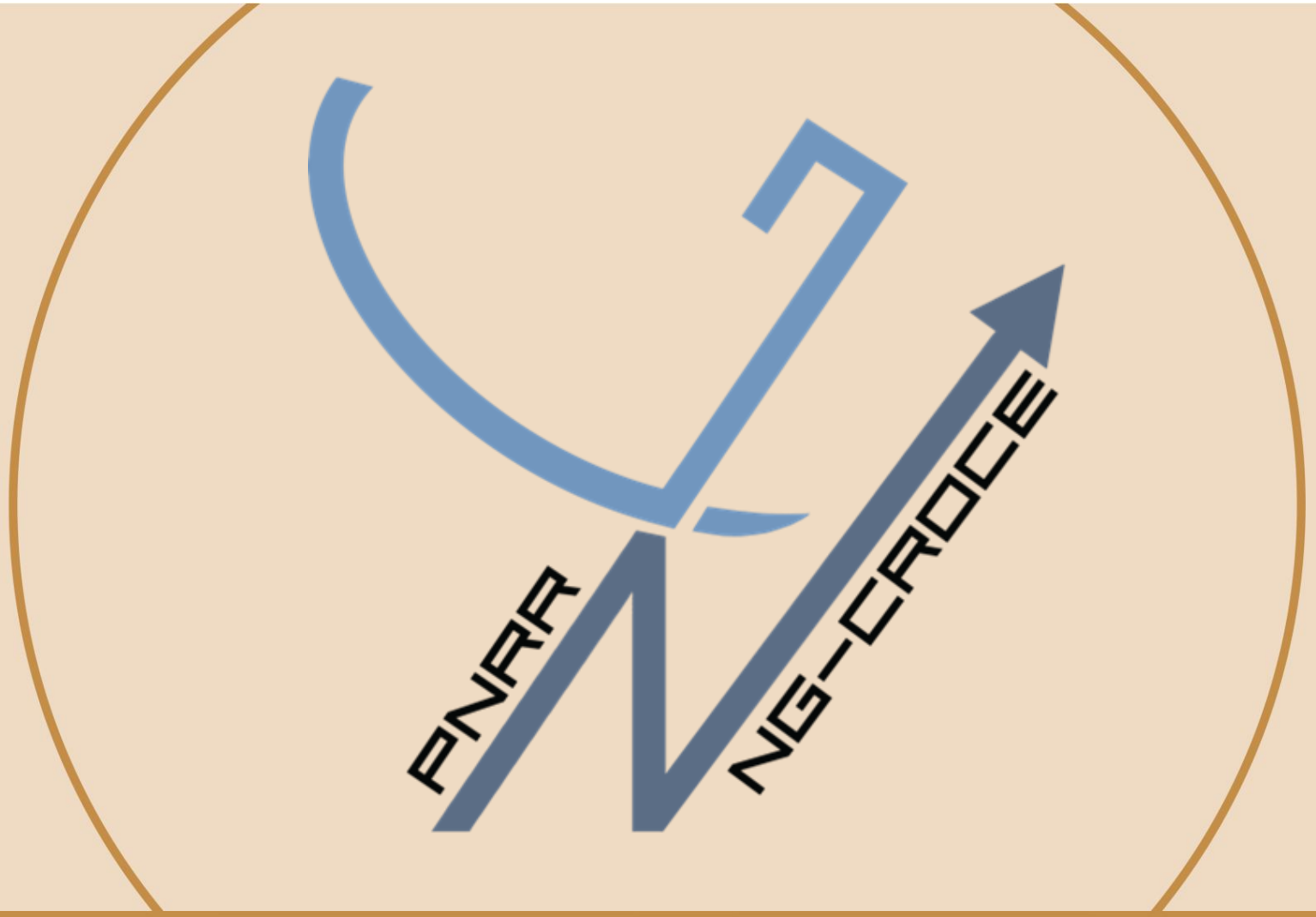
Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INAF ISTITUTO NAZIONALE DI ASTROFISICA

Space cataloguing and intelligence: the potential disclosed by MATER algorithm and by the East-West branch

Final Meeting

Martedì 30 Giugno – Giovedì 02 Luglio

OAC - Osservatorio Astrofisico di Arcetri

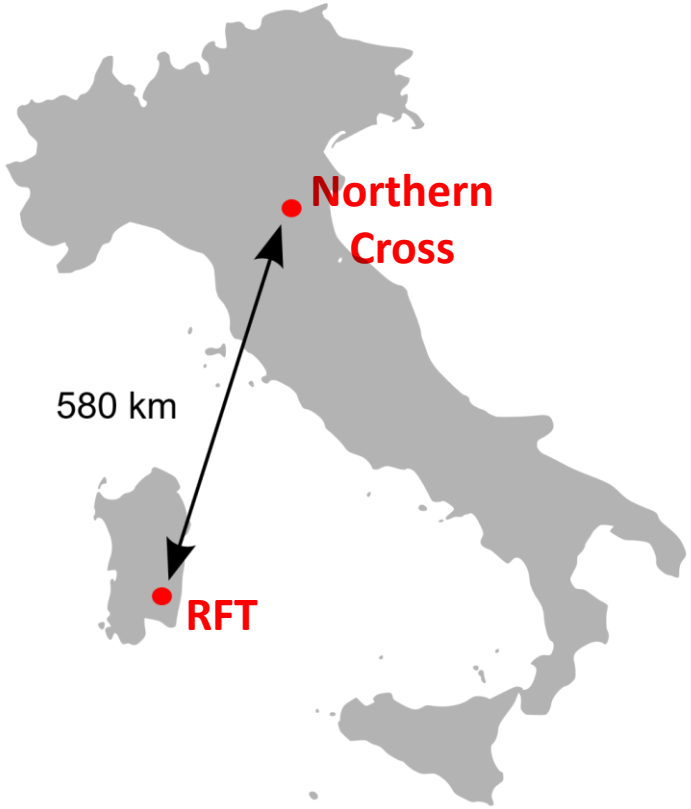


M.F. Montaruli

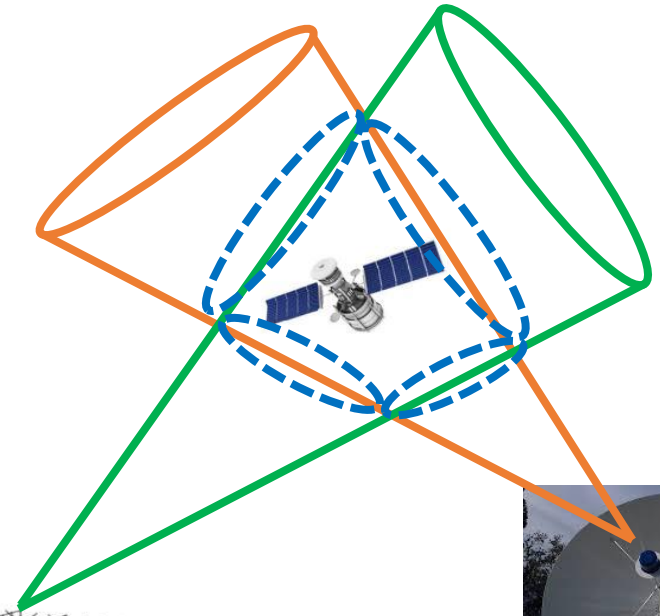
OUTLINE

OUTLINE

BIstatic Radar for Leo Survey (BIRALES)



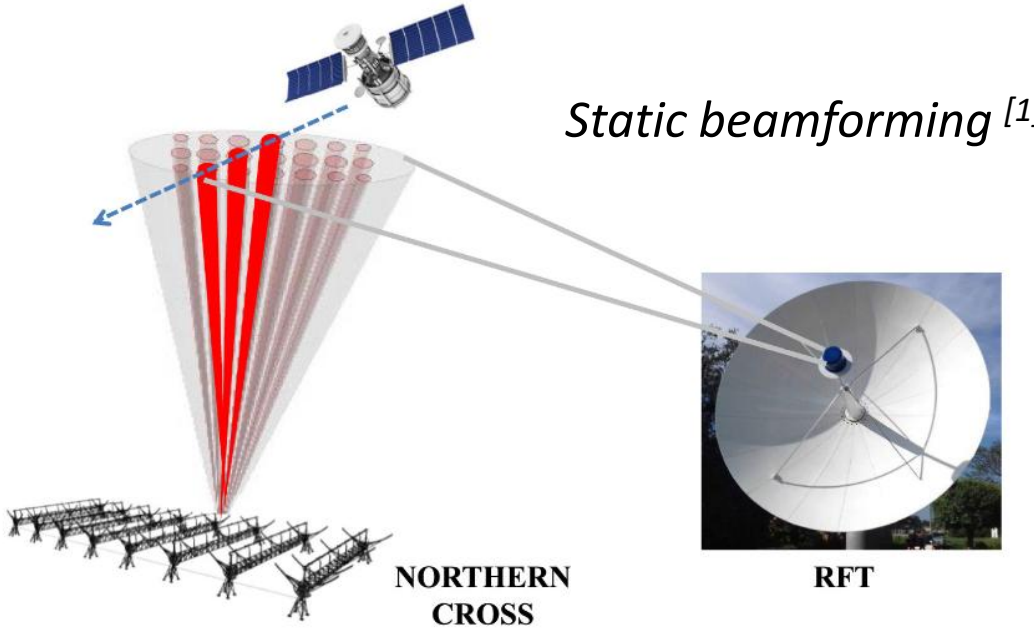
Northern Cross (Bologna)



RFT (Sardinia)

- Angular profile
- Slant Range
- Doppler Shift

BIRALES: Multibeam Approach



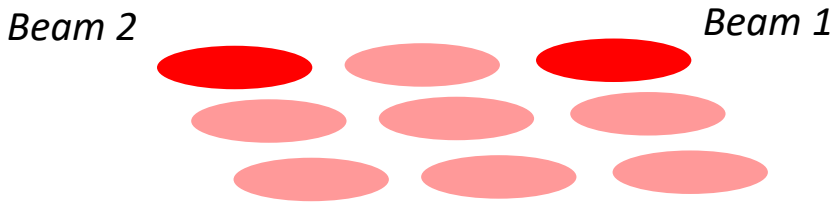
Static beamforming [1]

Medicina (Bologna)

Salto di Quirra (Sardinia)

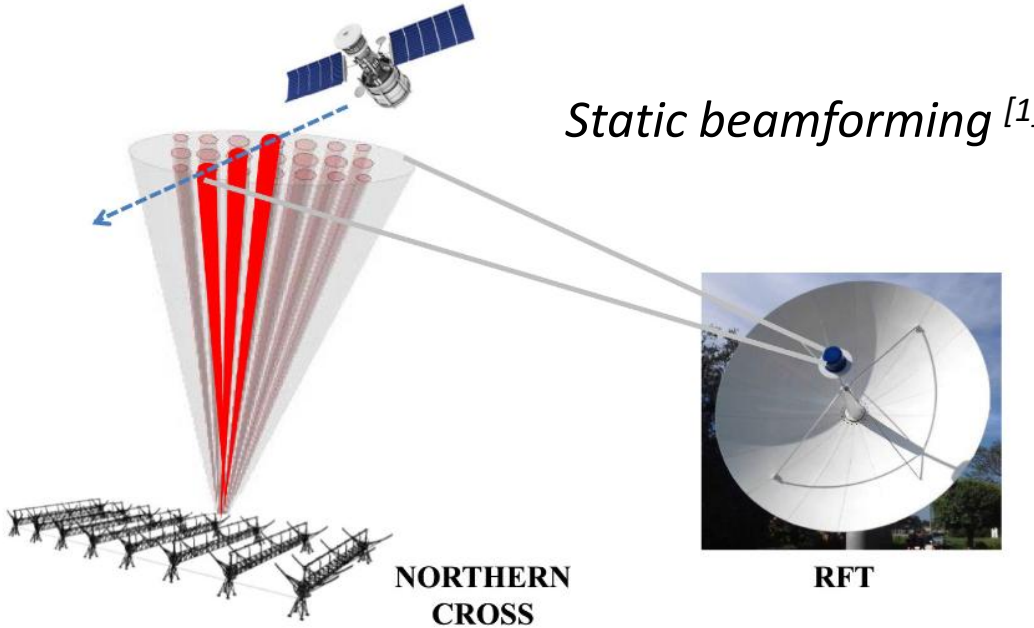
Angular profile

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



M. Losacco, et al., Initial orbit determination with the multibeam radar sensor BIRALES, 2020

BIRALES: Multibeam Approach



Static beamforming [1]

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Salto di Quirra (Sardinia)

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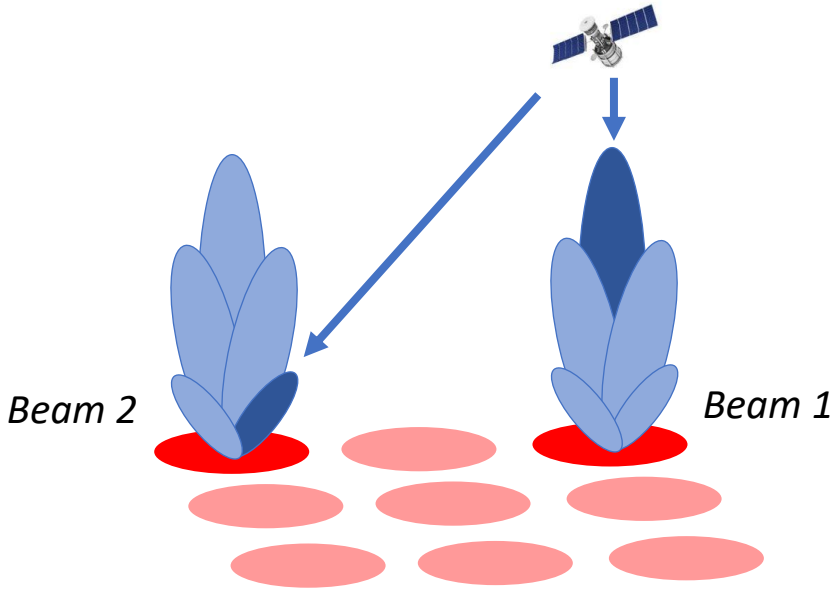
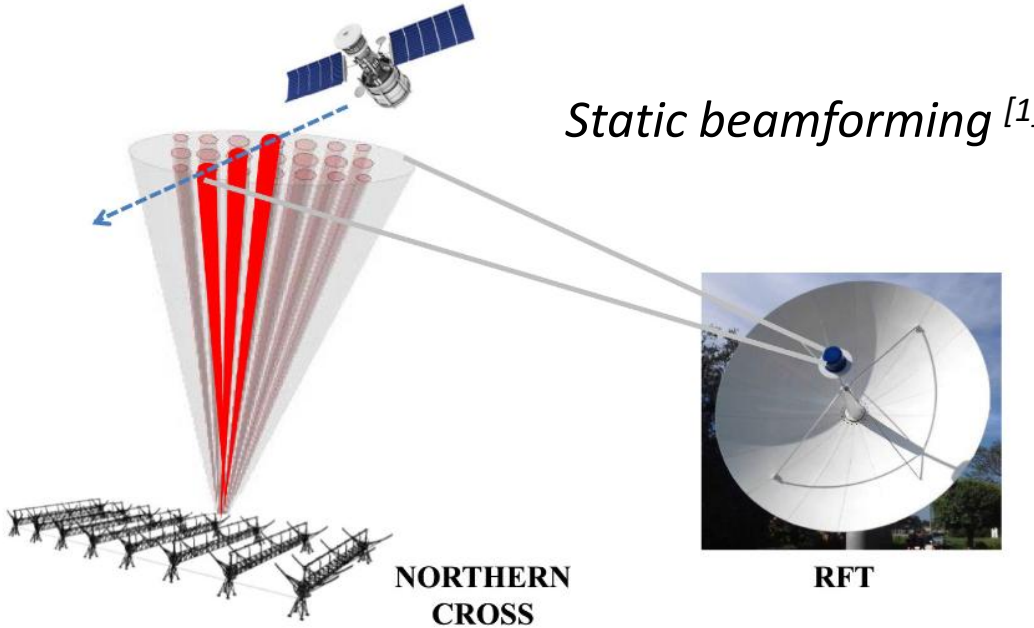


M. Losacco, et al., Initial orbit determination with the multibeam radar sensor BIRALES, 2020

BIRALES: Multibeam Approach



Static beamforming [1]

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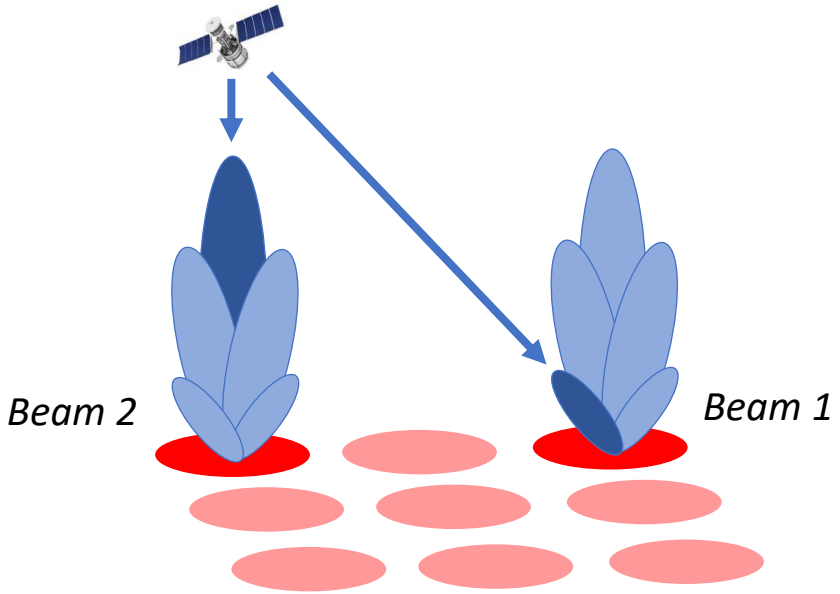
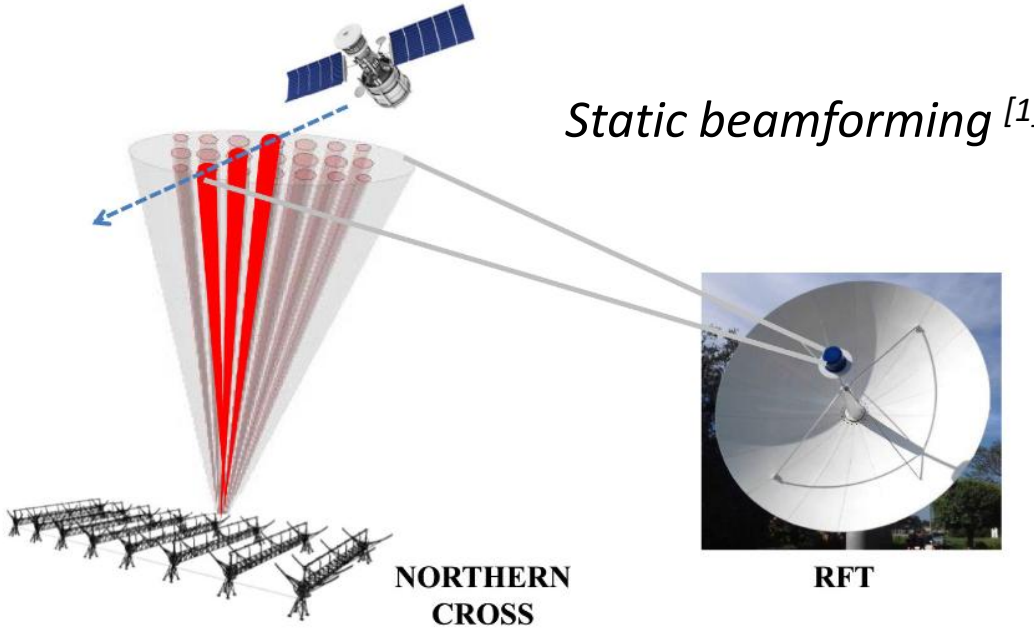


M. Losacco, et al., Initial orbit determination with the multibeam radar sensor BIRALES, 2020

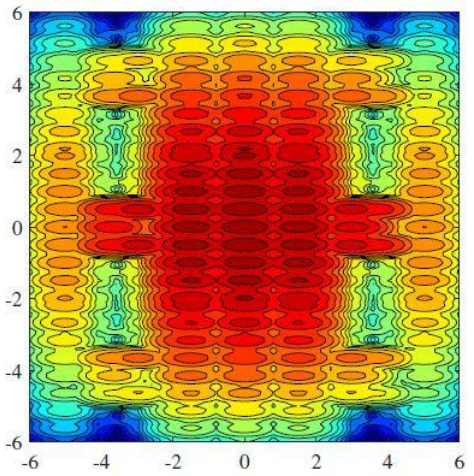
BIRALES: Multibeam Approach

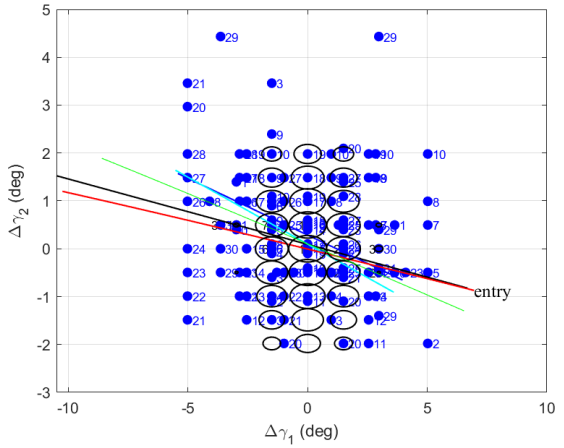


Static beamforming [1]

Medicina (Bologna)

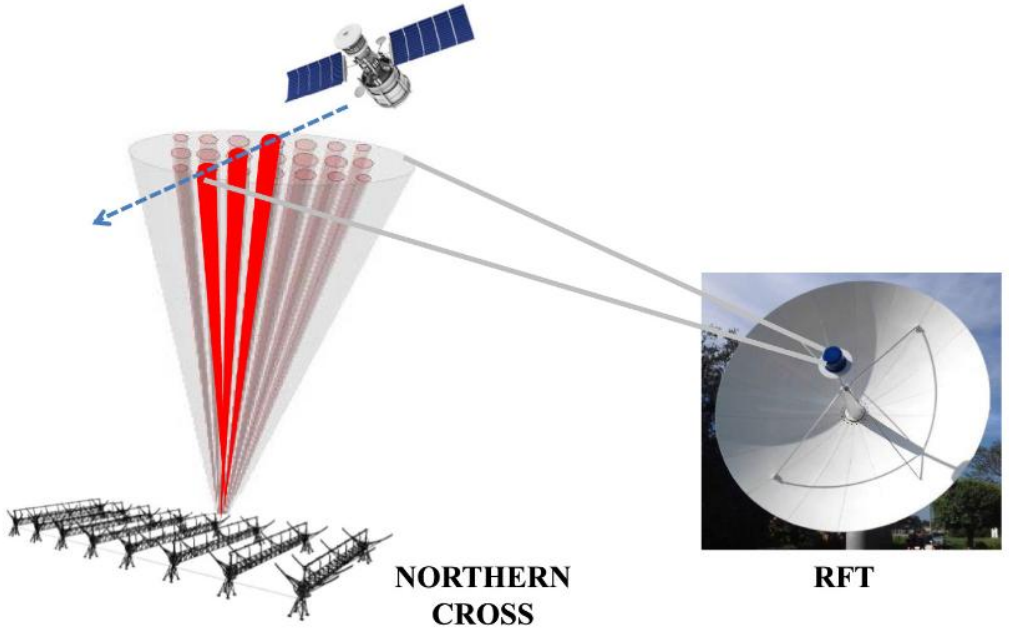
Salto di Quirra (Sardinia)





M. Losacco, et al., Initial orbit determination with the multibeam radar sensor BIRALES, 2020

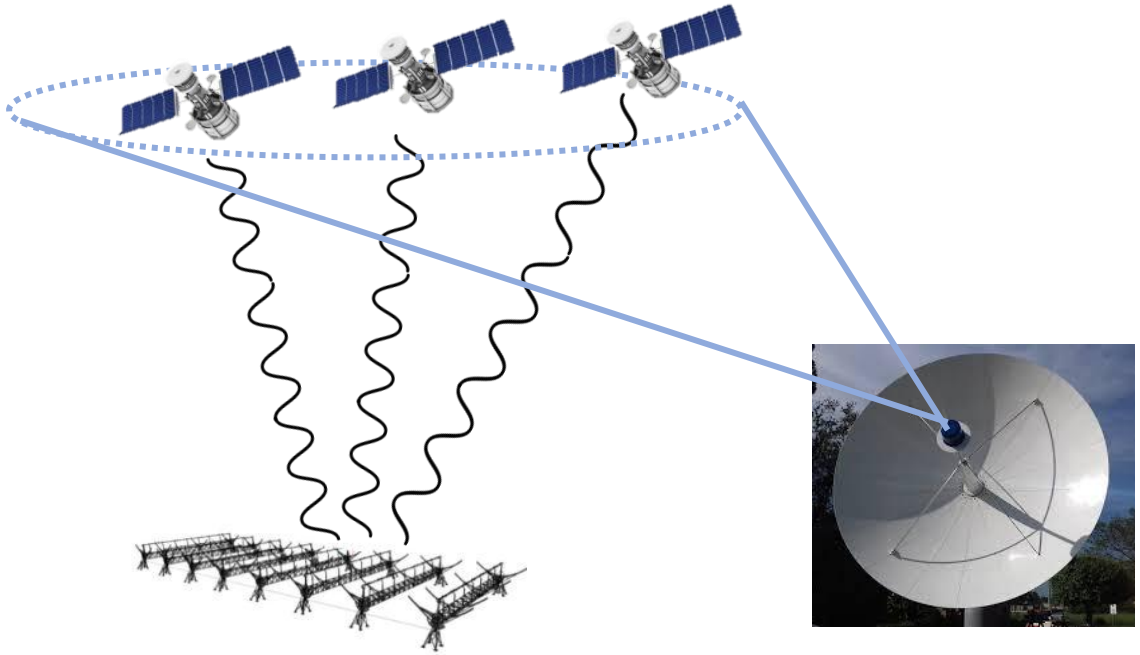
BIRALES: Multibeam Approach



Medicina (Bologna)

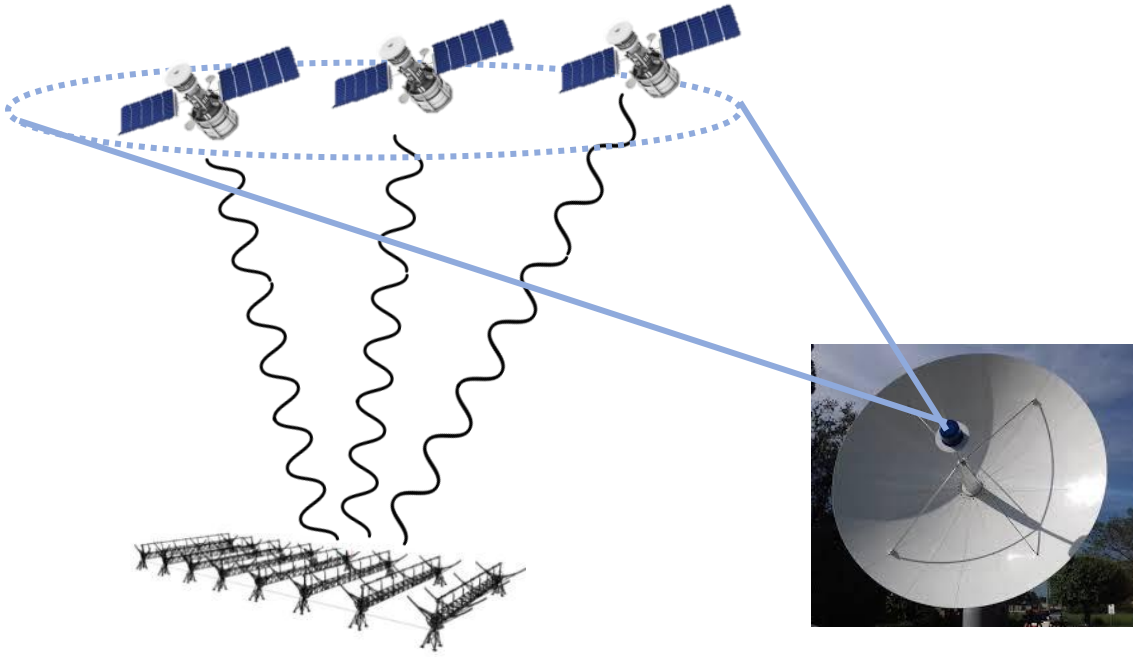
Salto di Quirra (Sardinia)

Adaptive beamforming

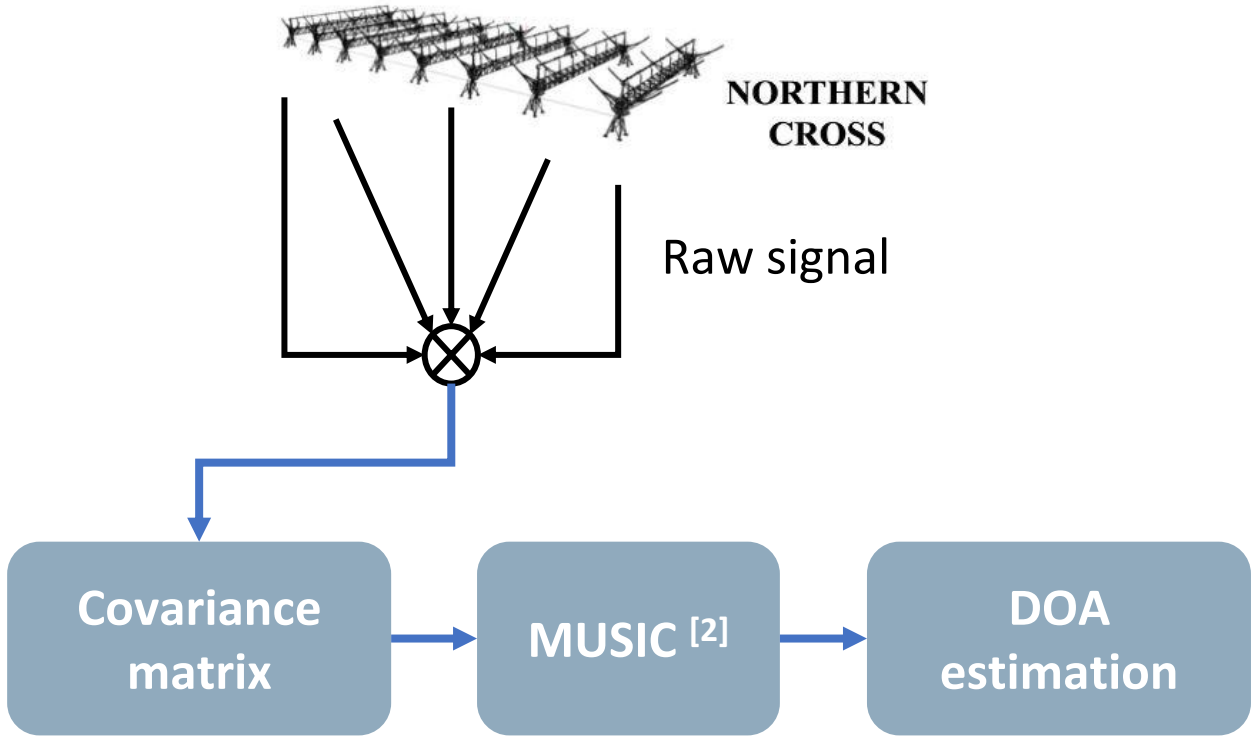


R. Schmidt et al., IEEE Transactions on Antennas and Propagation, 1986

BIRALES: Adaptive Beamforming Approach

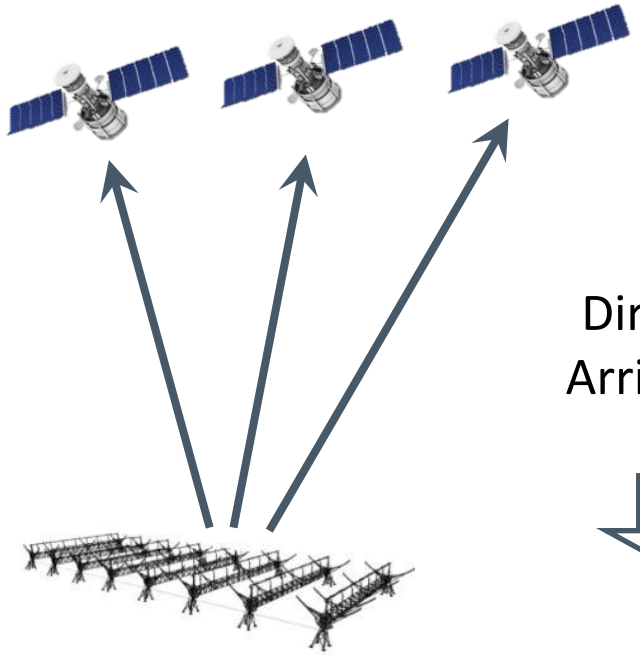


MUSIC *- MUltiple SIgnal Classification* [2]



R. Schmidt et al., IEEE Transactions on Antennas and Propagation, 1986

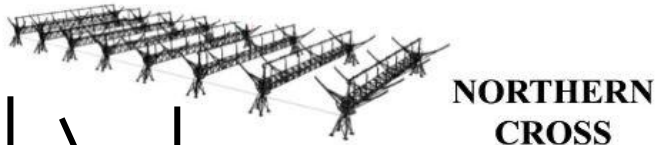
BIRALES: Adaptive Beamforming Approach



Direction of Arrival (DOA)

Angular track

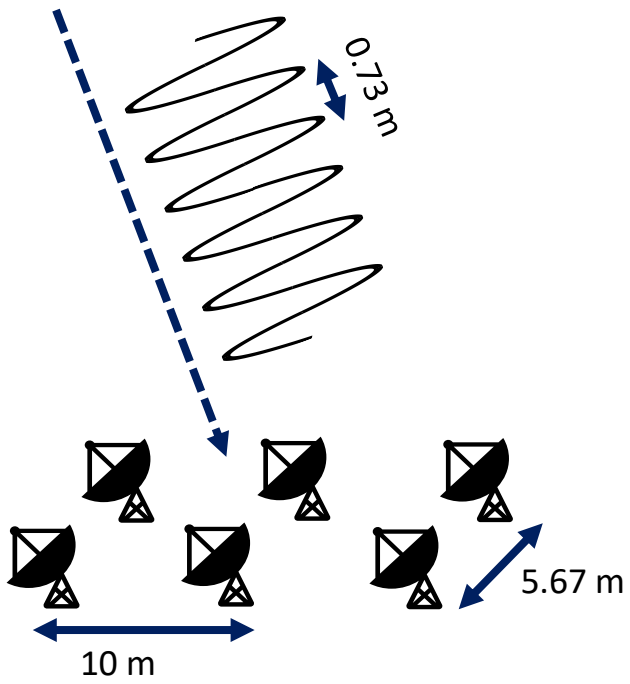
MUSIC *- MUltiple SIgnal Classification* [2]

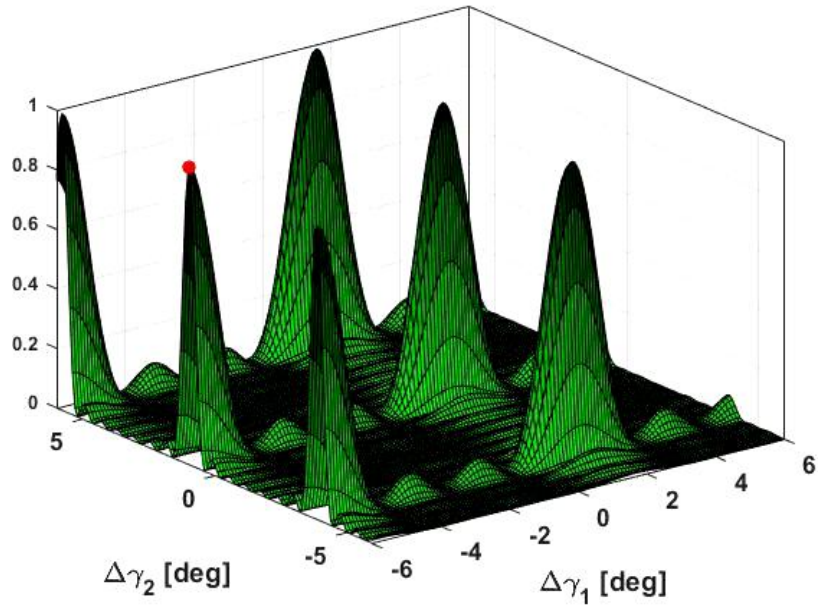


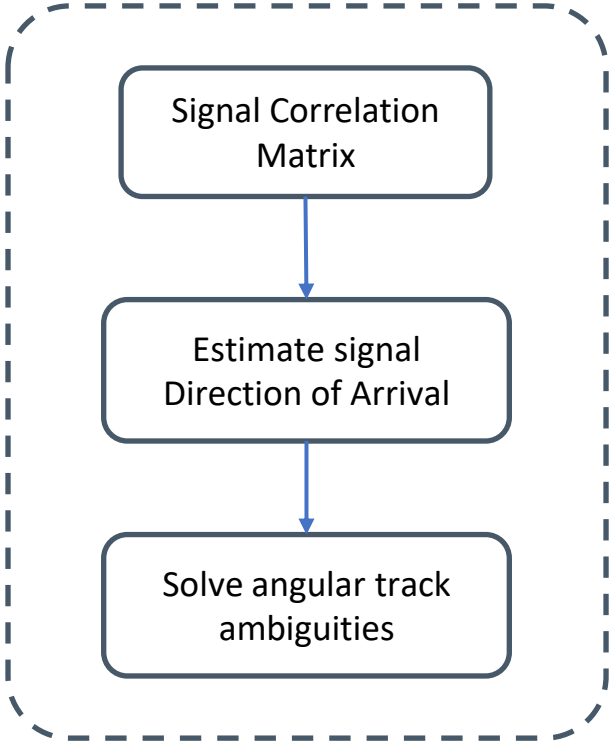
Raw signal

R. Schmidt et al., IEEE Transactions on Antennas and Propagation, 1986

Music Approach for Track Estimate and Refinement (MATER)





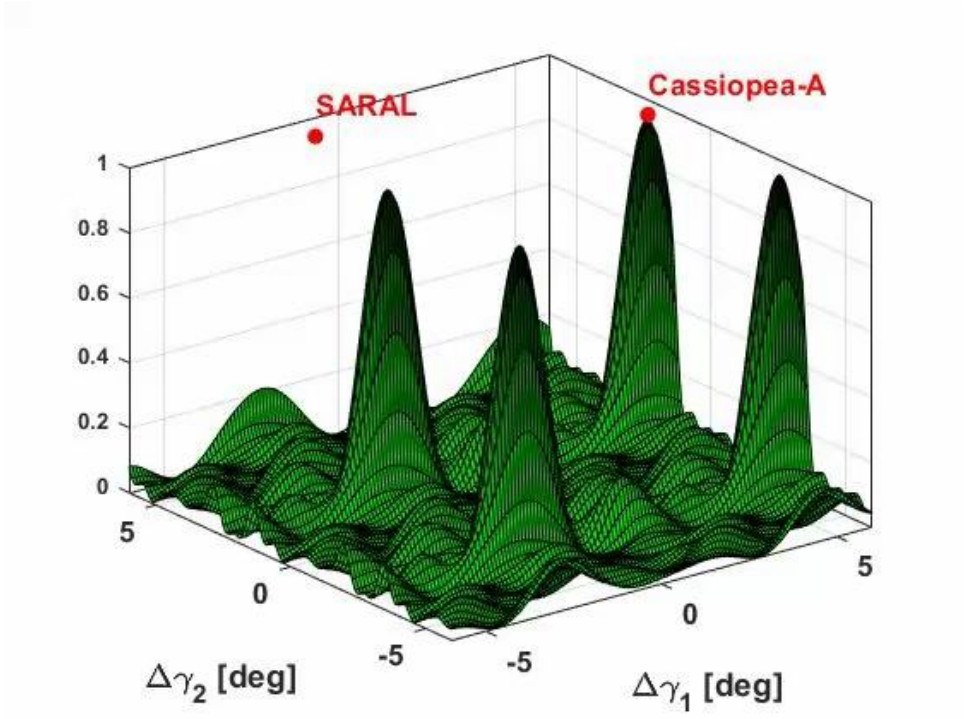


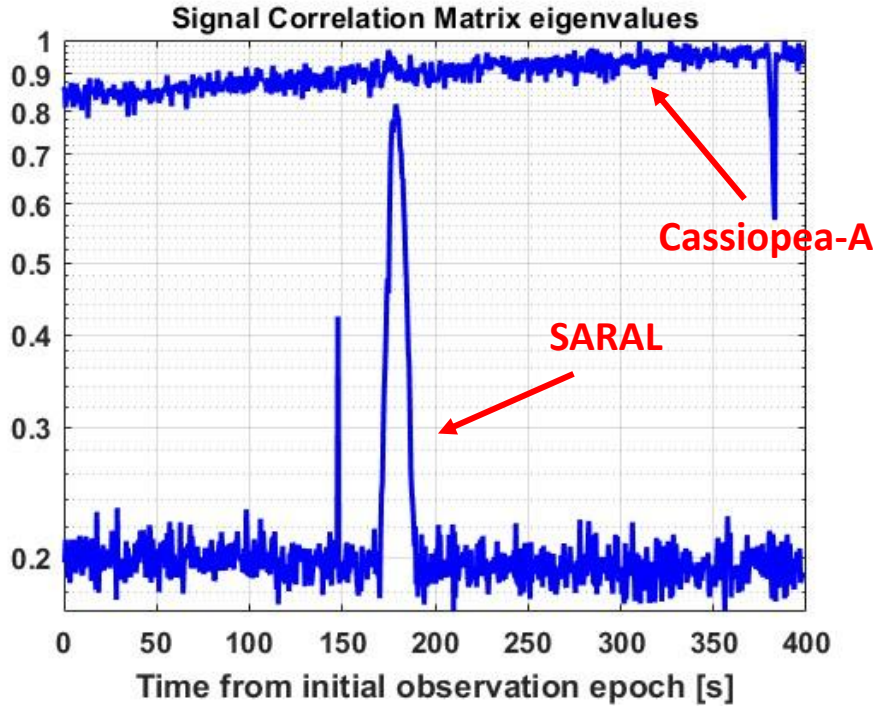
M.F. Montaruli, et al., Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, 2022
M.F. Montaruli, et al., Adaptive track approach for multiple sources scenario in space surveillance applications, Aerospace Science and Technologies, 2024
M.F. Montaruli, et al., Delta-k approach for space surveillance multireceiver radars. Astrodynamics, 2024

Real data processing - channelisation

SARAL transit

- December 2°, 2022
- Target: SARAL (norad ID 39086)
- Radiosource: Cassiopea-A





Real data processing - channelisation

8192 channels → Detection block → Channel selected → Correlate

$BW_{RX} \sim 85000\ Hz$

↓

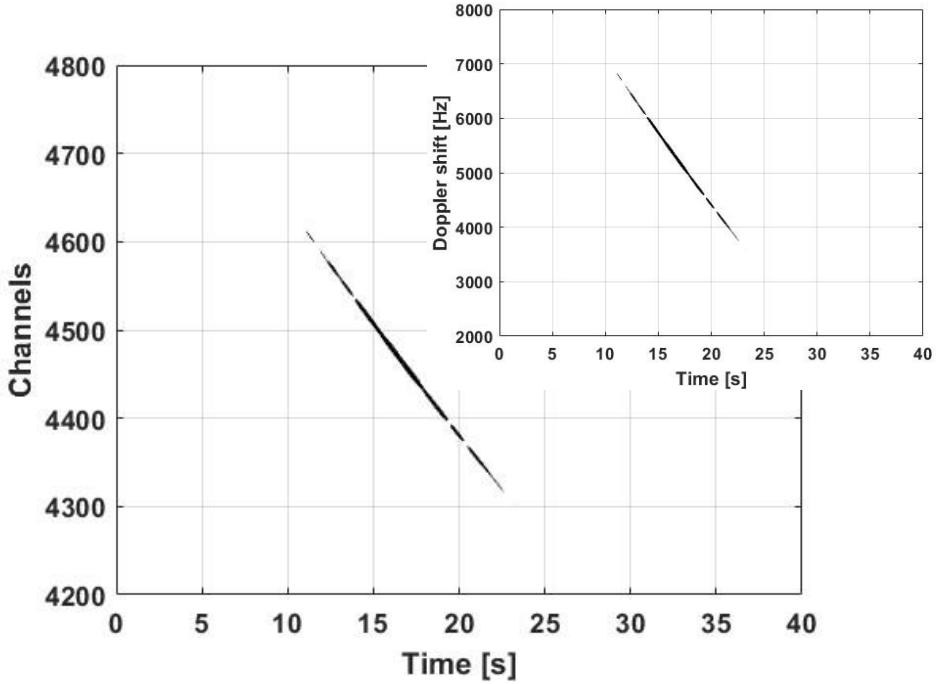
$BW_{RX} \sim 10\ Hz$

⇩

$SNR \propto \frac{1}{BW_{RX}}$ ⬆

⇨

- Angular track accuracy ⬆
- Detection rate ⬆
- Multiple sources scenario ⬇

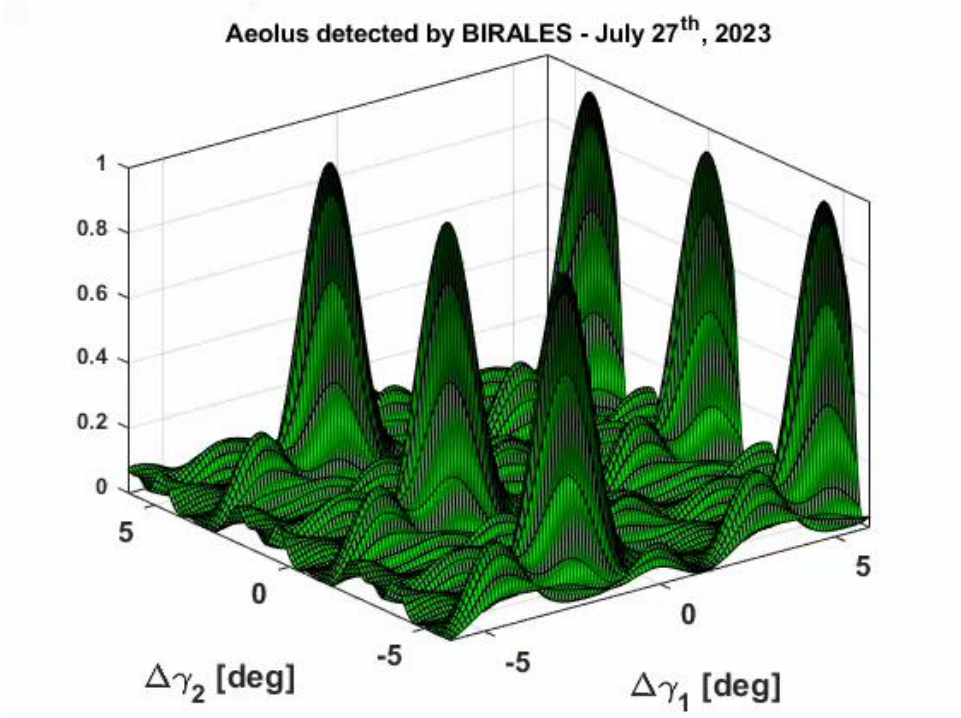


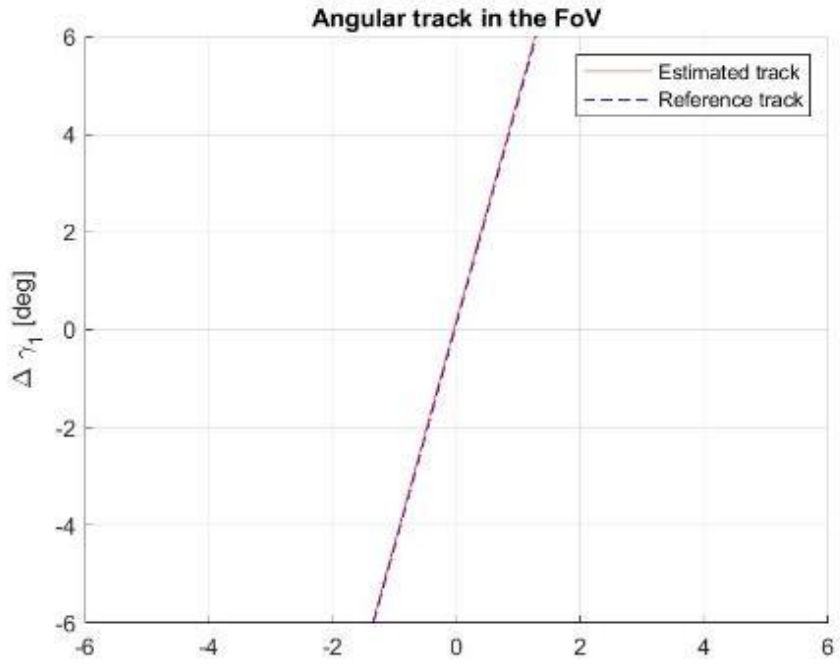
M.F. Montaruli, et al., Operational angular track reconstruction in survey radars through an adaptive beamforming approach, MDPI Aerospace, 2024

Real data processing - channelisation

Aeolus re-entry campaign

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





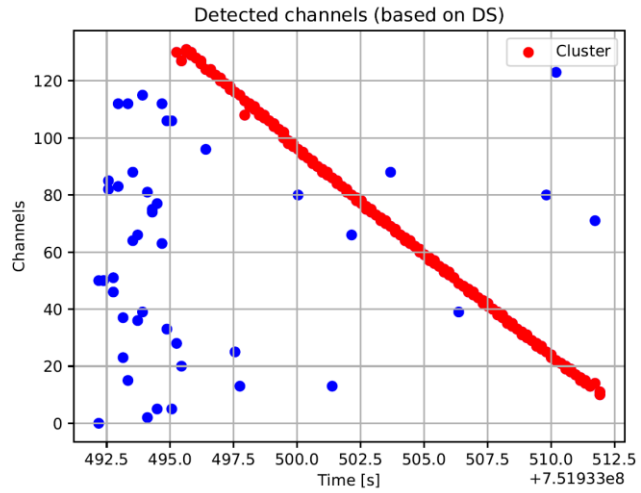
OUTLINE

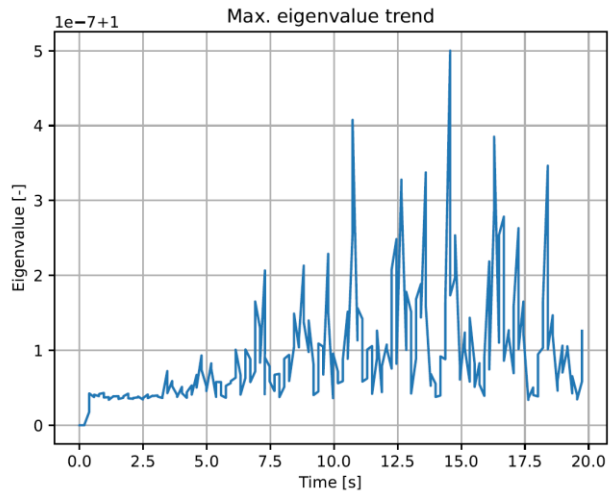
Input

- Signal Correlation Matrix
- Detection epochs
- Detection channels
- Other data

MATER

CM calibration → Remove outliers → Signal power cut



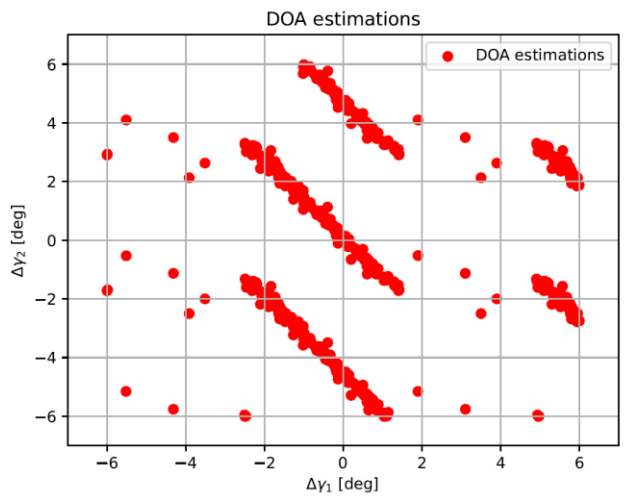


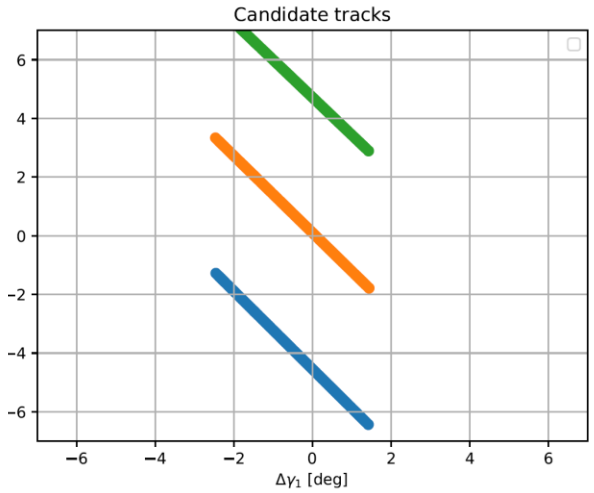
Input

- Signal Correlation Matrix
- Detection epochs
- Detection channels
- Other data

MATER

- CM calibration
- Remove outliers
- Signal power cut
- Estimate signal Direction of Arrival
- Cluster solutions
- Compute angular track candidates



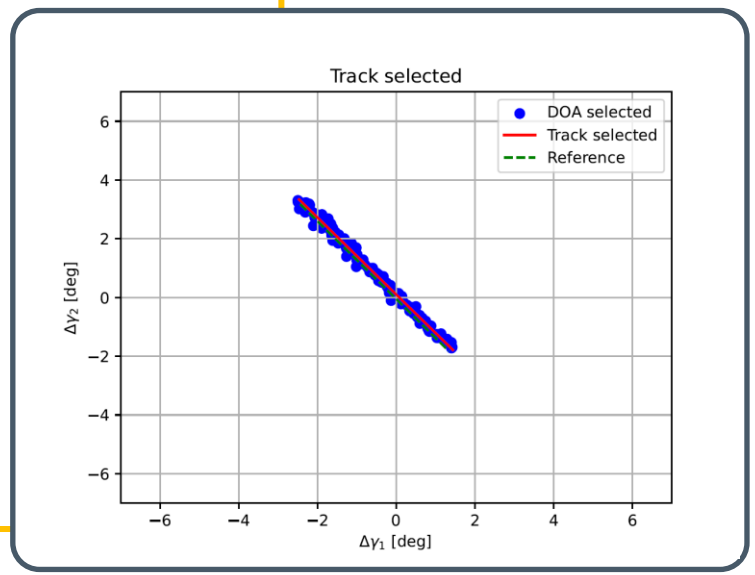


Input

- Signal Correlation Matrix
- Detection epochs
- Detection channels
- Other data

MATER

- CM calibration
- Remove outliers
- Signal power cut
- Estimate signal Direction of Arrival
- Cluster solutions
- Compute angular track candidates
- Track-to-orbit correlation
- Select the track best correlating

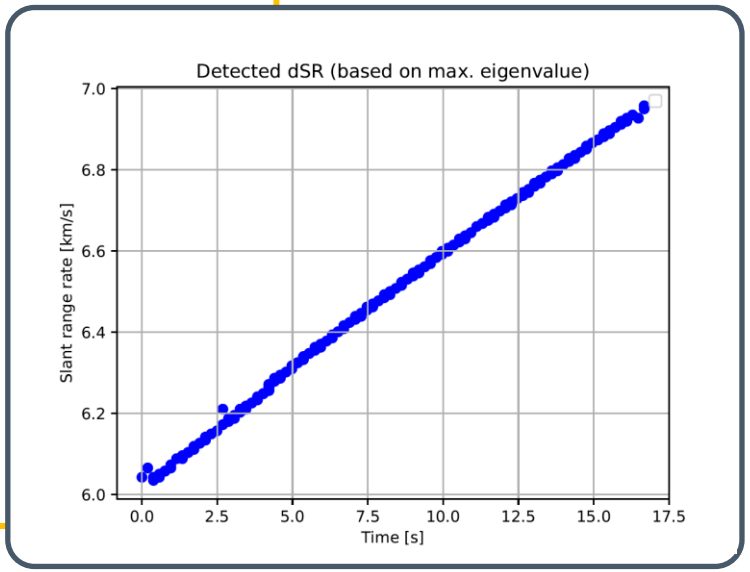


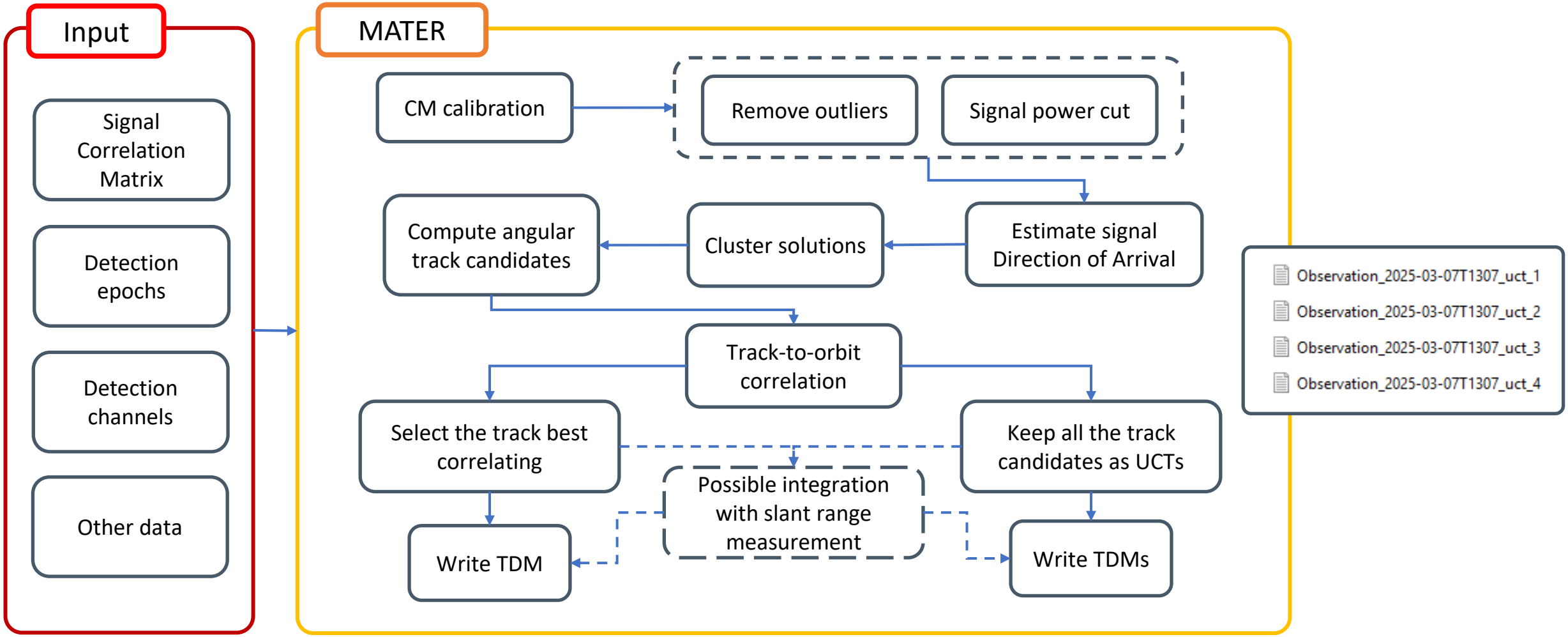
Input

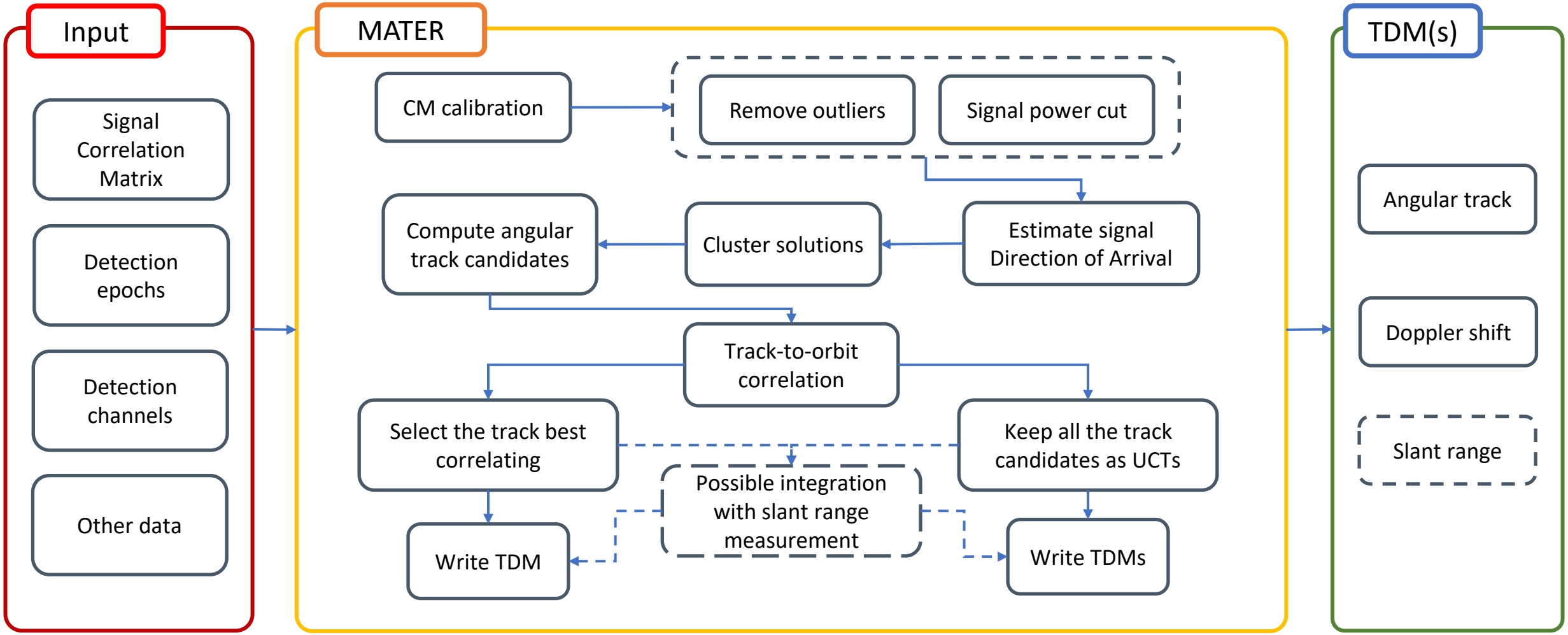
- Signal Correlation Matrix
- Detection epochs
- Detection channels
- Other data

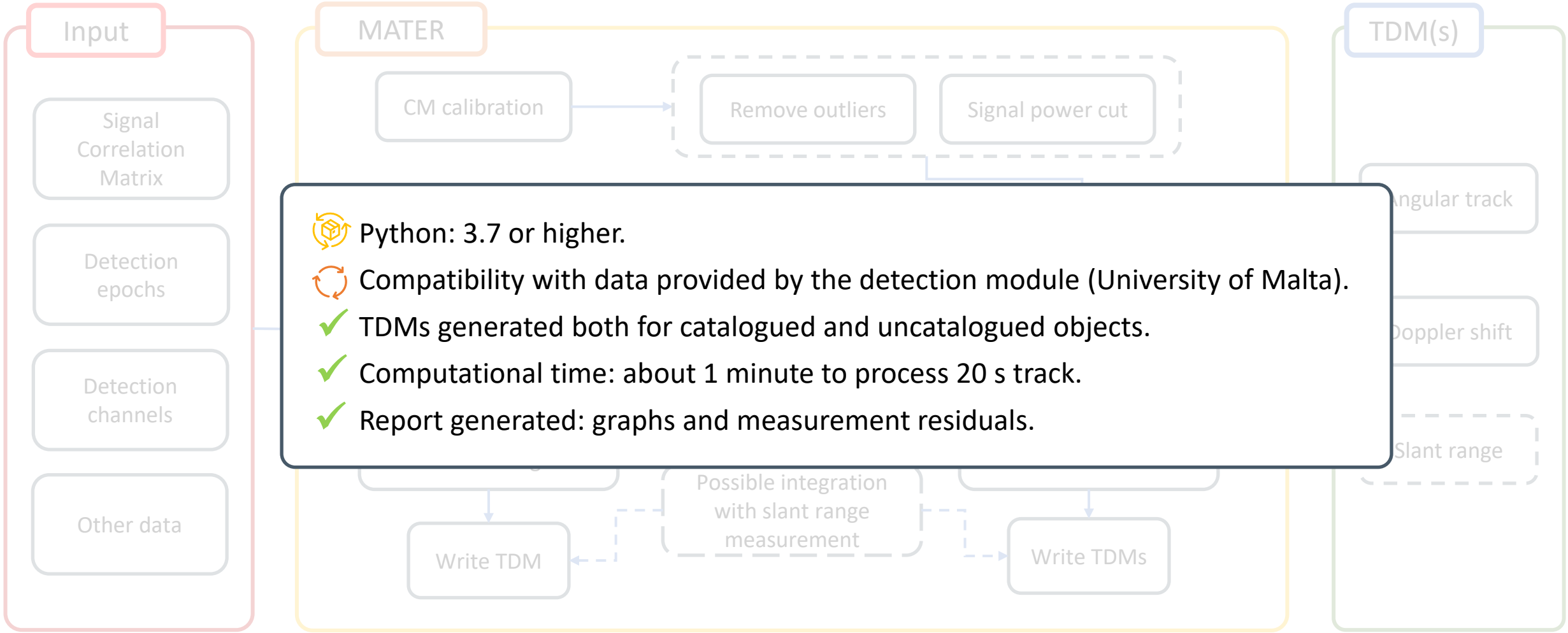
MATER

- CM calibration
- Remove outliers
- Signal power cut
- Estimate signal Direction of Arrival
- Cluster solutions
- Compute angular track candidates
- Track-to-orbit correlation
- Select the track best correlating
- Possible integration with slant range measurement
- Write TDM




Input
Signal Correlation Matrix
Detection epochs
Detection channels
Other data
MATER
CM calibration
Remove outliers
Signal power cut
Estimate signal Direction of Arrival
Cluster solutions
Compute angular track candidates
Track-to-orbit correlation
Select the track best correlating
Keep all the track candidates as UCTs
Possible integration with slant range measurement
Write TDM
Write TDMs
Observation_2025-03-07T1307_uct_1
Observation_2025-03-07T1307_uct_2
Observation_2025-03-07T1307_uct_3
Observation_2025-03-07T1307_uct_4

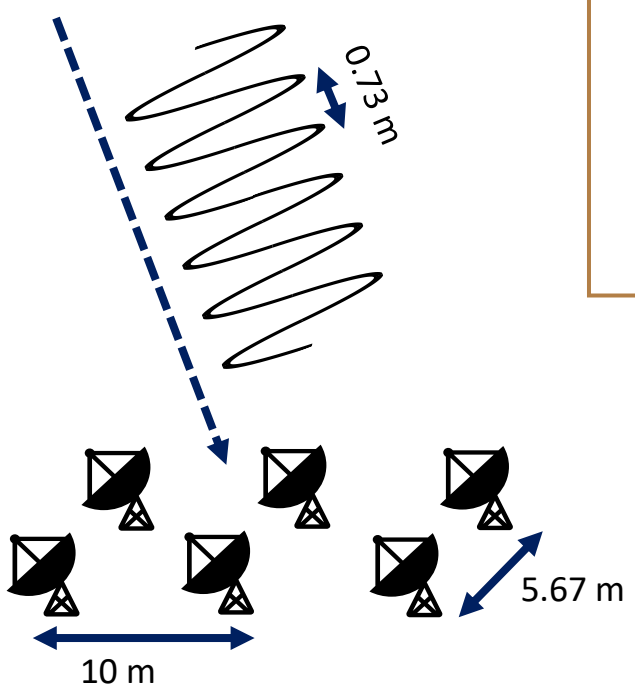

Input
Signal Correlation Matrix
Detection epochs
Detection channels
Other data
MATER
CM calibration
Remove outliers
Signal power cut
Estimate signal Direction of Arrival
Cluster solutions
Compute angular track candidates
Track-to-orbit correlation
Select the track best correlating
Keep all the track candidates as UCTs
Possible integration with slant range measurement
Write TDM
Write TDMs
TDM(s)
Angular track
Doppler shift
Slant range

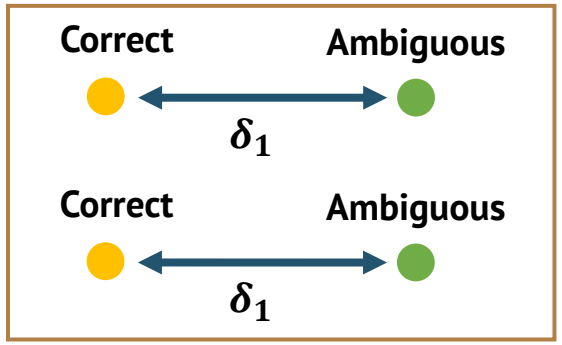


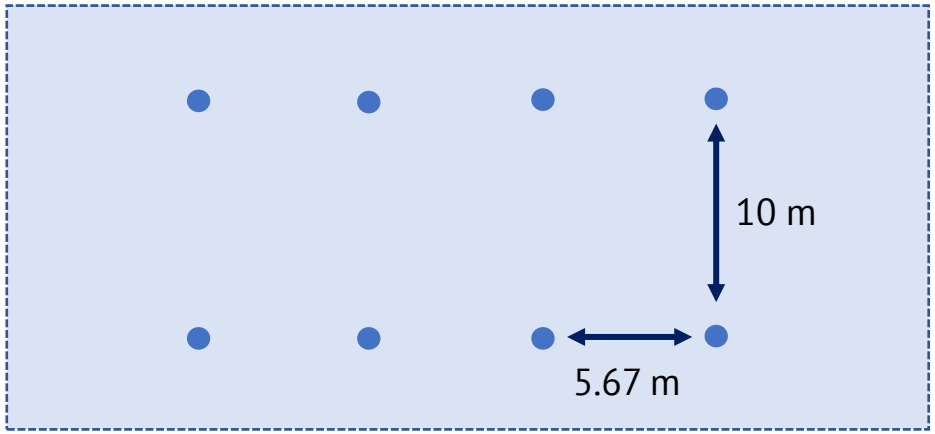
- Python: 3.7 or higher.
- Compatibility with data provided by the detection module (University of Malta).
- ✓ TDMs generated both for catalogued and uncatalogued objects.
- ✓ Computational time: about 1 minute to process 20 s track.
- ✓ Report generated: graphs and measurement residuals.

OUTLINE

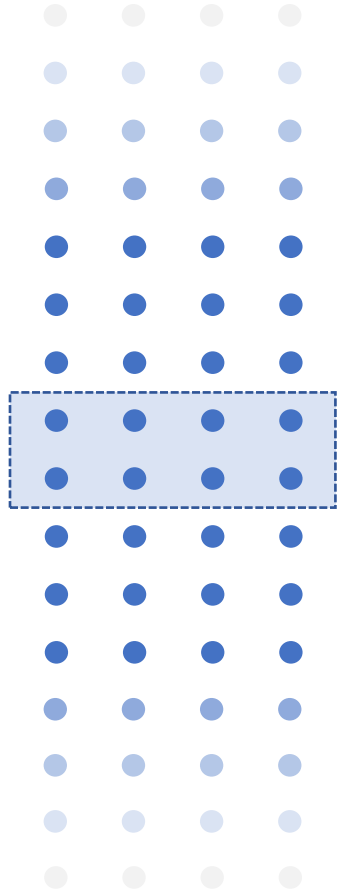
Ambiguity solving through East-West branch



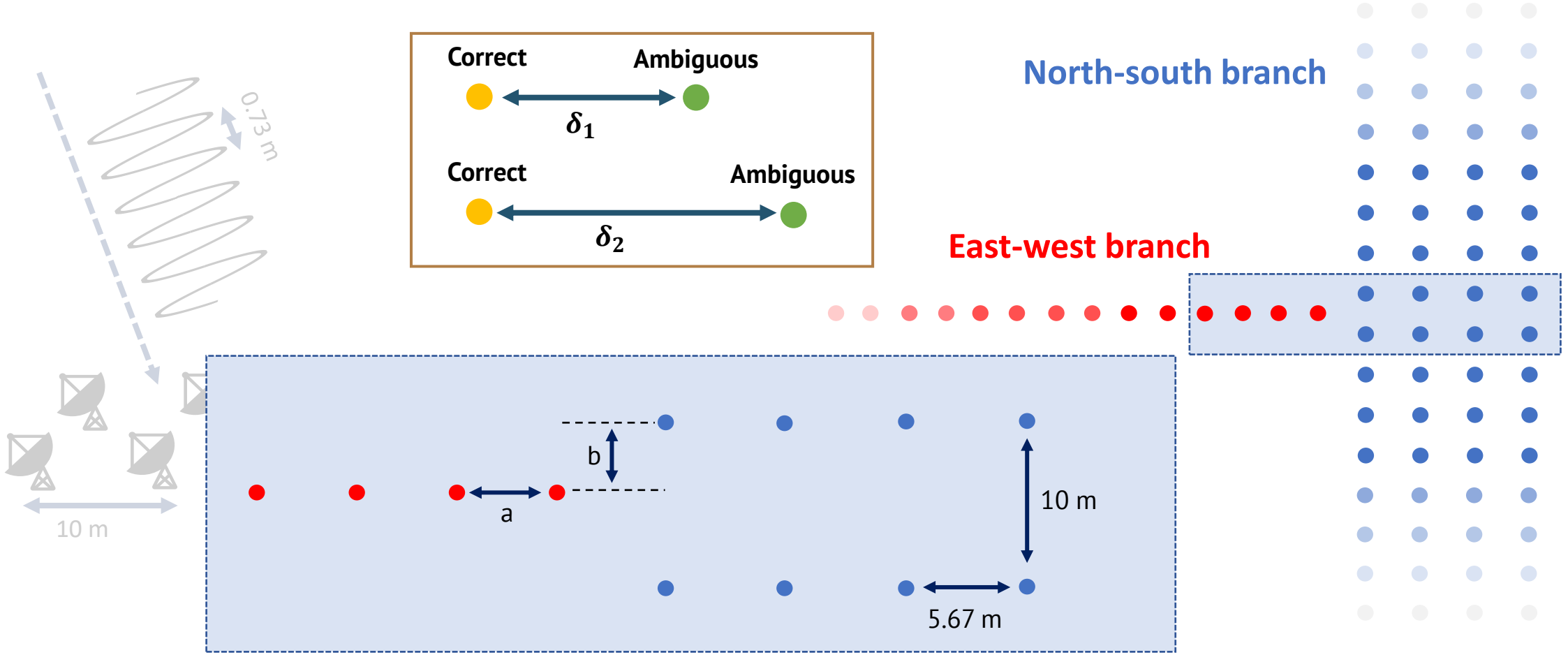




North-south branch

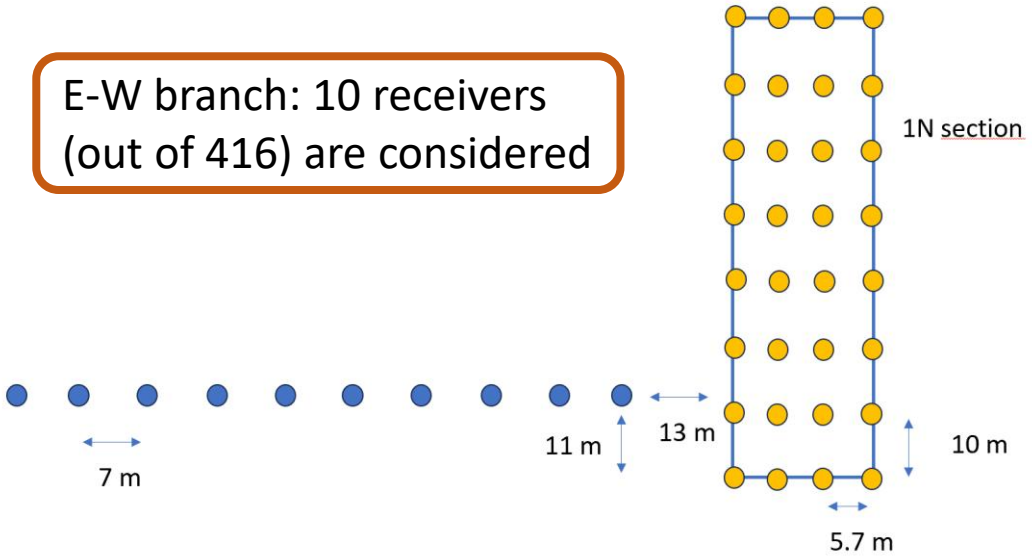


Ambiguity solving through East-West branch

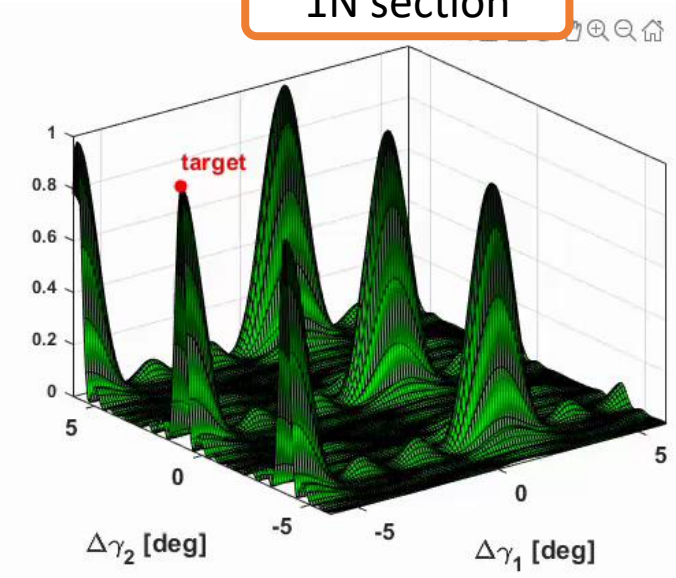


Ambiguity solving through East-West branch

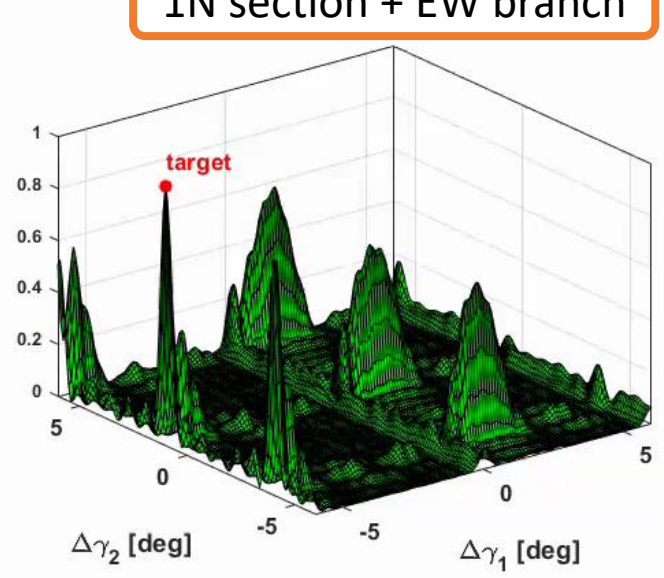
E-W branch: 10 receivers (out of 416) are considered



1N section



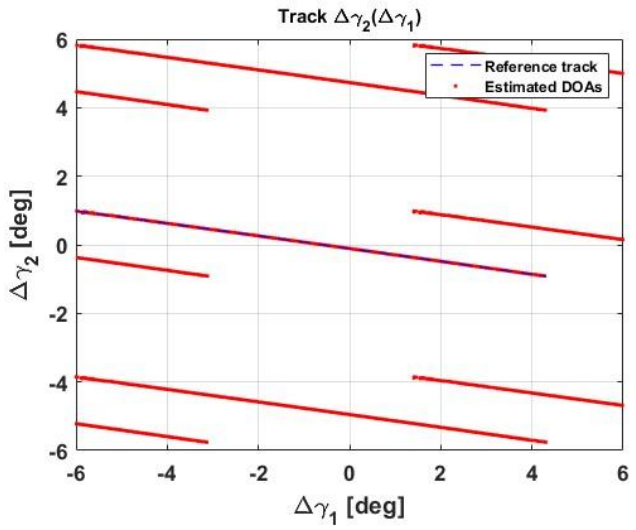
1N section + EW branch



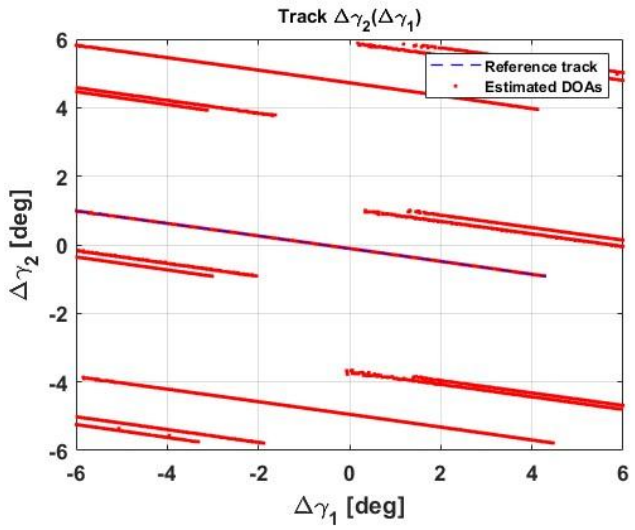
- Improved resolution in E-W direction.
- The N-S shift between the 1N section and the E-W branch depends on the E-W pointing direction.
  - Performance partially change

Ambiguity solving through East-West branch

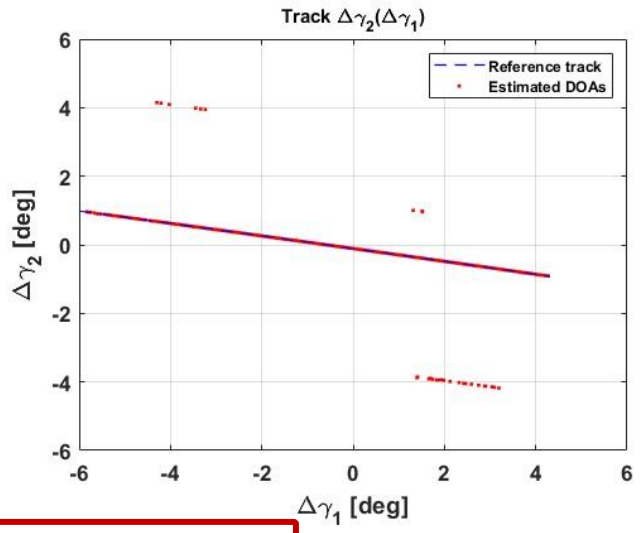
1N section



1N section
EW branch



Most fixed solution



- The algorithm is tested against a data set of LEO 899 transits.
- ✓ The ambiguity resulted to be solved in 100% of cases (98% with 0 m shift).
- ✓ RMSE: $\Delta\gamma_1$: 6.9e-03 deg; $\Delta\gamma_2$: 1.1e-02 deg.

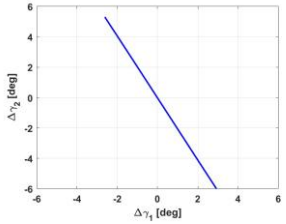
Operationally

No need of track-to-orbit correlation:

- Improves reliability.
- Solve the ambiguity in the UCT case.

OUTLINE

IOD angles and DS



$$\boldsymbol{r} = \boldsymbol{q} + \rho\,\hat{\boldsymbol{\rho}}$$

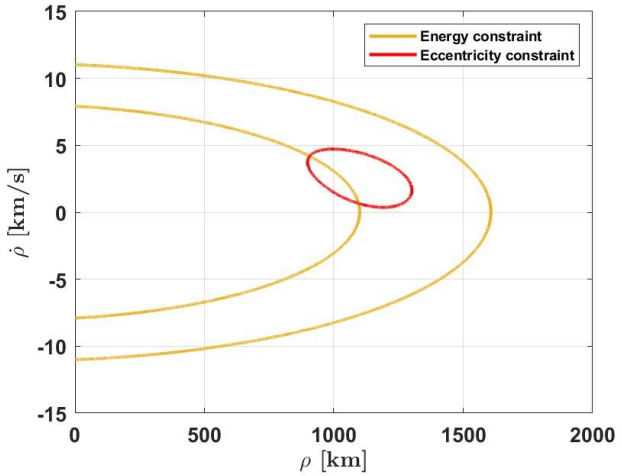
$$\dot{\boldsymbol{r}} = \dot{\boldsymbol{q}} + \dot{\rho}\hat{\boldsymbol{\rho}} + \rho\frac{d\hat{\boldsymbol{\rho}}}{dt}$$

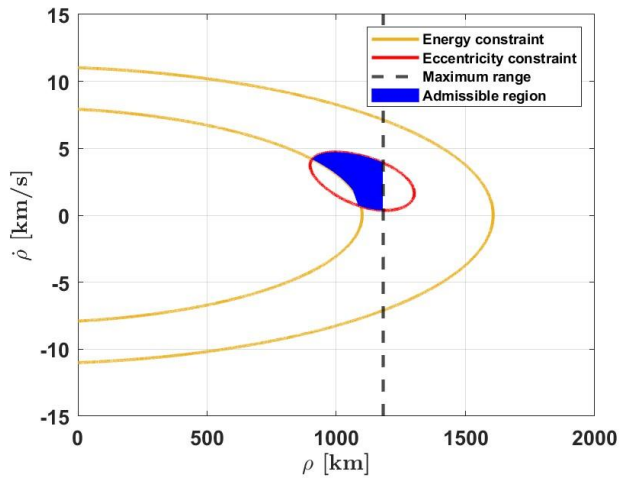
Angular track compression

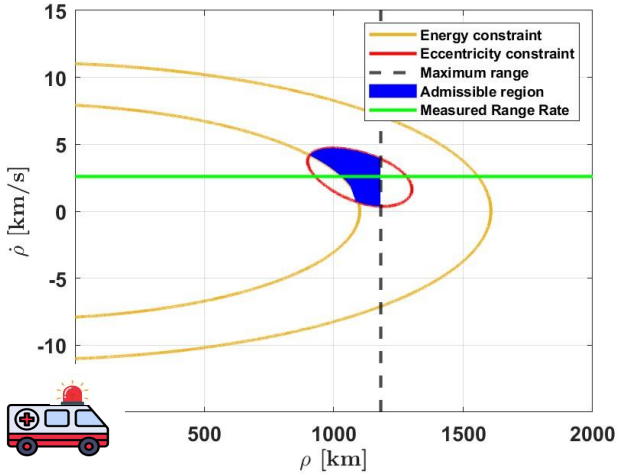
Optical admissible region

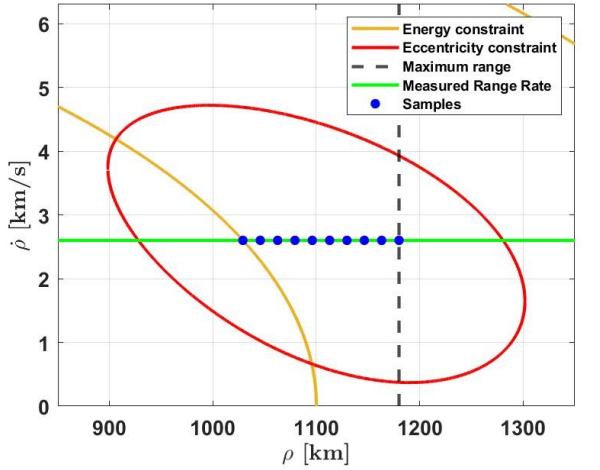
Add radar constraints

Orbital states candidates



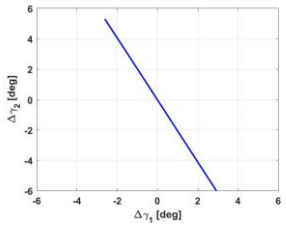






A. Milani, et al., Orbit determination with very short arcs. I admissible regions, Celestial Mechanics and Dynamical Astronomy, 2004
M.F. Montaruli, Radar initial orbit determination method from angular track and Doppler shift measurements, Astrodynamics, 2025

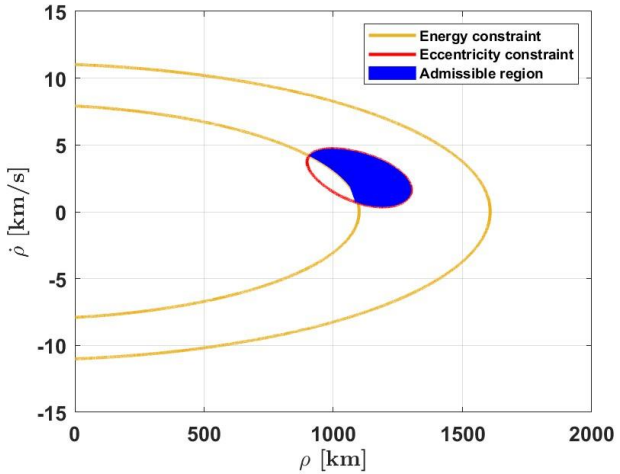
IOD angles and DS

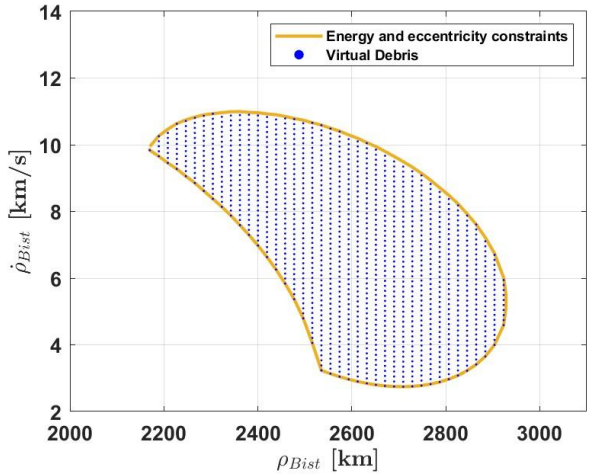


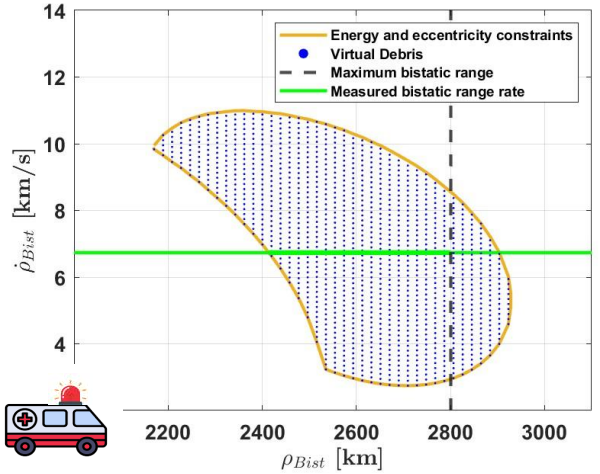
$$\boldsymbol{r} = \boldsymbol{q} + \rho\,\hat{\boldsymbol{\rho}}$$

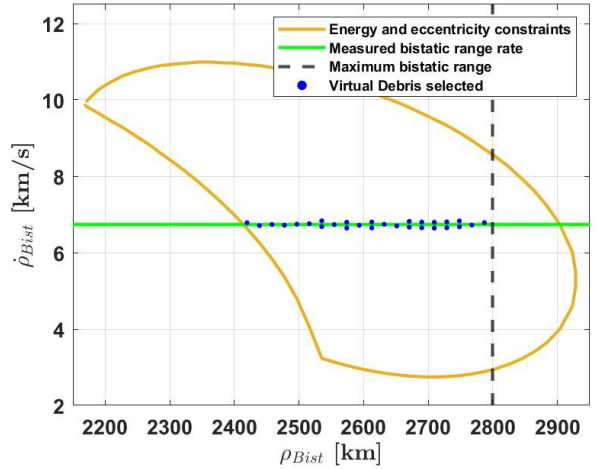
$$\dot{\boldsymbol{r}} = \dot{\boldsymbol{q}} + \dot{\rho}\hat{\boldsymbol{\rho}} + \rho\frac{d\hat{\boldsymbol{\rho}}}{dt}$$

- Angular track compression
- Optical admissible region
- Bistatic case
  - Project VDs in the bistatic plane
- Add radar constraints
- Orbital states candidates









A. Milani, et al., Orbit determination with very short arcs. I admissible regions, Celestial Mechanics and Dynamical Astronomy, 2004
M.F. Montaruli, Radar initial orbit determination method from angular track and Doppler shift measurements, Astrodynamics, 2025

IOD angles and DS

$$\boldsymbol{r} = \boldsymbol{q} + \rho\,\hat{\boldsymbol{\rho}}$$

$$\dot{\boldsymbol{r}} = \dot{\boldsymbol{q}} + \dot{\rho}$$

Angular track compression

Optical admissible region

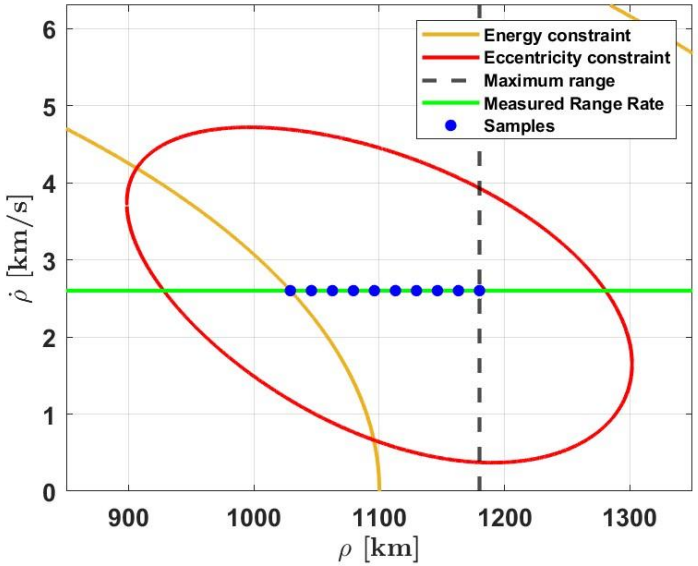
Bistatic case

Project VDs in the bistatic plane

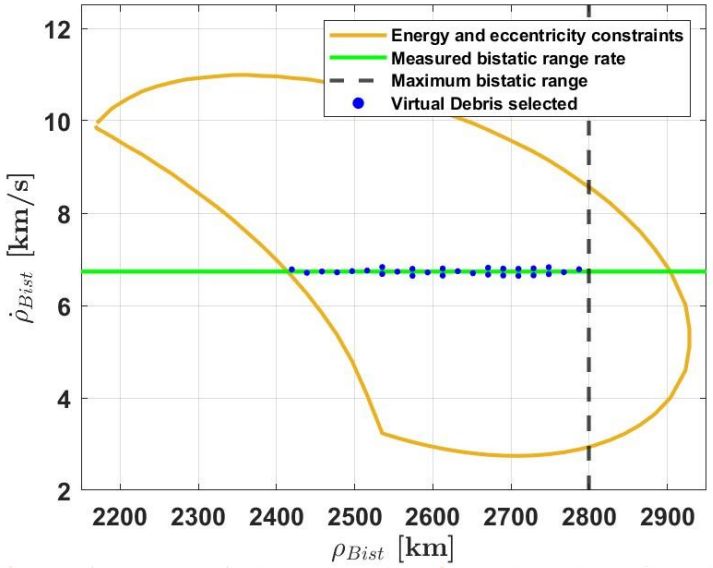
Add radar constraints

Orbital state

Monostatic case



Bistatic case



- Select the candidate with the minimum eccentricity
- Run a batch filter

A. Milani, et al., Orbit determination with very short arcs. I admissible regions, Celestial Mechanics and Dynamical Astronomy, 2004
M.F. Montaruli, Radar initial orbit determination method from angular track and Doppler shift measurements, Astrodynamics, 2025

IOD angles and DS

Measurements accuracy

- Angles: 5e-02 ÷ 5e-01 [deg]
- Range rate: 1.4e-02 ÷ 3.2e-02 [km/s]

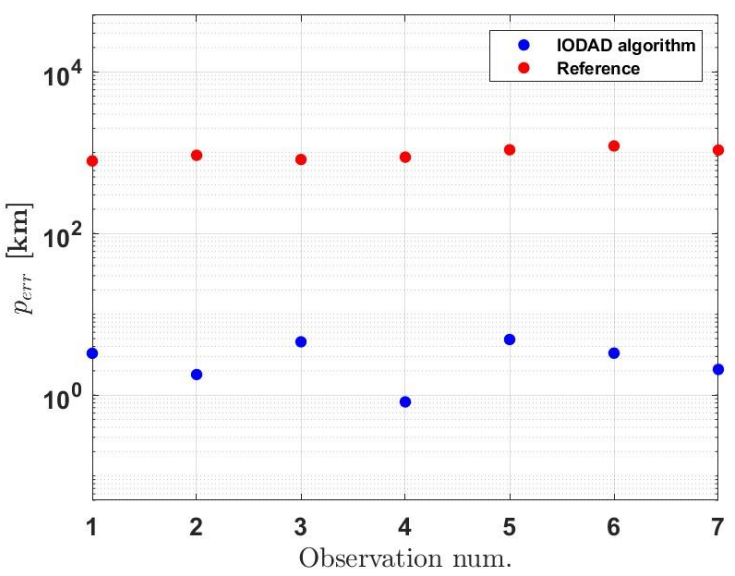
Duration: 20 s ÷ 45 s

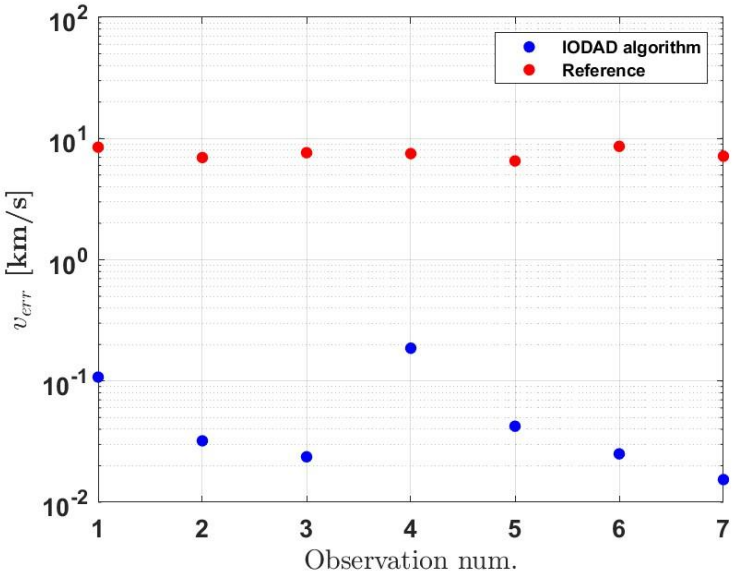
IODAD errors:

- Position: 8.2e-01 ÷ 4.9e+00 km
- Velocity: 1.5e-02 ÷ 1.9e-01 km/s

Reference methodology errors[1]:

- Position: 7.9e+02 ÷ 1.2e+03 km
- Velocity: 6.5e+00 ÷ 8.6e+00 km/s





✓ Remarkably improvement with respect the state of the art

✓ Cataloguing capability from UCTs wihout range

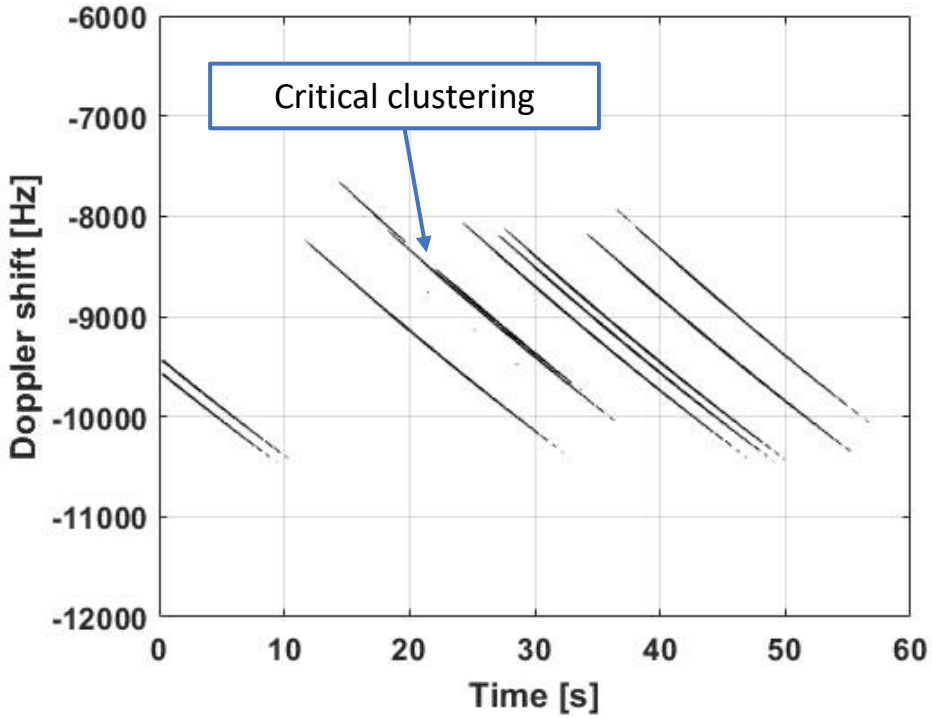
C. Yanez, et al., A Novel Initial Orbit Determination Algorithm from Doppler and Angular Observations, 2017

OUTLINE

Fragmentation CZ-6A

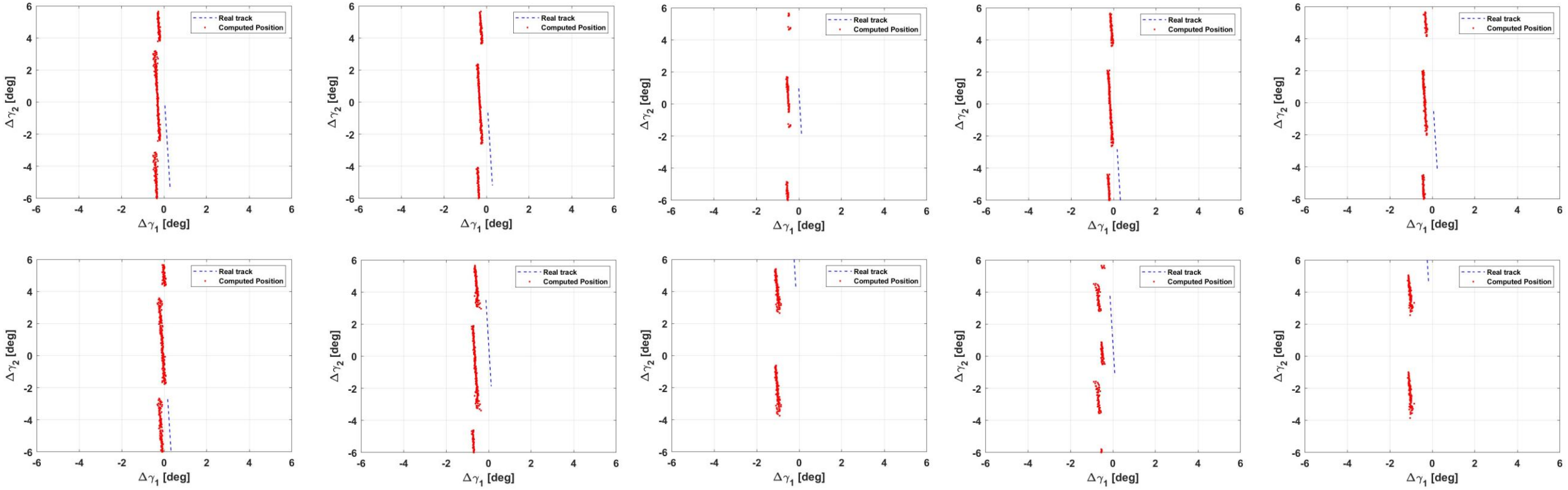
- September 3°, 2024
- Target: CZ-6A DEB (norad id 60649)

- August 7°, 2024: break-up of the launcher carrying QIANFAN constellation satellites
- QIANFAN constellation detected by 1N and 2N
- Signal transmitted: 60% CHIRP + 40% CW



Fragmentation CZ-6A

- Red dots: signal direction of arrival detected.
- Dashed blue line: target prediction.



Fragmentation CZ-6A

2 fragments detected

		TDM A	TDM B	TDM C	TDM D	TDM E	TDM F	TDM G	TDM H	TDM I	TDM L
QIANFAN-1	60379							0.38			
QIANFAN-5	60383						0.31				
QIANFAN-6	60384				0.35	10.35					
QIANFAN-7	60385			0.84						1.06	
QIANFAN-8	60386	1.36	0.49								
QIANFAN-9	60387	15.53	5.59			0.36					
QIANFAN-11	60389			0.29					0.29	0.5	
QIANFAN-12	60390								0.37		4.73
QIANFAN-13	60391								2.78		0.34
QIANFAN-14	60392					5.58					
CZ-6A DEB	60649			13.61						12.23	
CZ-6A DEB	60800										18.9

Fragmentation CZ-6A

We keep one track per target and one track per target

		TDM A	TDM B	TDM C	TDM D	TDM E	TDM F	TDM G	TDM H	TDM I	TDM L
QIANFAN-1	60379							0.38			
QIANFAN-5	60383						0.31				
QIANFAN-6	60384				0.35	10.35					
QIANFAN-7	60385			0.84						1.06	
QIANFAN-8	60386	1.36	0.49								
QIANFAN-9	60387	15.53	5.59			0.36					
QIANFAN-11	60389			0.29					0.29	0.5	
QIANFAN-12	60390								0.37		4.73
QIANFAN-13	60391								2.78		0.34
QIANFAN-14	60392					5.58					
CZ-6A DEB	60649			13.61						12.23	
CZ-6A DEB	60800										18.9

Fragmentation CZ-6A

TDM A remains not correlated. Possible fragment?

		TDM A	TDM B	TDM C	TDM D	TDM E	TDM F	TDM G	TDM H	TDM I	TDM L
QIANFAN-1	60379							0.38			
QIANFAN-5	60383						0.31				
QIANFAN-6	60384				0.35						
QIANFAN-7	60385									1.06	
QIANFAN-8	60386		0.49								
QIANFAN-9	60387					0.36					
QIANFAN-11	60389			0.29							
QIANFAN-12	60390								0.37		
QIANFAN-13	60391										0.34
QIANFAN-14	60392										
CZ-6A DEB	60649										
CZ-6A DEB	60800										

Fragmentation Starlink 34343

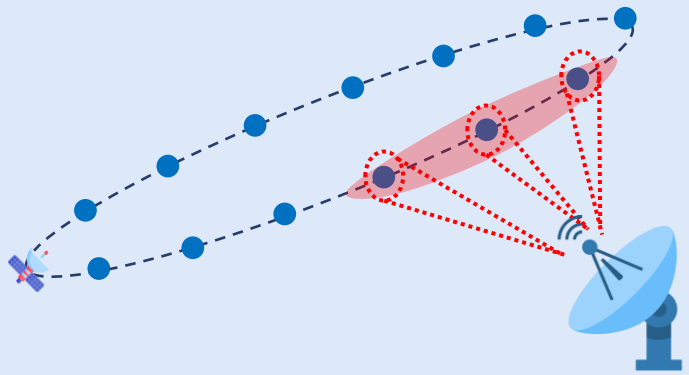
Fragmentation epoch: around 2026-03-29T19:30:00.000

Parent orbit geometry

Visibility constraints

→ Computation of pointing → Two visibility intervals of ~10 minutes per day

Orbital plane scanning



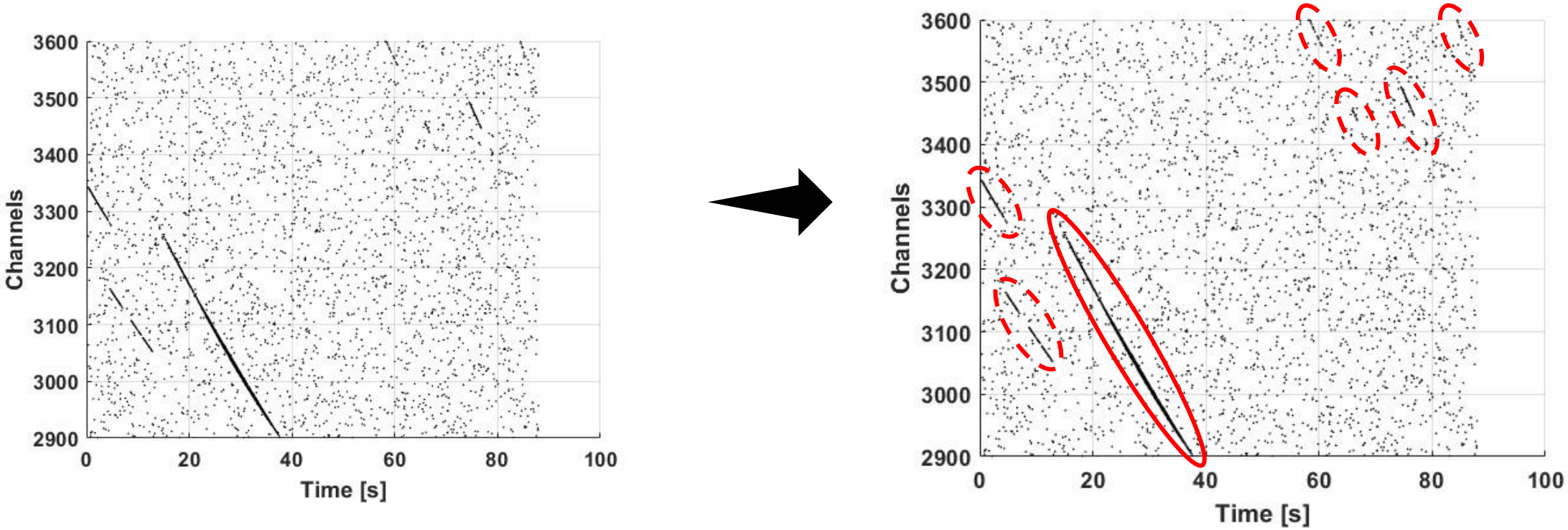
+

Meridian crossing

Fragmentation Starlink 34343

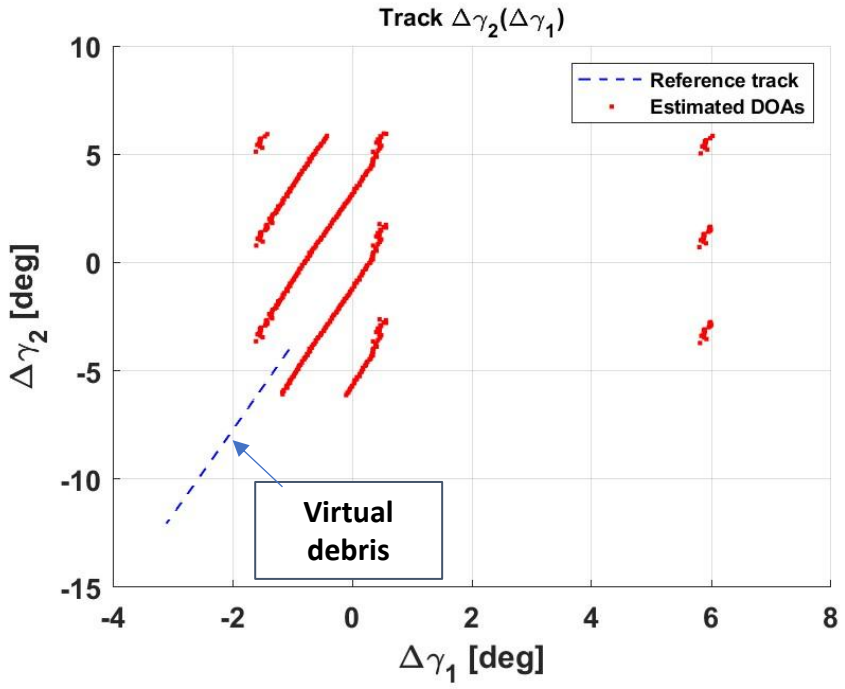
Fragmentation epoch: around 2026-03-29T19:30:00.000

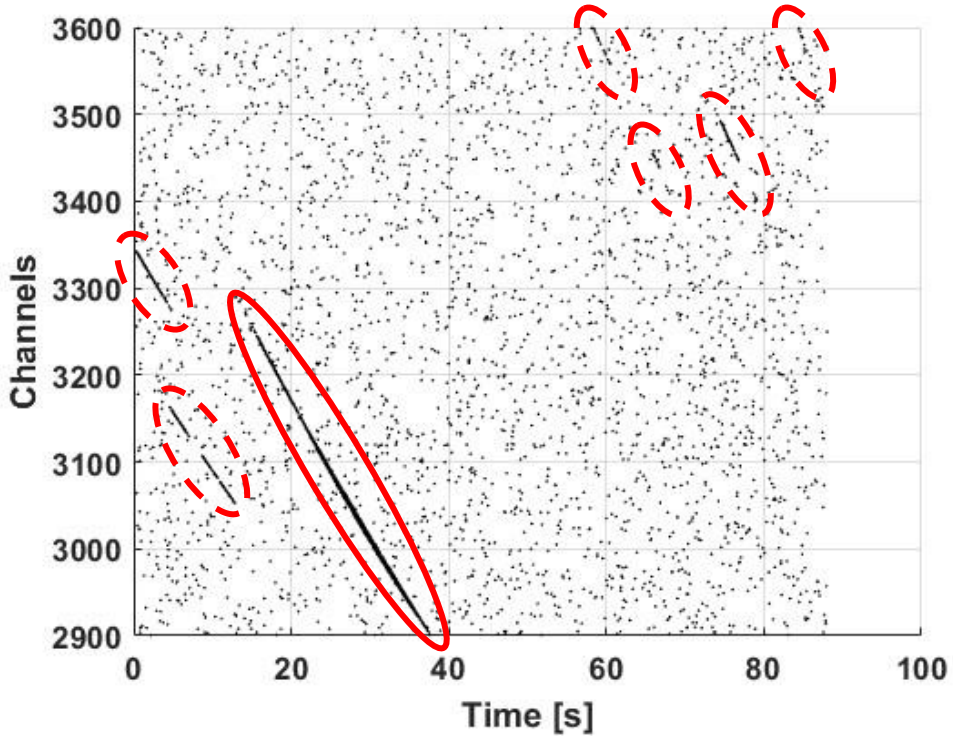
BIRALES detection from 02/04/2026 – h. 19:38 UTC



Fragmentation Starlink 34343

BIRALES detection from 02/04/2026 – h. 19:38 UTC

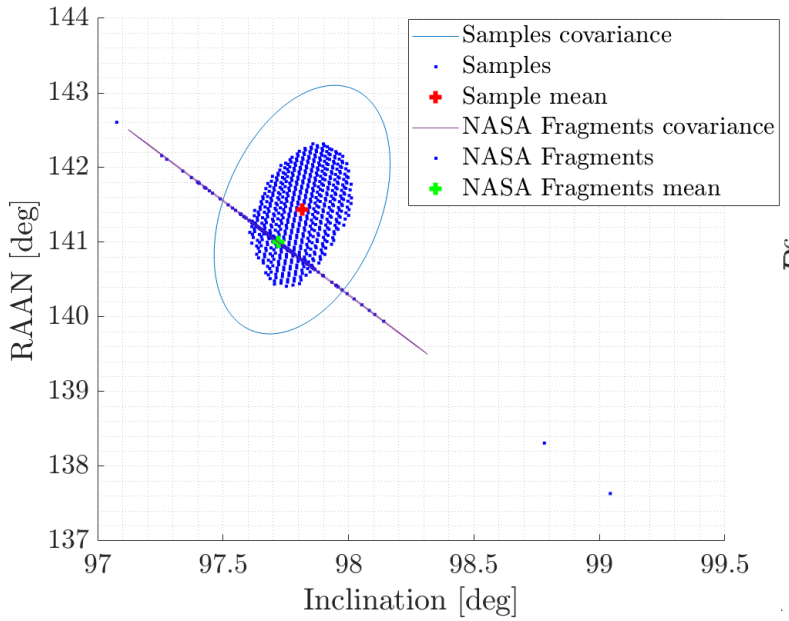




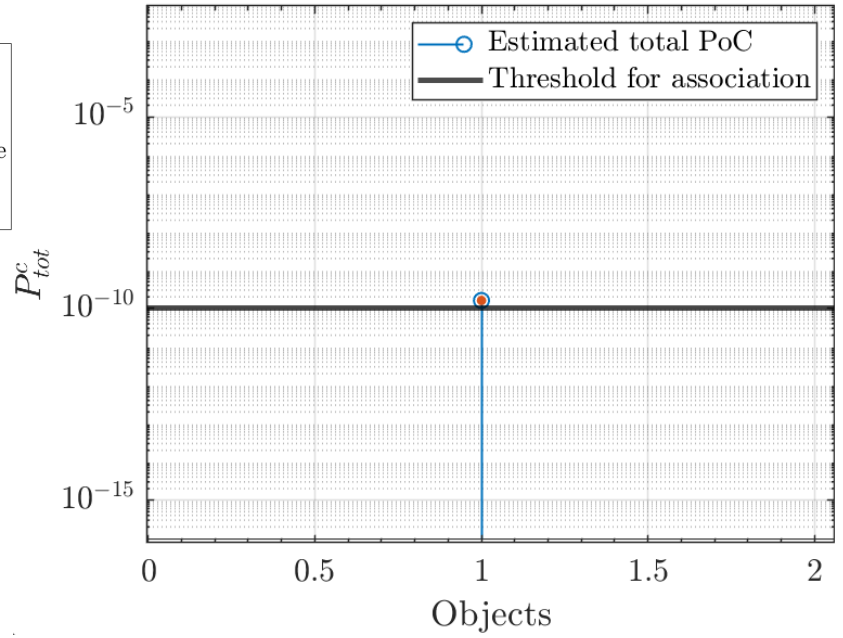
Fragmentation Starlink 34343

Fragmentation forensic analysis

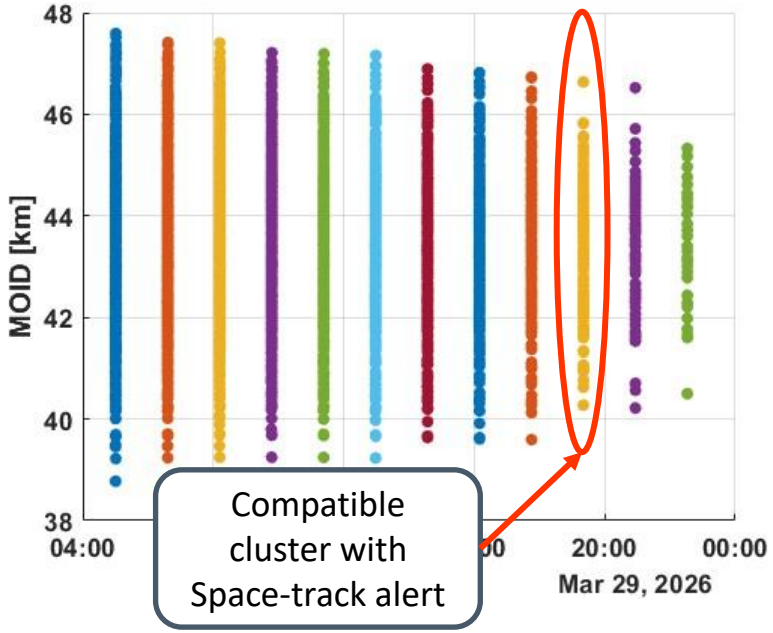
Measurement space
(no IOD result exploited)



Orbital space
(based on IOD result)



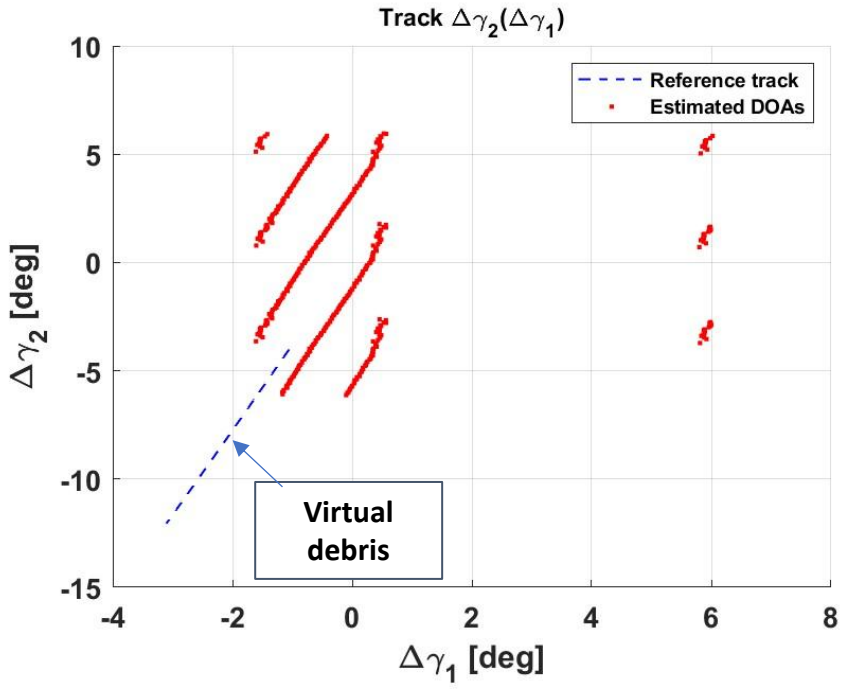
FRED: Fragmentation Epoch Detector

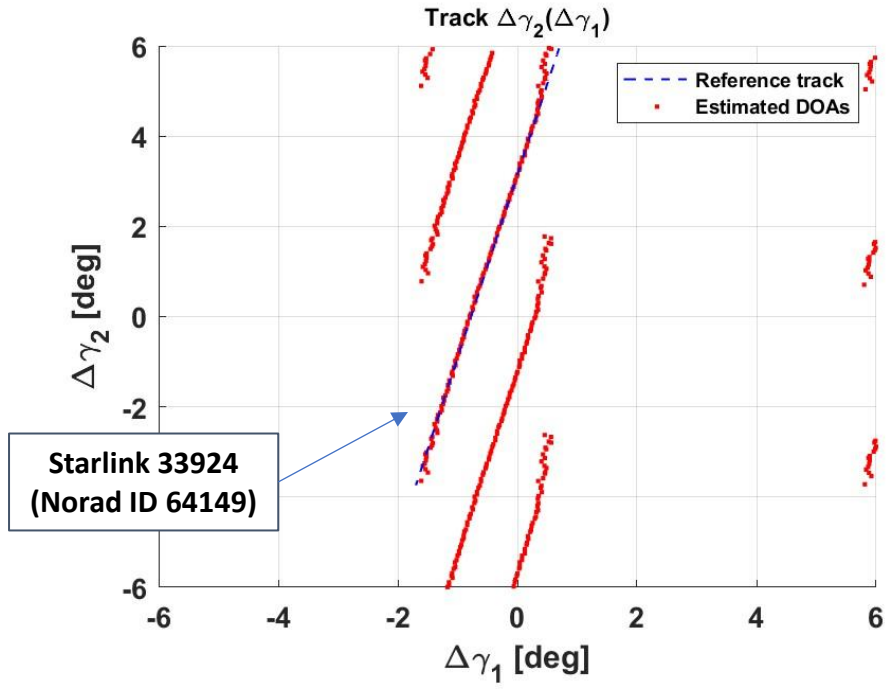


M.F. Montaruli, et al., A stochastic approach to detect fragmentation epoch from a single fragment orbit determination, Advances in Space Research, 2023
Space-track website: https://www.space-track.org/
P. Grattagliano, et al. Early stage characterization of on-orbit fragmentation events, Acta Astronautica, 2025
P. Grattagliano, et al., Advanced techniques for the stochastic fragmentation event characterization from a single fragment orbital state, Advances in Space Research, 2026

Fragmentation Starlink 34343

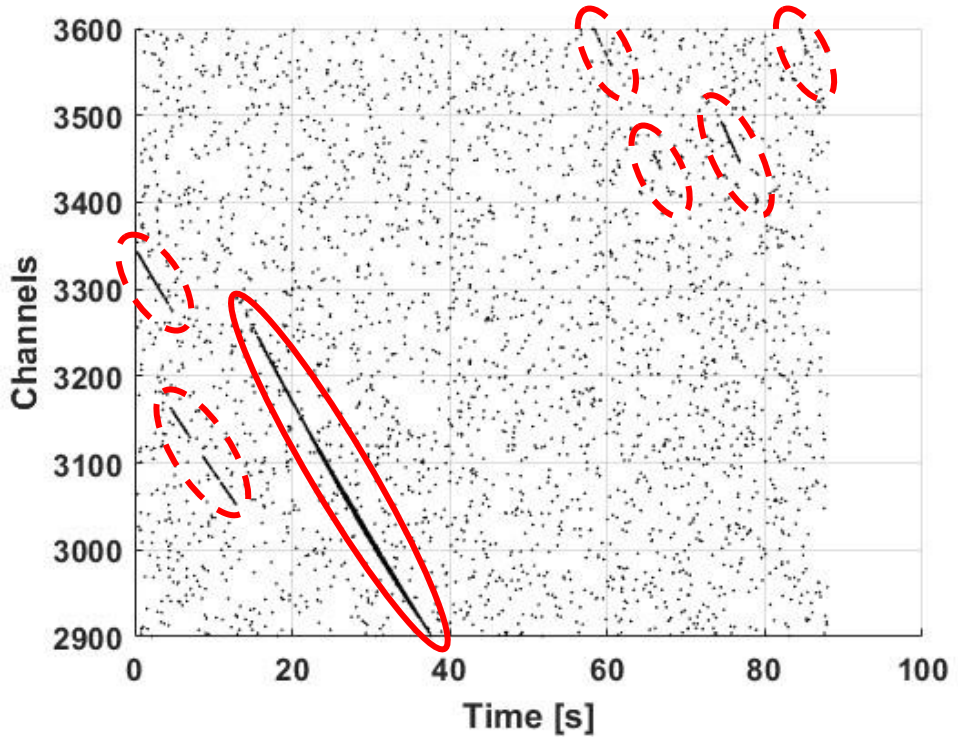
BIRALES detection from 02/04/2026 – h. 19:38 UTC

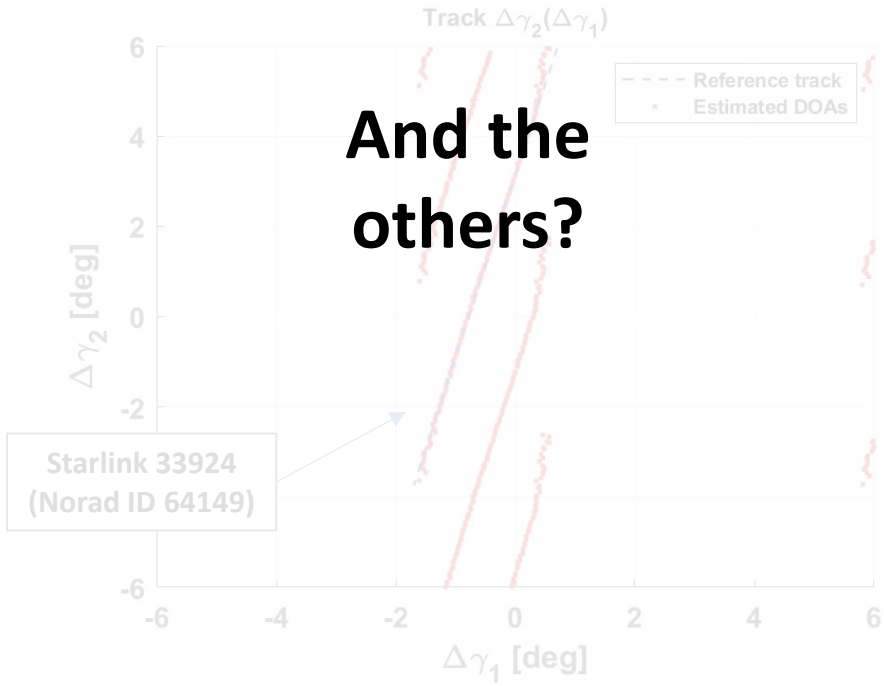




Fragmentation Starlink 34343

BIRALES detection from 02/04/2026 – h. 19:38 UTC





And the others?

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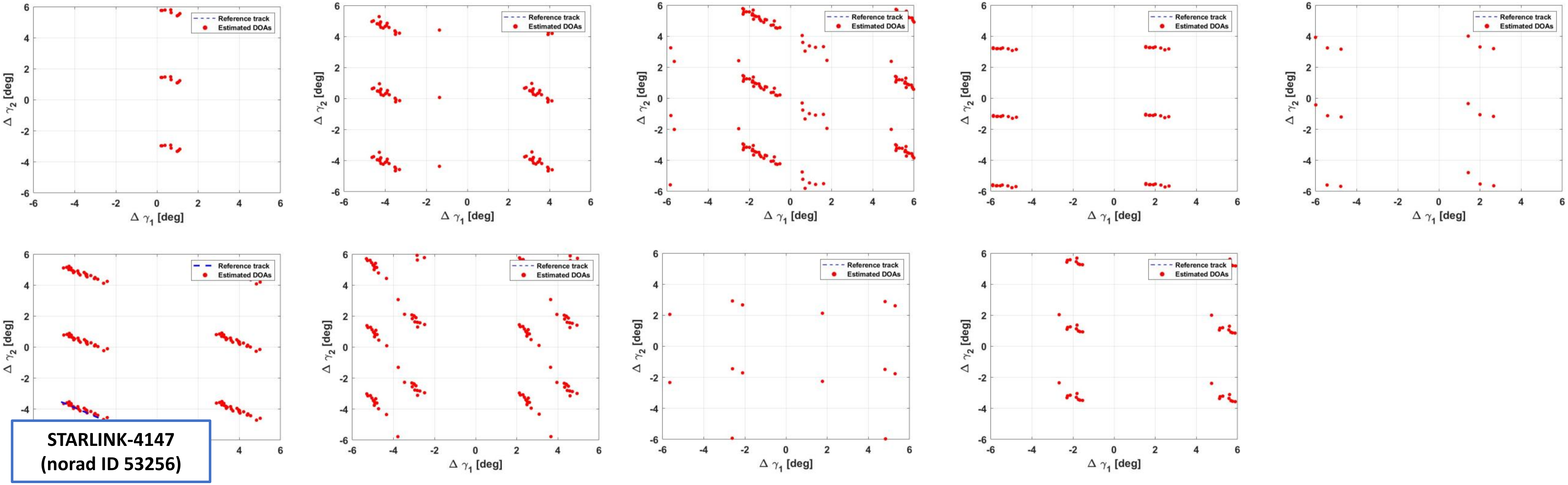
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INAF ISTITUTO NAZIONALE DI ASTROFISICA

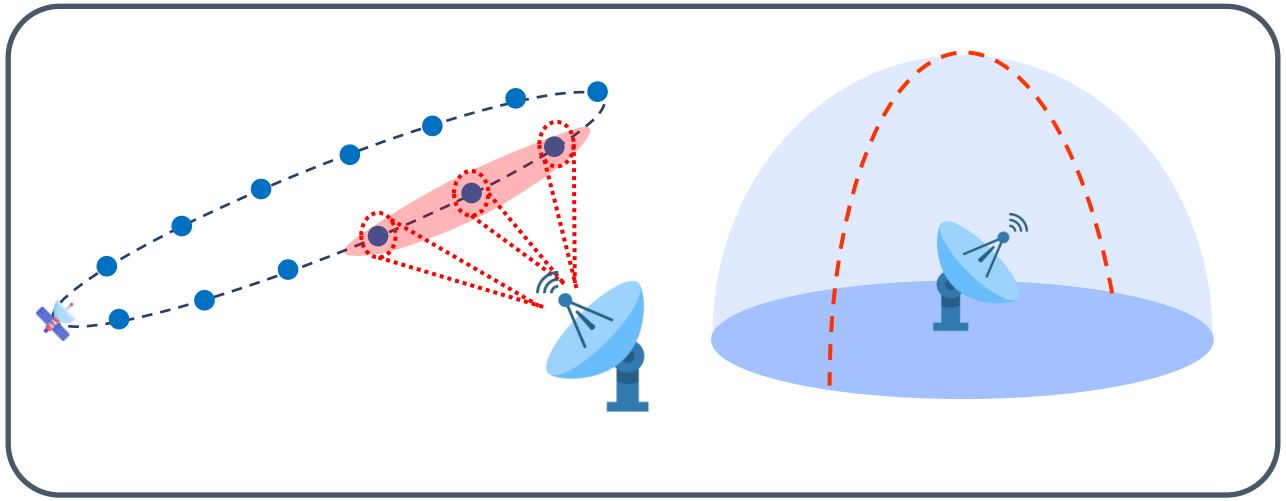
Fragmentation Starlink 34343



- Uncatalogued, but not associated to the events.
- Starlinks not yet in the catalogue?

Fragmentation ZQ-2E R/B

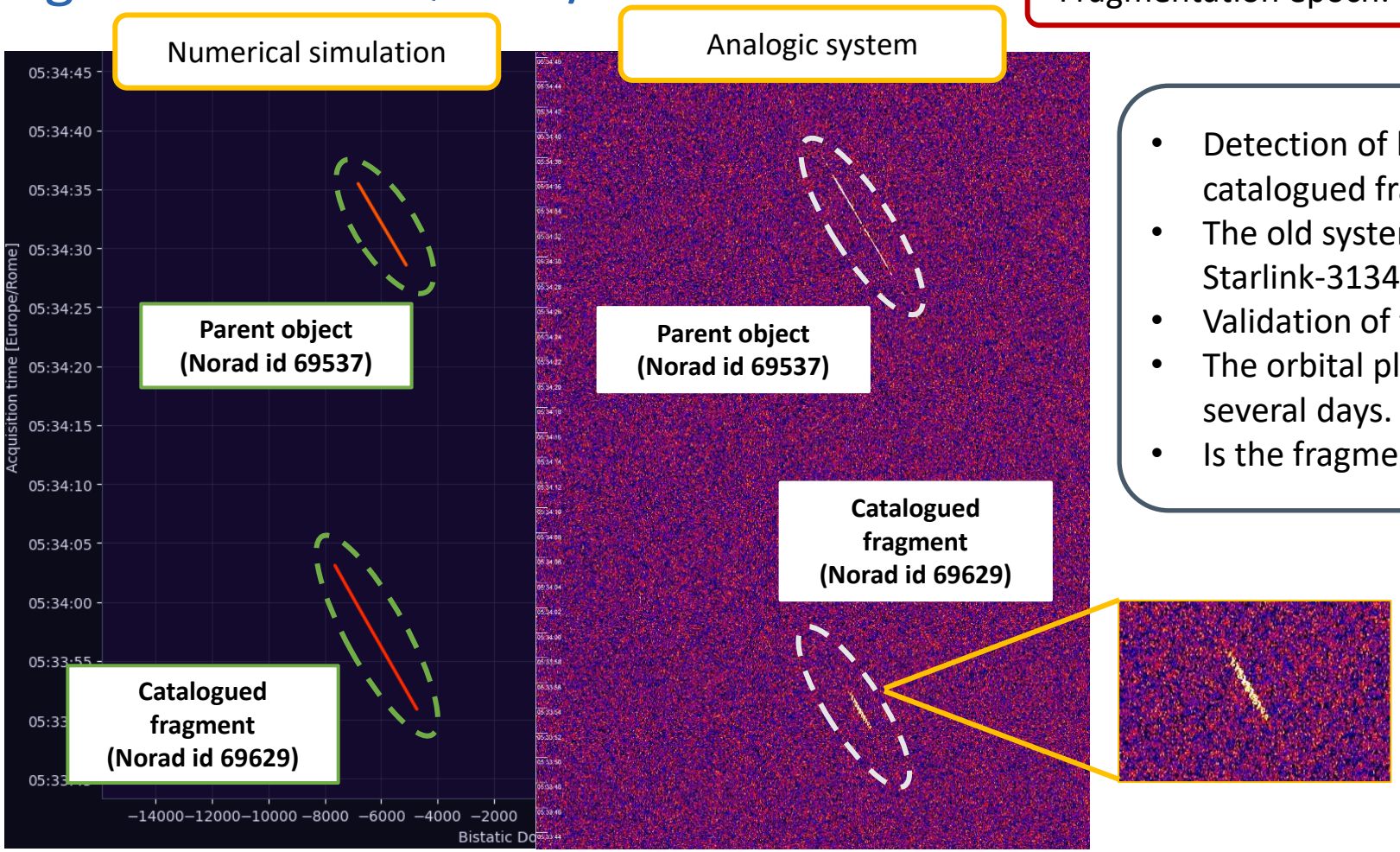
Fragmentation epoch: around 2026-06-09T08:47:00.000



2026-06-20T03:33:31.603	+/- 5 minutes	✓
2026-06-20T10:00:07.230	+/- 5 minutes	
2026-06-21T09:38:03.110	+/- 5 minutes	
2026-06-22T02:36:11.689	+/- 5 minutes	
2026-06-22T09:08:09.316	+/- 5 minutes	
2026-06-23T02:08:42.894	+/- 5 minutes	✓
2026-06-23T08:34:03.196	+/- 5 minutes	

Fragmentation ZQ-2E R/B

Fragmentation epoch: around 2026-06-09T08:47:00.000



- Detection of both parent object (the target) and a catalogued fragment.
- The old system correlated the catalogued fragment to a Starlink-31342 (Norad Id 59166).
- Validation of the observation strategy.
- The orbital plane based strategy remains robust for several days.
- Is the fragment tumbling?

Importance of migrating to the new operational system

OUTLINE

Conclusions

- ✓ MATER algorithm operationally implemented
- ✓ Potential of E-W branch contribution to solve the angular track ambiguity
  - No ambiguous tracks for uncorrelated tracks
- ✓ Radar Initial Orbit Determination from angles and Doppler shift
  - Capability to determine the target orbital state even if the range is not present
- ✓ Effectiveness in fragmentation campaigns
  - Dedicated observation strategy validated
  - Criticalities posed by mega-constellations
  - Uncorrelated tracks detected

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

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Thank you

Final Meeting

Martedì 30 Giugno – Giovedì 02 Luglio

OAC - Osservatorio Astrofisico di Arcetri

PNRR NG-CROCE

M.F. Montaruli