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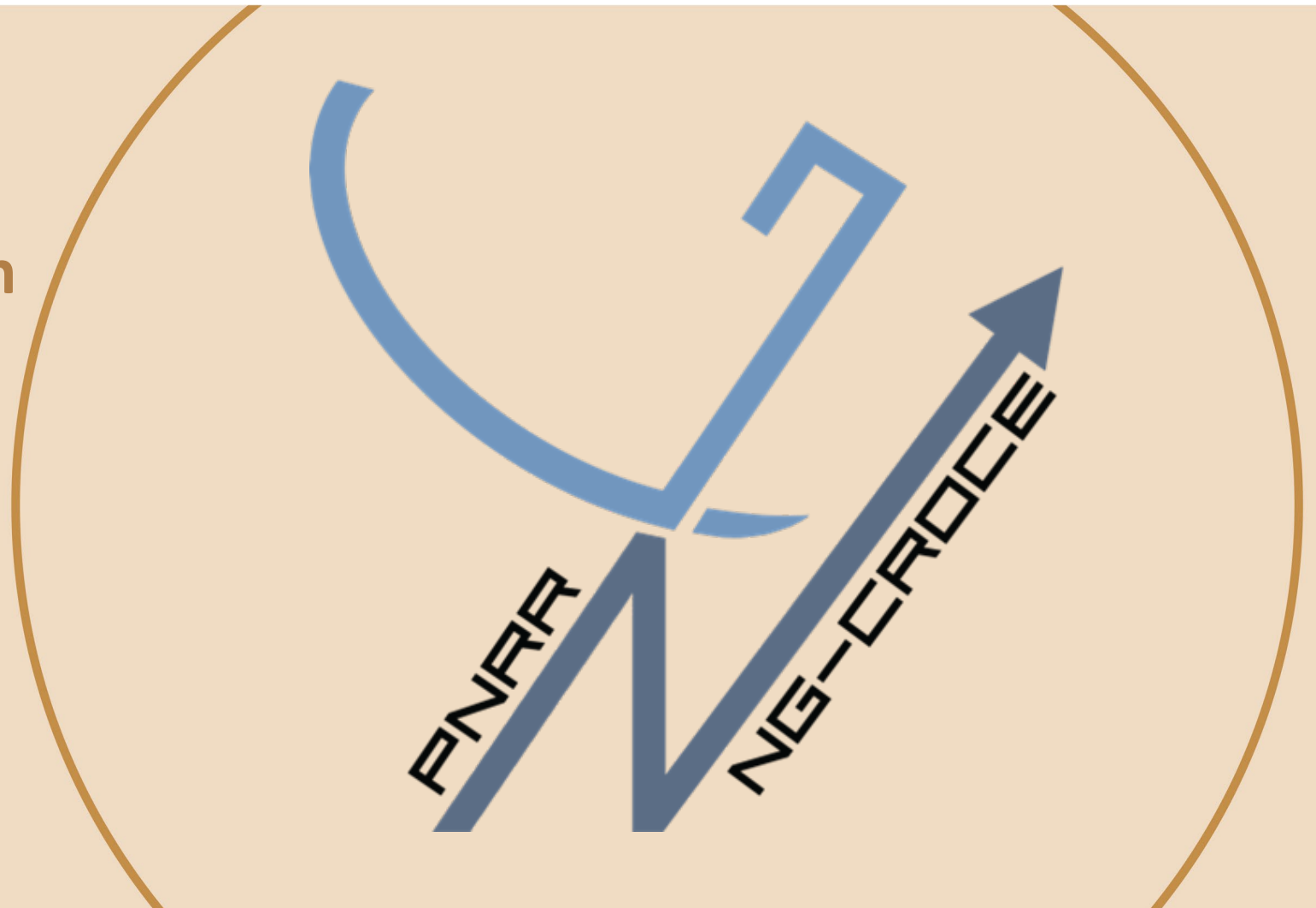
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Radar Measurements for the Characterization of Resident Space Objects

Final Meeting

Martedì 30 Giugno – Giovedì 02 Luglio

OAC - Osservatorio Astrofisico di Arcetri



M.A. De Luca



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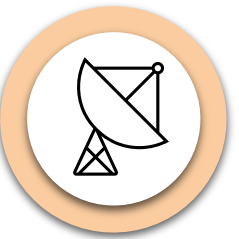
01

Background



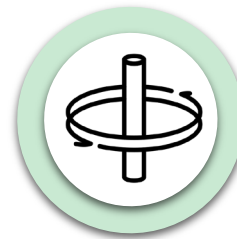
02

Synodic Spin Period Estimation



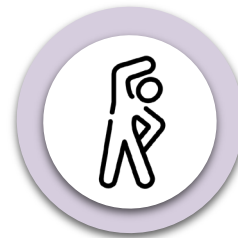
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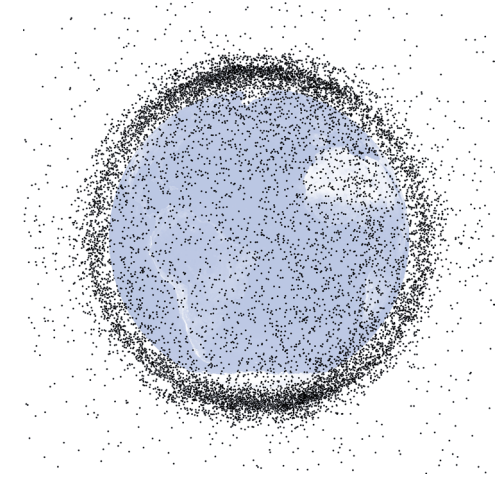
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BACKGROUND

Resident Space Object (RSO)

active satellites, decommissioned spacecrafts, orbital debris

~**54000** RSO in orbit (> 10 cm)*



For space traffic monitoring,
effective **characterization of
orbiting objects** is essential

Orbital Motion

Rotational Motion

Physical Properties

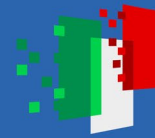
* <https://sdup.esoc.esa.int/discosweb/statistics/> (Accessed 29/06/26)



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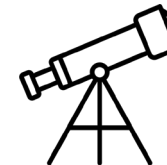
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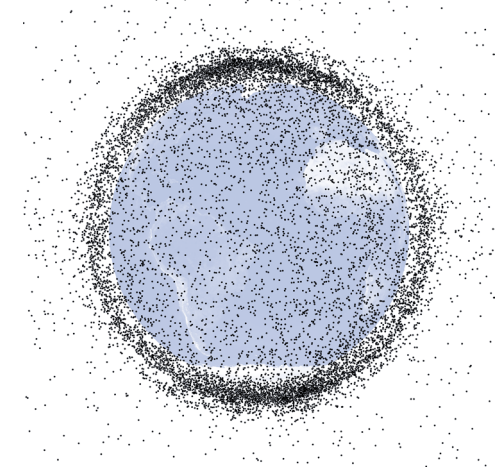
OPTICAL SENSORS

- Light Curves



RADAR SENSORS

- RCS time series
- Range and Doppler measurements



* <https://sdup.esoc.esa.int/discosweb/statistics/> (Accessed 29/06/26)



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Determining the **full attitude vector** is inherently **challenging**.
It requires:

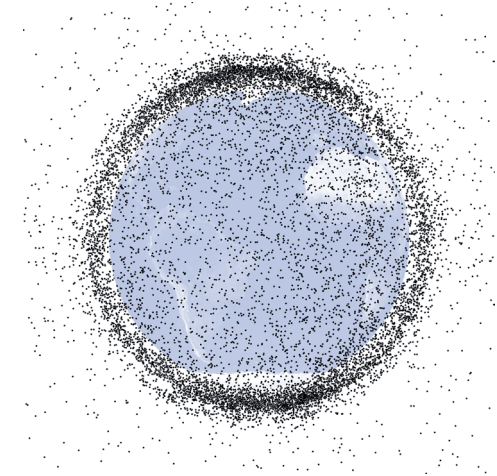
- Accurate **shape**
- Reliable **surface properties**

Data rarely available in SSA
operations



RADAR SENSORS

- RCS time series
- Range and Doppler measurements



* <https://sdup.esoc.esa.int/discosweb/statistics/> (Accessed 29/06/26)



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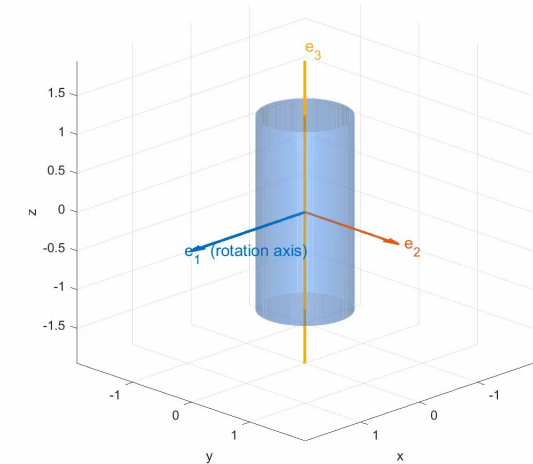
- Accurate **shape**
- Reliable **surface properties**

Data rarely available in SSA operations



CORE RESEARCH IDEA

- Estimate only **key attitude-related parameters** of rotating targets:
 - **Spin Period**
 - **Spin Axis Direction**
- **Model-Free approach**: No prior knowledge of the target is exploited



* <https://sdup.esoc.esa.int/discosweb/statistics/> (Accessed 29/06/26)

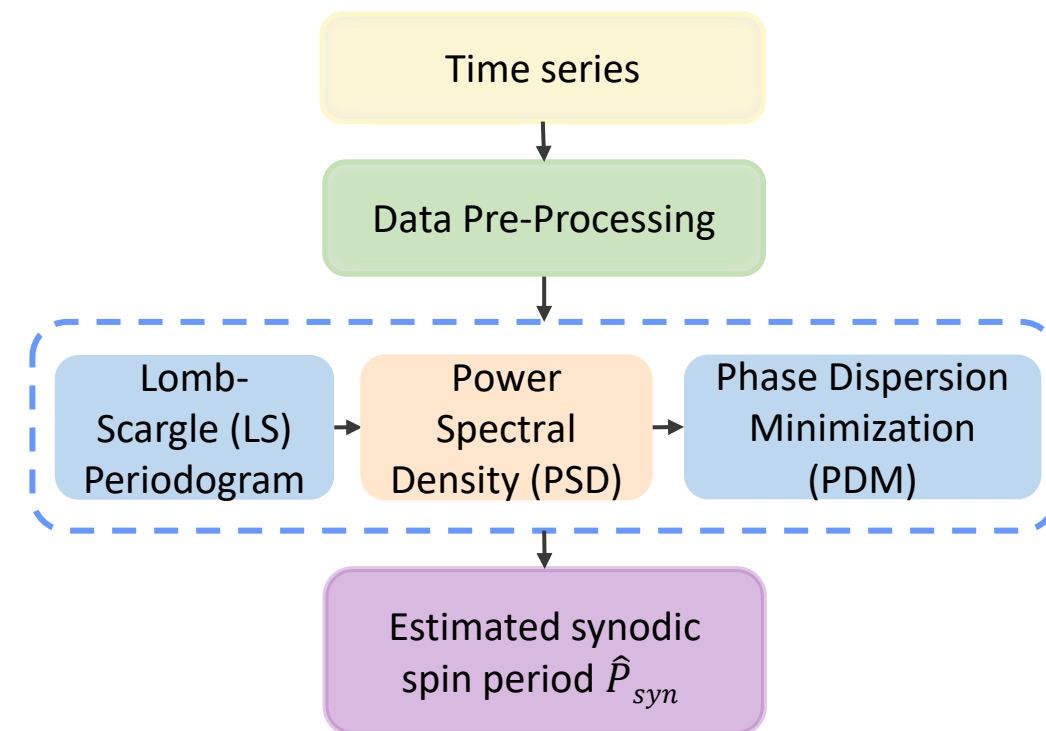
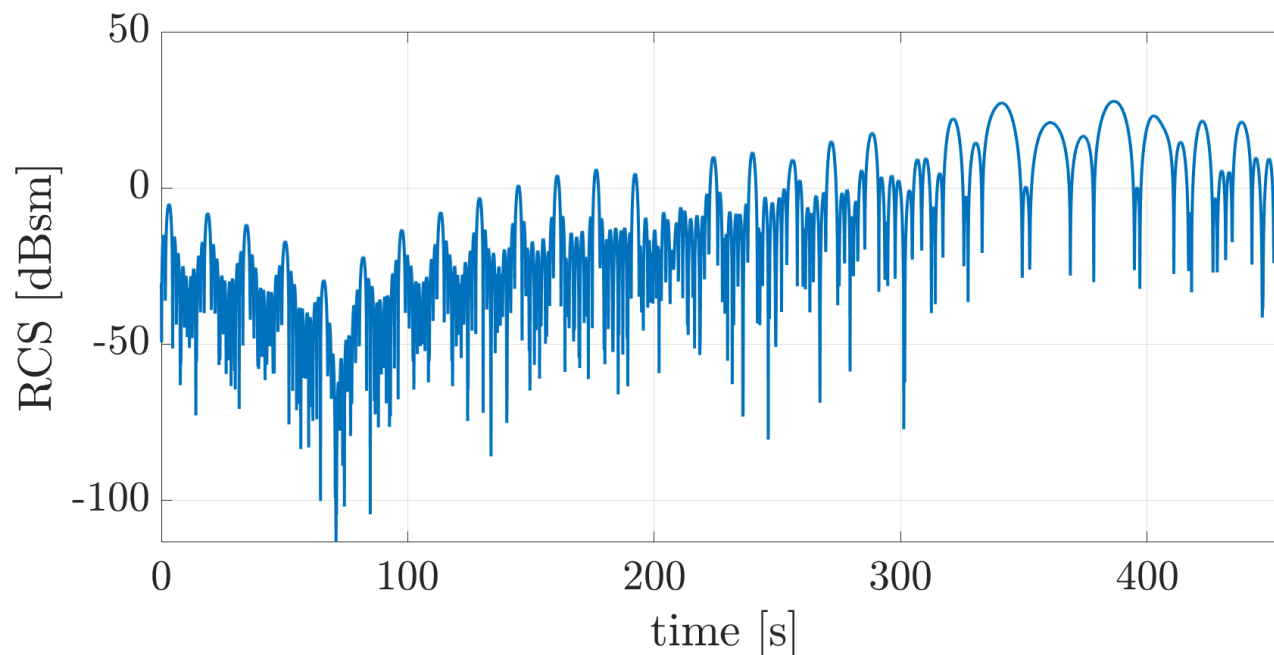


SYNODIC SPIN PERIOD ESTIMATION

The estimation strategy depends on the **nature of the available measurements** :

1

RCS time series



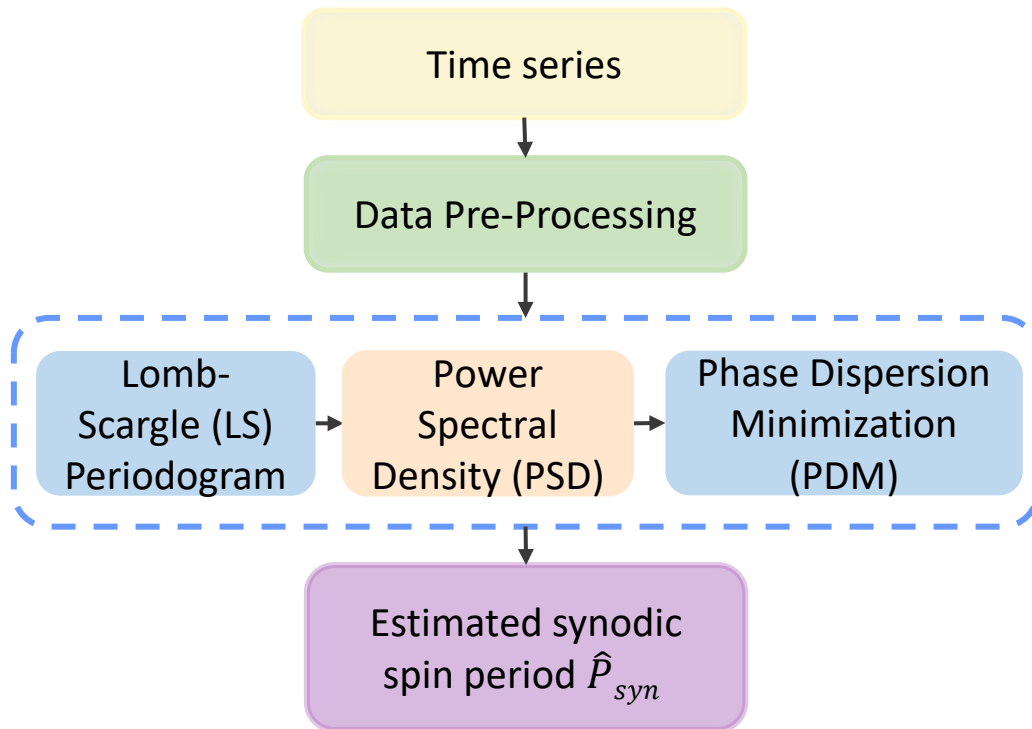


SYNODIC SPIN PERIOD ESTIMATION

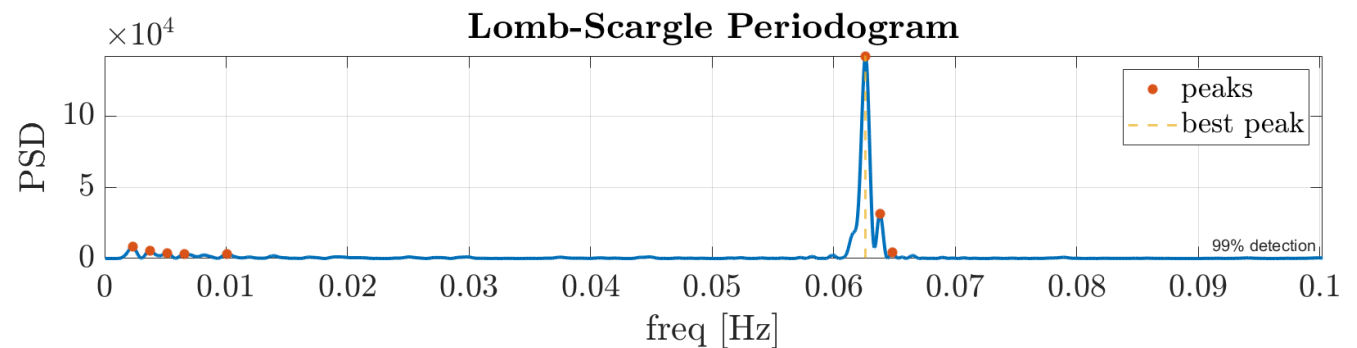
The estimation strategy depends on the **nature of the available measurements** :

1

RCS time series



Lomb-Scargle Periodogram is used to estimate the **PSD** of the RCS time-series
The strongest peaks in the **PSD** are used to identify **candidate rotation periods**



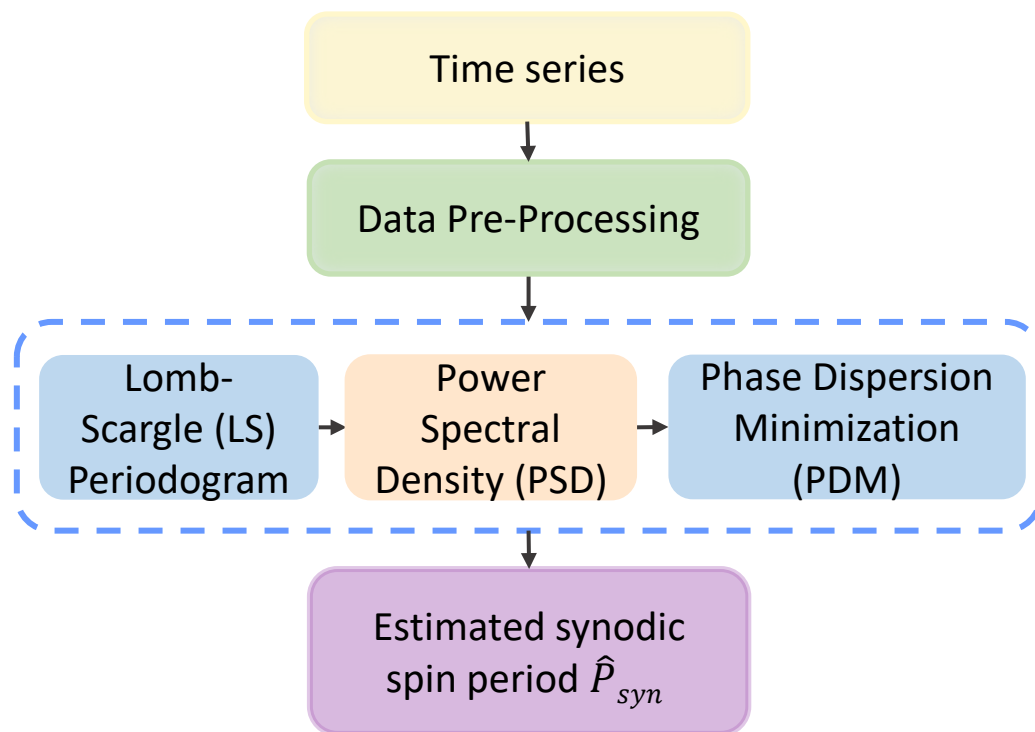


SYNODIC SPIN PERIOD ESTIMATION

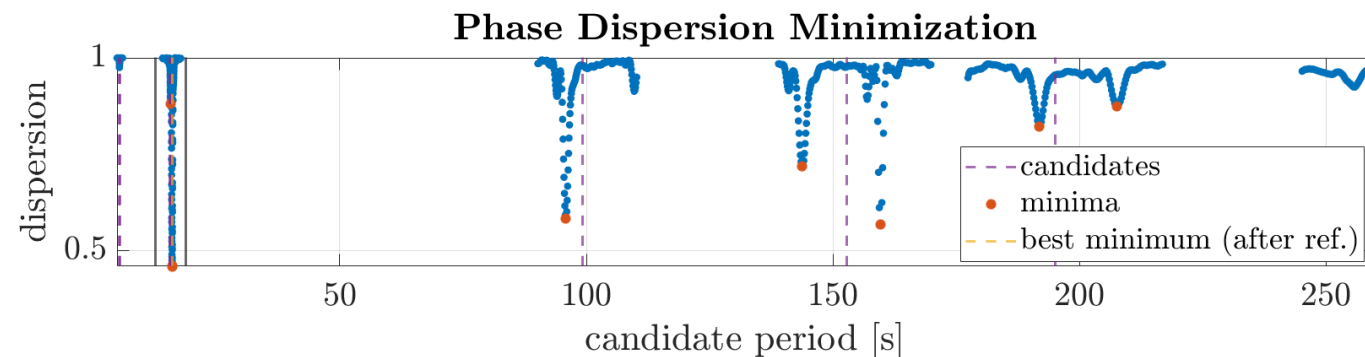
The estimation strategy depends on the **nature of the available measurements** :

1

RCS time series



The candidates are given as input to the **Phase Dispersion Minimization**: calculates which one returns the lowest **dispersion statistic**



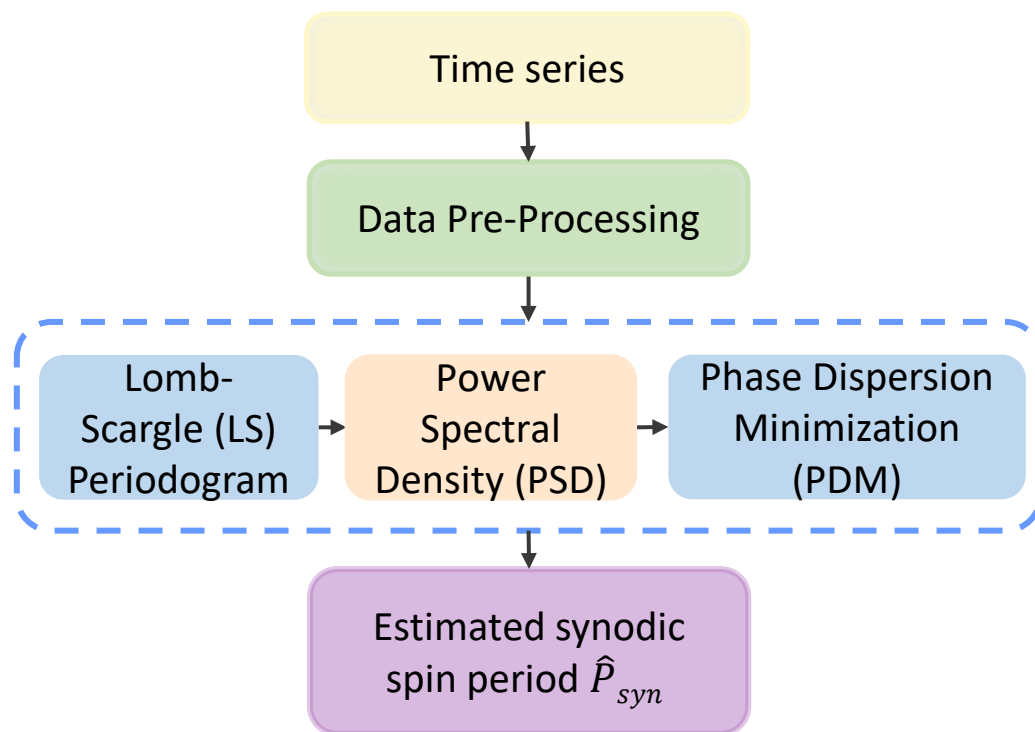


SYNODIC SPIN PERIOD ESTIMATION

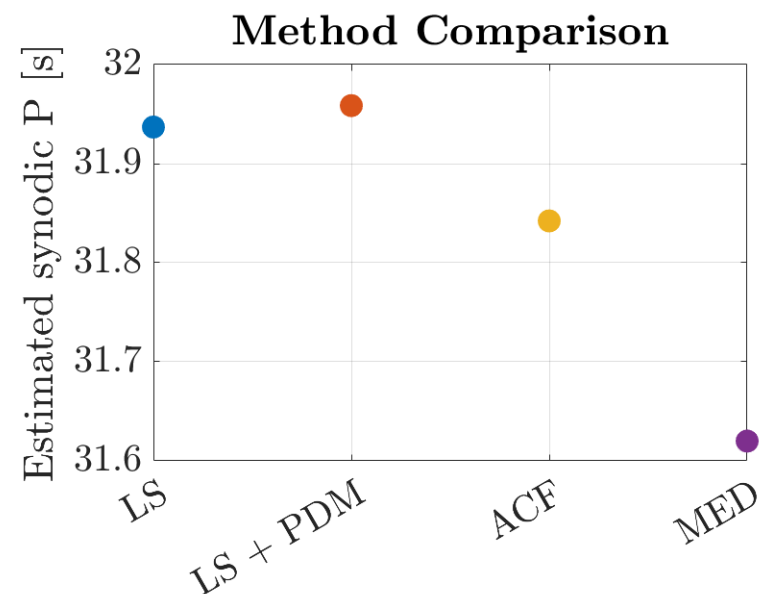
The estimation strategy depends on the **nature of the available measurements** :

1

RCS time series



Depending on the available input measurements, **other strategies** can be adopted and compared:



- ACF: Autocorrelation Function
- MED: Maximum Entropy Deconvolution
-

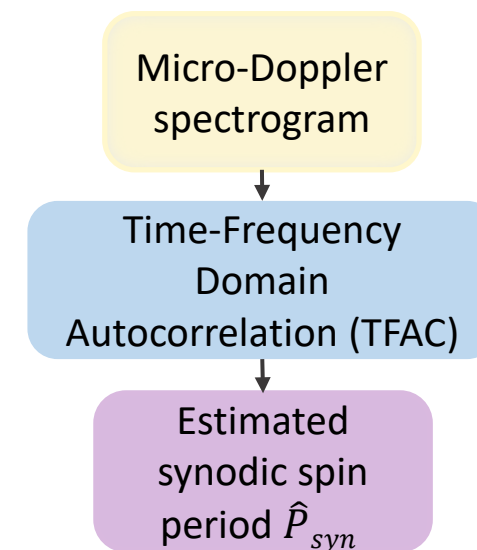
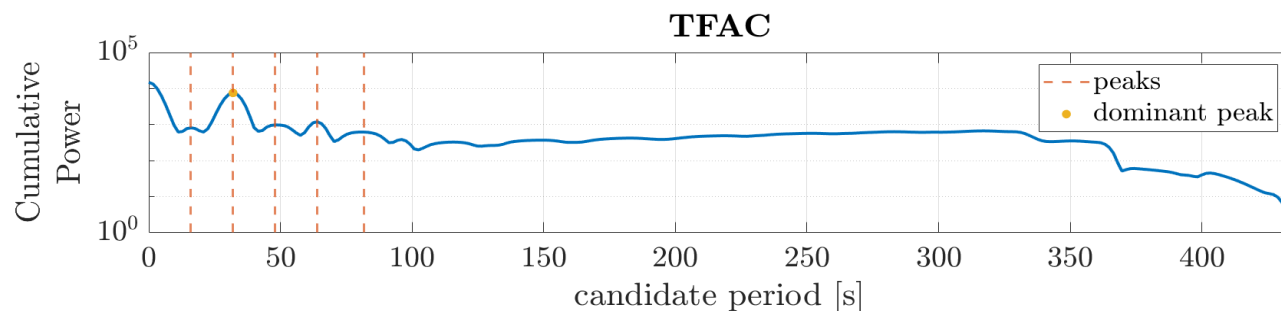
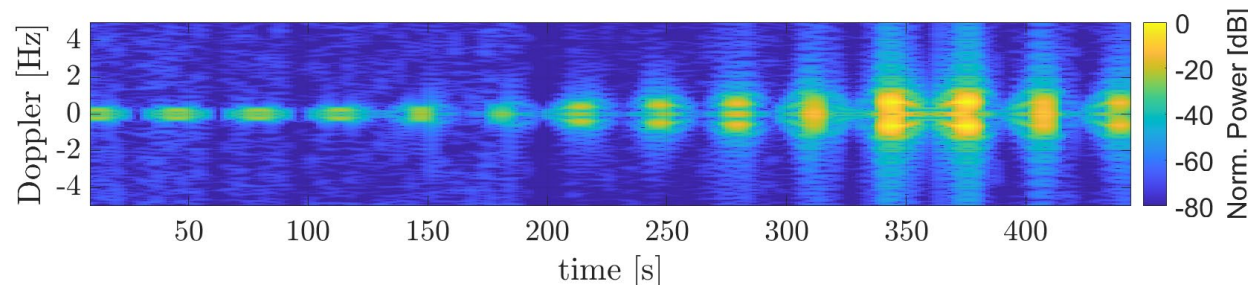


SYNODIC SPIN PERIOD ESTIMATION

The estimation strategy depends on the **nature of the available measurements** :

2

Micro-Doppler Spectrogram



TFAC: variant of the classic autocorrelation algorithm specific for time-frequency data [1]

$$R(t)_{TFAC} = \sum_{\hat{f}_b} \left| \int_{-\infty}^{\infty} \overline{X(f_D, t)} X(f_D, t + \tau) dt \right|$$



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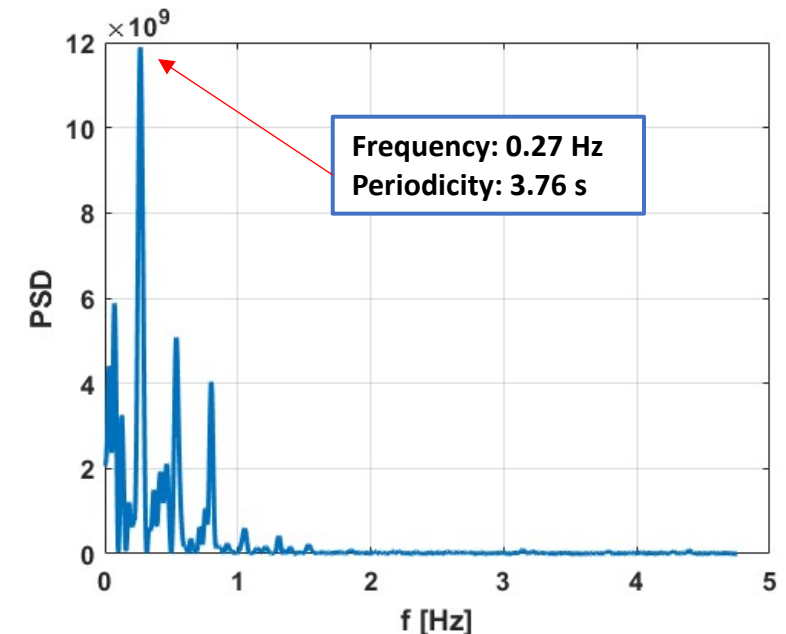
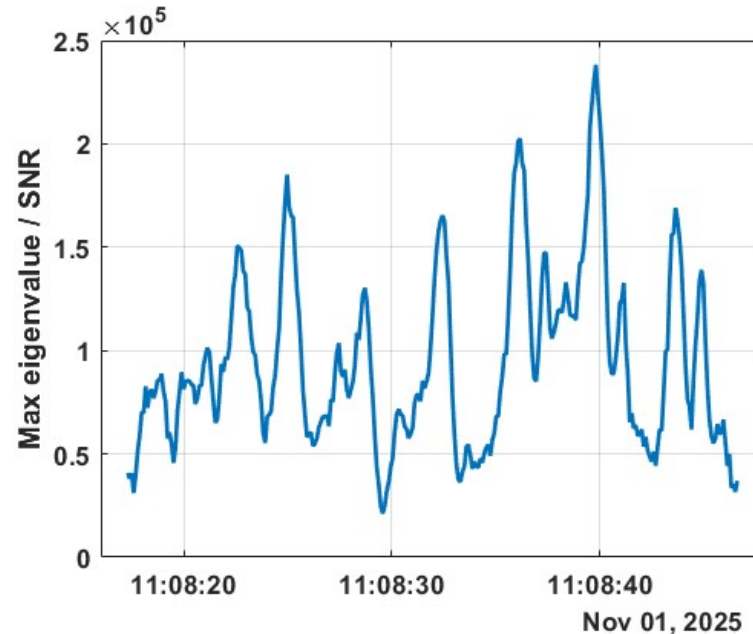
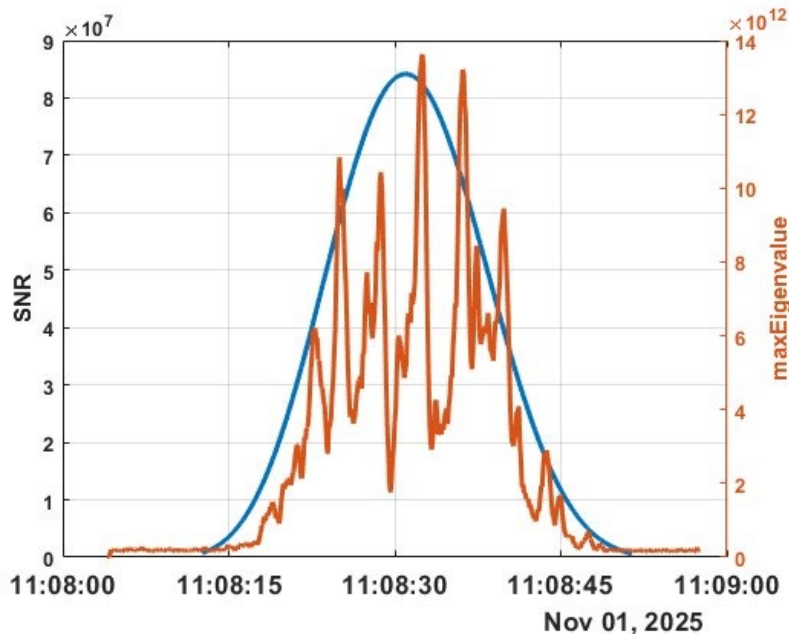
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BIRALES TEST CASE

Signal power trend

- BIRALES detection on November 1st, 2025
- Target: Haiyang 2C (Norad ID 46469)
- Reference target periodicity: 3.5-4 s

Bandwidth: 10.43 Hz



Estimated periodicity: 3.76 s



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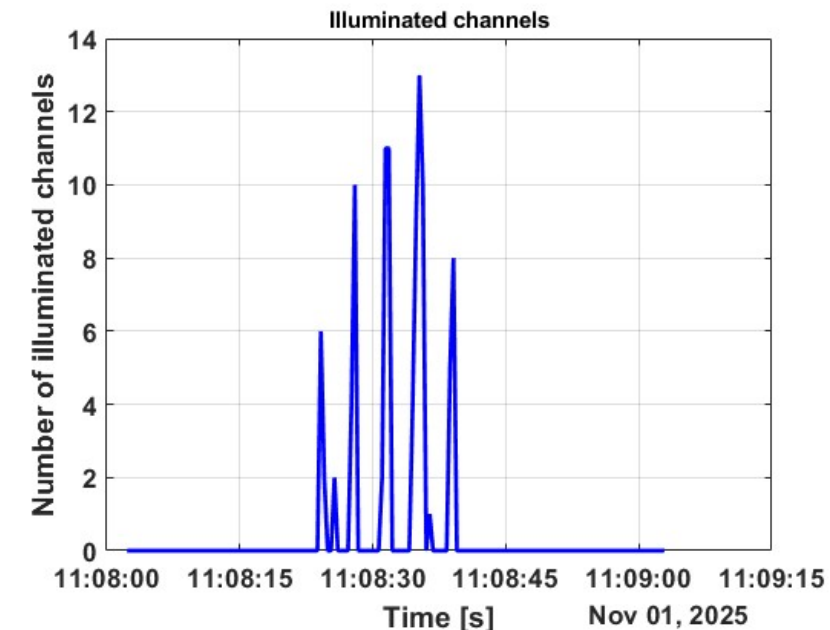
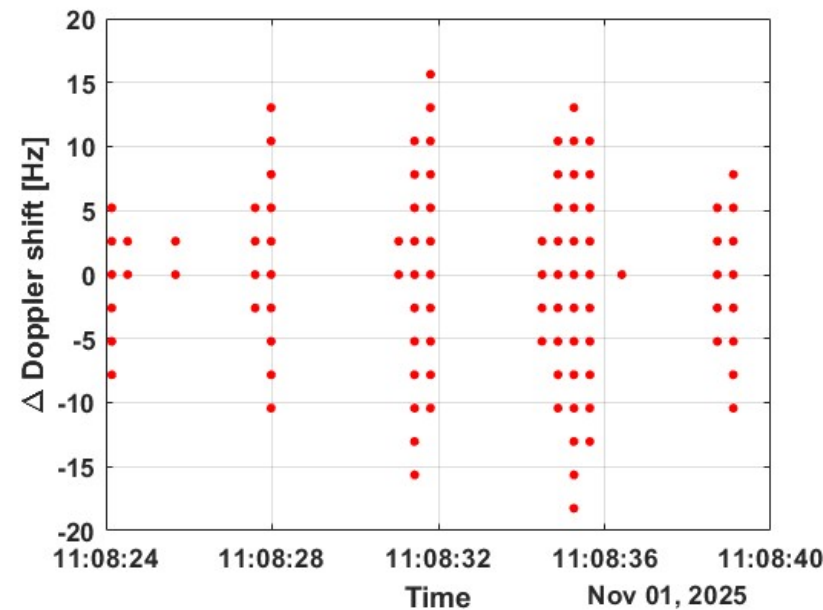
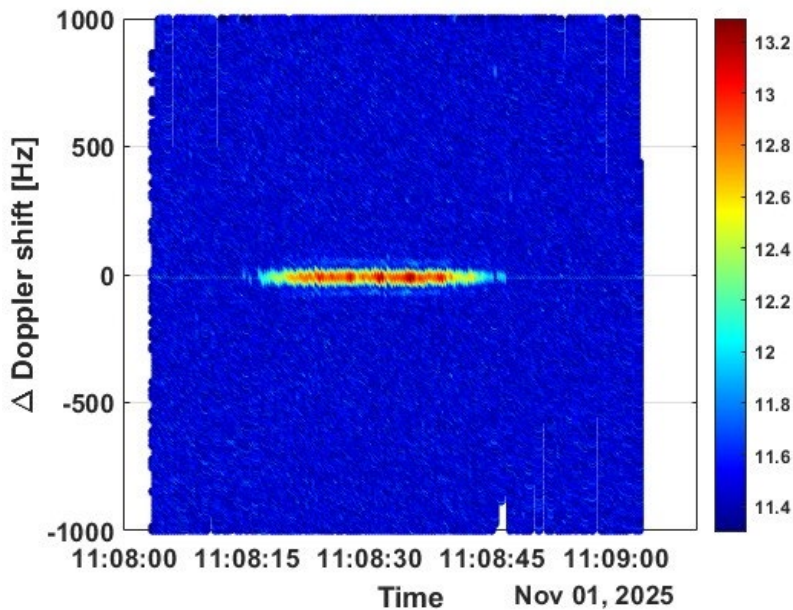
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BIRALES TEST CASE

Micro-Doppler

- BIRALES detection on November 1st, 2025
- Target: Haiyang 2C (Norad ID 46469)
- Reference target periodicity: 3.5-4 s

Bandwidth: 2.61 Hz



Estimated periodicity: 3.76 s

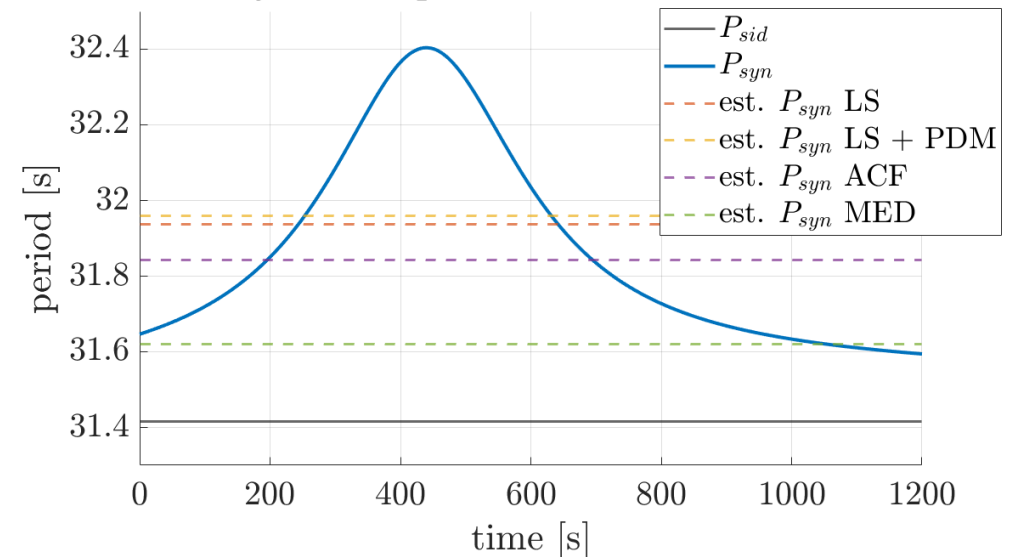


SIDEREAL SPIN PERIOD + SPIN AXIS ESTIMATION (FROM RCS TIME SERIES)

Goal: estimate the **sidereal (inertial) spin period** P_{sid} and **spin-axis direction** $[\alpha, \beta]$

Key idea: Even if P_{sid} is constant, the synodic period P_{syn} changes over time as the observation geometry varies → *this variation is exploited*

Synodic Spin Period Estimation



1 Estimate $\hat{P}_{syn}$

(synodic spin period
estimation)

2 Patternsearch

Constrained optimization
over 3 variables $[\alpha, \beta, P_{sid}]$

3 Clustering & Cleaning

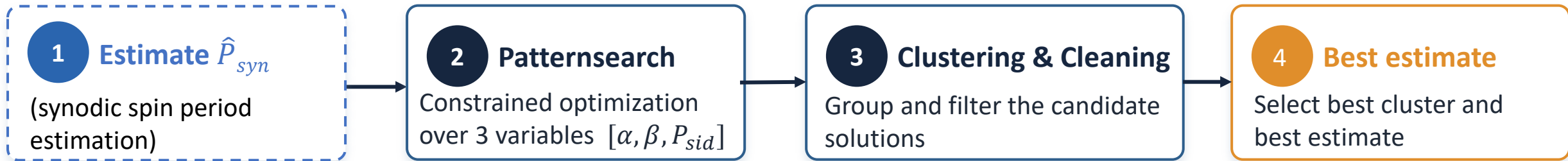
Group and filter the candidate
solutions

4 Best estimate

Select best cluster and
best estimate



SIDEREAL SPIN PERIOD + SPIN AXIS ESTIMATION (FROM RCS TIME SERIES)



• Search Domain

	LB	UB
α	-180°	180°
β	-90°	90°
P_{sid} [s]	3	250

- **Multi-Start:** 500 *Latin-Hypercube* start points



Objective function

Based on a **variant of Phase Dispersion Minimization**



Constraint function

Predicted synodic period $P_{syn,pred}(t)$ from $[\alpha, \beta, P_{sid}]$ must be compatible with $\hat{P}_{syn}$



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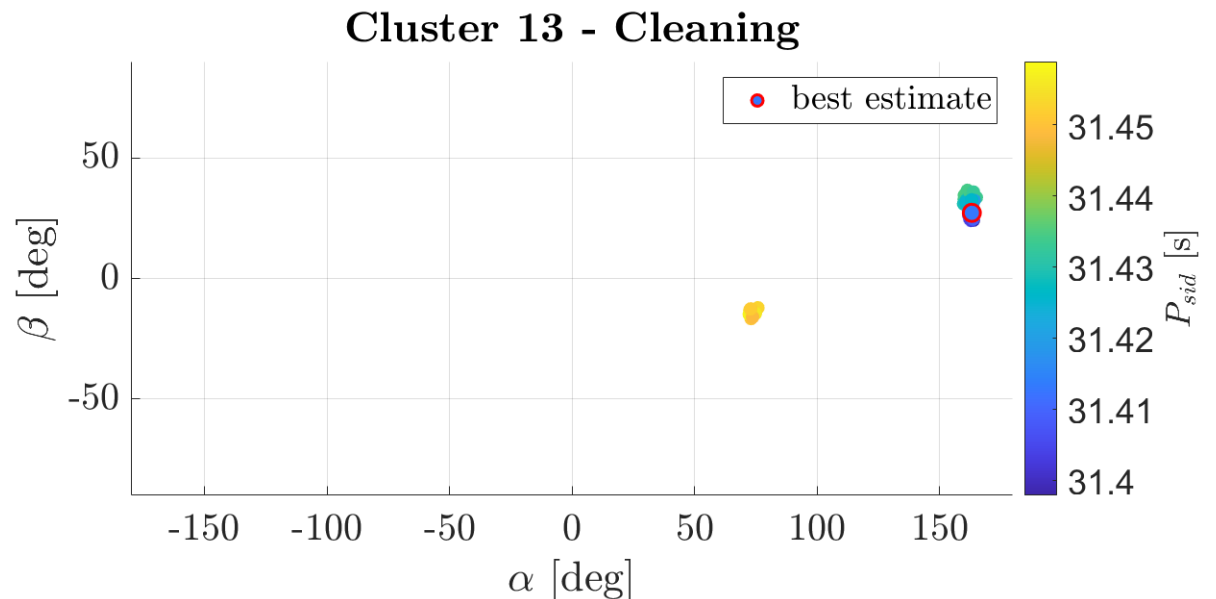
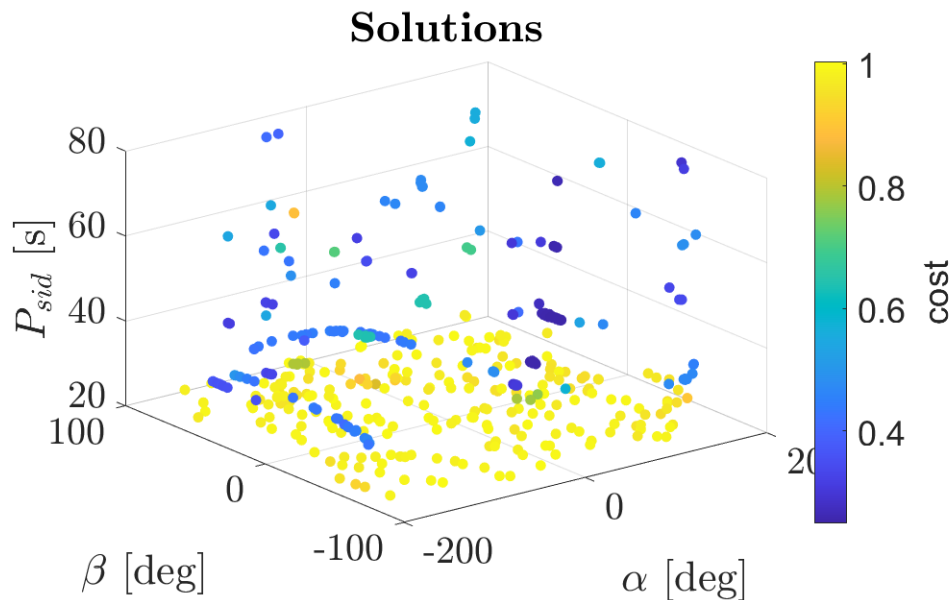
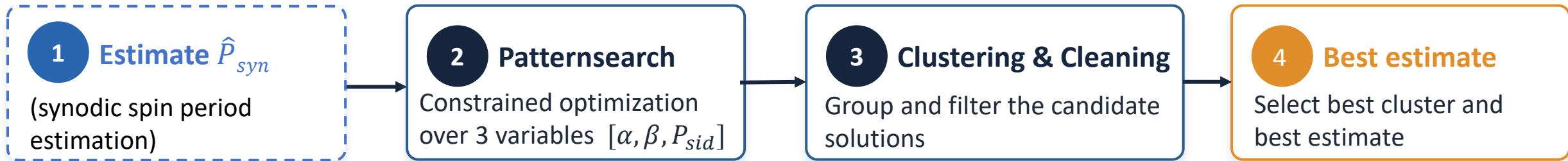


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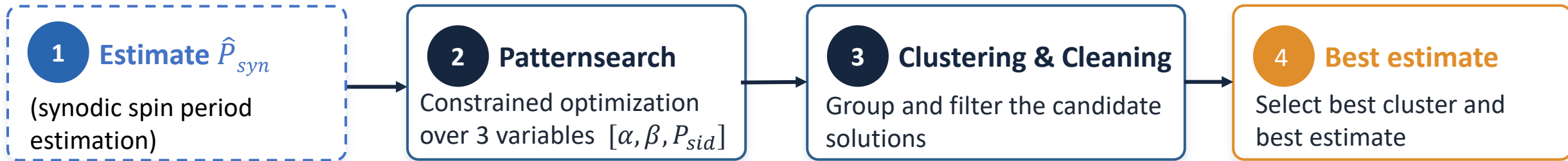
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SIDEREAL SPIN PERIOD + SPIN AXIS ESTIMATION (FROM RCS TIME SERIES)



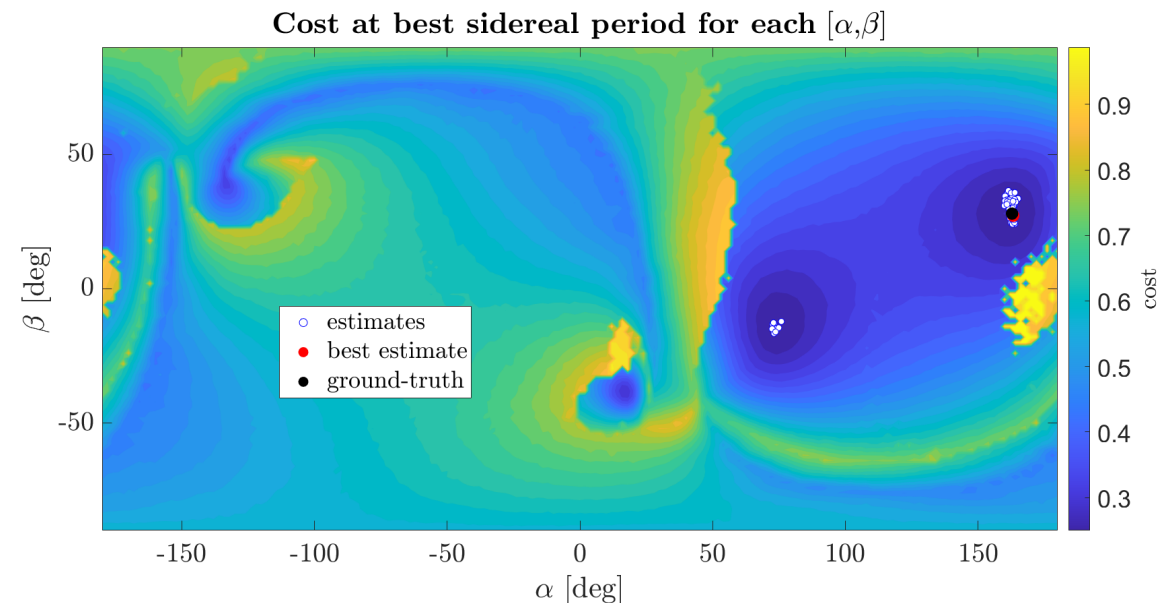


SIDEREAL SPIN PERIOD + SPIN AXIS ESTIMATION (FROM RCS TIME SERIES)



As a final step, a **grid search** is carried out around the identified best-fit P_{sid} to map all local minima of the objective function in $[\alpha, \beta]$

→ **Geometrically ambiguous solutions:**





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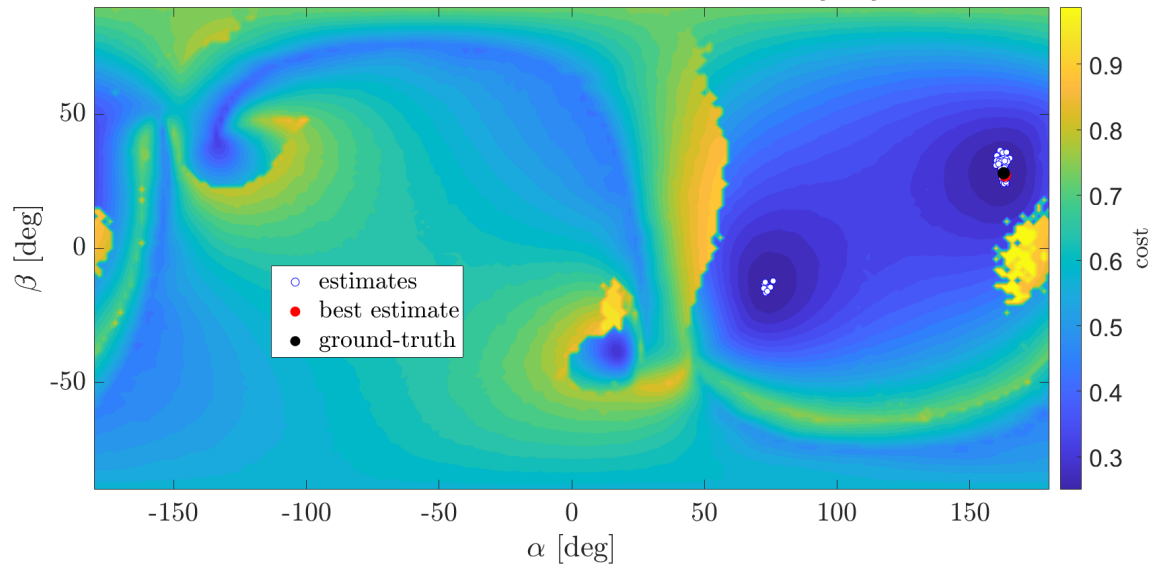
SIDEREAL SPIN PERIOD + SPIN AXIS ESTIMATION (FROM RCS TIME SERIES)



Can the **ambiguities be resolved** by simultaneously observing the object from **multiple locations**?

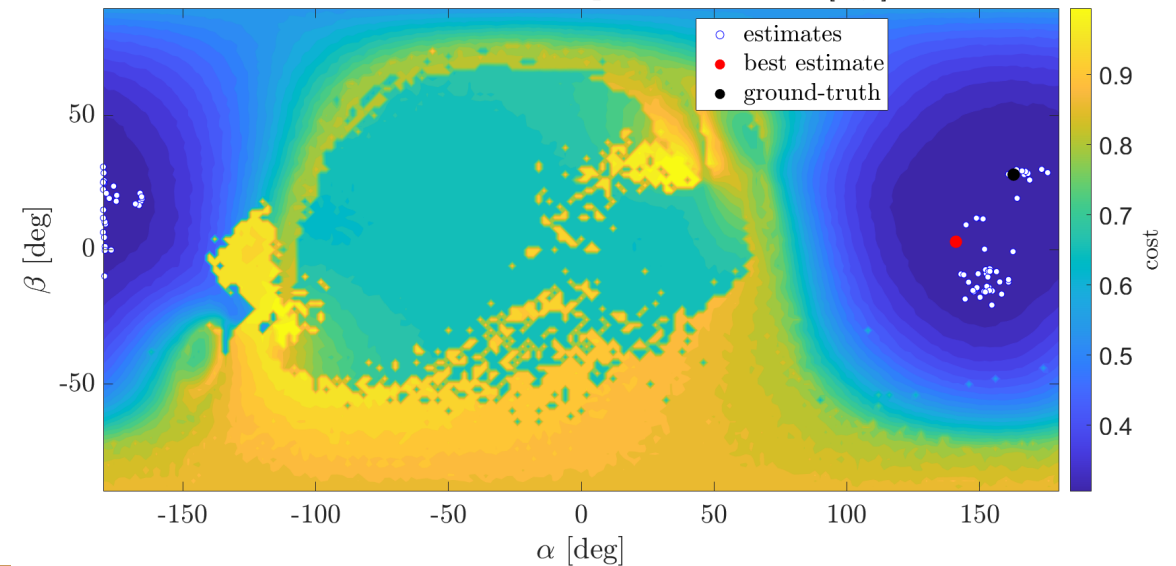
TIRA LOCATION

Cost at best sidereal period for each $[\alpha, \beta]$



MEDICINA LOCATION

Cost at best sidereal period for each $[\alpha, \beta]$





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CONCLUSIONS

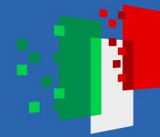
- **Different radar measurements** can characterize spinning objects:
 - **RCS**: estimates spin period and spin-axis direction
 - **Micro-Doppler**: estimates spin period (spin-axis direction estimation is under development)
- **Ambiguities are intrinsic to the problem**, arising from the observation geometry:
 - **Multiple simultaneous observations** of the same object from different locations may resolve or reduce them
- **BIRALES test case** → **potential for spin-axis characterization**:
 - Acquisition time window increase thanks to the FoV extension
 - Conduct analysis with CW only



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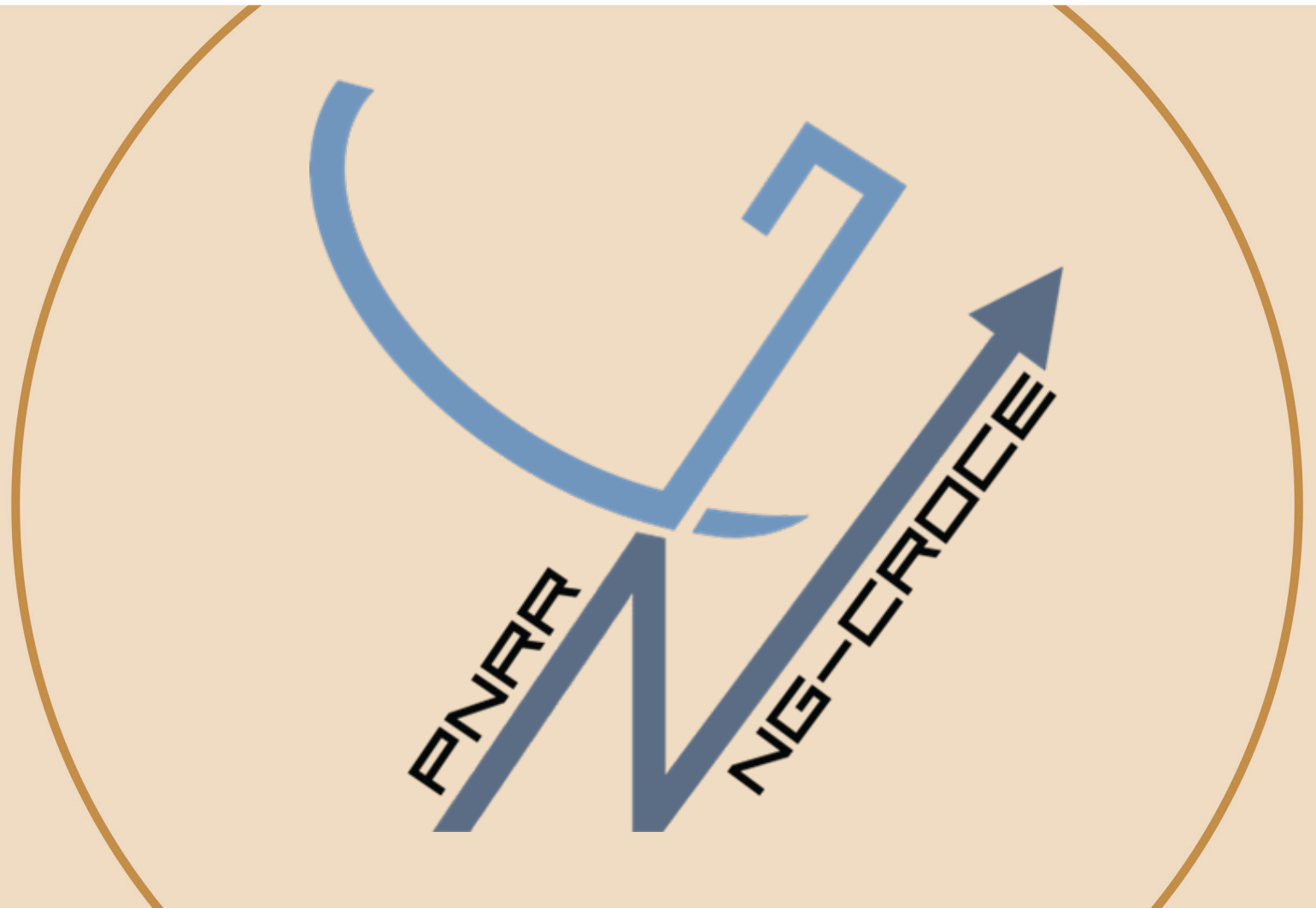
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Thank You For Your Attention!

Final Meeting

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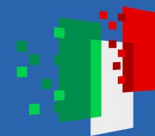
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beneficiario

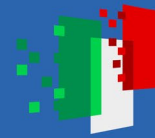
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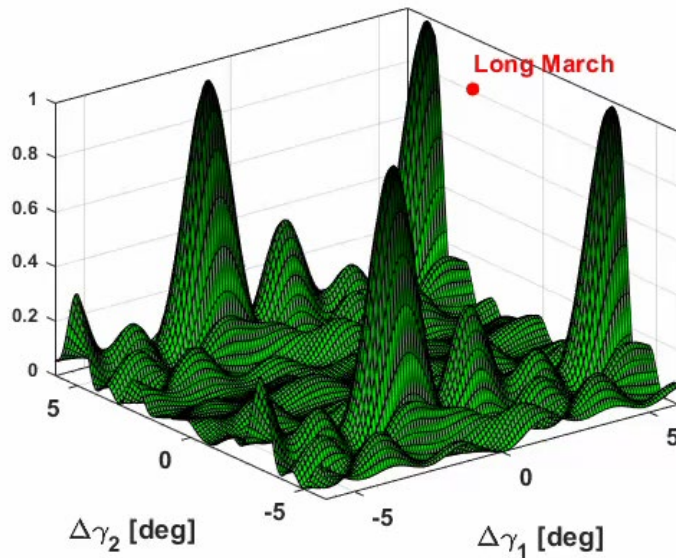
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Real data processing

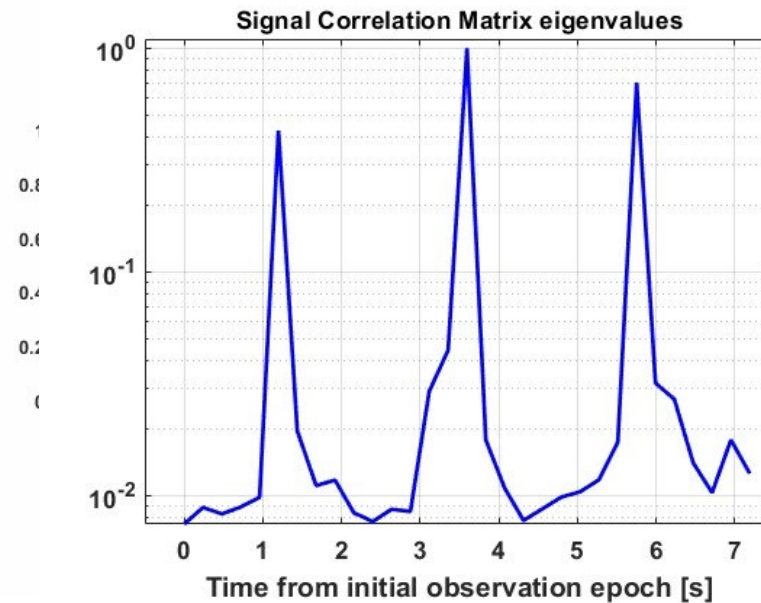
3rd Long March re-entry

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

November 1st, 2022
h. 08:40 UTC



November 2nd, 2022
h. 08:24 UTC



November 4th, 2022
h. 07:29 UTC

