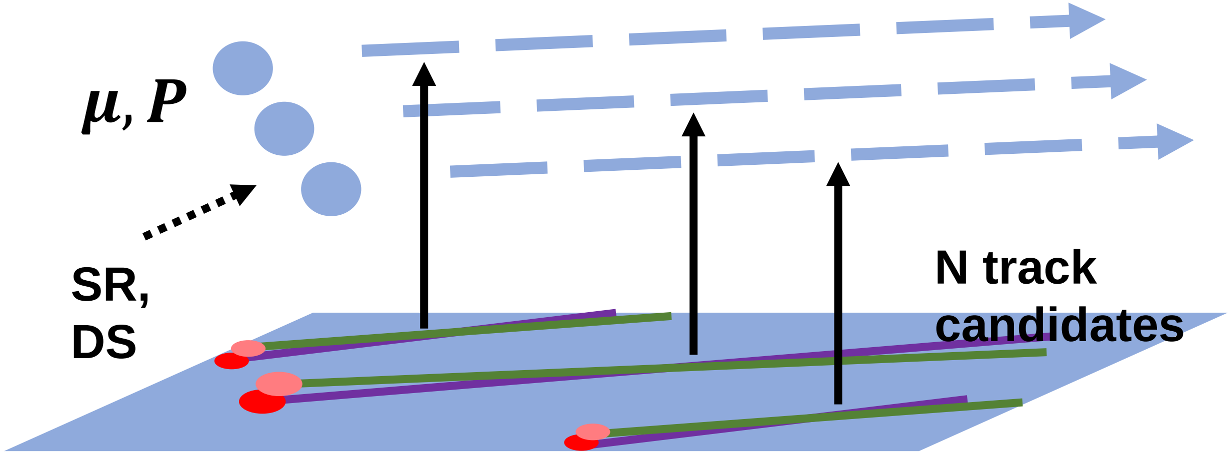
[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case



- 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



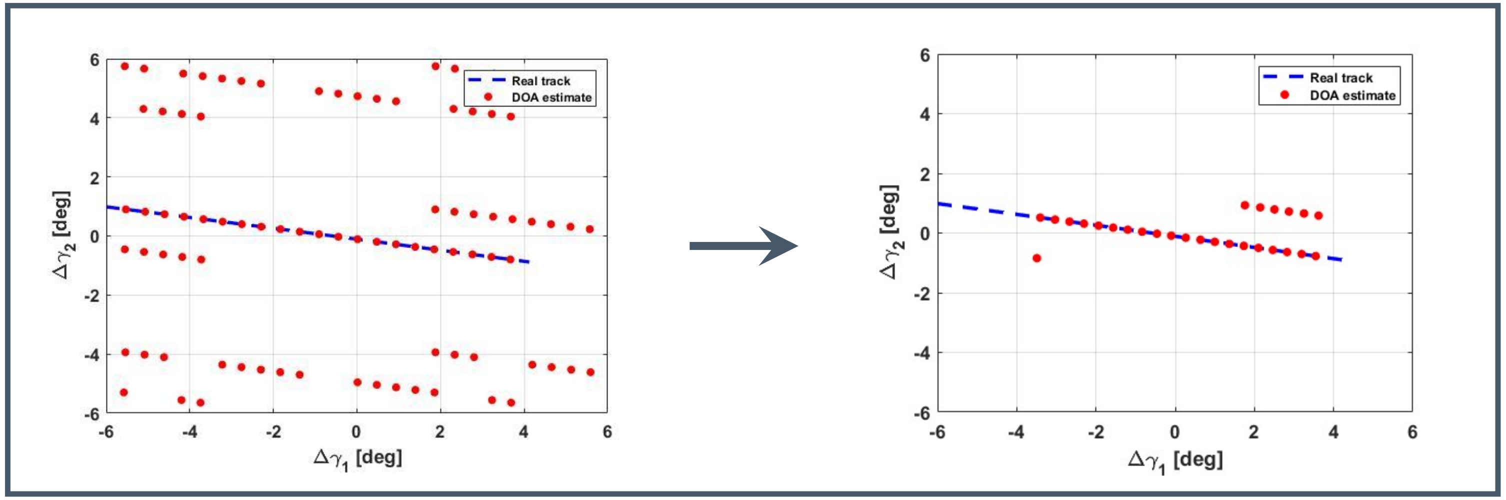
[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

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

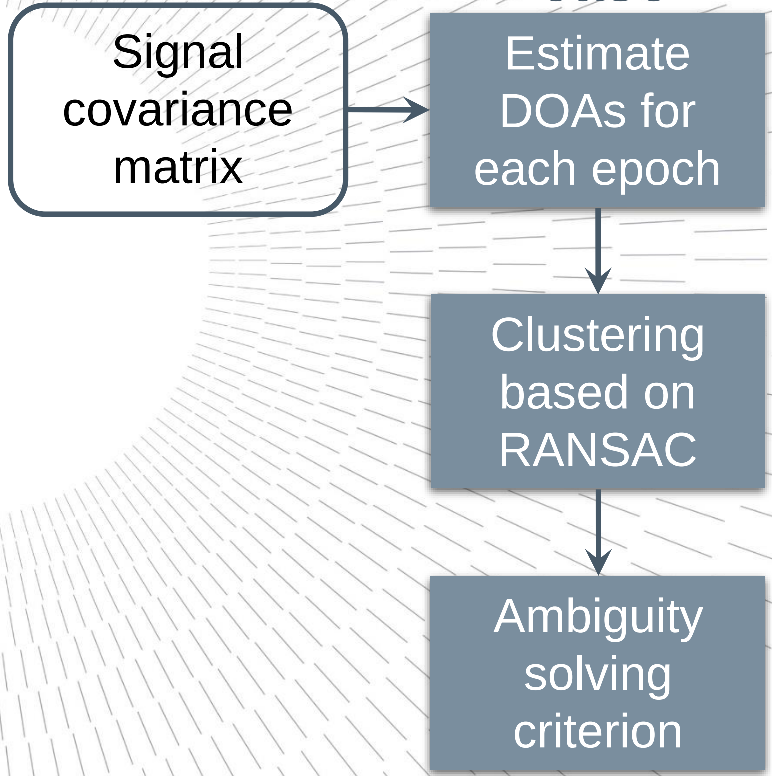
- Exploit additional data
- Statistical approach
- Signal processing approach



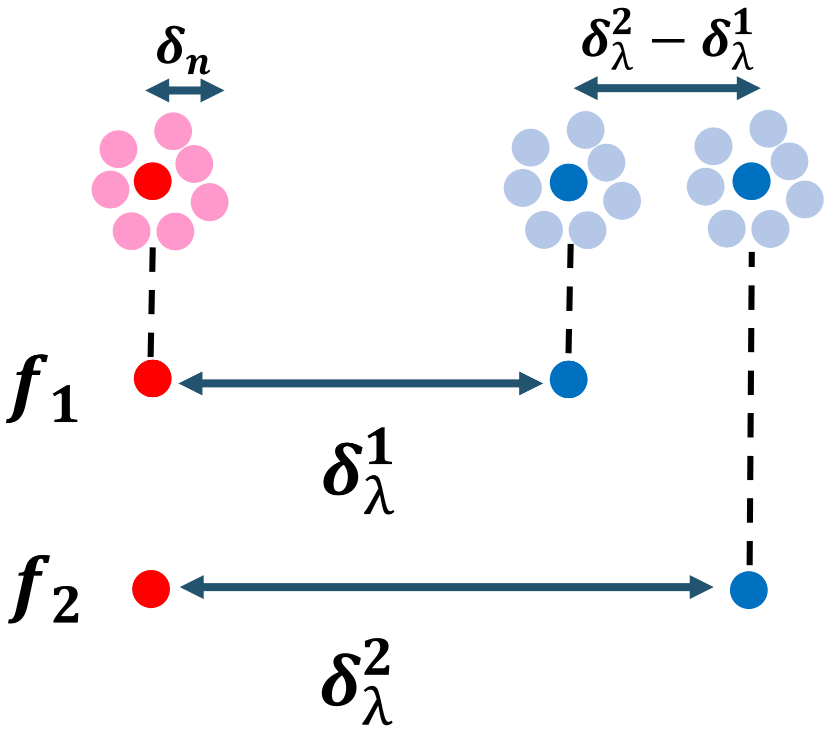
[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case



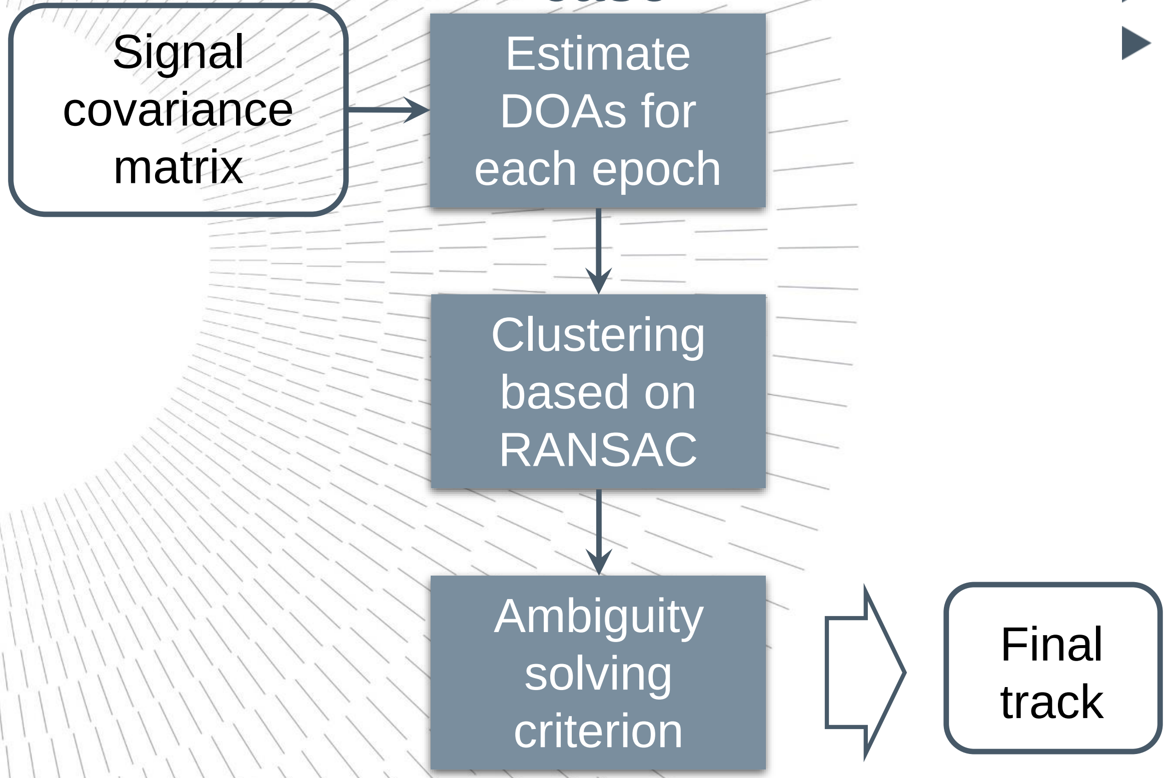
- Exploit additional data
- Statistical approach
- Signal processing approach



$$\delta_\lambda^2 - \delta_\lambda^1 > \delta_n$$

Music Approach for Track Estimate and Refinement (MATER)

Uncatalogued case



- Exploit additional data
- Statistical approach
- Signal processing approach

Numerical Validation

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

[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

04 OPERATIONS

REAL OBSERVATIONS

Operations

ISS transit

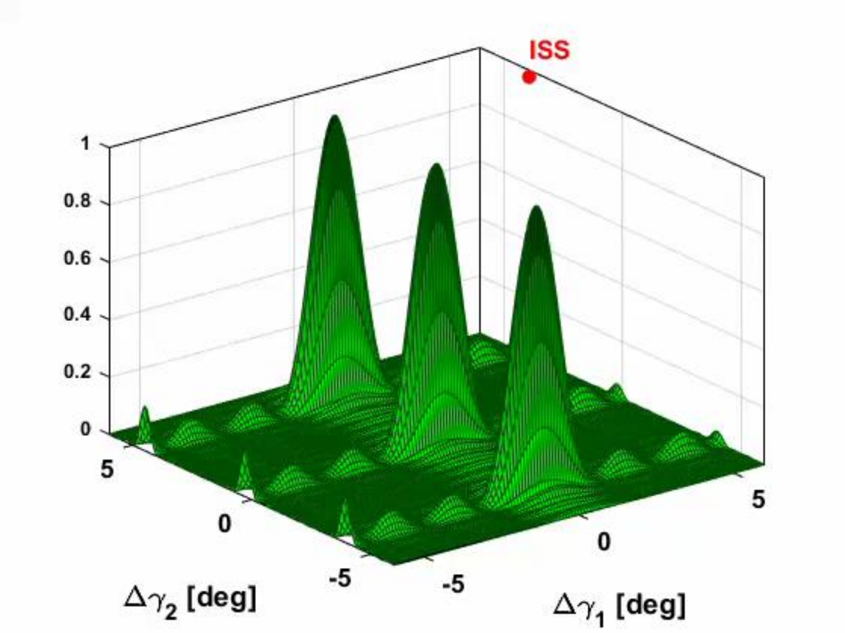
- April 28°, 2021
- Accuracy: 1e-02 - 1e-01 deg

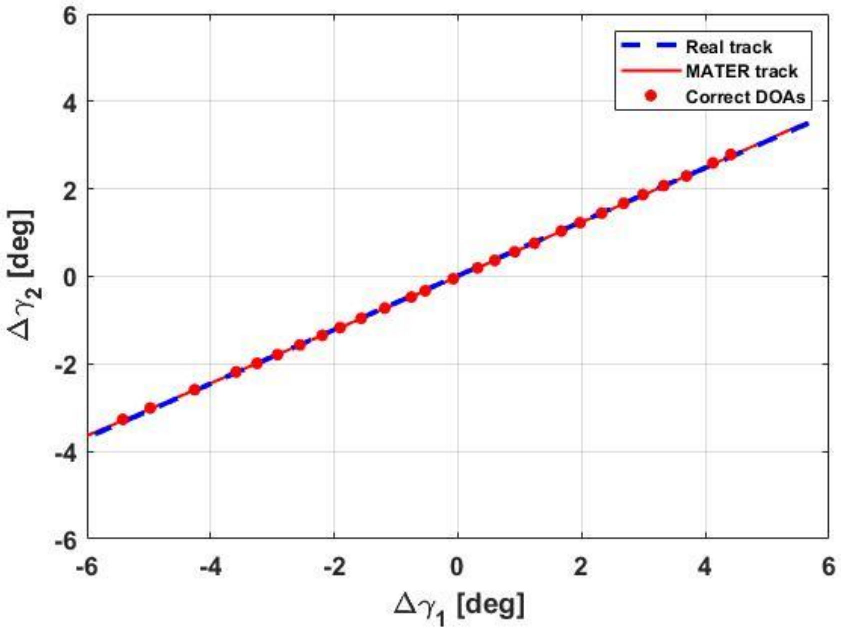
Previous signal processing chain:
- Still designed for static beamforming
- Very noisy covariance matrices

⇩

Only large objects with small SR

Array response





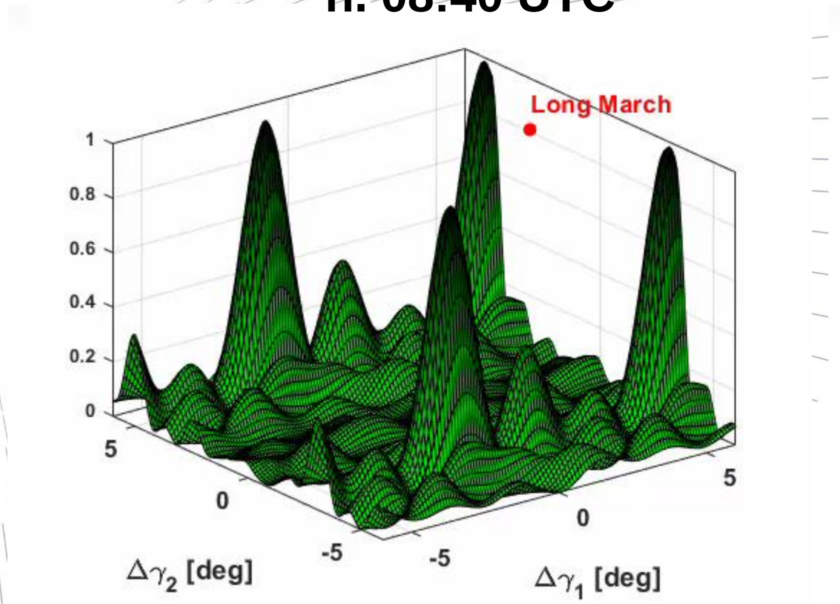
[5] *M.F. Montaruli et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022*

Operations

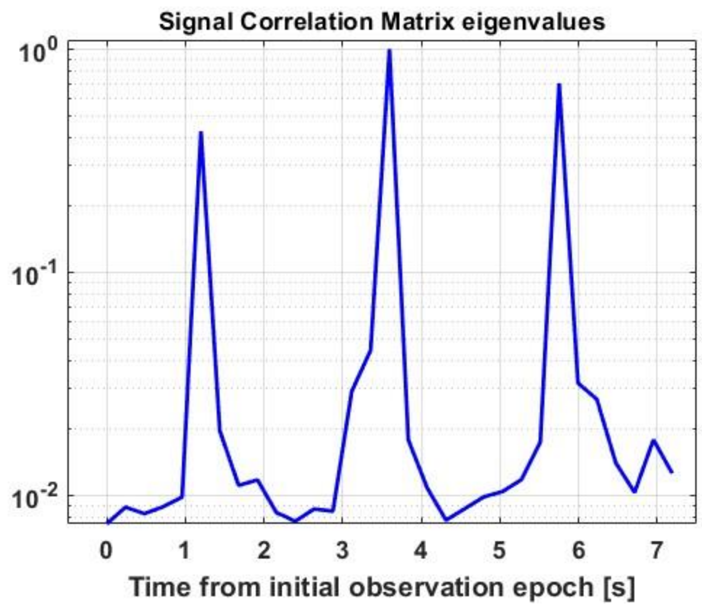
- From October 31st to November 4th, 2022
- First operational involvement in SST services

3rd Long March re-entry

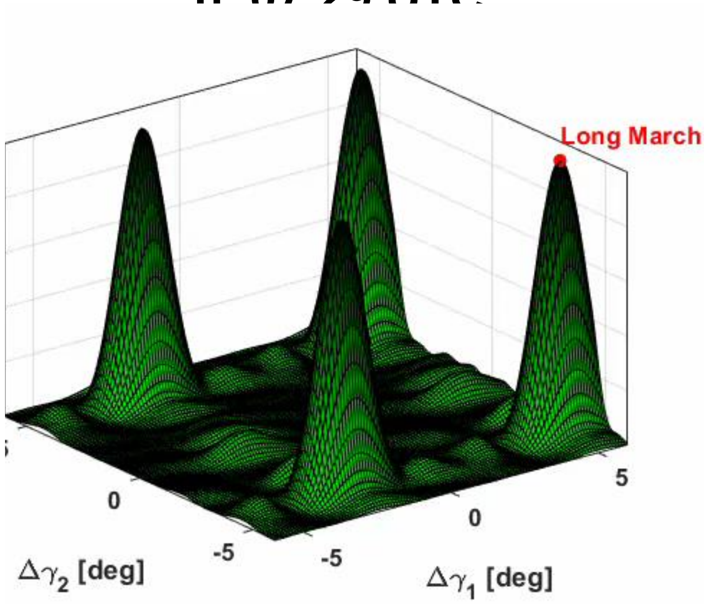
November 1st, 2022
h. 08:40 UTC



November 2nd, 2022
h. 08:24 UTC



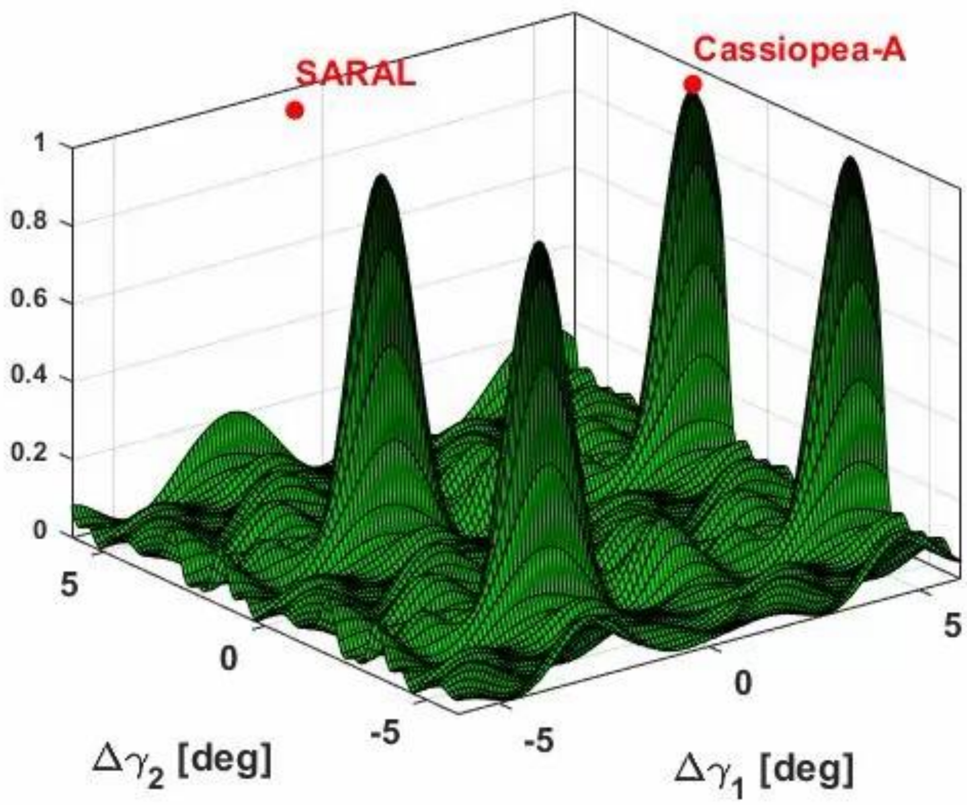
November 4th, 2022
h. 07:29 UTC

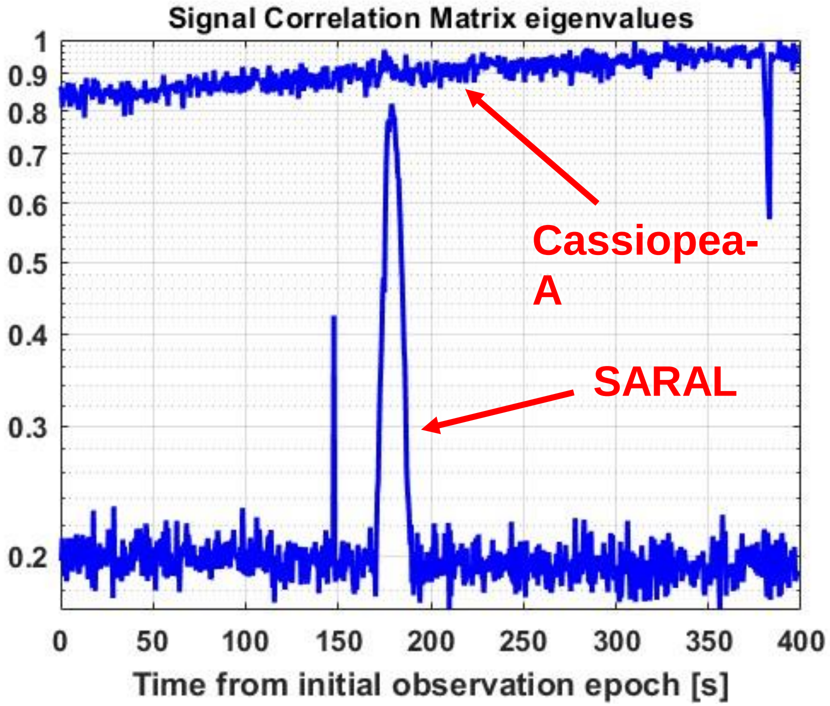


Operations

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

$BW_{RX} \sim 85000\ Hz$

↓

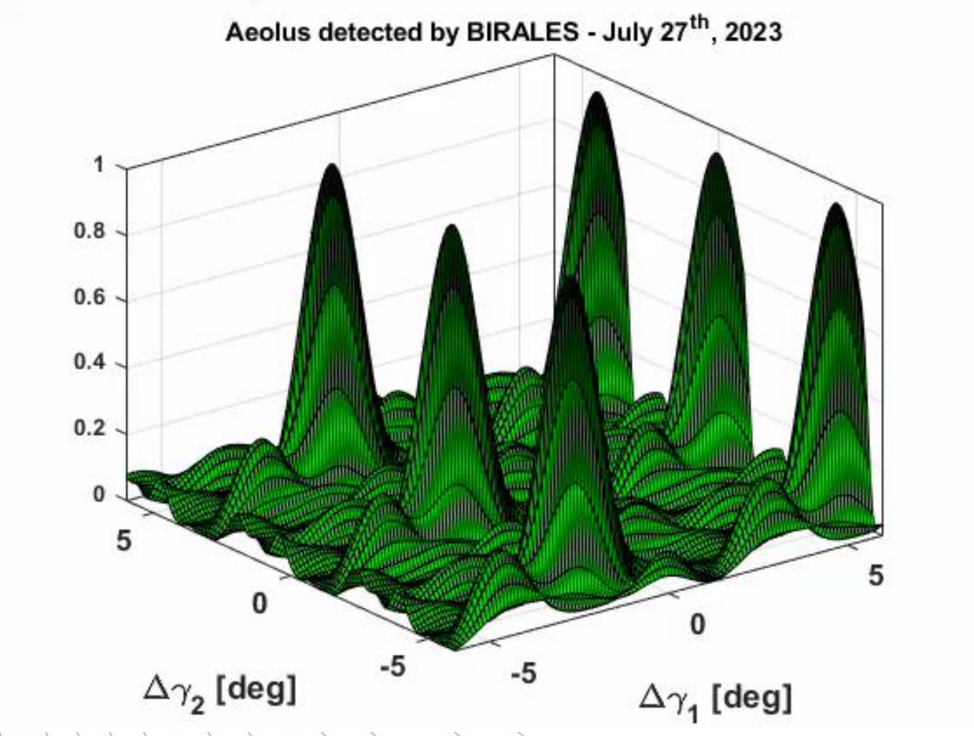
$BW_{RX} \sim 10\ Hz$

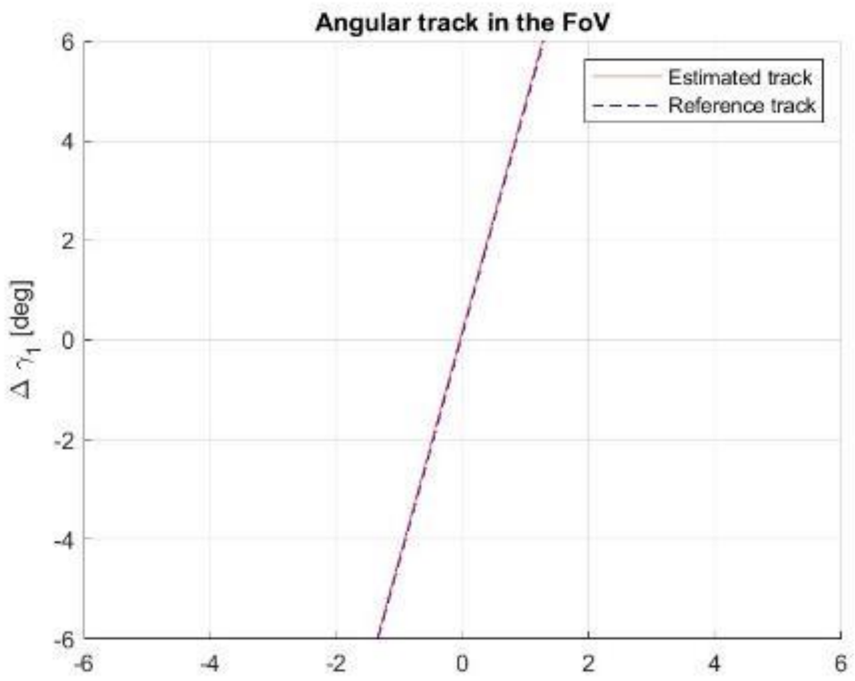
⇨ $SNR \propto \frac{1}{BW_{RX}}$ ⬆ ⇨ Angular track accuracy ⬆

Operations – new processing pipeline

Aeolus re-entry campaign

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





Operations – validation

Calibrators

- ILRS and DORIS catalogue
- 46 observations of LEO satellites

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

⇨ Error will be reduced by compensating the elevation-depending distortion (ongoing activity)

05 CONCLUSIONS

Conclusions

To recap:

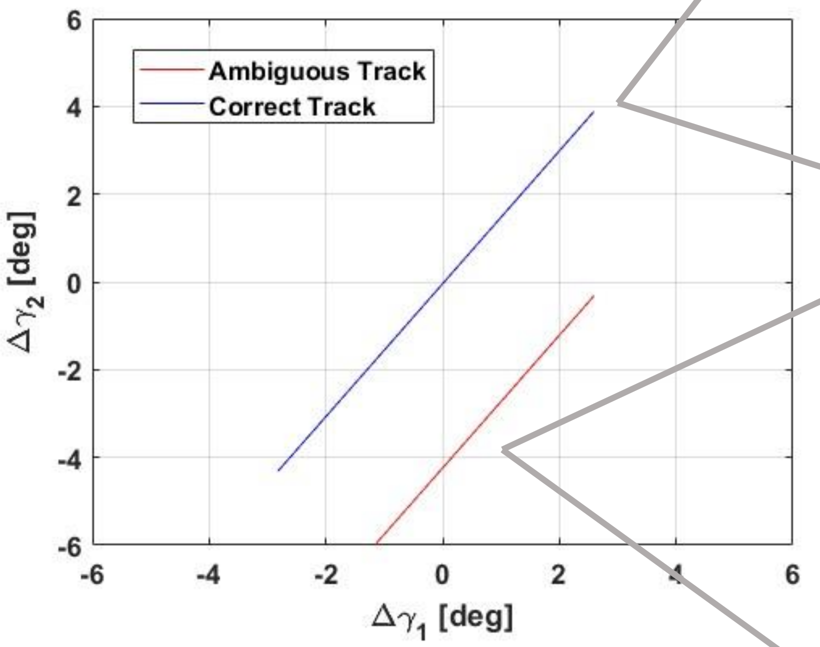
- Architecture defined
- Validation campaign
- First operational involvements in SST services
- Multiple sources simultaneously detected (fragmentations, proximity operations)

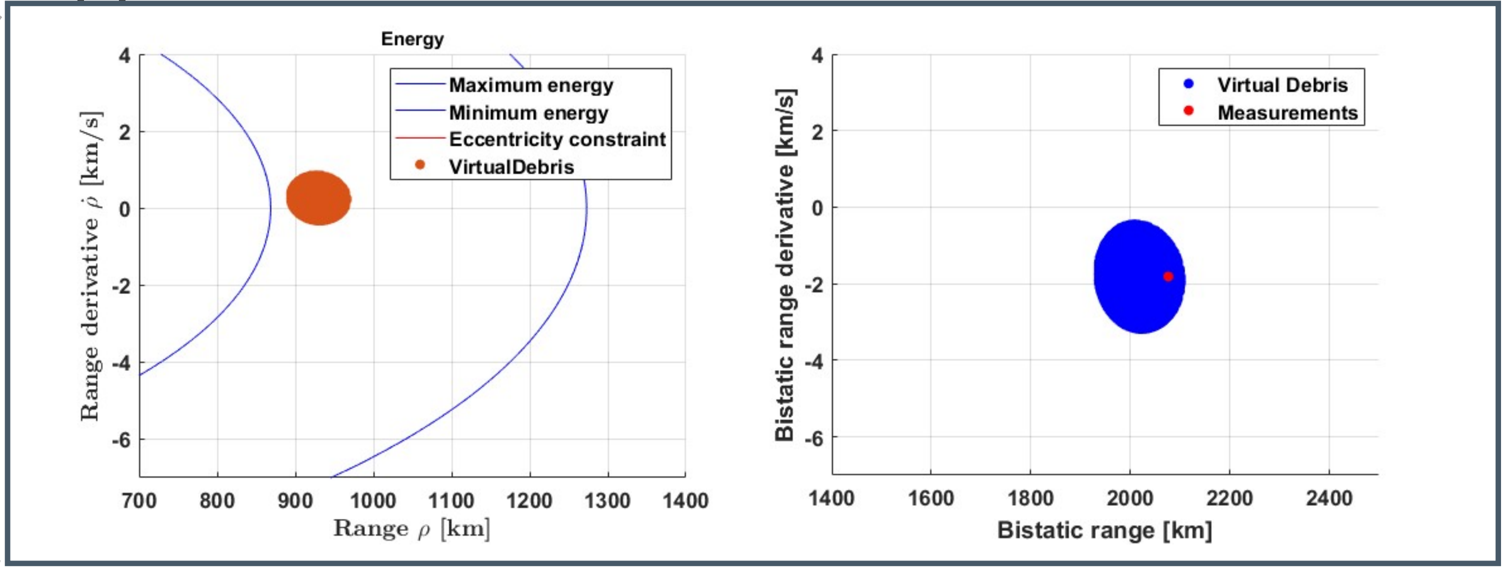
Next steps:

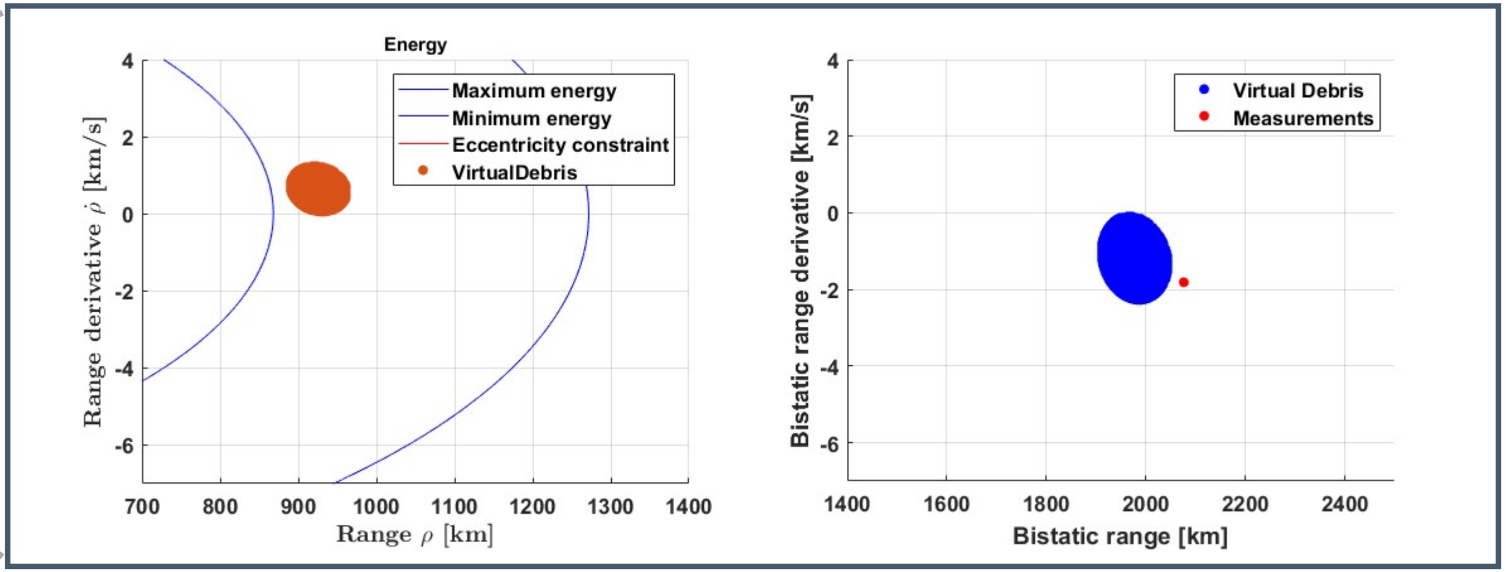
- Compensation of the elevation-depending distortion
- Operational architecture implementation
- RSO characterization
- Admissible Regions approach to solve ambiguity in DOA estimation

MATER – Admissible Region Approach

- Optical AR [6] for each candidate
- Conversion to bistatic plane (Virtual Debris)
- Cross check with DS and SR







[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?

Acknowledgments

*Research performed within the **European Commission** Framework Programme H2020 and Copernicus “SST Space Surveillance and Tracking” contracts N. 952852 (2-3SST2018-20) and N. 237/G/GRO/COPE/16/8935 (1SST2018-20) with further support from the **Italian Space Agency** through the grant agreement n. 2020-6-HH.0*

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