Using genetic algorithms to design satellite constellations for recovering daily Earth system mass change

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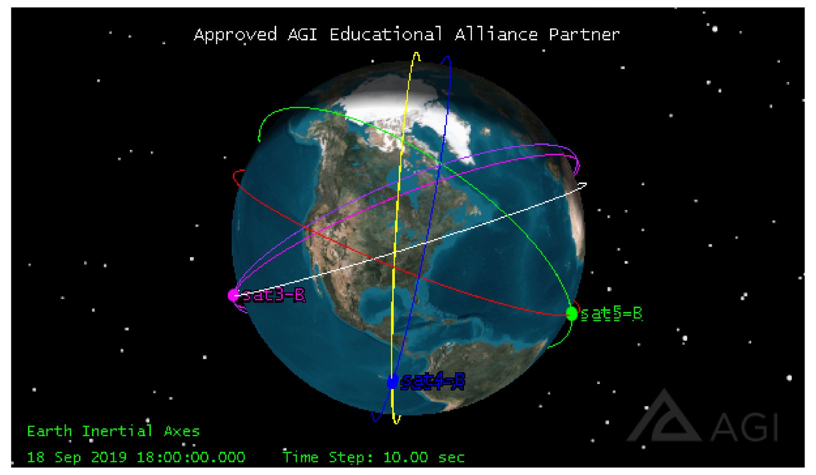
I. Background



Single pair of satellites like the Gravity Recovery and Climate Experiment (GRACE) mission and GRACE-FO have provided two decades of near-continuous information on the Earth's time-varying gravity field. These missions are, through their design, inherently limited in their spatio-temporal coverage, spatially to a few hundred kilometers and temporally to roughly monthly resolution. To increase the global spatio-temporal resolution and therefore allow for the determination of sub-monthly time-varying gravity field events, a constellation of GRACE-type pairs is a possible path forward. Small satellite instrumentation is becoming increasingly affordable, reliable, and more precise. This will soon allow a constellation of GRACE-type small satellites to be deployed.

In this work, we investigate the viability and limitations of a genetic algorithm-based optimization and its objective function to generate satellite constellations aimed at recovering daily Earth system mass changes. The developed approach is used to create constellations that are optimally designed for both daily as well as monthly recovery of Earth's time-varying gravity field. By using a simplified analysis of the constellation's performance, we can navigate through a very large search space in a relatively short period of time. This allows us to estimate the relative performance of constellations to each other and using Darwinian theory converge towards a set of optimal orbits. The performance of the designed constellations has then been validated using high-fidelity numerical simulations. We will summarize these results and discuss their implications for possible future constellations of GRACE-like satellite pairs.

The resulting constellations have an inherent improved spatio-temporal performance which will reduce temporal aliasing errors and allow the characterization of daily mass-change effects. This improved spatio-temporal performance allows us to evaluate the improvement gained from such future mission architectures.

II. Objective function

$$\vec{\mathbf{v}}_{local} = \left[\hat{\mathbf{R}}\hat{\mathbf{E}}\hat{\mathbf{N}}\right] \vec{\mathbf{v}}_{ECEF} \tag{1}$$

$$\mathbf{A} = \begin{bmatrix} \hat{\mathbf{v}}_i \\ \hat{\mathbf{v}}_{i+1} \\ \vdots \\ \hat{\mathbf{v}}_n \end{bmatrix}_{[4551x1]}, \mathbf{B} = 1 - \frac{\mathbf{A}^T\mathbf{A}}{N_{obs}} = \begin{bmatrix} B_{ew} & B_c \\ B_c & B_{ns} \end{bmatrix}, \mathbf{C} = \begin{bmatrix} n_i \\ n_{i+1} \\ \vdots \\ n_n \end{bmatrix}_{[4551x1]} \tag{2}$$

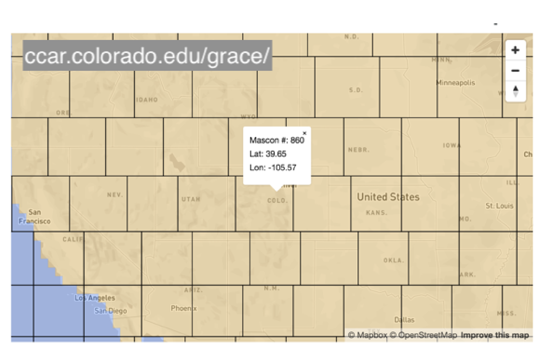
$$J_{bew} = \frac{1}{2}\bar{B}_{ew} + \frac{1}{2}\left(\frac{\sum\sum|\mathbf{B}_{ew} - \mathbf{B}_{ew}^T|}{2 \cdot N_{obs} \cdot N_{mscn}}\right) \tag{3}$$

$$J_{bns} = \frac{1}{2}\bar{B}_{ns} + \frac{1}{2}\left(\frac{\sum\sum|\mathbf{B}_{ns} - \mathbf{B}_{ns}^T|}{2 \cdot N_{obs} \cdot N_{mscn}}\right) \tag{4}$$

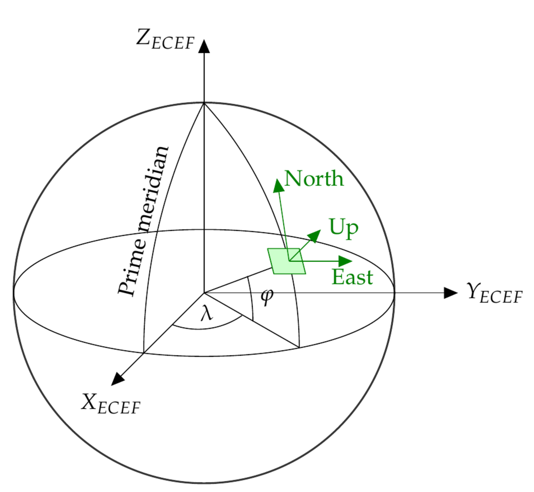
$$J_{SC} = W_{obs} \cdot \left(1 - \bar{\mathbf{N}}\right) + W_{gin} \cdot \left(\frac{\sum\sum|\mathbf{C} - \mathbf{C}^T|}{2 \cdot N_{obs} \cdot N_{mscn}}\right) + W_{ew} \cdot J_{bew} + W_{ns} \cdot J_{bns} \tag{5}$$

$$\mathbf{TG}_i = \begin{bmatrix} m_j \\ m_{j+1} \\ \vdots \\ m_m \end{bmatrix}_{[16*Tx1]}, \mathbf{D}_i = \left(\frac{\sum\sum|\mathbf{TG} - \mathbf{TG}^T|}{2 \cdot N_{obs} \cdot N_{mscn}}\right) \tag{6}$$

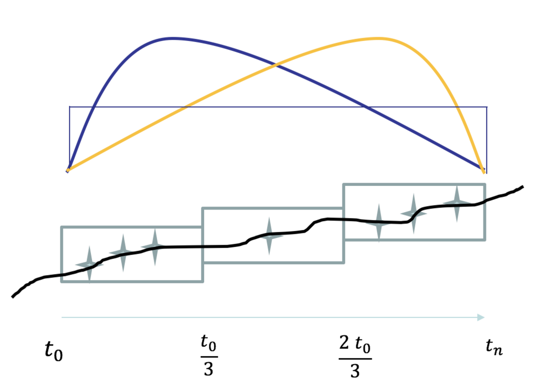
$$J_{TC} = \frac{1}{2}\bar{\mathbf{D}} + \frac{1}{2}\left(\frac{\sum\sum|\mathbf{D} - \mathbf{D}^T|}{2 \cdot N_{obs} \cdot N_{mscn}}\right) \tag{7}$$



Spatial grid



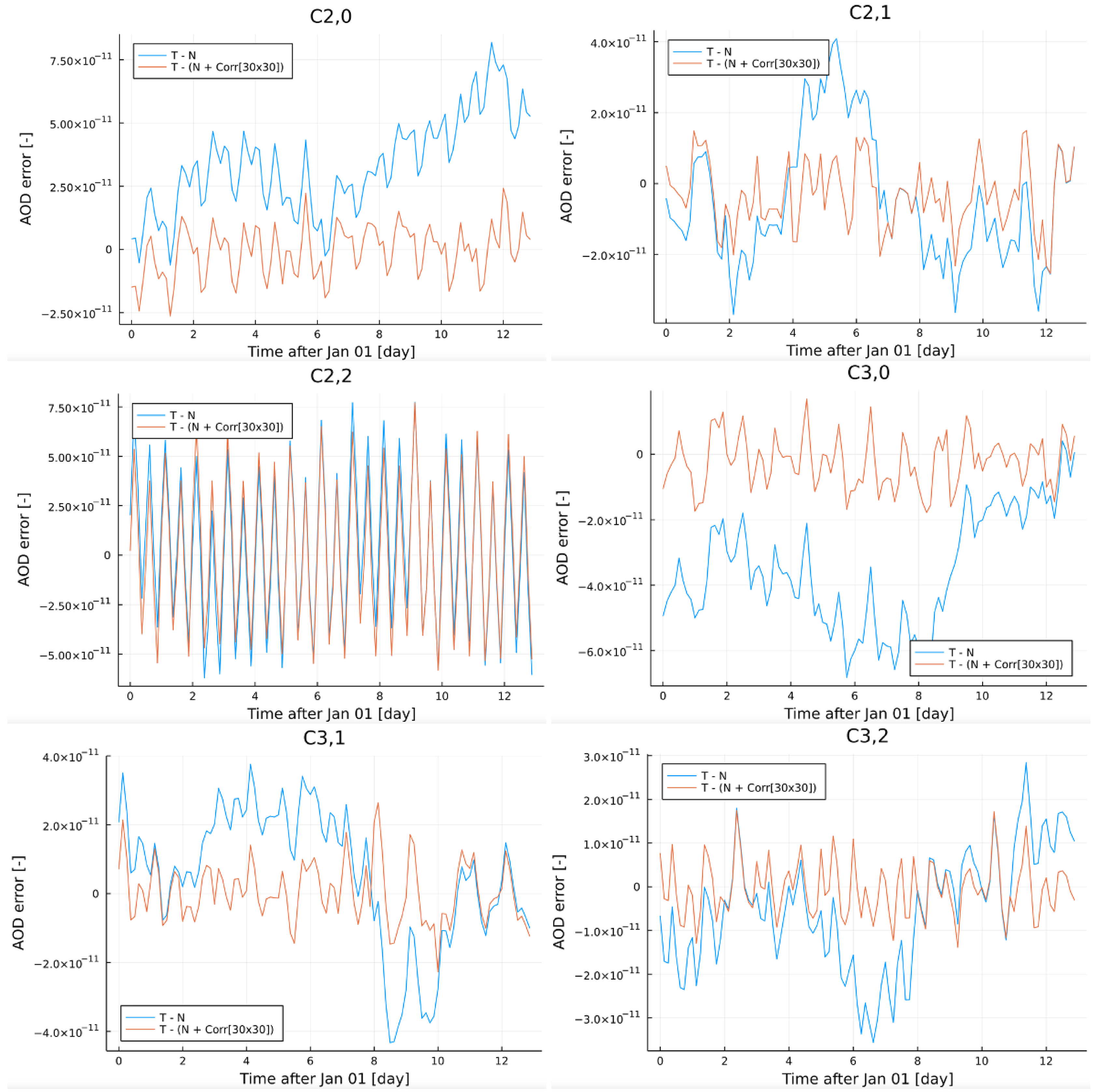
N-S vs E-W information



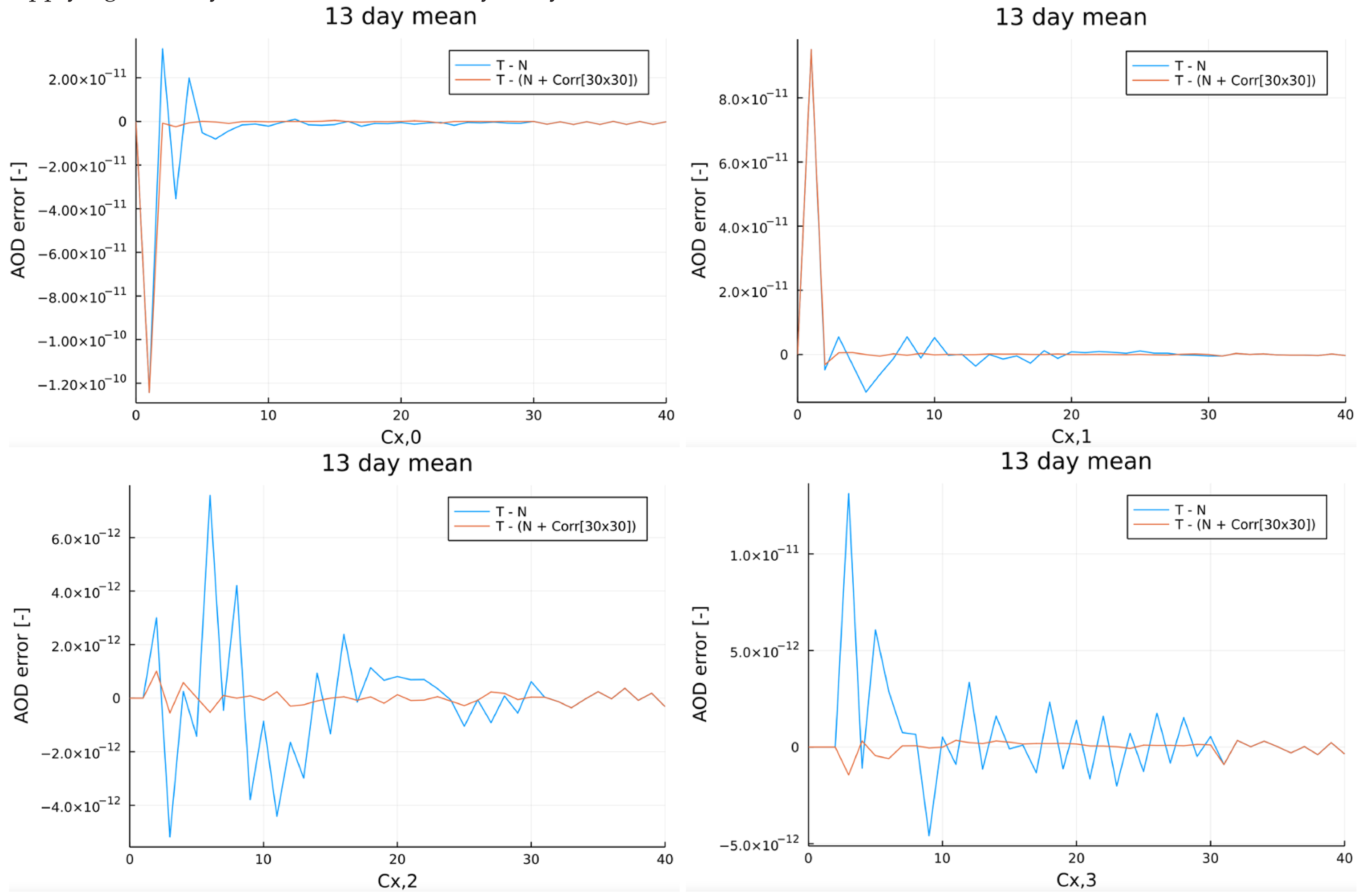
Temporal grid

III. Daily AOD error

Observing the daily correction that can be achieved with the designed constellation especially in the low degree spherical harmonics we can see trends in the AOD errors being cancelled out.



Applying the daily corrections for a 13-day analysis we then have a substantial decrease in AOD error.

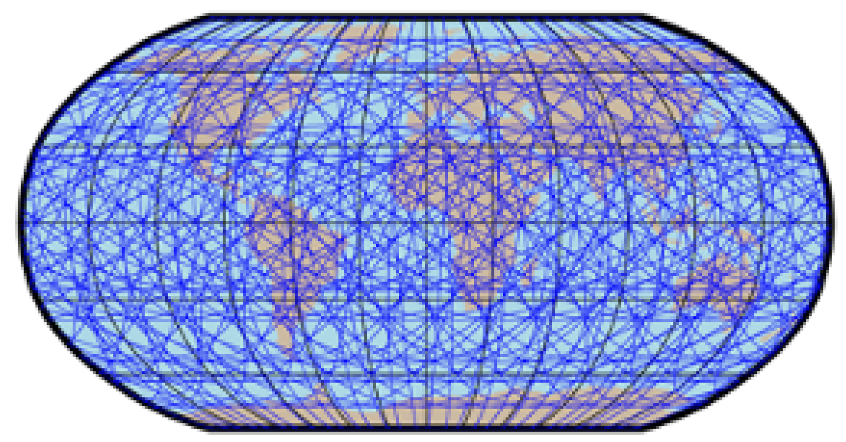


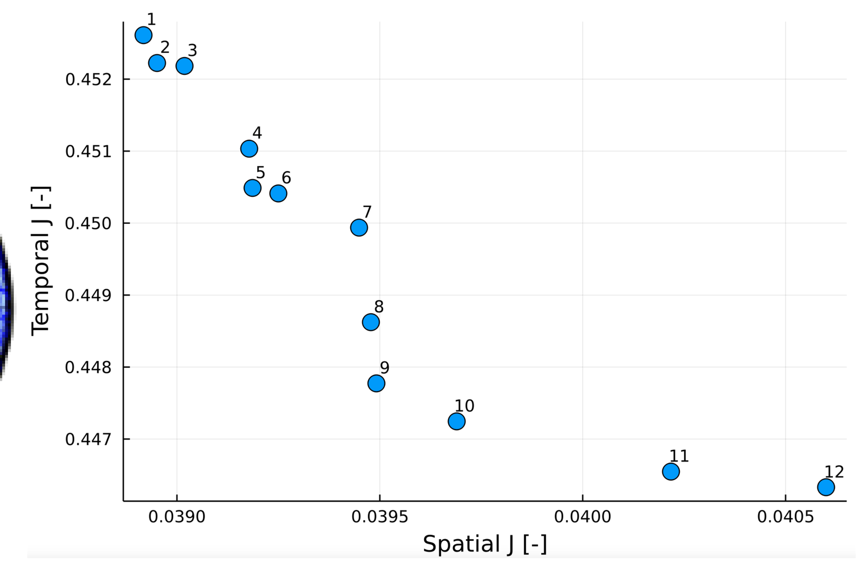
IV. Constraints & models

Variable	Value	Unit
Number of sat. pair	6	[-]
Propagation time	13	day
Orbit altitude	500	km
Eccentricity	0	[-]
Argument of perigee	90	deg
Mean anomaly	45	deg
Distance between sat.	100	km

Models	Truth	Nominal
Static gravity field	EIGEN-GL04C	EIGEN-GL04C
Atmospheric	ECMWF	NCEP
Ocean	OMCT	MOG2D

V. Ground track and design space





VI. Resulting constellation design

ID	$i_1[°]$	$i_2[°]$	$i_3[°]$	$i_4[°]$	$i_5[°]$	$i_6[°]$	J_{SC}	J_{TC}
01	81.3871	69.129	105.194	91.0	105.194	49.2581	0.0389183	0.45261
02	98.6129	89.0	113.71	63.4516	54.9355	80.4839	0.0389513	0.452223
03	69.9032	110.871	108.032	122.226	91.0	80.4839	0.0390189	0.452179
04	144.548	91.0	86.1613	54.9355	108.032	77.6452	0.0391785	0.451033
05	46.9355	122.226	91.0	96.6774	108.032	69.129	0.0391868	0.450483
06	81.3871	43.5806	91.0	108.032	119.387	110.871	0.0392504	0.45041
07	92.871	125.065	133.581	113.71	89.0	69.129	0.0394495	0.449934
08	133.065	102.355	139.258	99.5161	89.0	105.194	0.0394784	0.448619
09	104.355	63.4516	144.935	91.0	80.4839	127.903	0.0394924	0.447771
10	81.3871	125.065	110.871	89.0	150.613	113.71	0.0396896	0.447242
11	150.29	86.1613	122.226	108.032	86.1613	127.903	0.0402184	0.446546
12	121.581	113.71	74.8065	86.1613	153.452	125.065	0.0406001	0.446326

VII. Conclusions & future work

In this analysis, we focused on designing a GRACE-like satellite constellation that especially addresses temporal aliasing errors originating from improper global sampling, since they are one of the leading error sources for a GRACE-like mission design. Using a genetic algorithm, we have developed a method to characterize spatial and temporal sampling, to generate satellite constellations of any size and for any length of analysis time.
This simplified method allows us to estimate the performance of a constellation in a relatively short period of time. Using Darwinian theory, we then scan through a very large search space and converge towards a set of optimal constellation orbits.

The resulting constellations have an inherent improved spatio-temporal performance which will reduce temporal aliasing errors. This allows the characterization of sub-monthly time-varying gravity field events. This improved spatio-temporal performance allows us to evaluate the improvement gained from such future mission architectures.
From this analysis, we can deduce that:

- Six GRACE-like pairs can resolve daily global signals up to degree 30 to help reduce daily temporal aliasing, given GRACE-like inter-satellite ranging errors.
- This method provides a family of solutions that all perform similarly. A future design implementation team can select these constellations, giving them flexibility in their design choices.
- The weighting of each sub-objective function (W_{obs},W_{gin},W_{ew},W_{ns}) is critical in the calibration for the validity of the results of the optimization function.

Further development will be focused on:

- Analyze the inclusion of geophysical signals such as hydrology, ice, and ocean tides in the analysis.
- Examine how the size of the constellation affects the recovered spatial resolution.
- Explore the limitations of large-scale constellation designs.