# Design of GRACE-like Small Satellite Constellations for Improved Temporal Gravity Measurements

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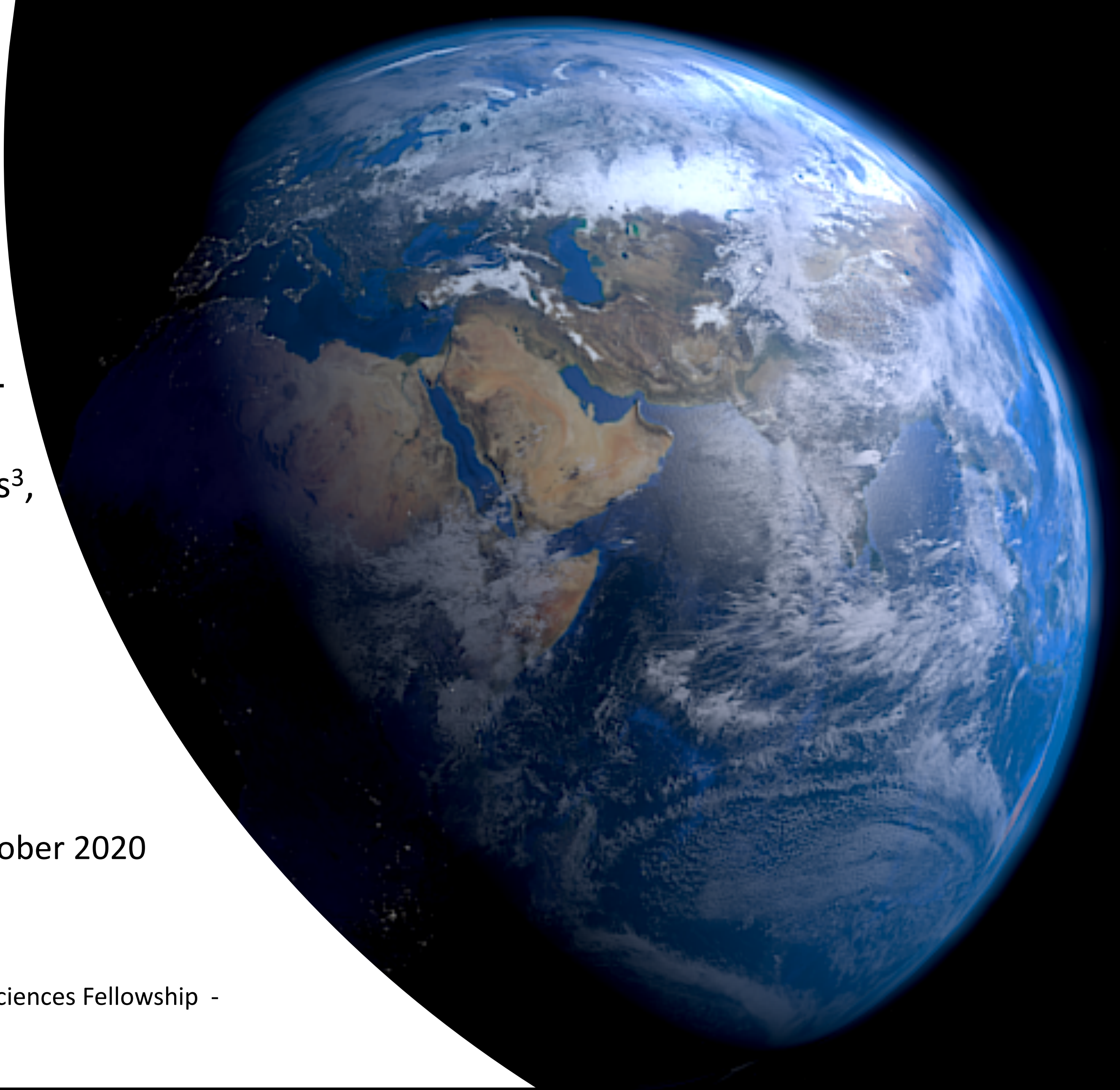

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# Outline

- Motivation
- Method
  - Numerical search algorithm
  - NSGA-II
  - Objective function
- Preliminary analysis
  - Setup
  - One day solutions
- Next steps & end goal

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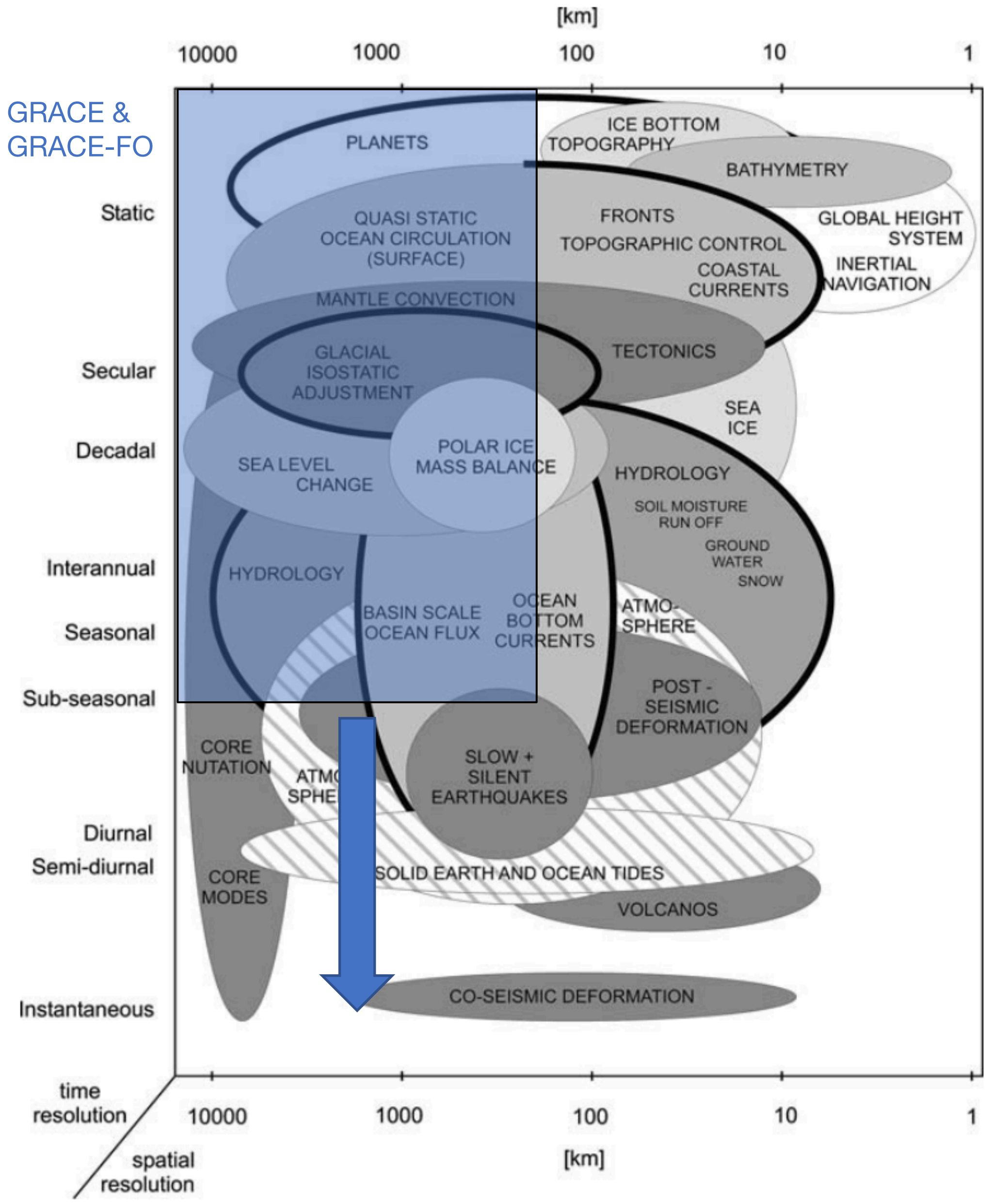
# Beyond GRACE-FO

**2016-2020**

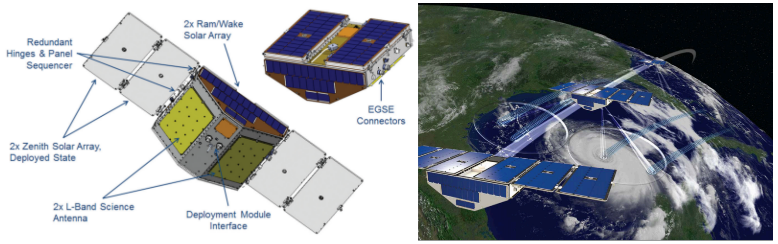
| | | | | |
|---|---|---|---|---|
| LIST | Land surface topography for landslide hazards and water runoff | LEO, SSO | Laser altimeter | 300 |
| PATH | High-frequency, all-weather temperature and humidity soundings for weather forecasting and sea-surface temperature[a] | GEO | Microwave array spectrometer | 450 |
| GRACE-II | High-temporal-resolution gravity fields for tracking large-scale water movement | LEO, SSO | Microwave or laser ranging system | 450 |
| SCLP | Snow accumulation for freshwater availability | LEO, SSO | Ku- and X-band radars<br>K- and Ka-band radiometers | 500 |
| GACM | Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction | LEO, SSO | UV spectrometer<br>IR spectrometer<br>Microwave limb sounder | 600 |
| 3D-Winds (Demo) | Tropospheric winds for weather forecasting and pollution transport | LEO, SSO | Doppler lidar | 650 |




Adapted from: Sneeuw et al. 2005

# Why Smallsats?

- Due to
  - Miniaturization of instruments
  - Increasing smallsats capabilities
  - Insensitive to single point failures




Source: CYGNSS Handbook/NASA

- Smallsats are beginning to be used for scientific missions
  - Antarctic Glacier and Sea Ice Observation with a 3U Cube Satellite (Wu et al., 2017)
    - Launched: Sept 25, 2015
  - CYGNSS : 8 Smallsats constellation (27.5 kg) measure ocean surface wind speed for hurricane forecasting (Ru et al., 2013)
    - Launched: Dec 15, 2016
- Smallsats could be **low-cost alternatives** to large missions
  - A GRACE-like smallsat production cost could be $5M–$10M for each satellite unit (T. Yunk, 2020)
- Can we use a smallsat constellation if they are good enough?

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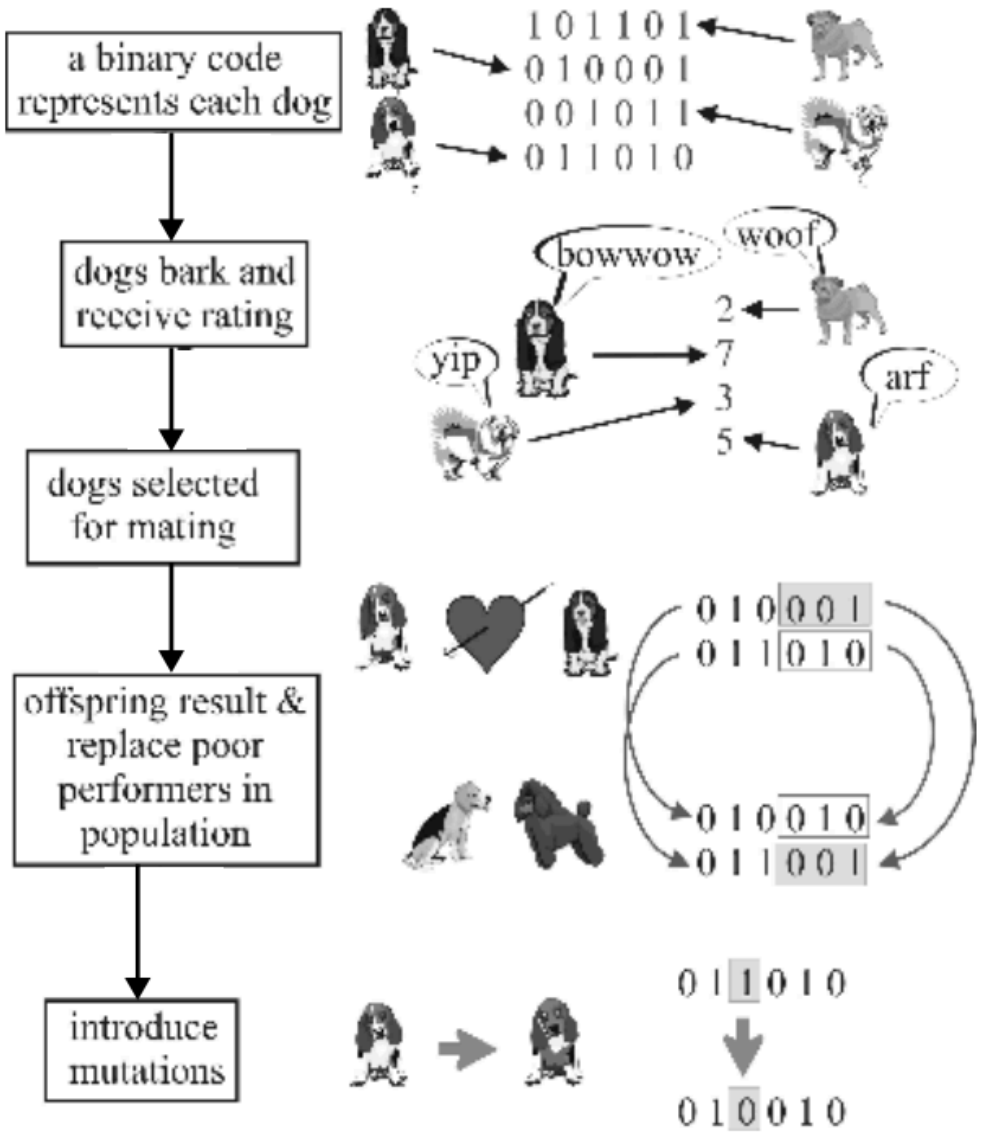
# Genetic algorithm

- Proven technique for large scale constellation design (Stern et al., 2018, Savitri et al., 2017, Iran-Pour et al., 2014)

- Advantage
  - Converges “fast” for nonlinear problems to the **vicinity** of the solutions

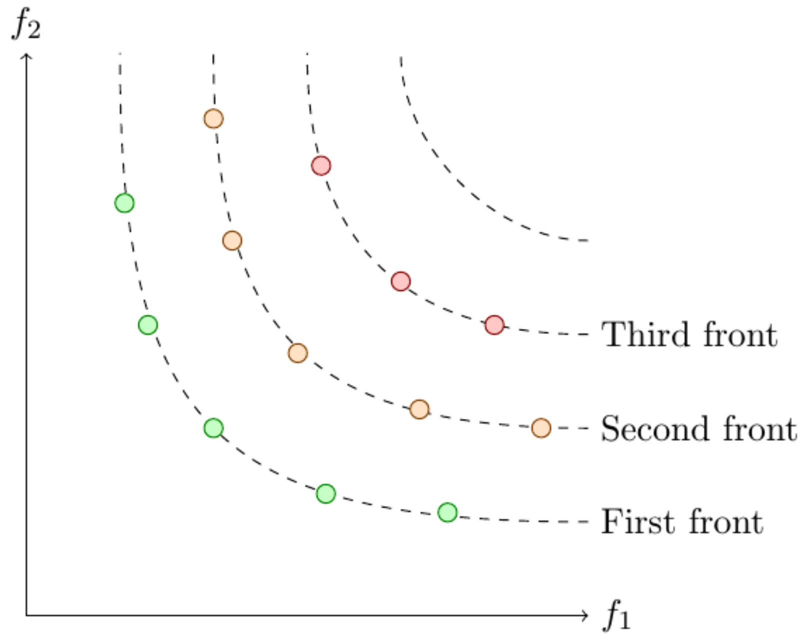
- Drawback
  - Does not converge fast to the final solution




Source: Haupt and Haupt 2004

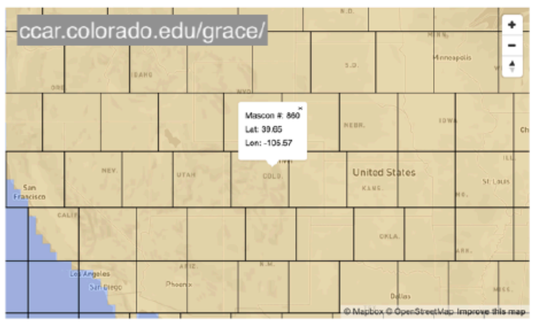
# Nondominated Sorting Genetic Algorithm (NSGA-II)

- Multi-objective GA
- Fast nondominated sorting
  - Pareto fronts
- Diversity through a crowded-comparison operator
- Repeated iterations lead to a global optimum

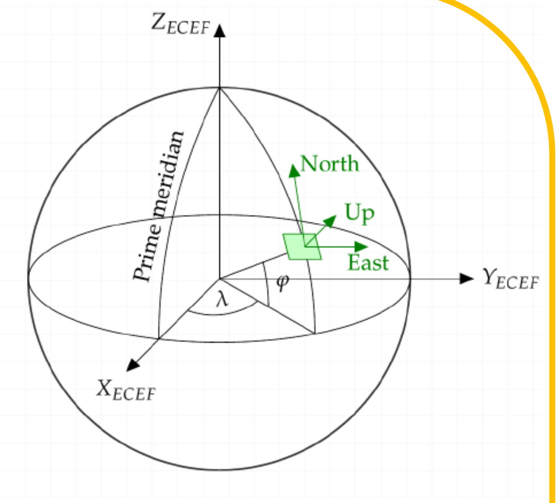


# Objective function

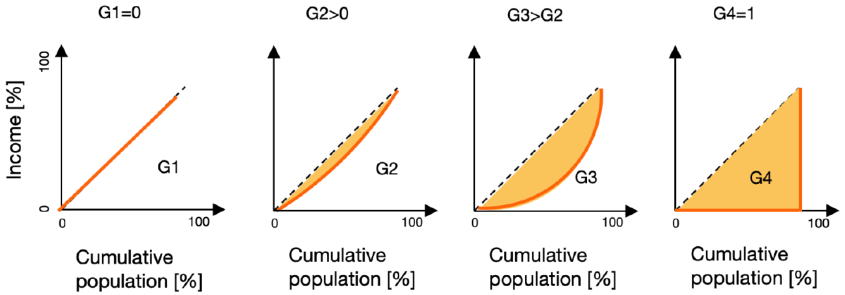
Spatial objective function ( $J_{SC}$ )




Spatial grid

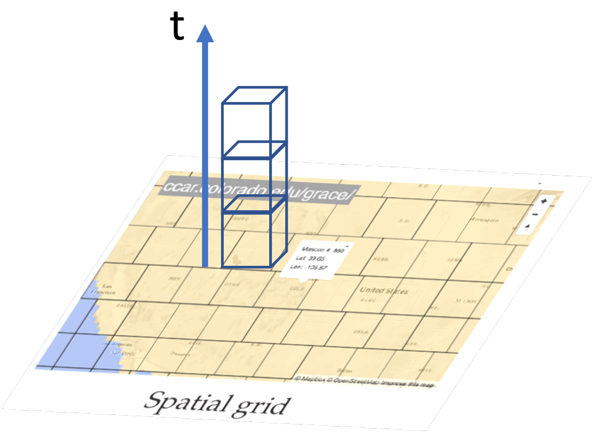


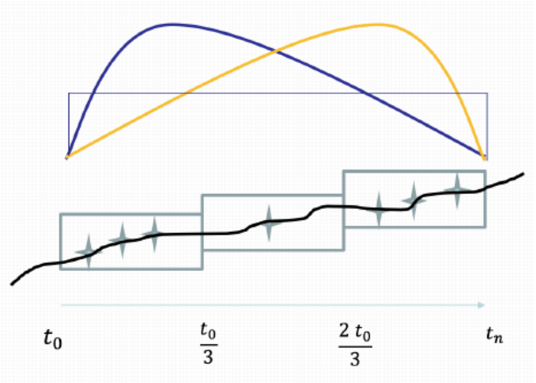

N-S vs E-W information




Uniformity

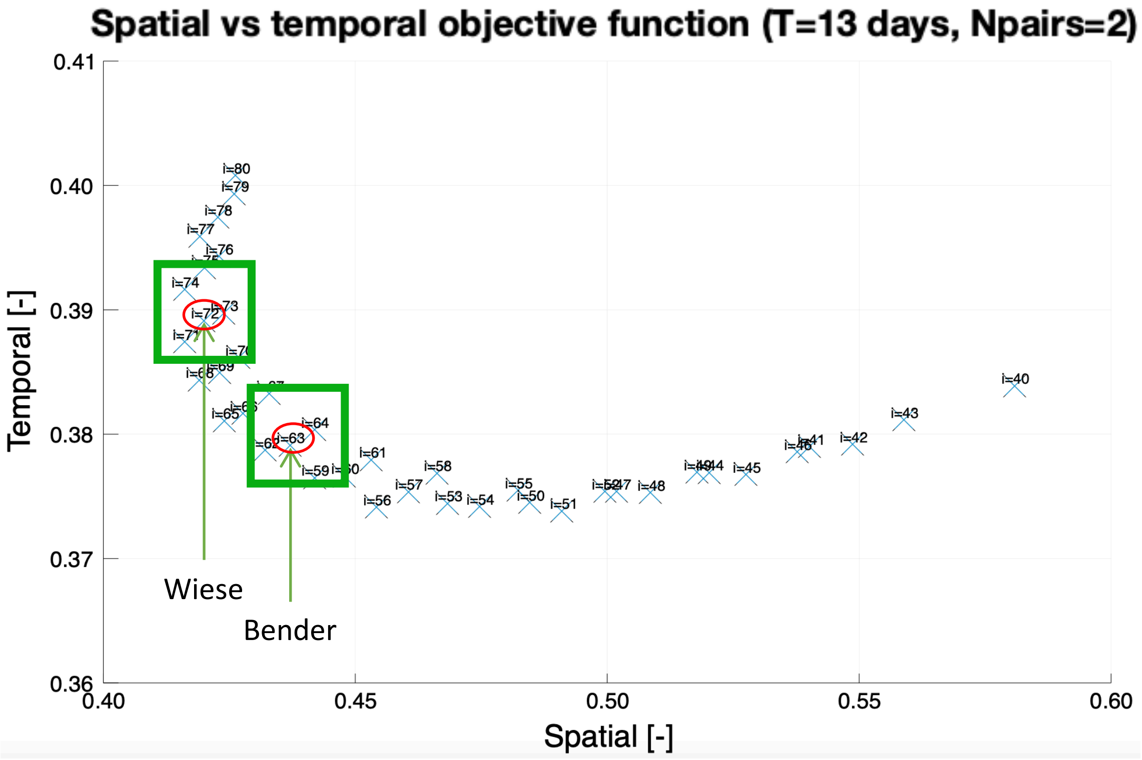
Temporal objective function ( $J_{TC}$ )




Temporal grid

# Selecting the desired constellation




Simulations from the literature have shown what the area of interest is.

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# GA variables

- Solution period
  - 1 day
- First satellite pair
  - $i_1$=90
  - $M_1$=5
  - $\Omega_1$=5
- Altitude
  - h ≈ 500(5) km

Fixed parameters

- Search space
  - $n_{pairs}$ = [6 9 12 24]
  - $i_{n>1}$ = [40 - 89, 91 - 140]
    - intervals of 3.26 deg
    - ➢ $2*2^4$ options
  - $M_{n>1}$ = [5 - 360]
    - intervals of 50 deg
    - ➢ $2^3$ options
  - $\Omega_{n>1}$ = [5 - 360]
    - intervals of 50 deg
    - ➢ $2^3$ options

➢ **Discrete** analysis of the search space

# GEODYN setup (Truth = Nominal)

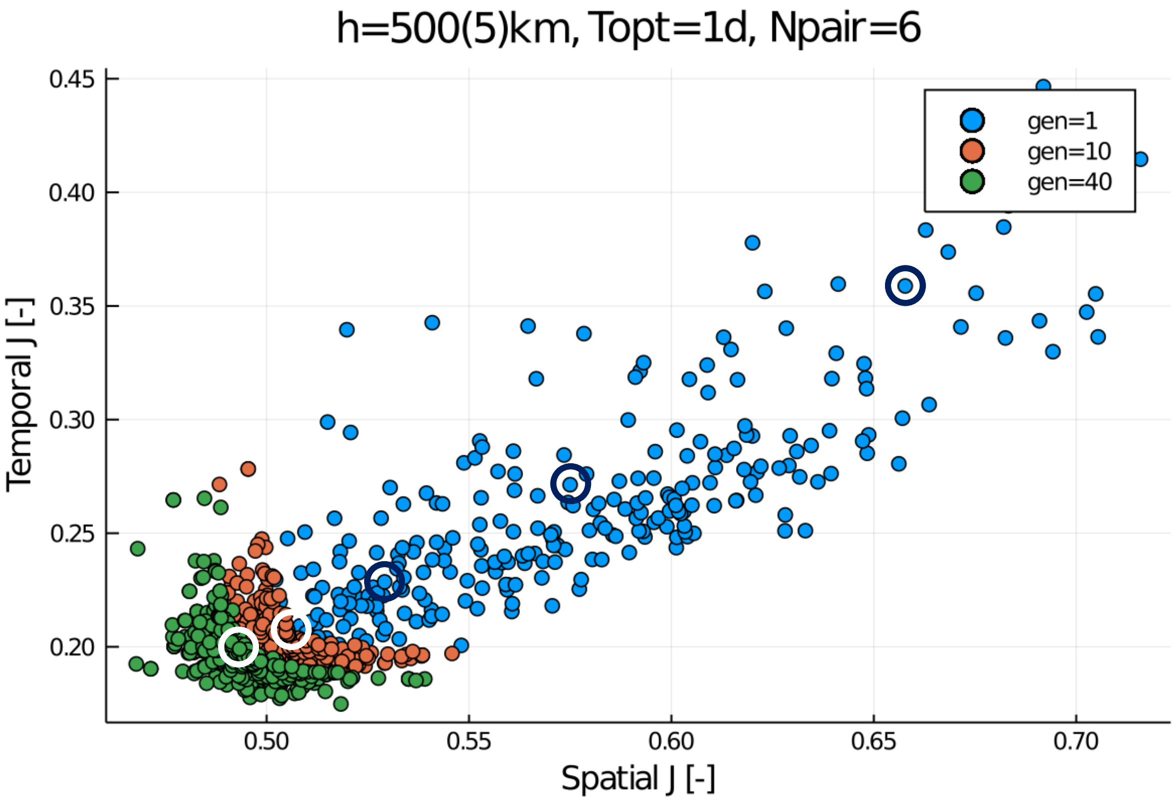
- Truth: EIGEN-GL04C + EMCWF + OMCT
- Nominal: EIGEN-GL04C + EMCWF + OMCT

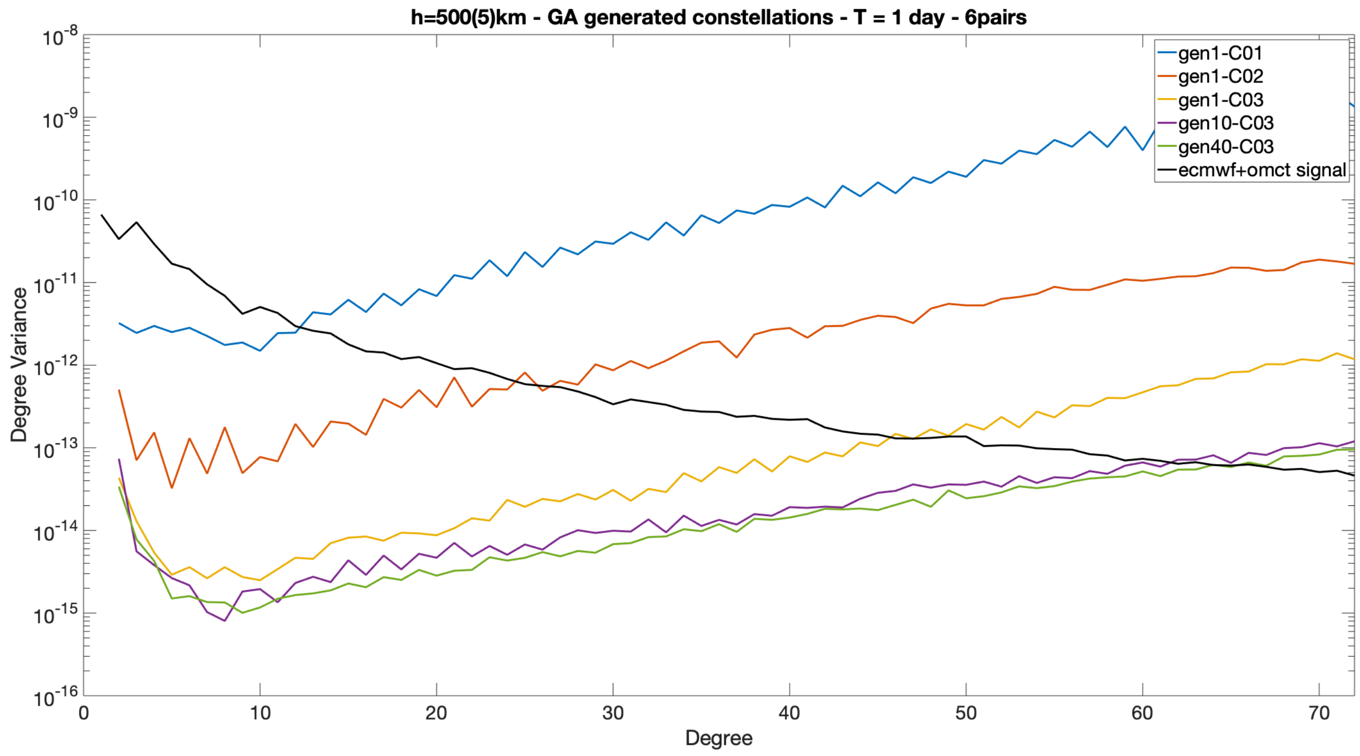
Static | Atm. | Ocean | Hydro | Ice

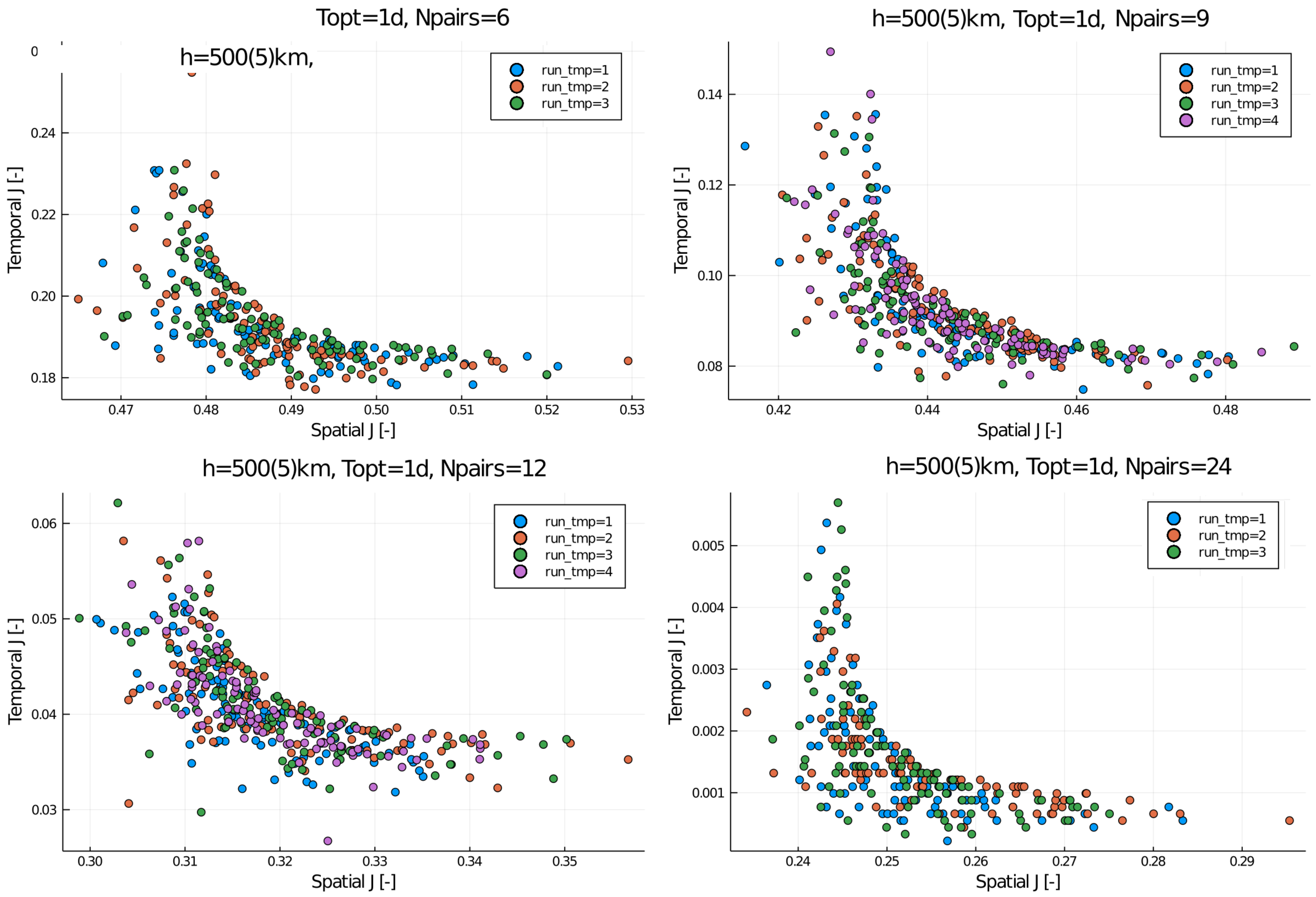
- Setup deck and initiation script includes:
  - Tidal aliasing (FES2004 - GOT.00)
  - AOD errors (EMCWF + NCEP) – (OMCT + MOG2D)
  - Range rate errors (GRACE-FO levels)
  - Accelerometer errors (GRACE-FO levels)
  - Satellite position errors (10 cm)

➢ Recovered CS error due only to Range rate + Accelerometer Error

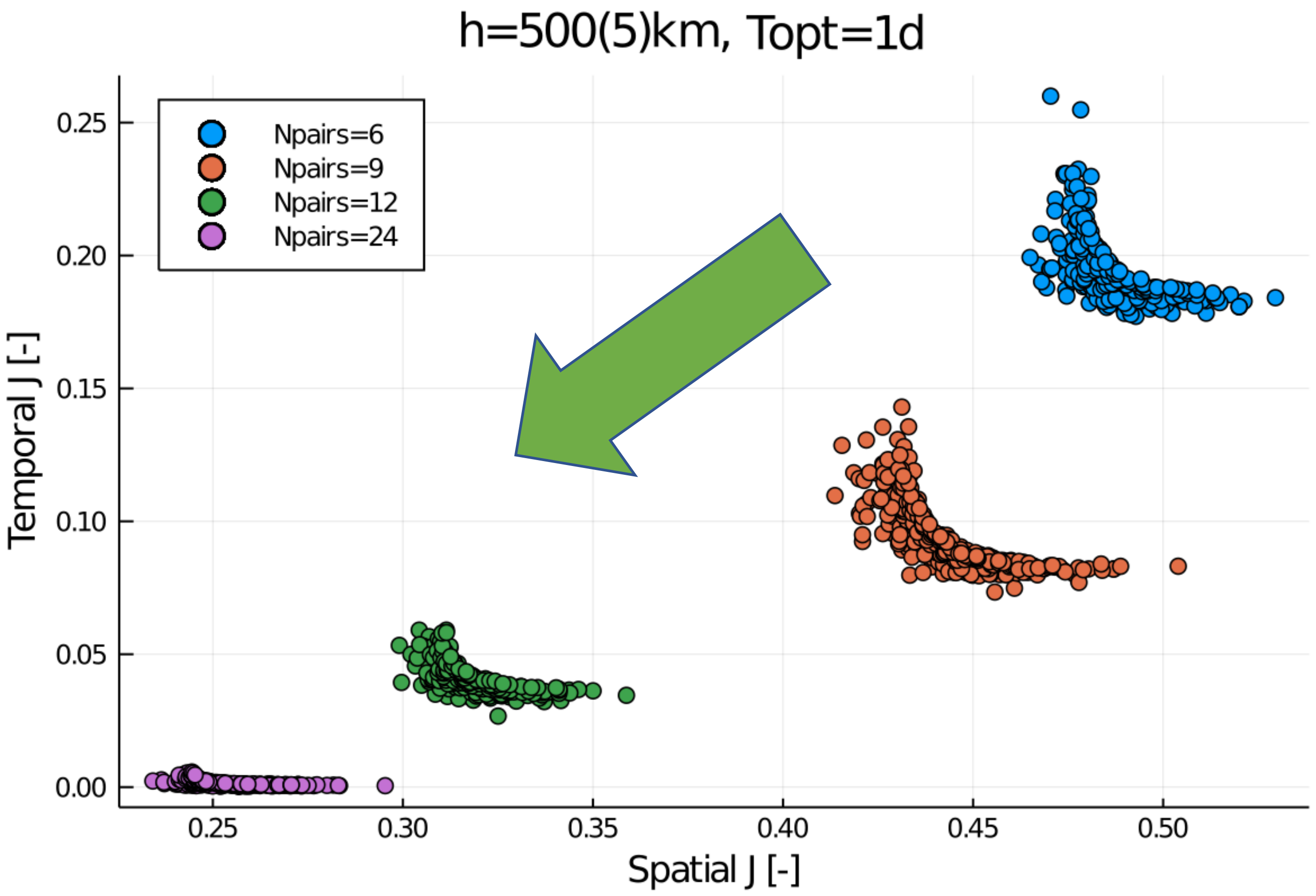
# Generational evolution

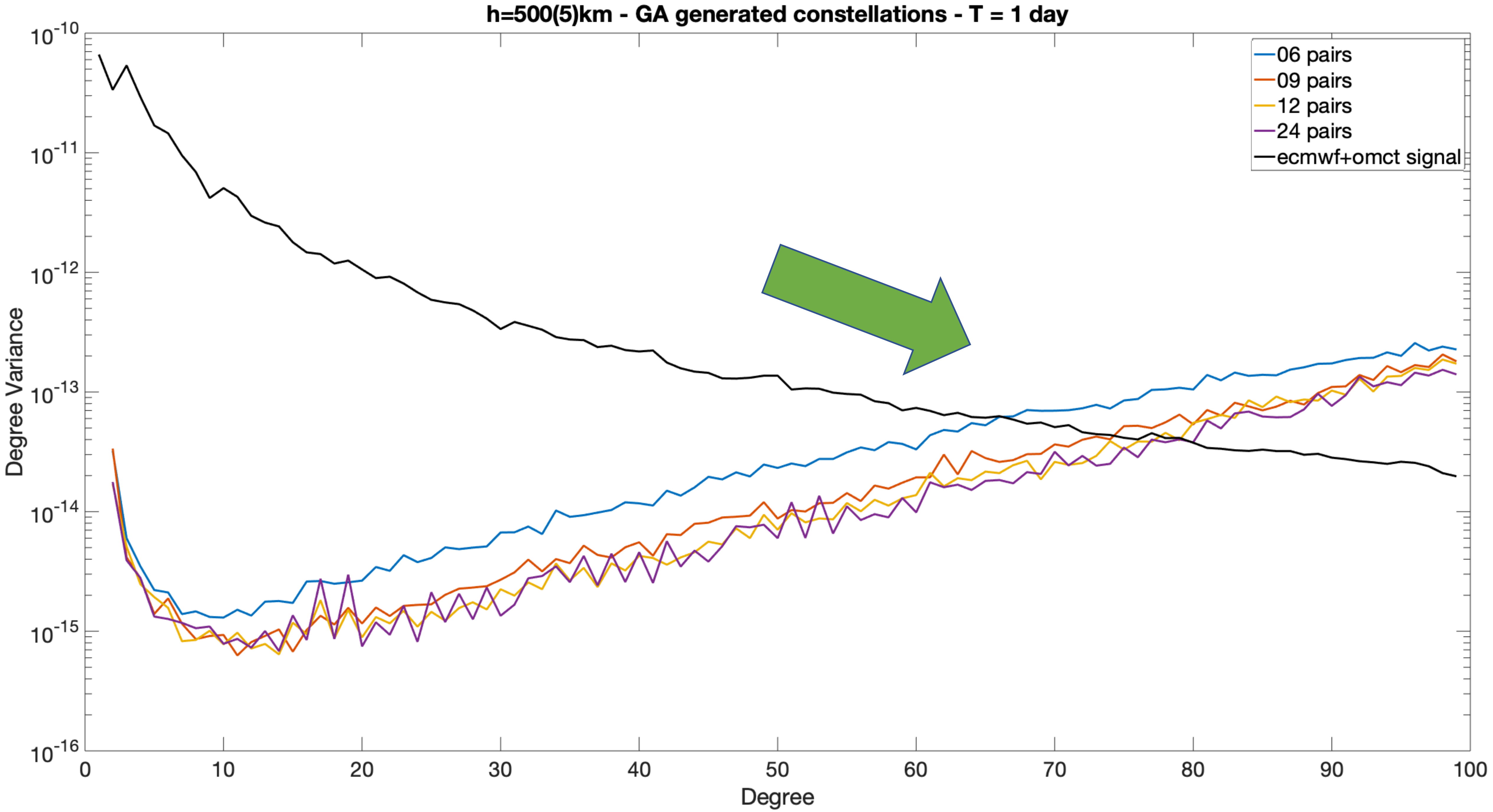



Topt=1d, Npairs=6
h=500(5)km,
run_tmp=1
run_tmp=2
run_tmp=3
Temporal J [-]
Spatial J [-]
h=500(5)km, Topt=1d, Npairs=9
run_tmp=1
run_tmp=2
run_tmp=3
run_tmp=4
Temporal J [-]
Spatial J [-]
h=500(5)km, Topt=1d, Npairs=12
run_tmp=1
run_tmp=2
run_tmp=3
run_tmp=4
Temporal J [-]
Spatial J [-]
h=500(5)km, Topt=1d, Npairs=24
run_tmp=1
run_tmp=2
run_tmp=3
Temporal J [-]
Spatial J [-]

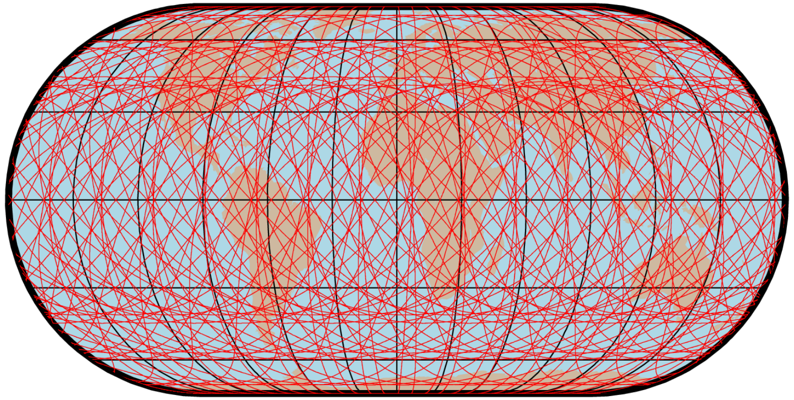
# Diminishing return



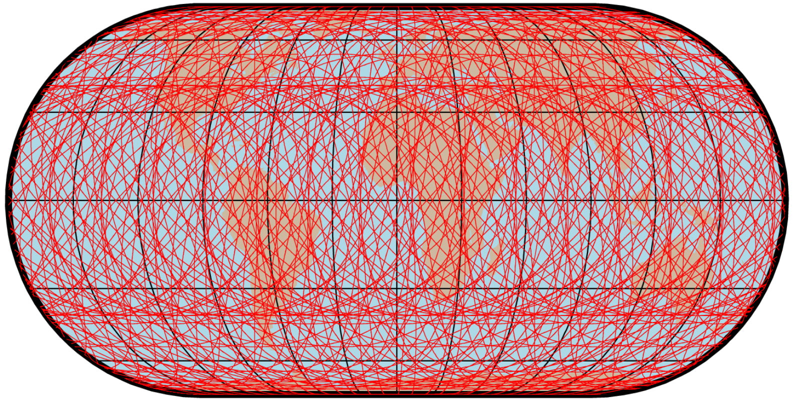


h=500(5)km - GA generated constellations - T = 1 day
Degree Variance
Degree
06 pairs
09 pairs
12 pairs
24 pairs
ecmwf+omct signal
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
0
10
20
30
40
50
60
70
80
90
100

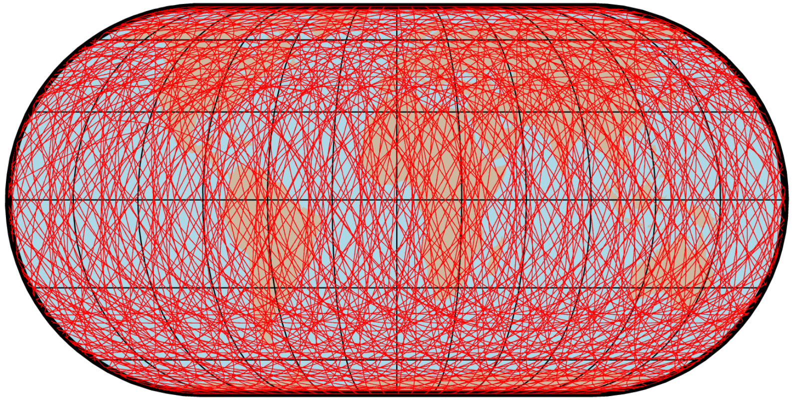
# Ground tracks



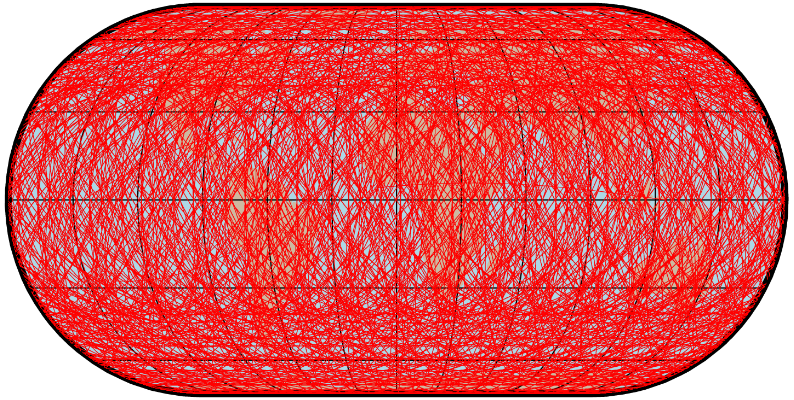
6 sat



9 sat



12 sat



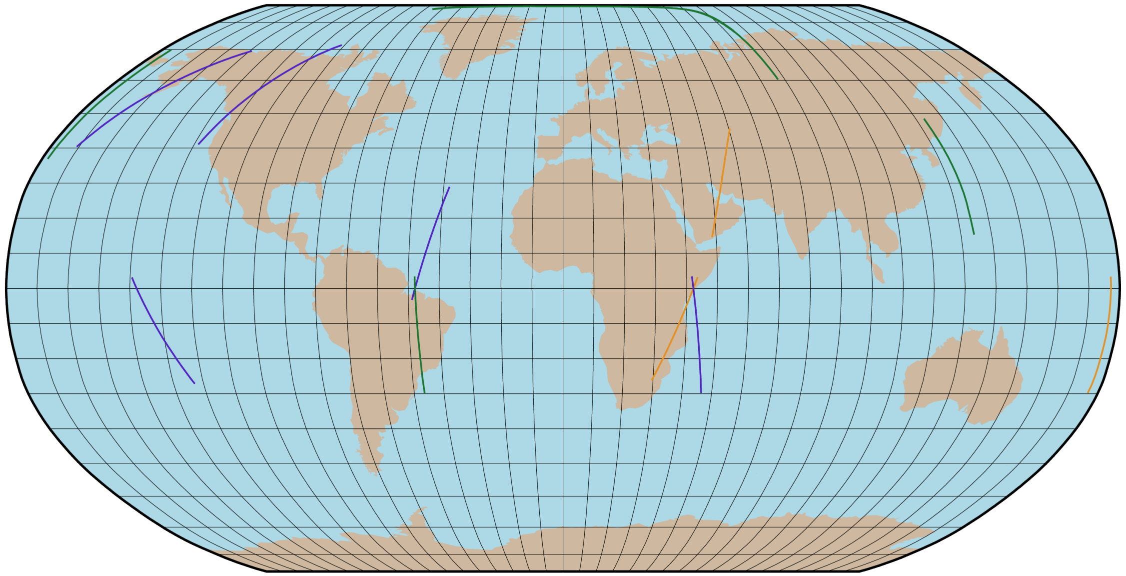
24 sat

# GA solution - 6, 9 pairs

| Pair | i [deg] | M [deg] | RAAN [deg] | Type [-] |
|---|---|---|---|---|
| 1 | 90.0 | 5 | 5 | polar |
| 2 | 100.8 | 90 | 270 | retrograde |
| 3 | 113.9 | 270 | 180 | retrograde |
| 4 | 126.93 | 90 | 270 | retrograde |
| 5 | 130.2 | 180 | 180 | retrograde |
| 6 | 136.73 | 360 | 270 | retrograde |

| Pair | i [deg] | M [deg] | RAAN [deg] | Type [-] |
|---|---|---|---|---|
| 1 | 90 | 5 | 5 | polar |
| 2 | 89 | 360 | 315 | polar |
| 3 | 91 | 45 | 270 | polar |
| 4 | 46.53 | 45 | 270 | prograde |
| 5 | 107.33 | 225 | 315 | retrograde |
| 6 | 110.6 | 225 | 135 | retrograde |
| 7 | 123.67 | 45 | 45 | retrograde |
| 8 | 130.2 | 90 | 90 | retrograde |
| 9 | 136.73 | 135 | 315 | retrograde |

# GA solution - 12 pairs



| Pair | i [deg] | M [deg] | RAAN [deg] | Type [-] |
|---|---|---|---|---|
| 1 | 90.0 | 5 | 5 | polar |
| 2 | 91.0 | 270 | 180 | polar |
| 3 | 91.0 | 315 | 180 | polar |
| 4 | 94.3 | 360 | 135 | polar |
| 5 | 43.3 | 135 | 45 | prograde |
| 6 | 53.1 | 135 | 135 | prograde |
| 7 | 79.2 | 90 | 135 | prograde |
| 8 | 113.9 | 135 | 135 | retrograde |
| 9 | 123.7 | 315 | 315 | retrograde |
| 10 | 123.7 | 315 | 45 | retrograde |
| 11 | 126.9 | 180 | 135 | retrograde |
| 12 | 140.0 | 90 | 180 | retrograde |

# GA solution - 24 pairs

| Pair | i [deg] | M [deg] | RAAN [deg] | Type [-] |
|---|---|---|---|---|
| 1 | 90.0 | 5 | 5 | polar |
| 2 | 91.0 | 225 | 180 | polar |
| 3 | 91.0 | 315 | 135 | polar |
| 4 | 91.0 | 315 | 270 | polar |
| 5 | 40.0 | 135 | 135 | prograde |
| 6 | 43.3 | 225 | 180 | prograde |
| 7 | 43.3 | 360 | 45 | prograde |
| 8 | 56.3 | 270 | 135 | prograde |
| 9 | 59.6 | 315 | 270 | prograde |
| 10 | 72.7 | 270 | 180 | prograde |
| 11 | 72.7 | 315 | 90 | prograde |
| 12 | 75.9 | 45 | 135 | prograde |

| Pair | i [deg] | M [deg] | RAAN [deg] | Type [-] |
|---|---|---|---|---|
| 13 | 75.9 | 180 | 135 | prograde |
| 14 | 79.2 | 315 | 180 | prograde |
| 15 | 85.7 | 270 | 90 | prograde |
| 16 | 104.0 | 180 | 315 | retrograde |
| 17 | 107.3 | 225 | 135 | retrograde |
| 18 | 113.9 | 225 | 225 | retrograde |
| 19 | 113.9 | 315 | 90 | retrograde |
| 20 | 113.9 | 360 | 45 | retrograde |
| 21 | 126.9 | 135 | 225 | retrograde |
| 22 | 130.2 | 180 | 180 | retrograde |
| 23 | 136.7 | 270 | 45 | retrograde |
| 24 | 140.0 | 225 | 315 | retrograde |

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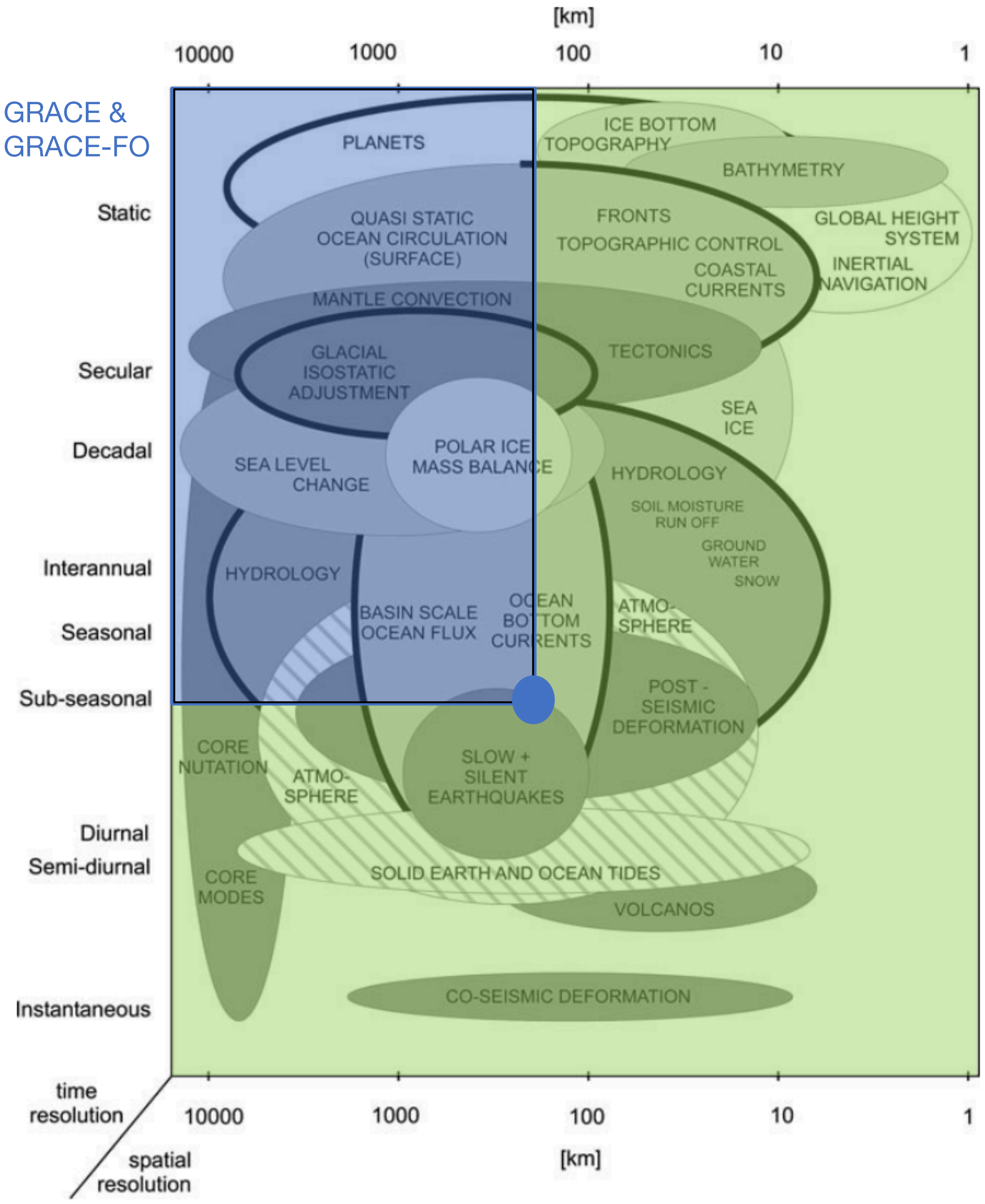
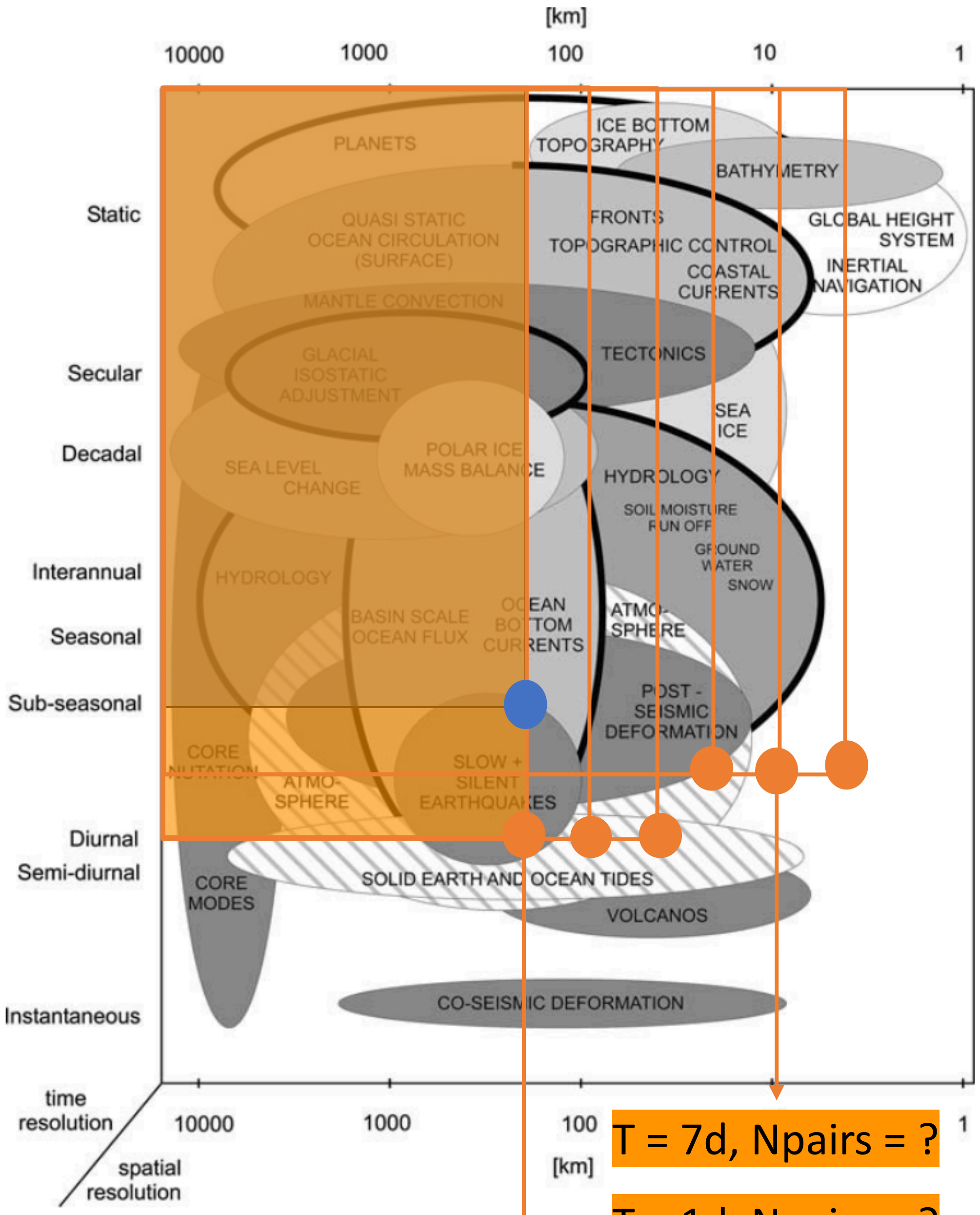



Adapted from: Sneeuw et al. 2005

# Next steps & end goal

- Relate
  - Given: Temporal resolution
  - Npairs required (& orbital config)
  - Spatial resolution achievable
  - To which level of accuracy

- Goal
  - Sub daily solutions
  - Significantly reduce temporal aliasing

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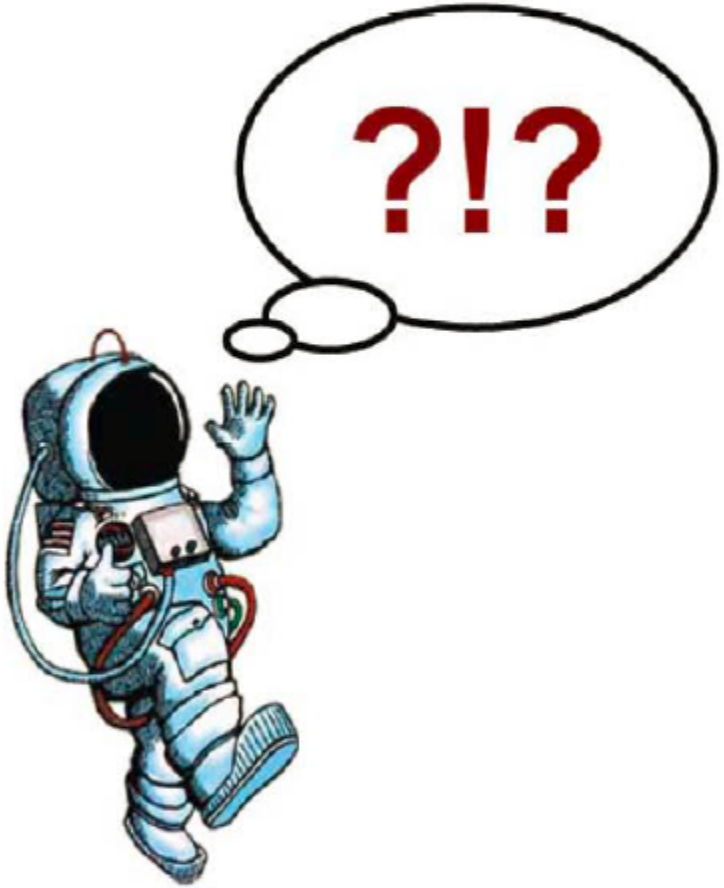

Source: TU Delft