# Improving Low-Degree Gravity Estimates with Future SLR Satellites and Stations

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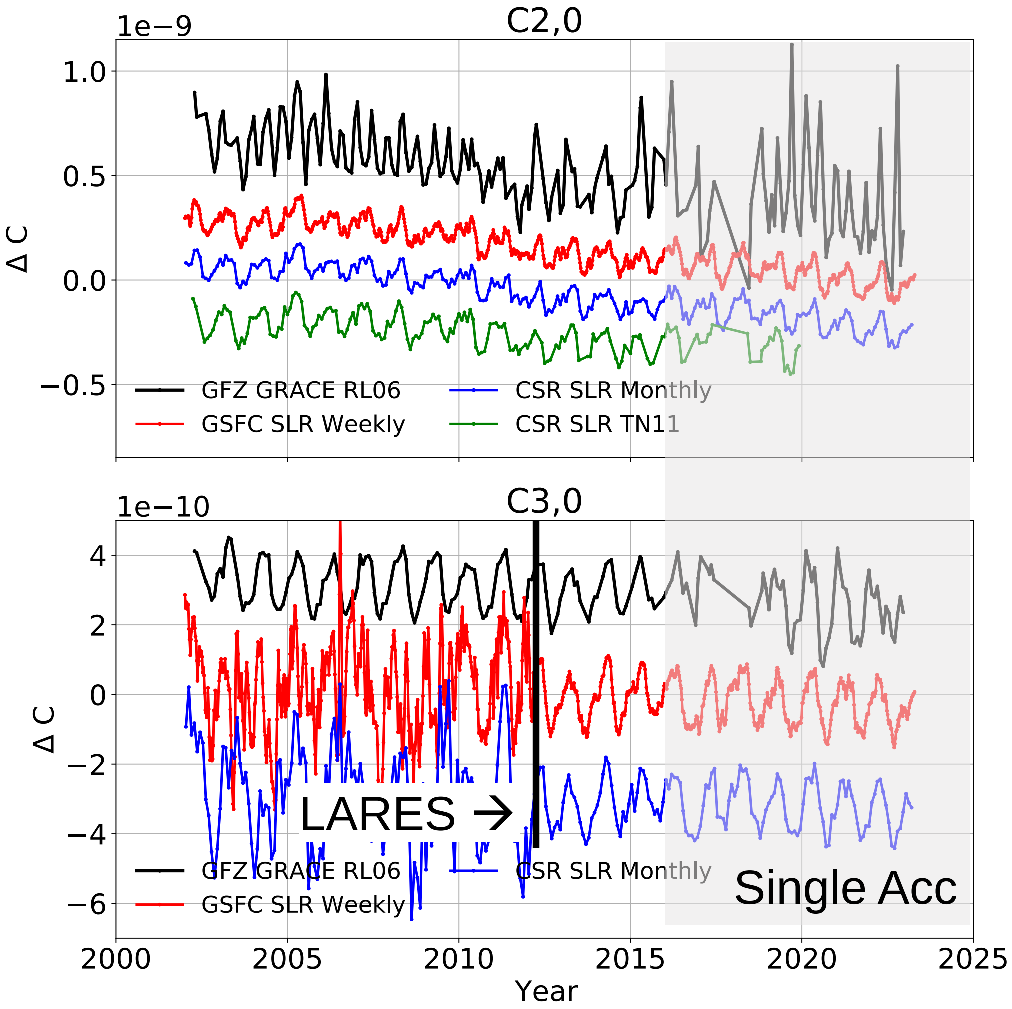
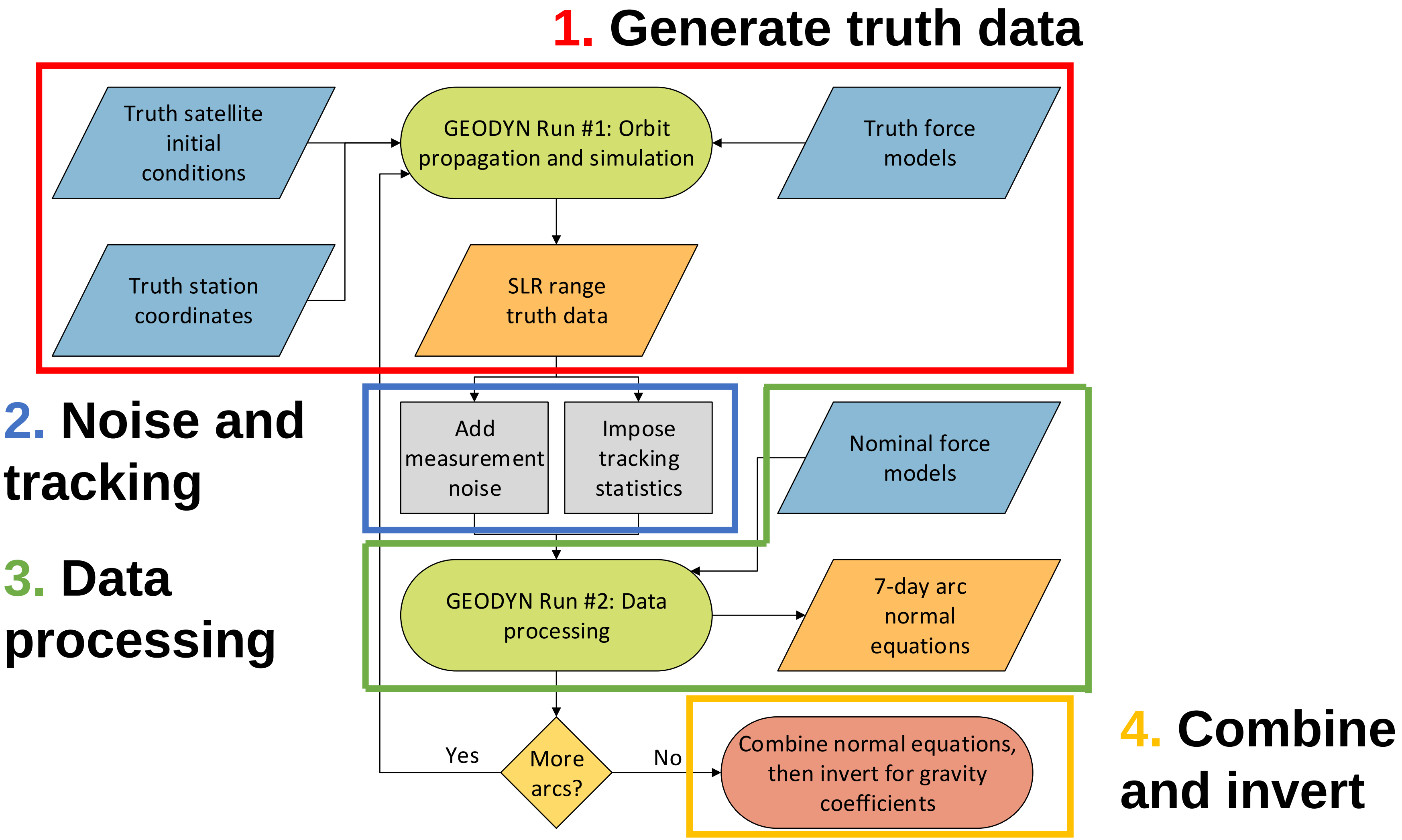
# Objectives & Motivation

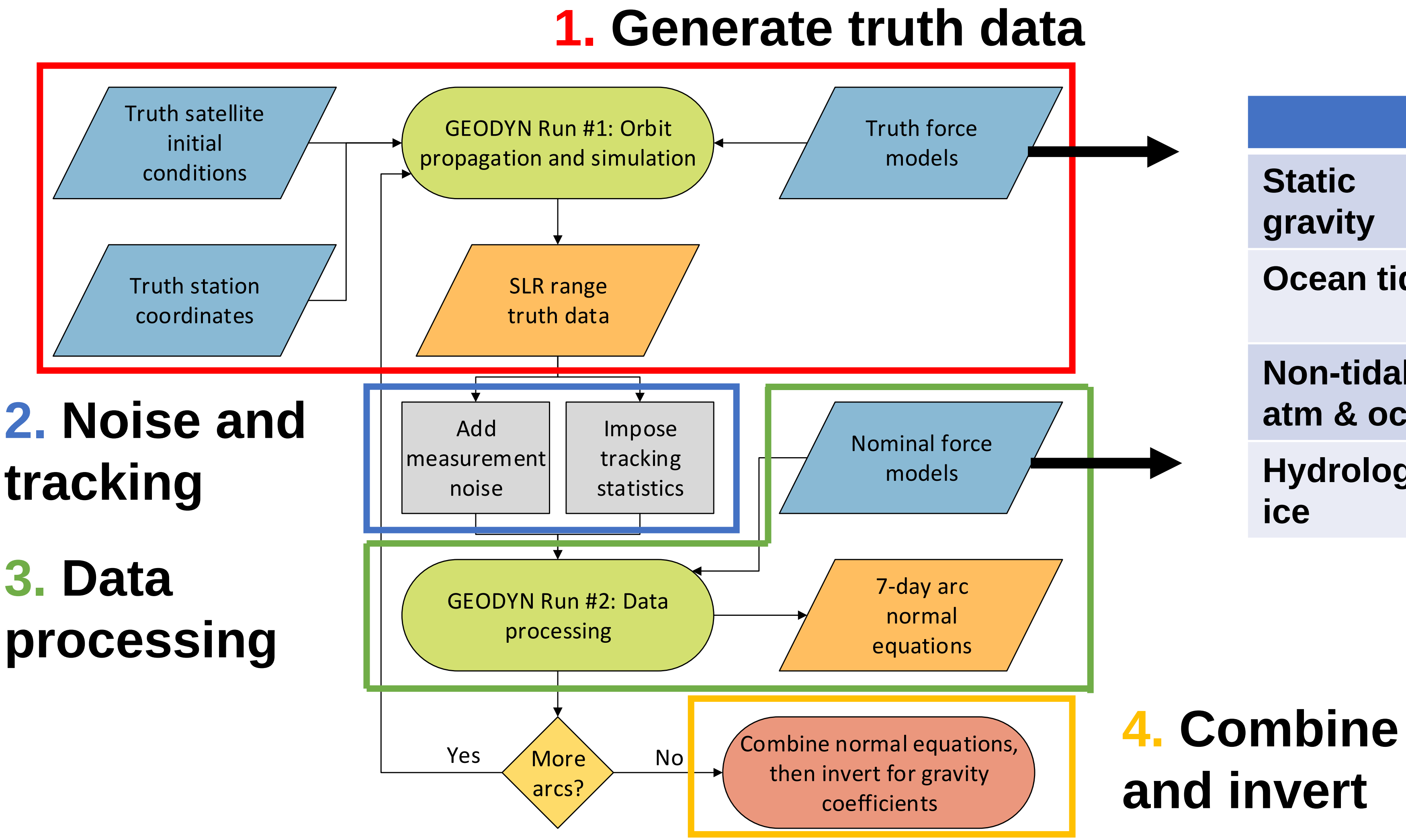



- Low degrees important for large scale ice, hydrology
- GRACE poorly recovers $C_{2,0}$
- SLR has replaced GRACE $C_{2,0}$ for 20 years
- Recently $C_{3,0}$ affected
- LARES essential for SLR $C_{3,0}$
- **Develop SLR simulation, investigate potential future improvements**

# Simulation Overview



# Force Models



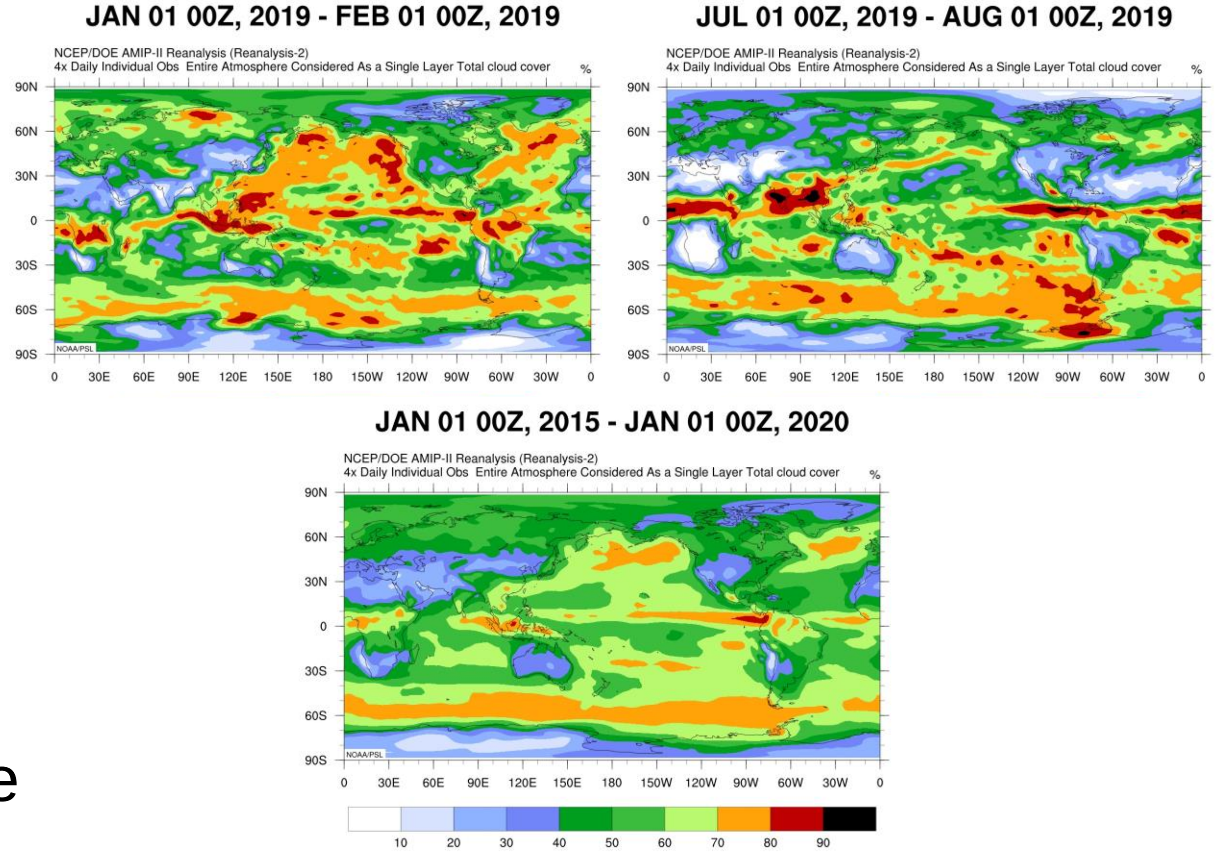

## Force Models

| | Truth | Nominal |
|---|---|---|
| **Static gravity** | GOCO06s | GOCO06s |
| **Ocean tides** | EOT11a | FES2014 |
| **Non-tidal atm & ocean** | ESA ESM A+O | ESA ESM DEAL+ AOerr |
| **Hydrology & ice** | ESA ESM H+I | None |

+drag, SRP, other

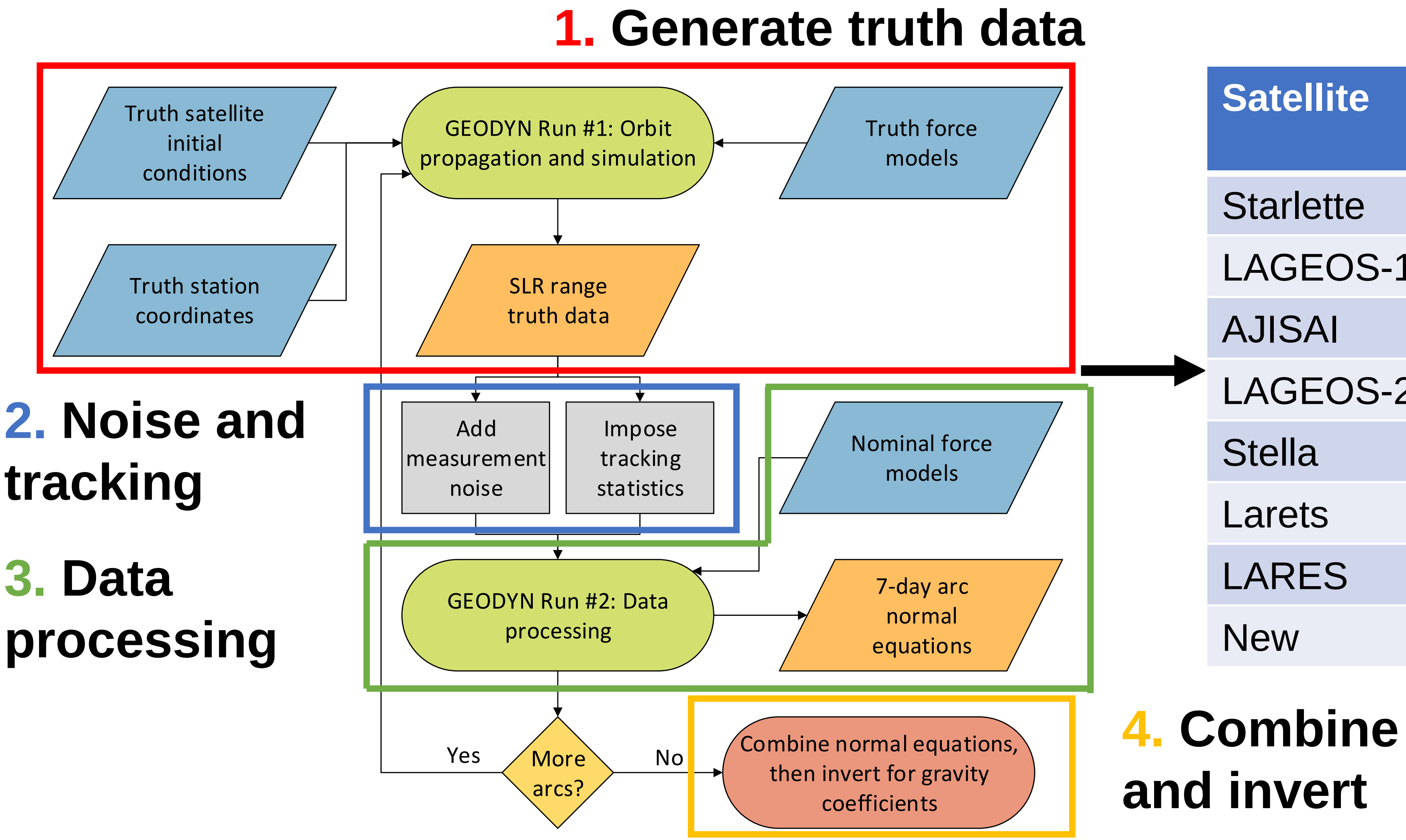
# Observation Numbers

- Tracking depends partially on:
  - Inclination/SMA
  - Local reasons
  - Cloud cover
- Real data files (current satellites)
- Enforce elevation cutoff
- Time-varying Total Cloud Cover used to select passes
  - Goal is to down-select truth data to more realistic numbers




Example months (top), 5 year mean (bottom)

# Satellites



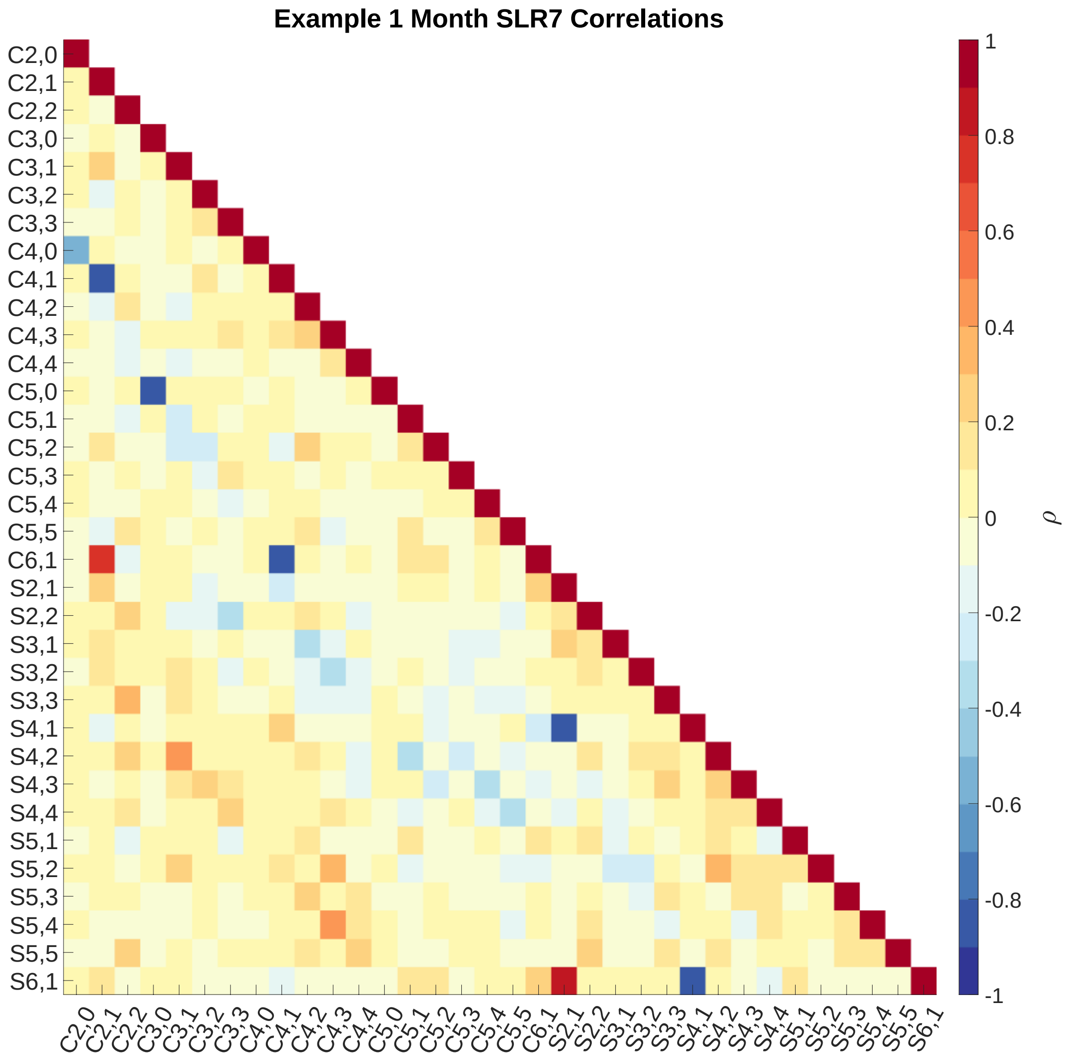

## Satellites

| Satellite | Altitude (km) | Inclination (°) | A2m ($m^2/kg$) |
|---|---|---|---|
| Starlette | 800-1100 | 49.8 | 9.6E-4 |
| LAGEOS-1 | 5860 | 109.9 | 6.9E-4 |
| AJISAI | 1500 | 50 | 58E-4 |
| LAGEOS-2 | 5620 | 52.7 | 7.0E-4 |
| Stella | 830 | 98.6 | 9.4E-4 |
| Larets | 691 | 98.2 | 15E-4 |
| LARES | 1440 | 69.5 | 2.7E-4 |
| New | 1440 | 10-170 | 2.7E-4 |

“SLR7 baseline” = 7 current sats
“SLR7+New” = 7 current + 1 new

# Correlated Parameters

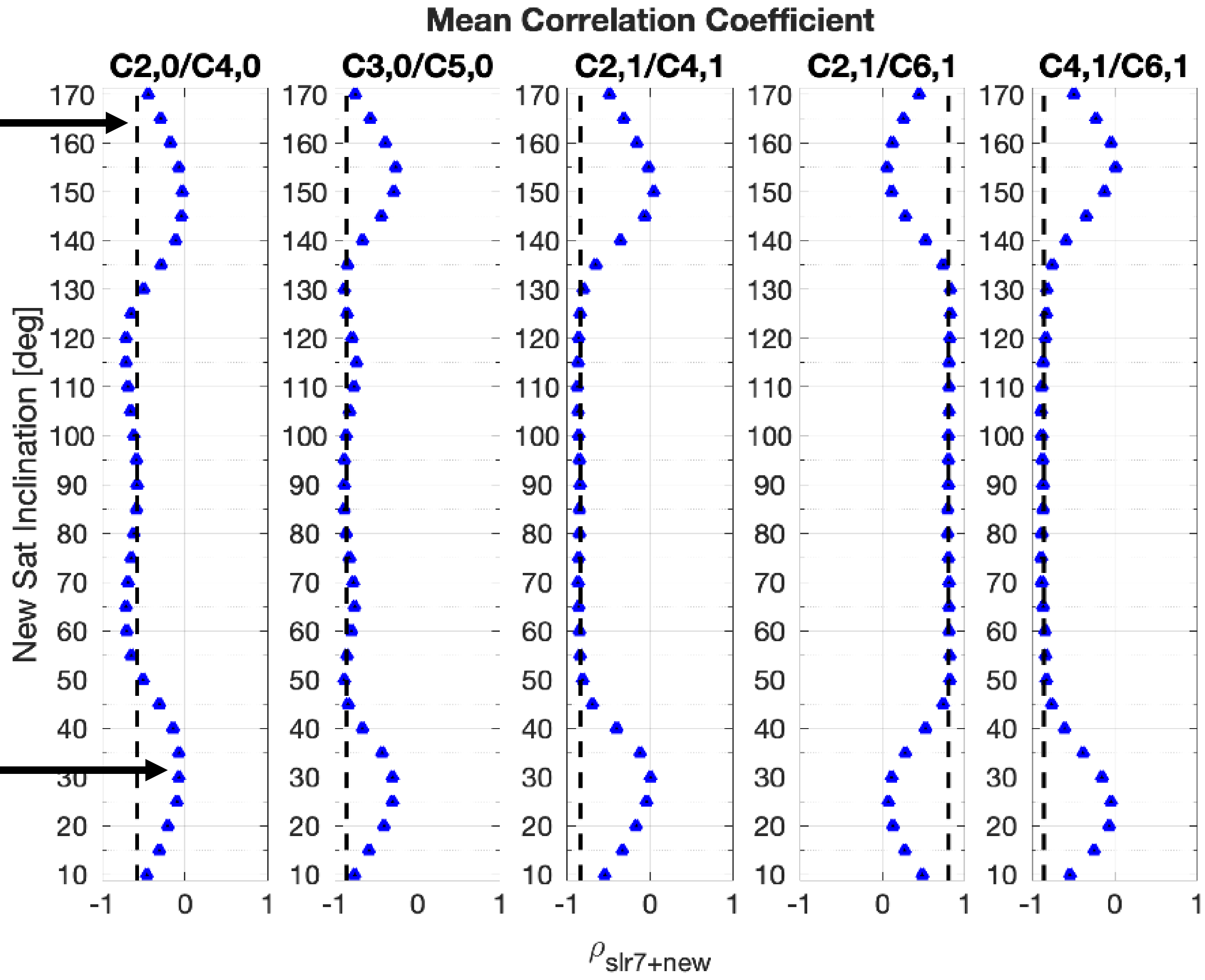
- Zonal, order 1 terms correlated in SLR7 solution
- Higher degree influences
- SLR J2, J3 substituted directly in to GRACE solution
- **Can a new satellite separate these coefficients?**



# Correlation with New Satellite

SLR7 limited by high correlations (black dash)

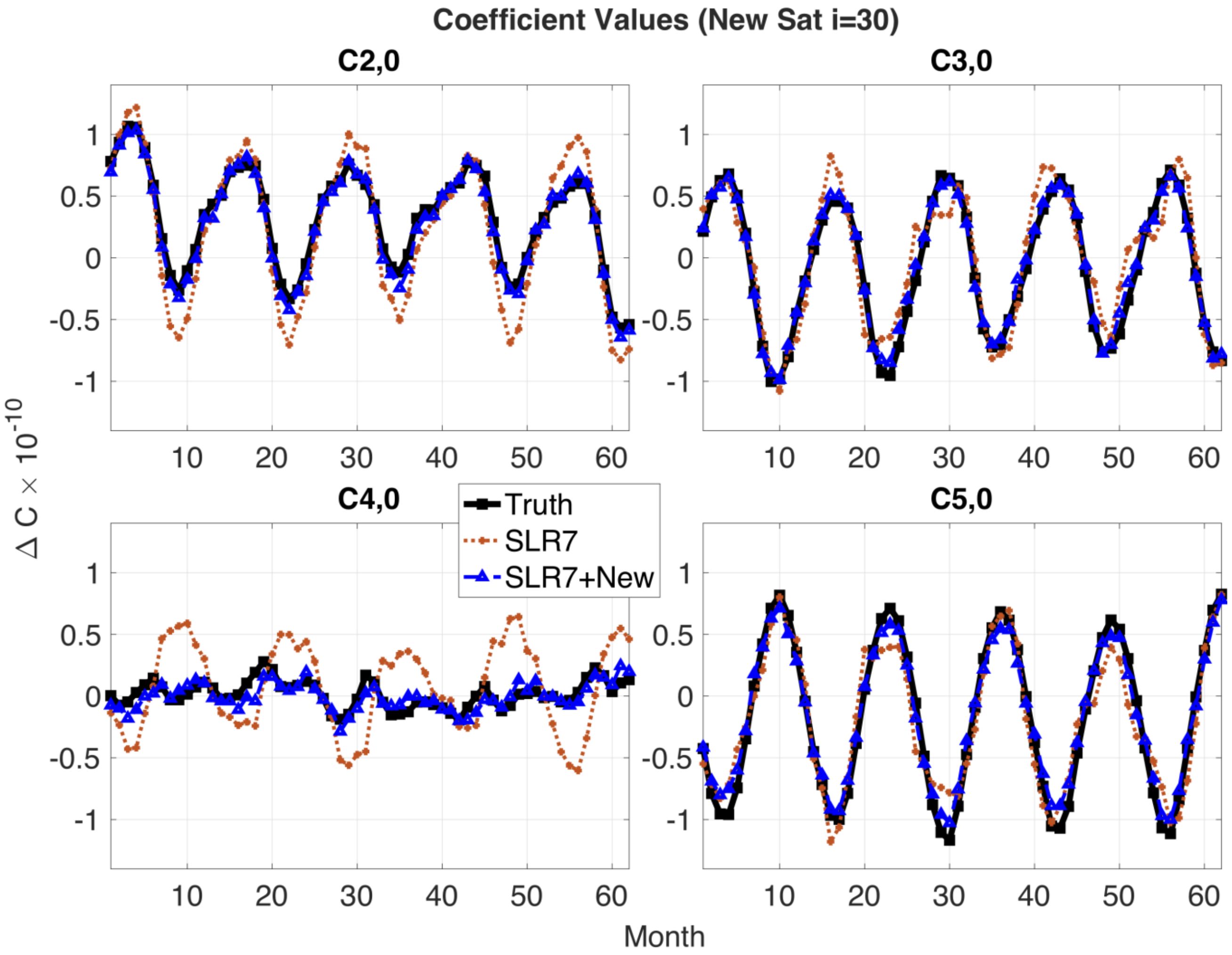
Each point is an 8-sat solution, SLR+New




Addition of low-inclination satellite mitigates correlations

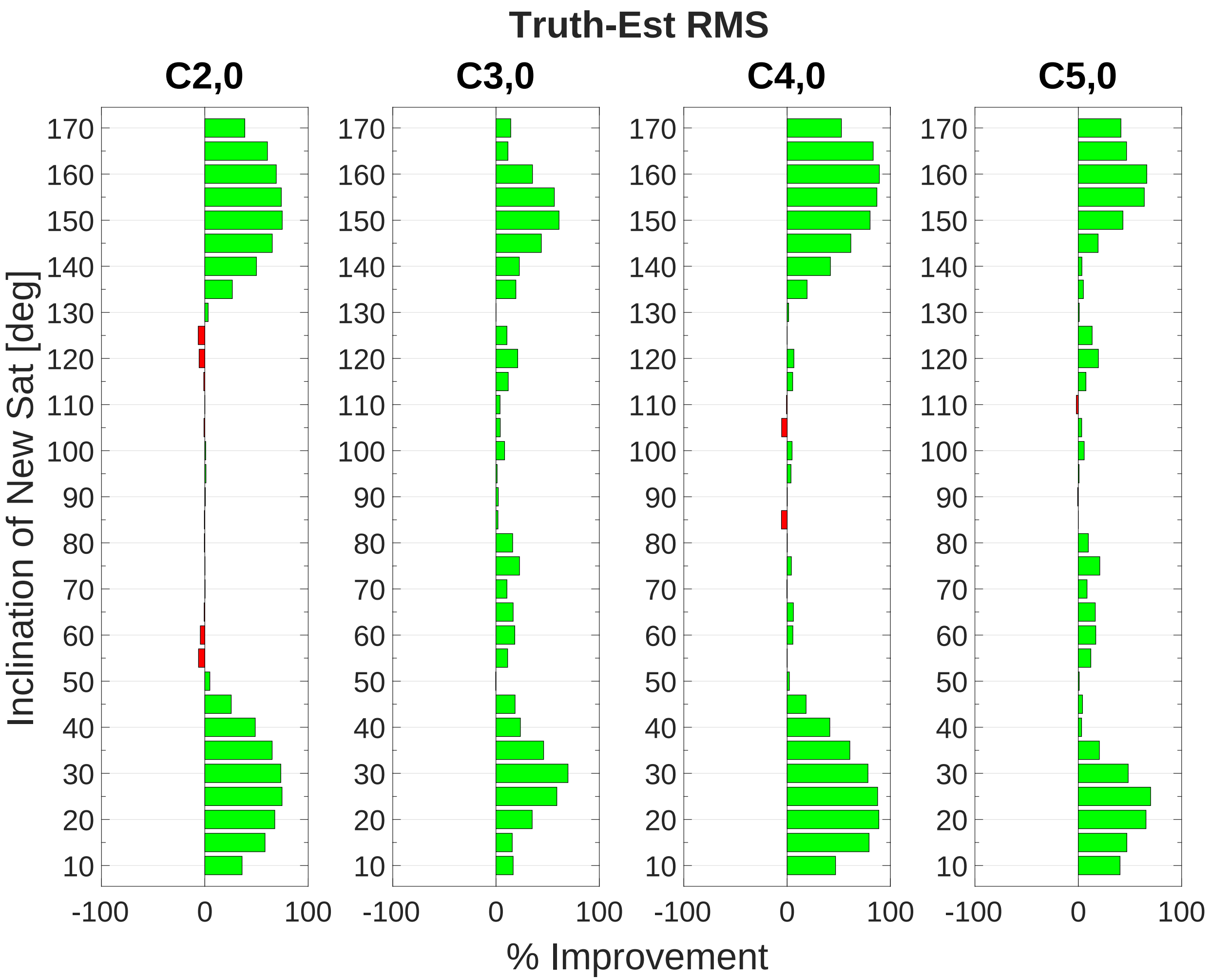
# Zonal Timeseries – Low Inclination

- J2 recovered reasonably well with SLR7, but can be improved
- J2/J4 clearly correlated
- Addition of low-inclination separates J2, J4
- Odd zonals improve, even with LARES in solution

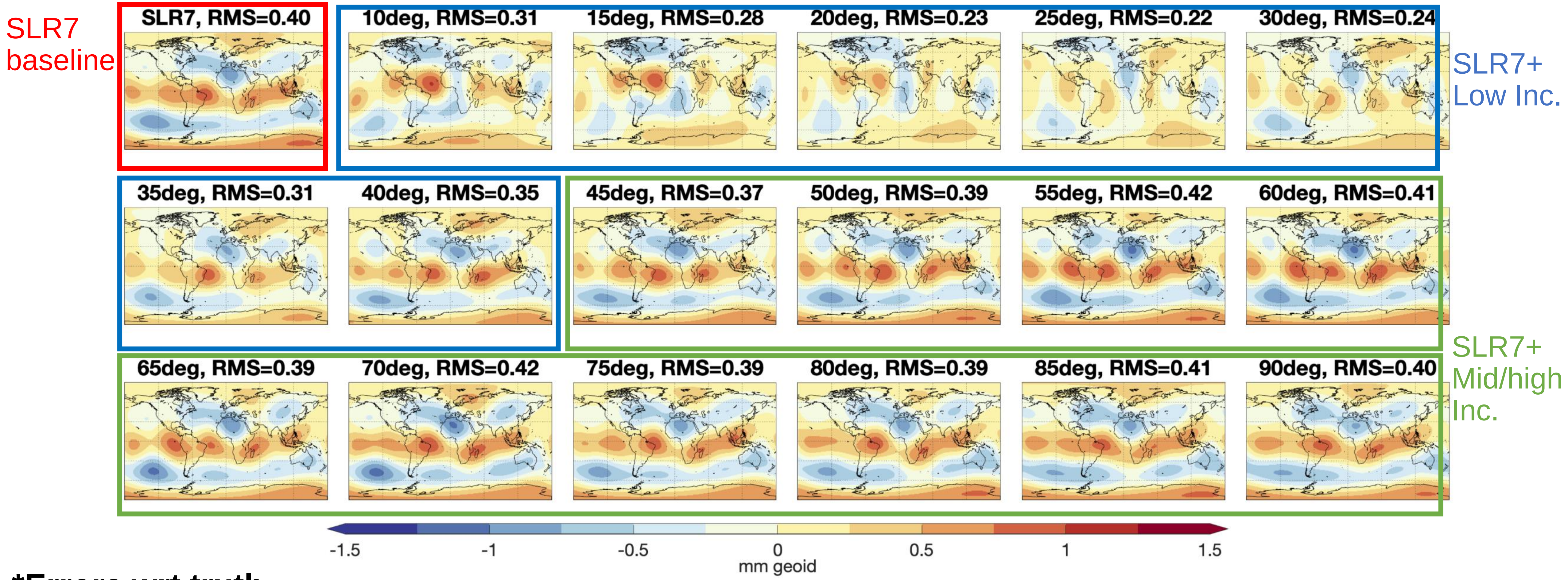


# Comparing New Satellite Inclinations

- Actual reduction in error consistent with decorrelation
- Improvement band (i.e. not simply the lowest possible *i*)
- Impact diminishes above 40°
- Similar pattern for order 1 coefficients
- Real data: Mitigate correlations with GRACE (Loomis et al., 2019, 2020)



# Sine Component of Annual Variation

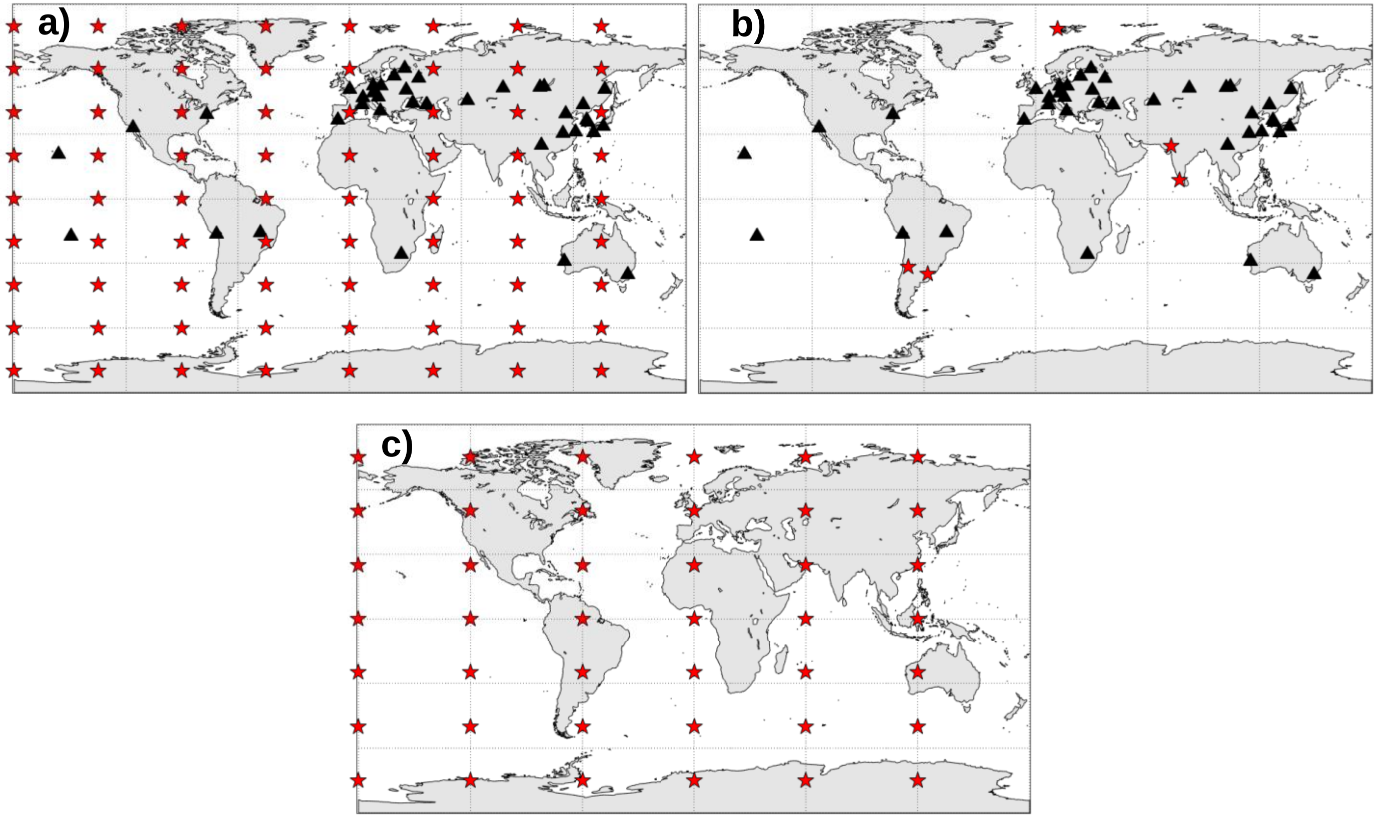



***Errors wrt truth**

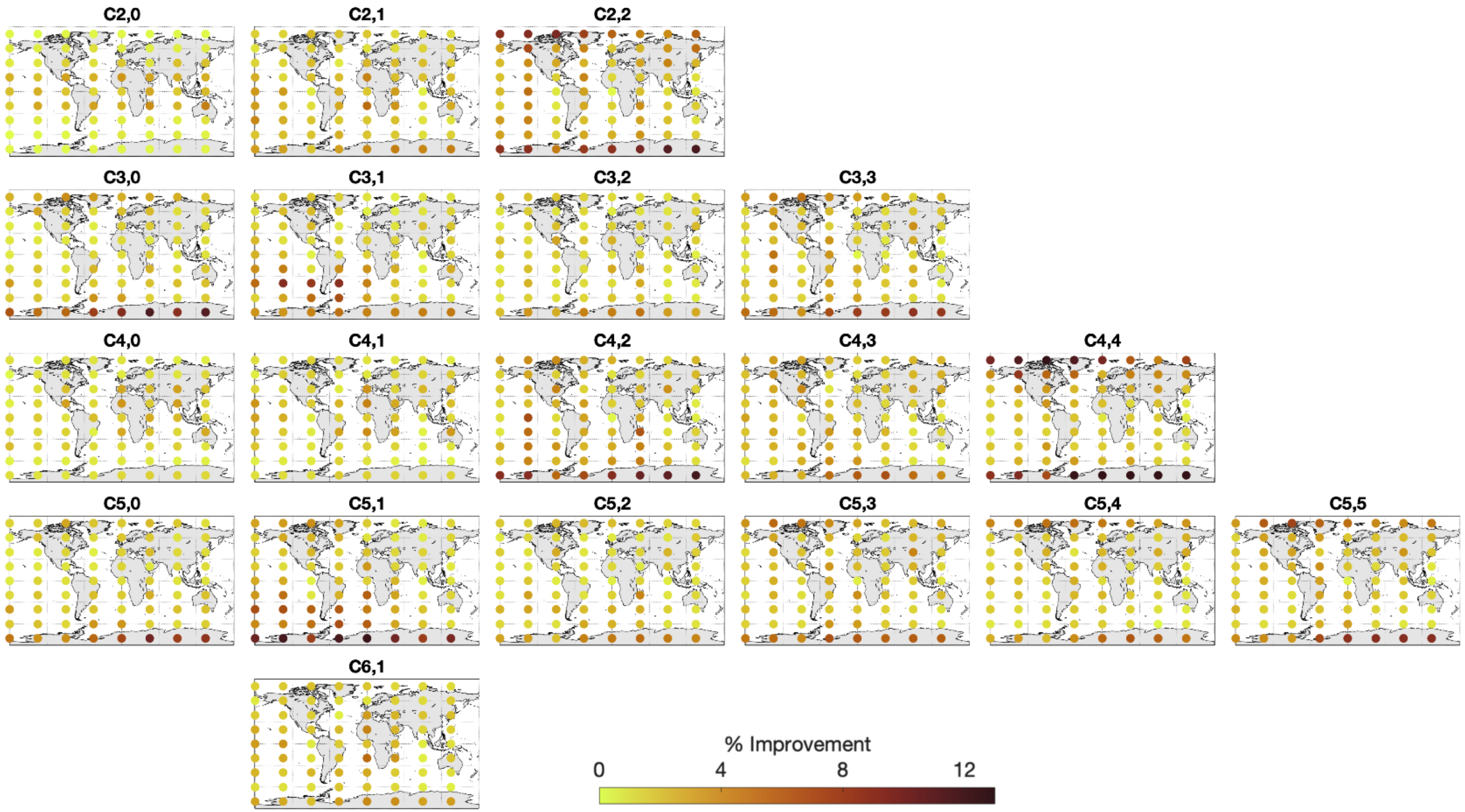
$N_{max} = 5$

# Investigated Cases

- Expand on studies of geocenter, TVG
- Goals:
    1. Filling geographic gaps
    2. Realistic scenario
    3. Limitations of new tracking stations
- Single new station is small compared to 40+ stations



# Case N-1

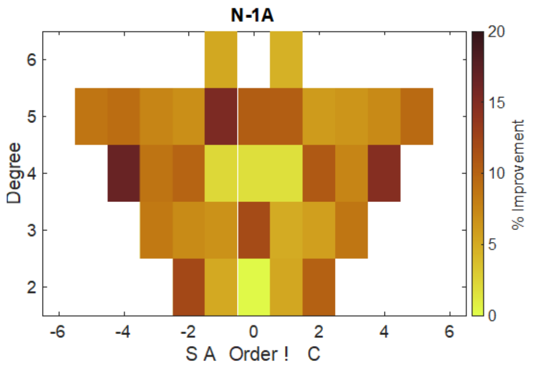


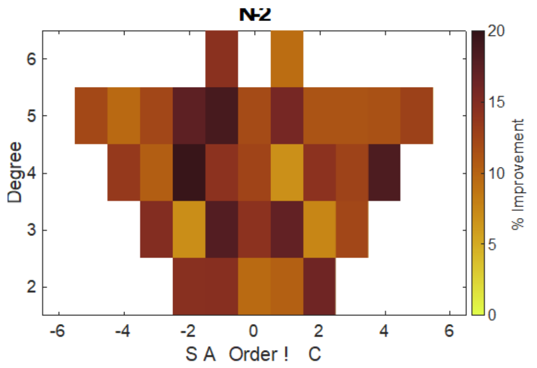

- Formal errors used for these smaller changes
- Sensitivity of expanded network to coefficients
- Odd zonals favor Antarctica
- Sectorals, tesserals favor S. hemisphere and poles

# Realistic Scenario: Case N-2

ILRS Future Stations List

| Site Name | Country | Timeframe | Comments |
|---|---|---|---|
| Irkutsk (Tochka) | Russia | 2024 | Co-located with Irkutsk (IRKL, 1891) (will move to Current Sta when data is provided) |
| La Plata (AGGO) ★ | Argentina | 2024 | TIGO re-location from Concepcion (https://www.sirgas.org/fileadmin/docs/GGRF_Wksp/47_Schu al_2019_BKG_core_infrastructure.pdf) |
| Mendeleevo (Tochka) | Russia | 2024 | Co-located with Mendeleevo (MDVS, 1874) (will move to Cur Stations when data is provided) |
| San Juan ★ | Argentina | 2023 | Upgrade of existing system |
| Yebes | Spain | 2023 | New SLR Station (https://cddis.nasa.gov/2019_Technical_Workshop/docs/2019 session4_Lopez_Perez_poster.pdf) |
| Metsahovi | Finland | 2024 | New SLR replacing old SLR system (METL, 7806) |
| Mount Abu ★ | India | 2024 | New SLR Station 2016 ILRS Workshop, Potsdam, Germany (Poster) |
| Ponmundi ★ | India | 2024 | New SLR Station 2016 ILRS Workshop, Potsdam, Germany (Poster) |
| Ny Ålesund, Svalbar ★ | Norway | 2024 | New SGSLR (NASA & Norwegian Mapping Agency) |
| McDonald, TX | USA | 2025 | New SGSLR replacing old SLR system (NASA) |
| Haleakala HI | USA | 2027 | New SGSLR replacing old SLR system (NASA) |



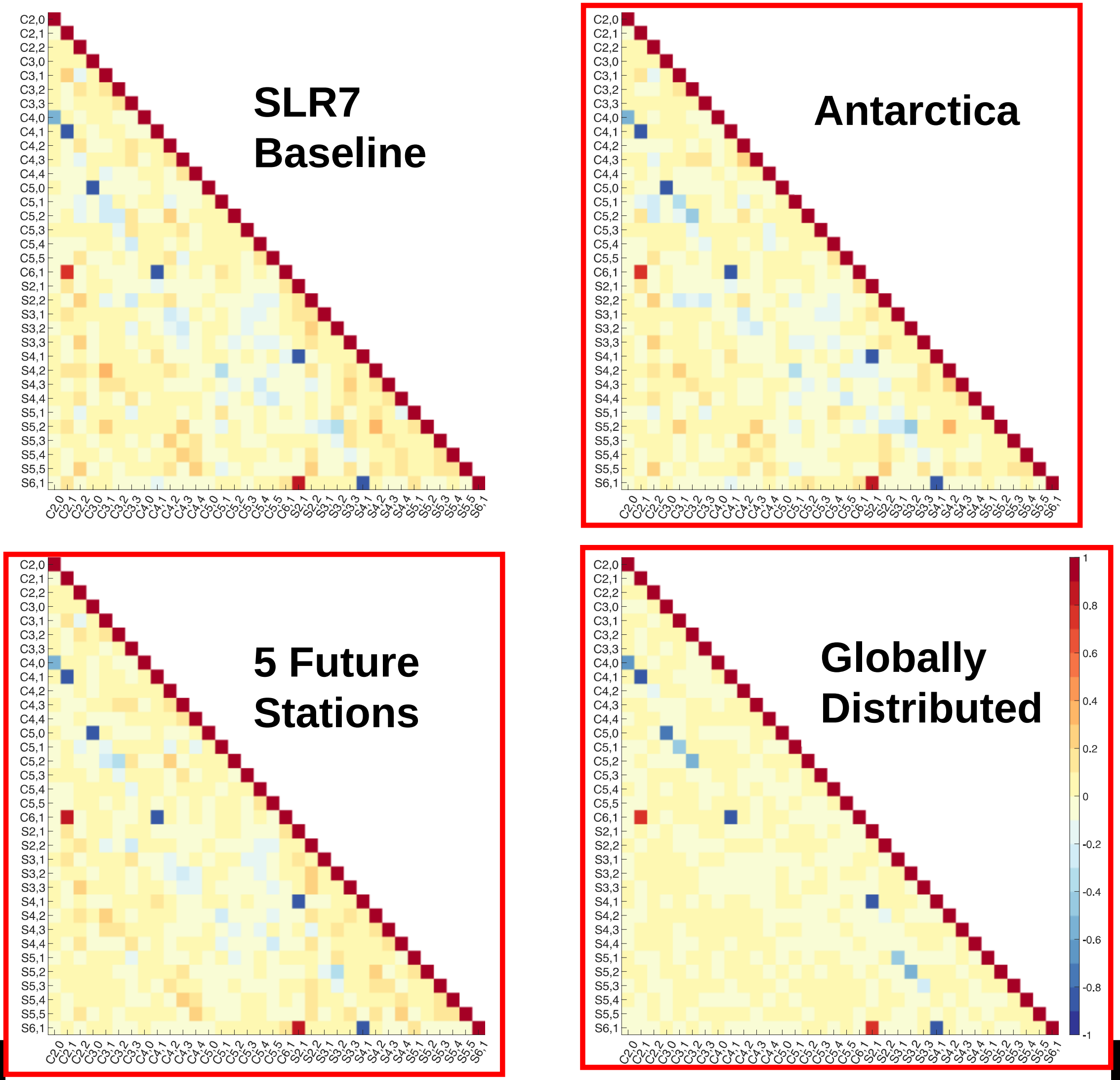




**5 station solution reduces errors 2-3x more than single Antarctic station**

**New stations in generally unique regions**

**N-1A = best case Antarctic**

# Persistent Correlations




Single or multiple new station does not systematically separate coefficients like a new satellite

Uniform case demonstrates that even in the extreme, stations do not separate certain terms

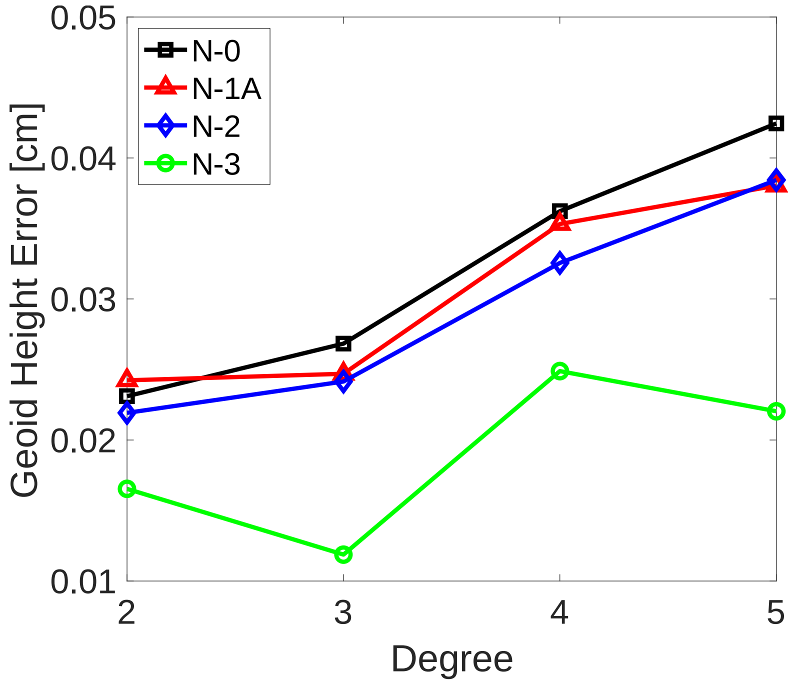
# Analytical Sensitivity

$$\Delta\dot{\Omega}_{\text{sec}} = \frac{\bar{n}}{(1-e^2)^{1/2}\sin i}\sum_{l=2}^{\infty}\left(\frac{R_E}{a}\right)^l G_{lp0}(e)\frac{\partial F_{l0p}(i)}{\partial i}\Delta C_{l,0}, \quad l = \text{even}, \quad p = l/2$$

- Determining TVG from SLR relies mainly on perturbations
- Individual satellites sense ”lumped” coefficients
  - Non-uniqueness for terms of given order *m*
- Ground stations therefore limited if combined satellite orbits do not allow separation

# Value of New Stations

- Correlations do not preclude an accurate solution
- New stations can improve actual errors without decorrelation
- Other factors:
  - Redundancy
  - Upgrading old hardware
  - Increasing automation
  - Portable hardware may open new regions
  - Other pillars of geodesy



# Summary

- Simulation study of future SLR satellites and ground stations focused on improving gravity estimates
- New low-inclination SLR satellite benefits estimates by separating coefficients and improving retrieval
- New stations do not significantly impact correlations, but important for filling gaps and increasing observations
- Tucker et al., 2022, 2023, *JGR: Solid Earth*

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