Genesis Science Workshop

3rd -4th April 2025

Matera, Italy

# ITRF and Combination of Techniques, System Aspects Session

## Working Group 1

# 2nd Genesis Scientific Workshop

## Genesis ESA WG1 :
## ITRF & Combination of Techniques

**Co-chairs: Zuheir Altamimi & Florian Seitz**

# ESA Genesis WG1

## Three main aspects to consider:

- ITRF: Combination of products
- Combination at the Observation Level (COLs)
- Precise Orbit Determination (PODs)

# Agenda of WG1 Session

- **14:00 – 14:05 Introduction by the co-chairs**

- **14:05 – 14:15 Heinkelmann, R. : Genesis-D project**

- **14:15 – 14:25 Ries, P., Haines, B., Heflin, M., Peidou, A.: Preparing for GENESIS with GipsyX and Ties of Opportunity**

- **14:25 – 14:35 Hugentobler, U.: Genesis Orbit Inclination and Nodal Precession**

- **14:35 – 15:00 Discussion**

# Main discussion issues

- **Short term objectives / goals:**
  - **Consolidate calibration of the Genesis Platform**
  - **Consolidate Genesis orbital parameters, including inclination**

- **Mid term objectives / goals**
  - **Upgrade Software packages to integrate future Genesis data**
  - **Form sub-group for questions of implementation** (coordinate work on theoretical concepts with IAG WG)**.**
  - **Create inventory:** who can do what? Who is ready to provide combined solutions as soon as Genesis observations are available / based on which observation techniques / software,…)
  - On the basis of the inventory: **initiate further steps, e.g. pilot projects**
    - **Combination at the observation level, including orbit combination**
    - **Combination of Genesis data with other satellites data**
    - **Technique specific solutions, integrating Genesis data**
  - **Simulations to assess the impact of Genesis on the ITRF and other geodetic products:**
    - **Technique systematic errors/differences : How to handle these differences ?**
    - **TRF parameters (origin, scale)**

# Planned scientific work in project GENESIS-D

Heinkelmann[(1)] R., Schuh[(2)] H., Thaller[(3)] D., Flohrer[(3)] C., Seitz[(4)] M., Bloßfeld[(4)] M., Seitz[(4)] F., Glaser[(5)] S., Männel[(1)] M., Schreiner[(1)] P., Flechtner[(1)] F.

(1) GFZ Helmholtz Centre for Geoscienes
(2) TU Berlin / GeoBM
(3) Federal Agency for Cartography and Geodesy (BKG)
(4) DGFI-TUM
(5) University Bonn

GFZ Helmholtz Centre for Geosciences  TUM  BKG Wir geben Orientierung.  UNIVERSITÄT BONN  TU berlin  HELMHOLTZ

# GENESIS-D Project – main features

- Title: GENESIS-D: geodetic contributions from Germany for the exploitation of GENESIS-data for science and research (50NA2402)
- Funding Agency: German Space Agency at DLR (Bonn)
- Main contractor: GFZ Helmholtz Centre for Geosciences
- Project partners:
  Agency: BKG Federal Agency for Cartography and Geodesy
  Universities: TU München DGFI, Univ. Bonn, TU Berlin
  Small-sized company: GeoBM GmbH
- Funding period: 2025-2028 and budget: ~2.1 Mill. Euro

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# GENESIS-D Project – goals

- Initiated and motivated by DLR-Agency to support the German contribution to the ESA GENESIS mission
- Main goal: establishment of a scientific network of the main German geodetic research centres and university institutes that contribute to realizing the goals of GGOS according to the UN Resolution on the Global Geodetic Reference Frame (GGRF) to establish a sustainable Global Geodesy Supply Chain
- Realization and application of four-technique space tie.
  Space tie: combination of satellite orbits of Genesis centre of mass (CM) applying ties from the antenna phase centres to the CM.

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# GENESIS-D Project – objectives

- Enable geodesists at German institutions to process, combine and validate Genesis observations consistently
- Generation of consistent solutions of the four space geodetic techniques (DORIS, GNSS, SLR, VLBI) for TRF, CRF, and EOP realization utilizing satellites that support co-location
- Extension of the SINEX format for satellite orbit parameters
- Simulation of VLBI- and SLR-scenarios for optimal mission support
- Development of concepts for the integration of Genesis observations into the TRF computation

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# GENESIS-D Project – objectives

- Extension of Software:
  BKG: Bernese GNSS Software BSW
  TUM-DGFI: DOGS
  GFZ: EPOS, PORT
- Preparation for and simulation of Genesis observations
- Real data tests of other co-location satellites (e.g. Jason, Sentinel)
- Simulation and real data analyses with DORIS, GNSS, SLR and VLBI
- Scheduling of SLR and VLBI observations

GFZ Helmholtz Centre for Geosciences

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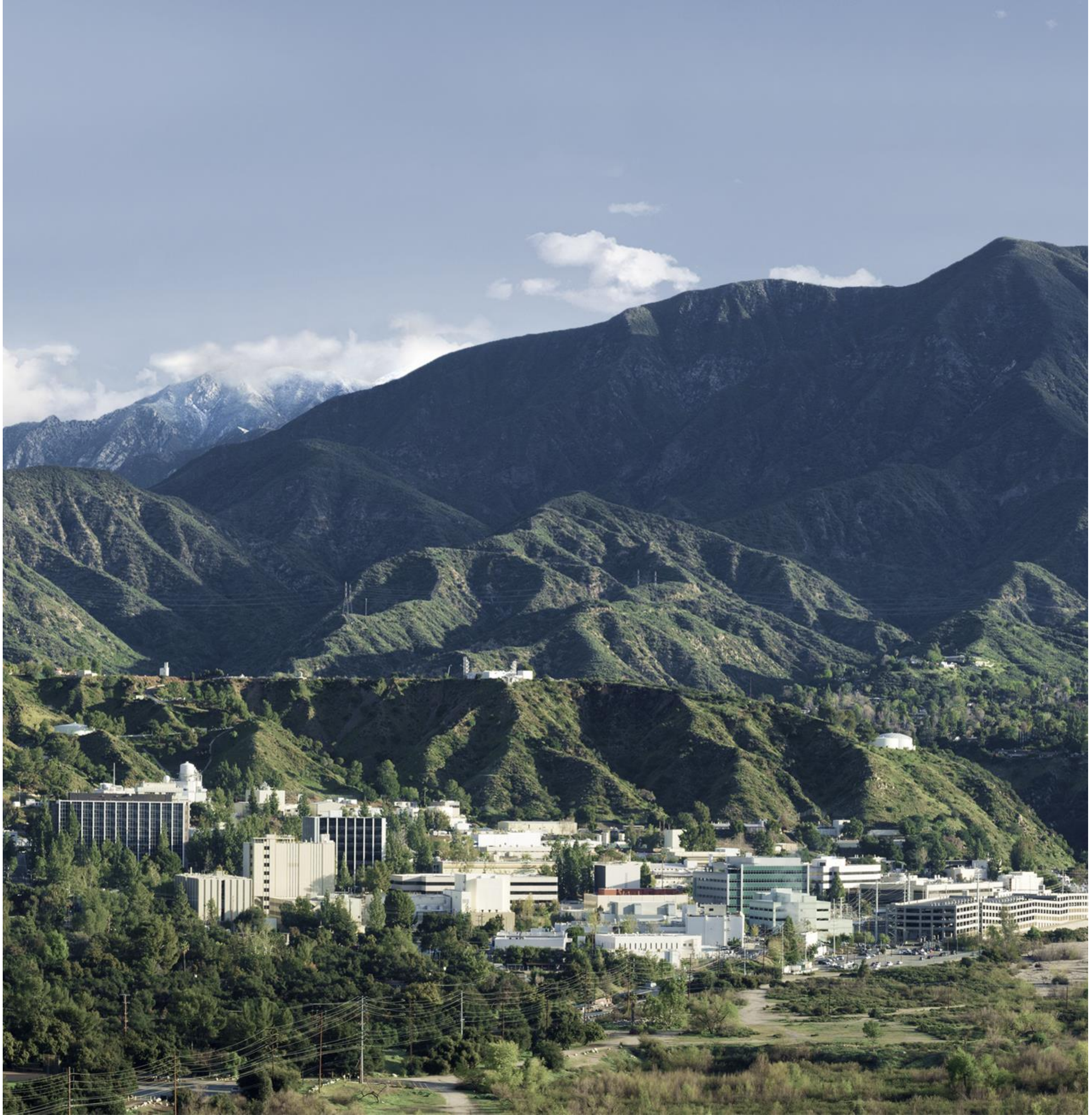


# Preparing for GENESIS with GipsyX and Ties of Opportunity – Part 1: Reference frames at Observation level

**Paul Ries,** Bruce Haines, Michael Heflin, Athina Peidou
Jet Propulsion Laboratory, California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

# Introduction to GipsyX

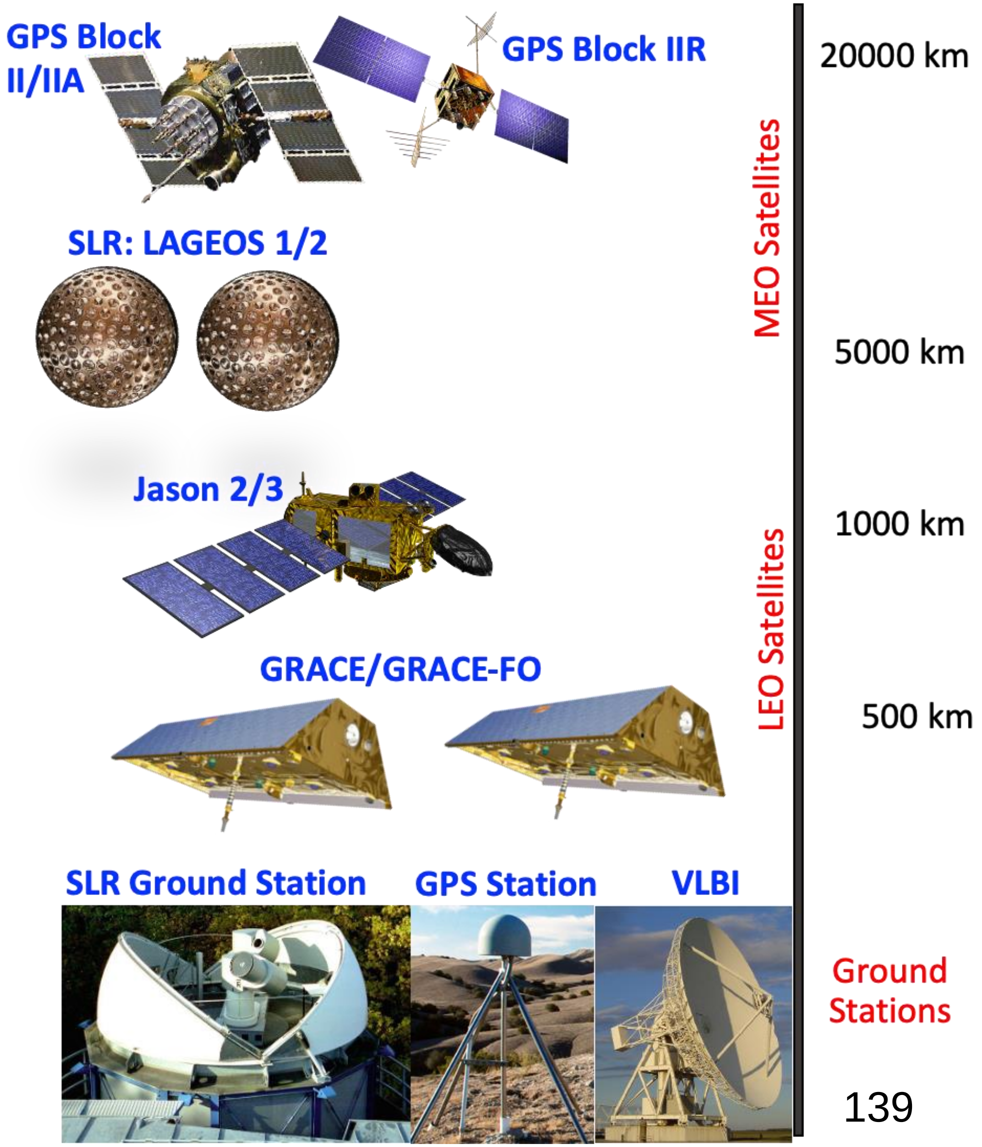


- GipsyX is a successor to (but not derived from) GIPSY-OASIS
  - First public beta release January 2016
  - Replaced GIPSY-OASIS in JPL IGS Analysis center in January 2017
  - Version 1.0 released Jan. 2019, most recent version 2.3 released in August 2024
  - Bertiger et al. (2020) GipsyX/RTGx, a new tool set for space geodetic operations and research. *Advances in Space Research.*
- GNSS support
  - Support for RINEX3 data types, multiple constellations especially GPS and Galileo
  - Support for all associated international file formats: SINEX, ANTEX, SP3, CLK, RINEX
  - Single station PPP ambiguity resolution using wide-lane data from network run
  - Network POD to produce GNSS orbit and clock products
  - Used to support precise LEO POD: Jason-2, Jason-3, Sentinel-6, GRACE, GRACE-FO, SWOT
- SLR support
  - Support for SLR added in September 2017
  - Support international file formats: NPT, NPT_V2, CPF

# Introduction to GipsyX (con'd)

- VLBI support
  - Added to GipsyX in December 2021
  - Support for international file formats: VGOSDB (delay measurements), ICRF
  - Validated extensively against JPL MODEST VLBI software
    - Ojars Sovers et al. (2004) MODEST: a tool for Geodesy and Astronomy. IVS General Meeting Proceedings
- DORIS support
  - Added to GipsyX in 2018
  - Support for international file formats: DORIS RINEX
  - Developed in collaboration with IPGP
- Inter-technique support
  - Support for multiple antennas/reflectors and multiple clocks on each platform
  - Support for constraints (e.g. site ties, trop tie)
- Reference frame tools
  - Generate time series, remove outliers, detect breaks, and fit positions, velocities, breaks, and seasonals
  - Process at station level or network level

- Combines techniques (GPS + SLR + VLBI) at the observation level
- Tie SLR and GPS networks using space ties of opportunity
  - LEO satellites with both GNSS receiver and SLR reflector
  - Examples: Jason2/3, GRACE
- Tie VLBI to GPS using traditional site ties
- Capitalizes on strength of GPS low-Earth orbiters (LEO) observations
  - De-couples frame estimates from systematic GPS draconitic errors
  - Improves observability and coverage relative to ground network
- Uses single software system (GipsyX) for all techniques
  - Ensures consistent standards.
- Products unified with the frame
  - Precise orbits for strategic LEOs, time variable gravity & EOP
  - Independent of ITRF releases and associated cadence (few years)
- Reduces burden on infrastructure and processing
- GENESIS mission would provide space tie for VLBI to GNSS and SLR



# Observation-Level Terrestrial Reference Frame

Jet Propulsion Laboratory
California Institute of Technology

JGR Solid Earth

Research Article | Open Access

## A Global Combination of Geodetic Techniques at the Observation Level: New Perspectives on the Terrestrial Reference Frame

B. Haines, W. Bertiger, S. Desai, M. Ellmer, M. Heflin, D. Kuang, G. Lanyi, C. Naudet, A. Peidou, P. Ries, A. Sibois, X. Wu

First published: 17 December 2024 | https://doi.org/10.1029/2024JB029527

Full-text

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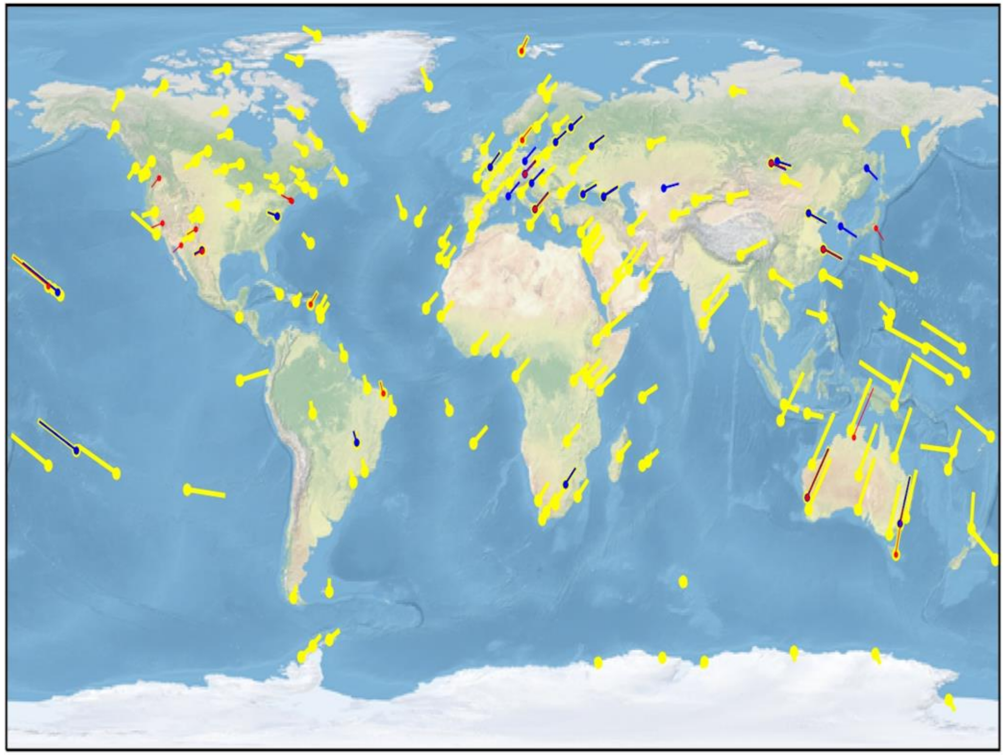
### Abstract

We describe the development and assessment of a new terrestrial reference frame (TRF) based on a combination of geodetic techniques at the observation level over the period 2010–2022. Included in the solution are observations from the Global Positioning System (GPS), Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI). A key feature of our solution strategy is the use of space ties in low-Earth orbit to connect SLR to GPS. Though the resulting TRF solution is based on only 12.6 years of data, it is competitive with the international (ITRF2020) standard in terms of fundamental frame parameters (origin and scale) and their temporal evolution, both linear and seasonal. The relative rates of origin (3D) and scale (at Earth's surface) are 0.2 mm $\mathrm{yr}^{-1}$ and 0.1 mm $\mathrm{yr}^{-1}$ respectively. Absolute scale and 3D origin (at epoch 2015.0) both differ by 2–3 mm. In addition to station positions and velocities, our combined solution includes Earth orientation parameters (EOP), low-degree zonal coefficients (J2 and J3) of the geopotential and precise orbit solutions for all participating satellites (GPS, GRACE and GRACE Follow-on tandems, Jason 2 and 3, and LAGEOS 1 and 2). We discuss potential benefits of our solution strategy and characterize the impacts of our new TRF on estimates of geocenter motion and sea level change from satellite altimetry.

doi.org/10.1029/2024JB029527



- From 12+ years of tracking data.
  - 2010.0 – 2022.6
- Arc length: 3.25 d
- Number of GPS stations per solution: 45
- Superset of nearly 500 stations.
  - Mostly GNSS (388), but also many SLR (47) and VLBI.

# TRF realization: Three different streams

- Testing contribution of different geodetic techniques: **GPS-Only, GPS+SLR, GPS+SLR+VLBI**
- **Geocenter** offset : All techniques are competitive to ITRF2020
- Long-term stability: All techniques are indistinguishable from ITRF2020 (0.0–0.3 mm $yr^{-1}$ per component).
- Scale: **GPS-only poor agreement with ITRF2020**

## Geocenter and scale offset (mm) at 2015.0

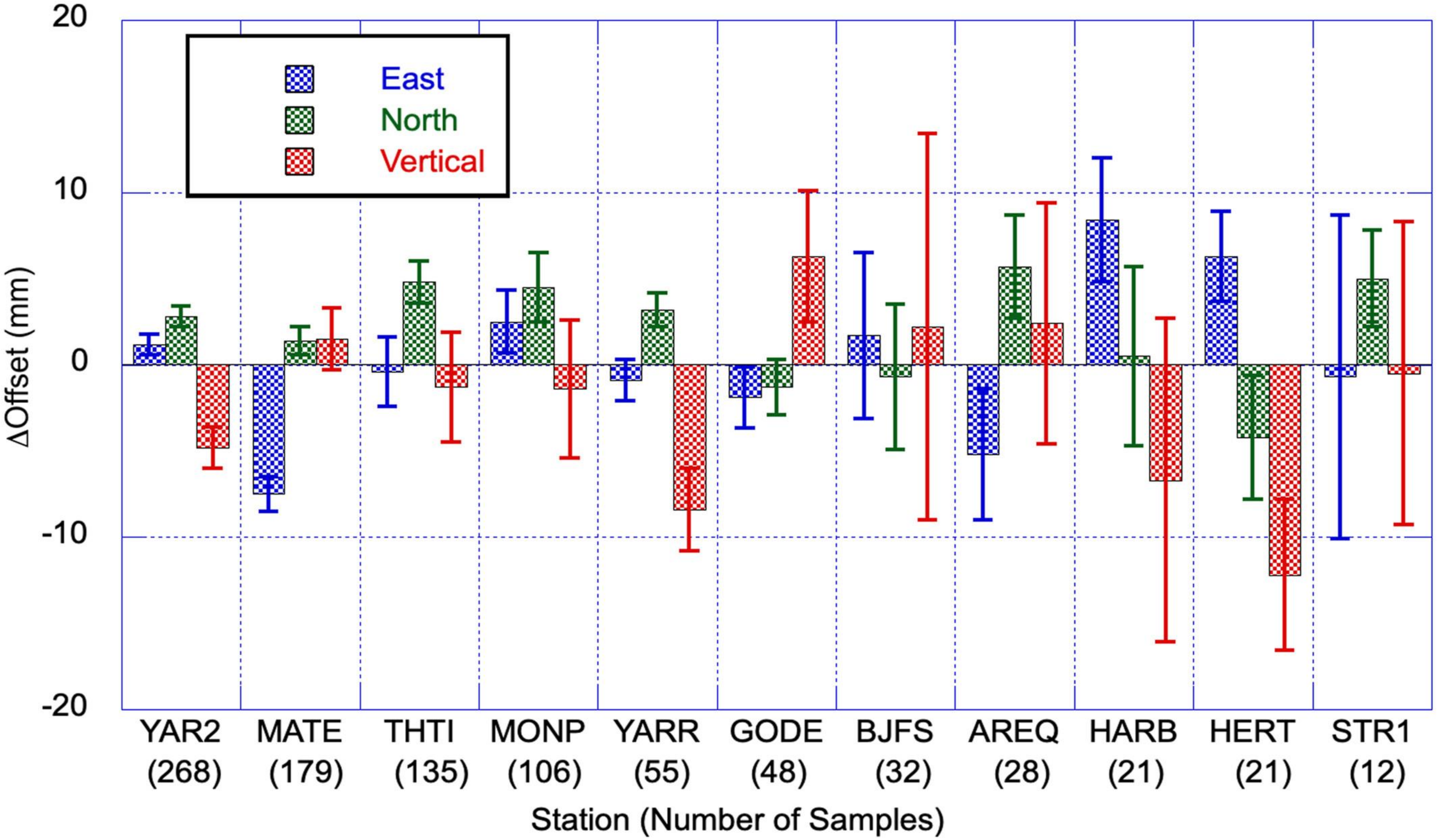
| Solution | Offset in mm at Epoch (January 1, 2015) | | | |
|---|---|---|---|---|
| | δX | δY | δZ | δScale |
| GPS Only (Ground + LEO) | –0.58 ± 0.67 | –1.49 ± 0.66 | –0.69 ± 0.83 | +6.01 ± 0.63 |
| GPS + SLR | +0.15 ± 0.37 | –1.78 ± 0.34 | +0.43 ± 0.55 | +2.32 ± 0.52 |
| GPS + SLR + VLBI | +0.05 ± 0.34 | –1.83 ± 0.31 | +1.11 ± 0.51 | +2.82 ± 0.41 |

## Relative Drift (mm $yr^{-1}$)

| Solution | Rate in mm $yr^{-1}$ | | | |
|---|---|---|---|---|
| | δX | δY | δZ | δScale |
| GPS (Ground +LEO) | +0.06 ± 0.05 | +0.32 ± 0.05 | –0.09 ± 0.11 | –0.12 ± 0.06 |
| GPS + SLR | +0.14 ± 0.04 | +0.24 ± 0.04 | –0.09 ± 0.10 | –0.22 ± 0.05 |
| GPS + SLR + VLBI | +0.11 ± 0.04 | +0.18 ± 0.04 | +0.02 ± 0.09 | –0.05 ± 0.05 |

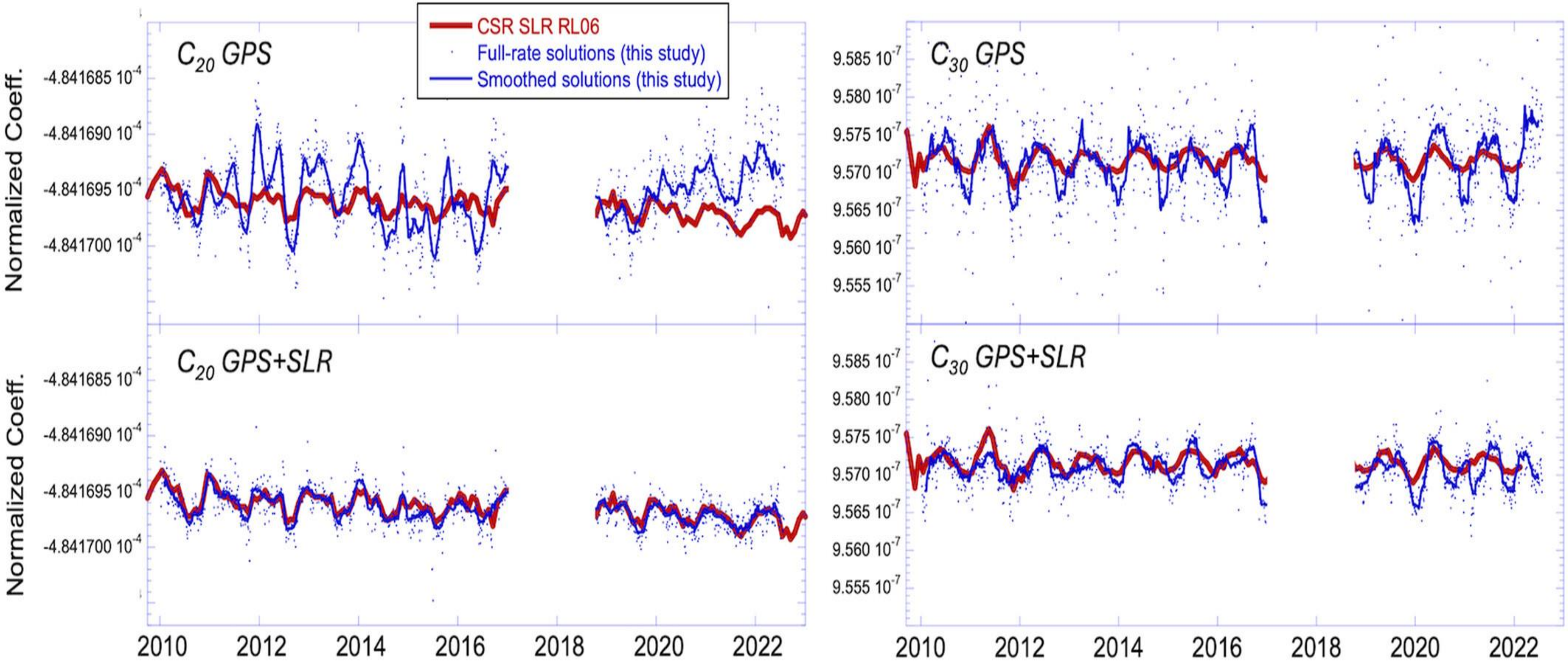
# Space Ties of Opportunity vs Ground Ties

- Able to replicate GNSS-SLR ties at better than 1 cm level



# How Does Experimental TRF measure J2?

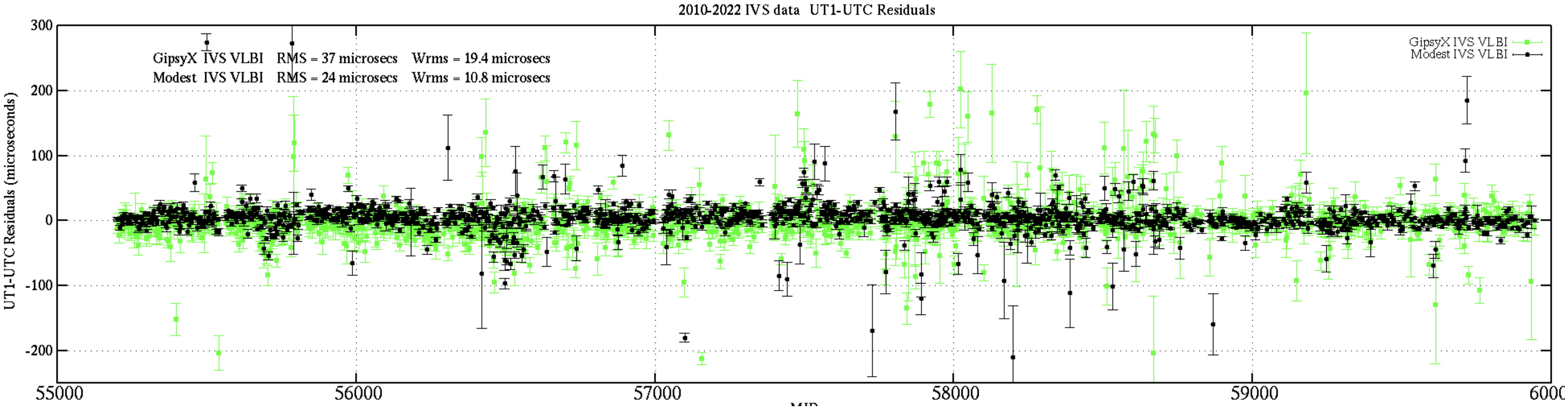
- Poor retrieval of J2 with GPS+LEO solutions
- Adding LAGEOS substantially improves retrieval of J2



# Latest Addition: VLBI

- Polar motion and UT1–UTC estimated using a random walk model with 2-hr updates.
- Inclusion of VLBI (for selected arcs) enables estimates of absolute UT1 (vs. UT1 variations from GPS).
- GipsyX estimates for UT1–UTC from VLBI approaching results from legacy (Modest) software.

UT1–UTC Residuals from IVS Data Set: GipsyX vs. MODEST



# Summary

## Observation Level TRF

- Combines three techniques (**GPS**, **SLR** and **VLBI**) at the observation level + strategic LEOs
- Advantages: Light infrastructure | immune to frame aging | unified geodetic byproducts.
- Currently uses space ties of opportunity to connect satellite geodetic techniques (SLR+GPS)
- GENESIS will provide dedicated SLR+GPS tie and enable tying VLBI+GPS and VLBI+SLR
- **Use of space ties (opportunistic and dedicated) at observation level provides additional information not available at product-level combinations**

## TRF performance

- Indistinguishable from ITRF2020 in terms of long-term stability.
- Shows significant benefit of LAGEOS/SLR for low-degree gravity (*J2*).
- Impact of observation level frame on global & regional sea level: fully competitive with ITRF.

## Work in Progress

- Optimize VLBI data editor
- Model VLBI for spacecraft (e.g. GENESIS)
- Tie VLBI and GNSS troposphere
- Optimize DORIS data processing → include DORIS to frame realization
  (GipsyX has the capability to process all 4 space geodetic techniques)

# Genesis Orbit Inclination and Nodal Precession

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Institute for Astronomical and Physical Geodesy, Technical University of Munich, Germany

GENESIS ESA WG1 ITRF

03. April 2025, Matera

# Genesis Orbit Inclination

- Originally planned inclination of Genesis orbit: 95°
- Discussion whether 60° is better
- Arguments (non-complete)
  - pro 60°:
    - Reduced mapping of crosstrack orbit errors into z-component of apparent geocenter
    - Smaller formal errors of datum z-translation
  - pro 95°:
    - Minimizing of eclipse periods
    - Radiation belts

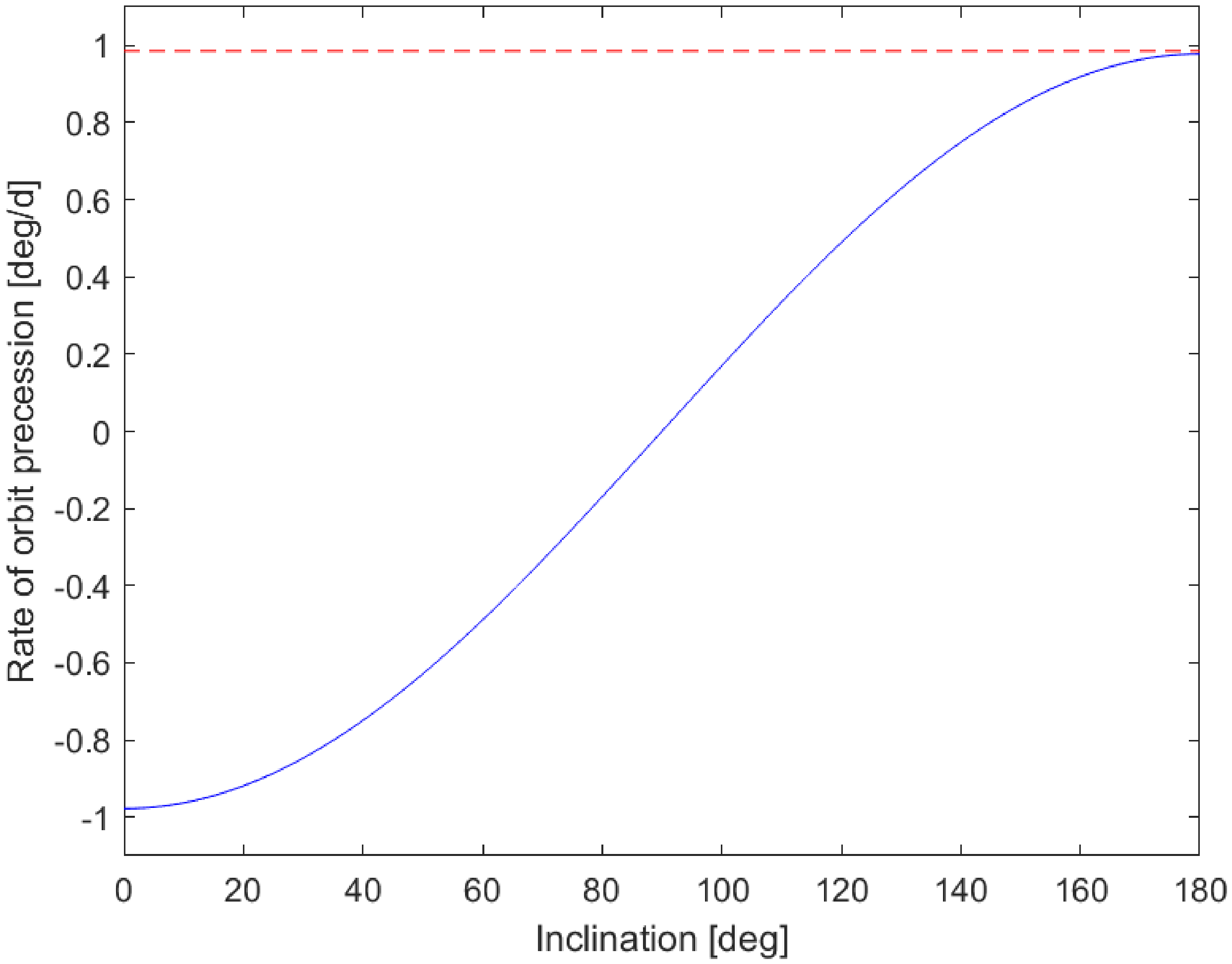
# Genesis Orbit Precession

- Orbit precession from secular perturbations caused by oblateness:

$$\left.\frac{d\Omega}{dt}\right|_{\text{secular}} = -\frac{\frac{3}{2}\sqrt{\frac{GM}{a_e^3}}J_2 \cos i}{\left(\frac{a}{a_e}\right)^{7/2}(1-e^2)^2} \cong -\frac{10.0°/d \cos i}{\left(\frac{a}{a_e}\right)^{7/2}}$$

| 95° | 85° | 60° | |
|---|---|---|---|
| 0.085 | -0.085 | -0.489 | °/d |

- Sun-synchronous orbit is not feasible at orbit height of Genesis



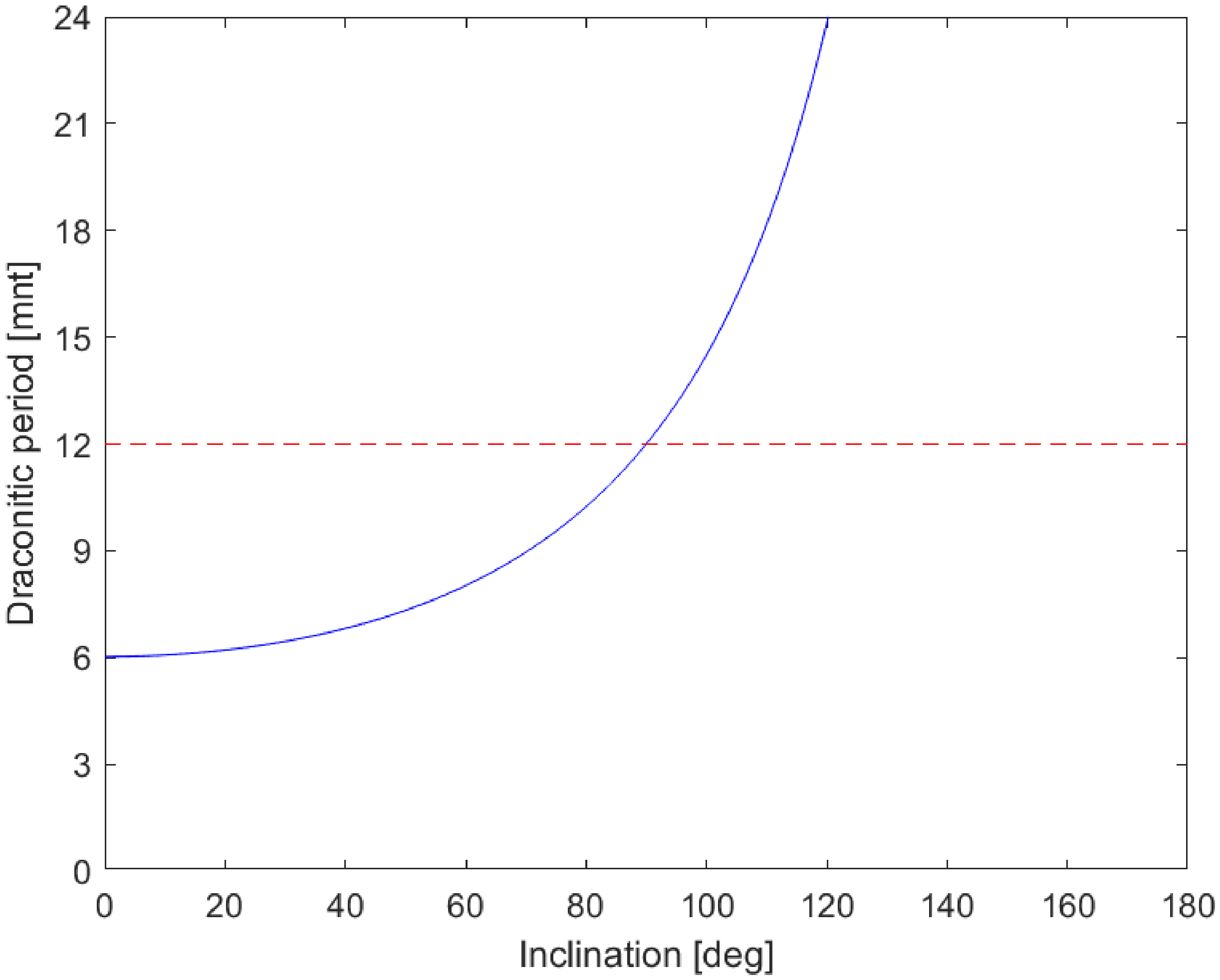
# Draconitic Period

- Draconitic period with considering nodal precession:

$$\frac{360°}{T_{drac}} = \frac{360°}{365.2422d} - \frac{360°}{\dot{\Omega}}$$

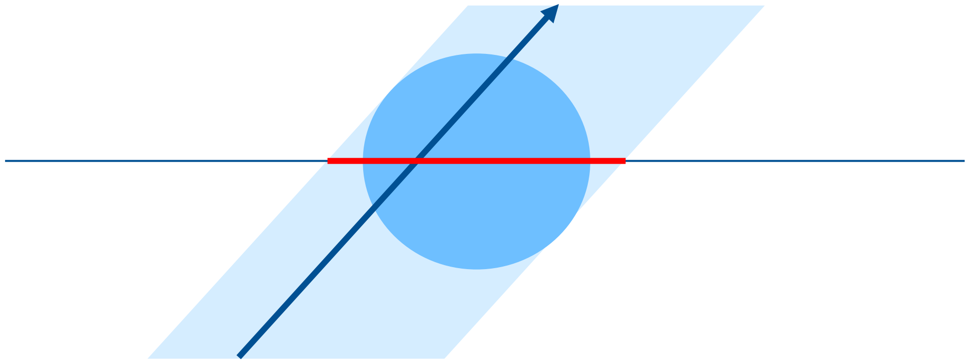
| 95° | 85° | 60° | |
|---|---|---|---|
| 400 | 336 | 244 | d |

- Lower inclination separates draconitic from annual period
- Advantage?

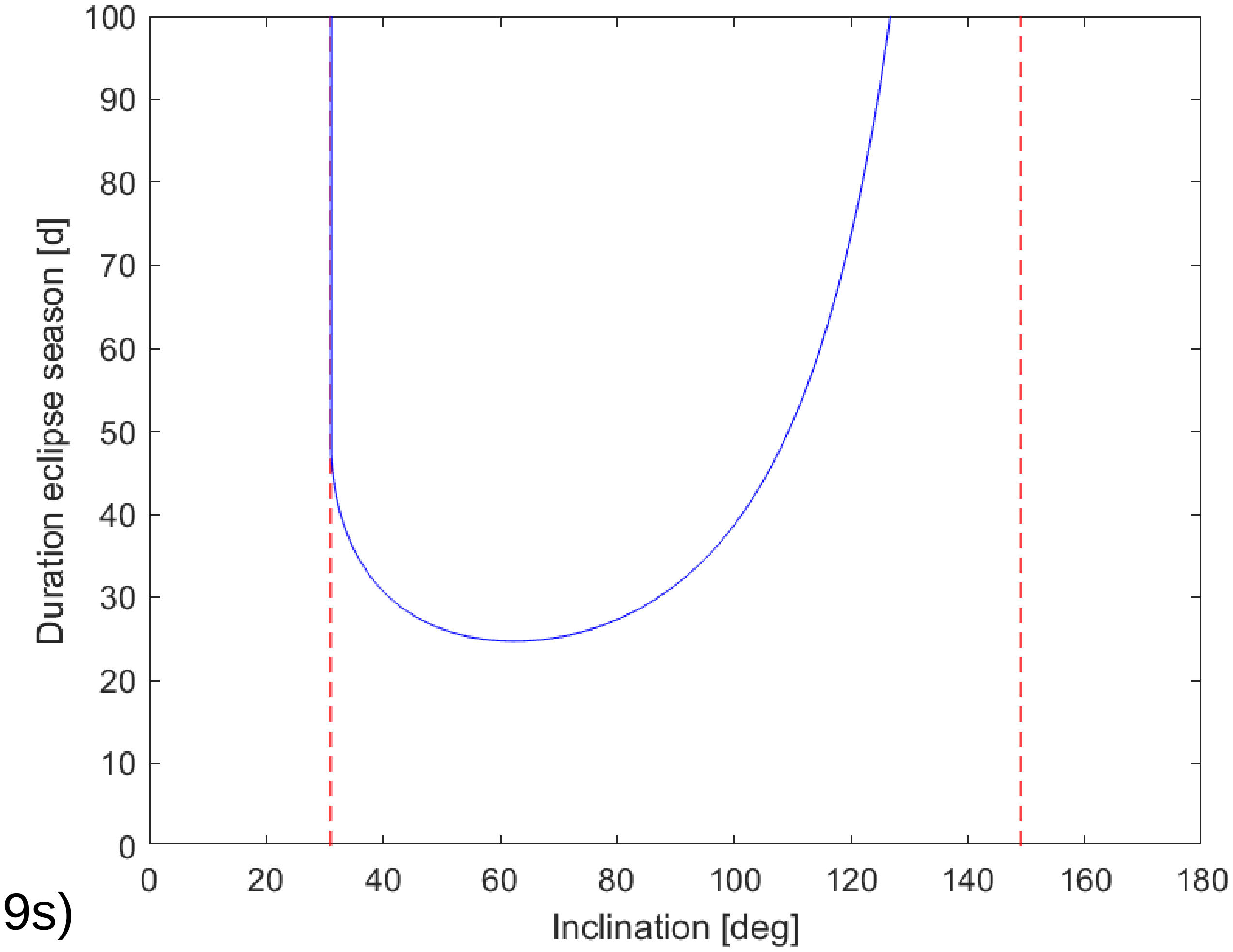


# Duration of Eclipse Season

- Duration of eclipse season considering nodal precession:



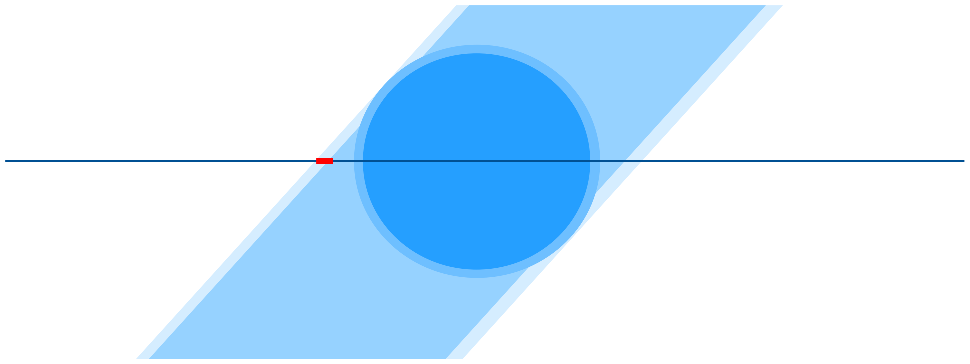
| 95° | 85° | 60° | |
|---|---|---|---|
| 34.6 | 29.1 | 24.8 | d |




- Due to nodal precession the duration of eclipse season wrt inclination is skew
- Eclipse period shortest for $i = 62.4°$
- Important for thermal modelling (penumbra ≥19s)

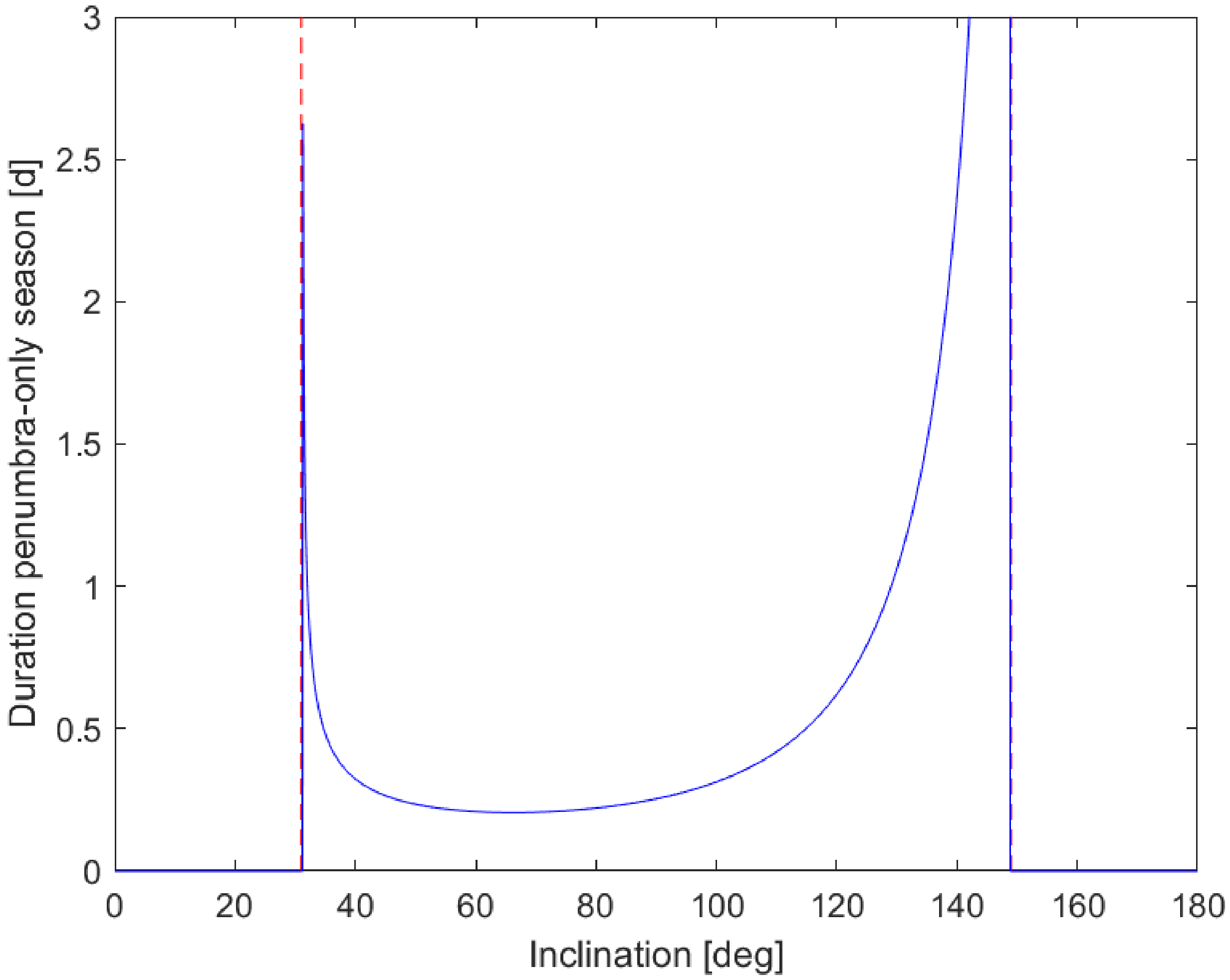
# Duration of Penumbra-only Season

- Duration of eclipse season considering nodal precession:



| | | | |
|---|---|---|---|
| 95° | 85° | 60° | |
| 6.7 | 5.6 | 5.0 | h |

- Penumbra-only period shortest for $i = 66.3°$
- Revolution period: 3.8 h
- 2x1 penumbra-only orbit per eclipse season



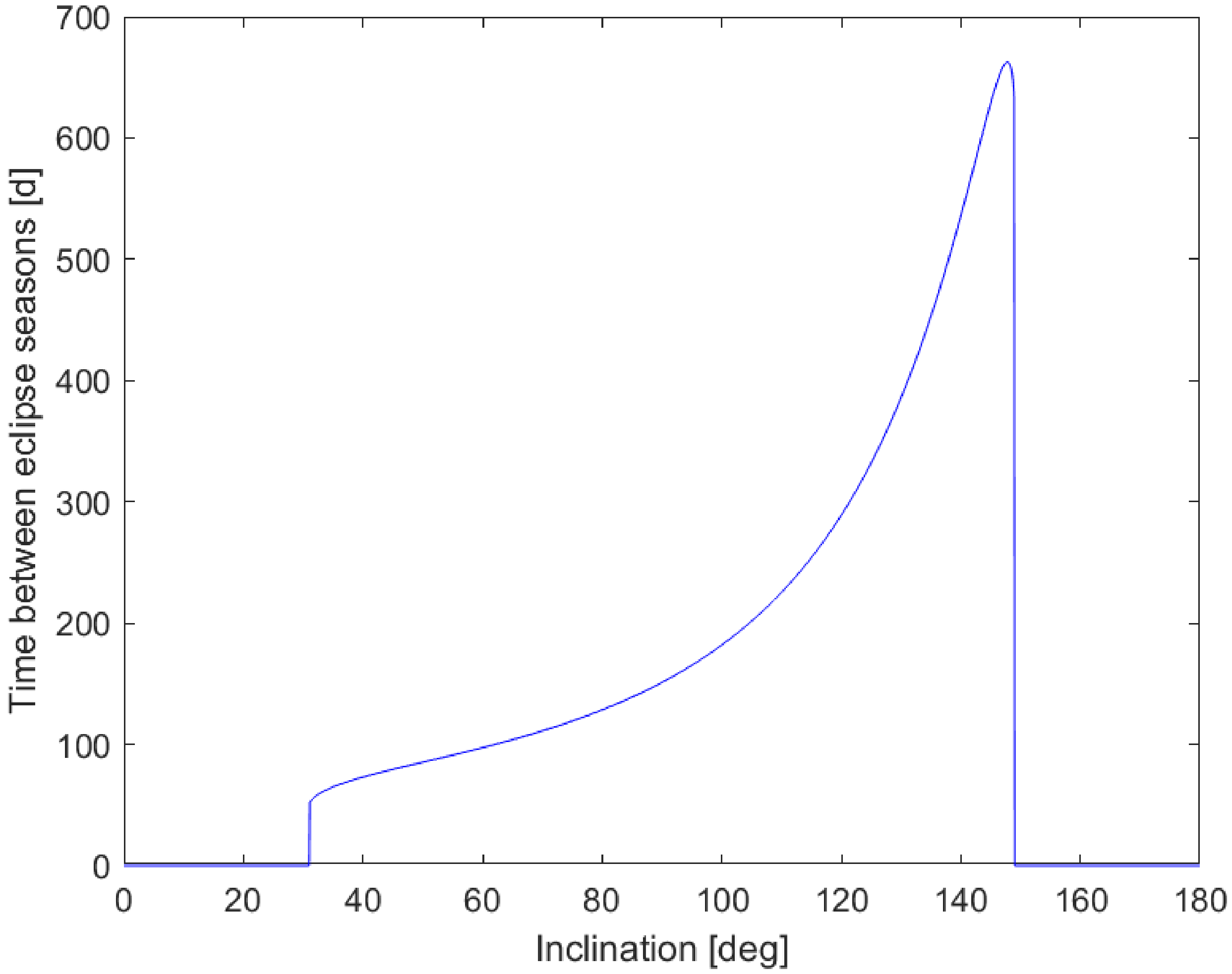
# Time Between Eclipse Seasons

- Time between eclipse season considering nodal precession:

$$T_{noecl} = \frac{1}{2}T_{drac} - T_{ecl}$$

| 95° | 85° | 60° | |
|---|---|---|---|
| 165.32 | 139.00 | 97.31 | d |

- For lower inclination the time between eclipse seasons is shorter
- Shorter but more eclipse seasons



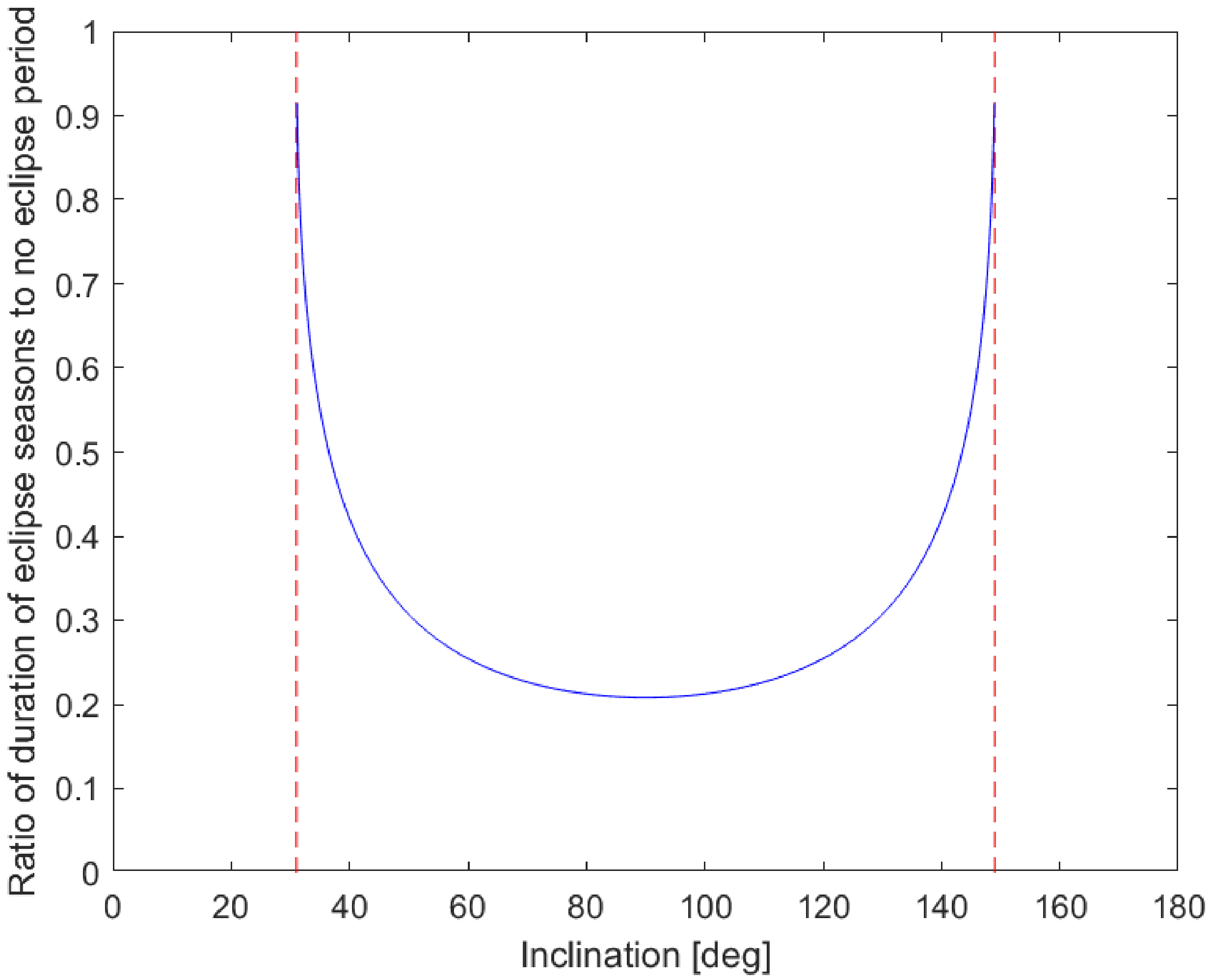
# Duration of Eclipse Season wrt. Eclipse-Free Seasons

- Ratio of eclipse season to eclipse-free period:

$$r = \frac{T_{ecl}}{T_{noecl}}$$

| 95° | 85° | 60° | |
|---|---|---|---|
| 20.9 | 20.9 | 25.4 | % |

- Relative number of eclipses smallest for $i = 90°$



# Discussion

- Separation of draconitic and annual period relevant? $\rightarrow i{\sim}60°$
- Minimize the duration of eclipse season or maximize the duration of the non-eclipse season (i.e., minimize the ratio between the two)? $\rightarrow i{\sim}95°$
- It’s all about systematic errors (thermal modelling etc.)

# Systematic Errors

- ITRF datum parameters will be contaminated mainly by systematic errors at draconitic period.
- Reducing the dynamics of the Genesis orbit reduces the sensitivity to datum parameters (and sensitivity to systematic errors affecting the ITRF).
- Reducing orbit dynamics? Main target of Genesis is the provision of precise space ties between techniques, datum parameters are only secondary target.
- Translation parameters shall still be dominated by Lageos (but not contaminated by Genesis).
- What is required? Information about satellite design options (attitude, shape and size, surface optical and thermal properties, radiators) for assessing potential systematic error profiles as function of inclination.
- Systematic errors are nasty (in their impact on the solution, but also for realistic simulation).
- Systematic errors will be always there, for any inclination.