Overview of Software for DORIS processing

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- Reference models
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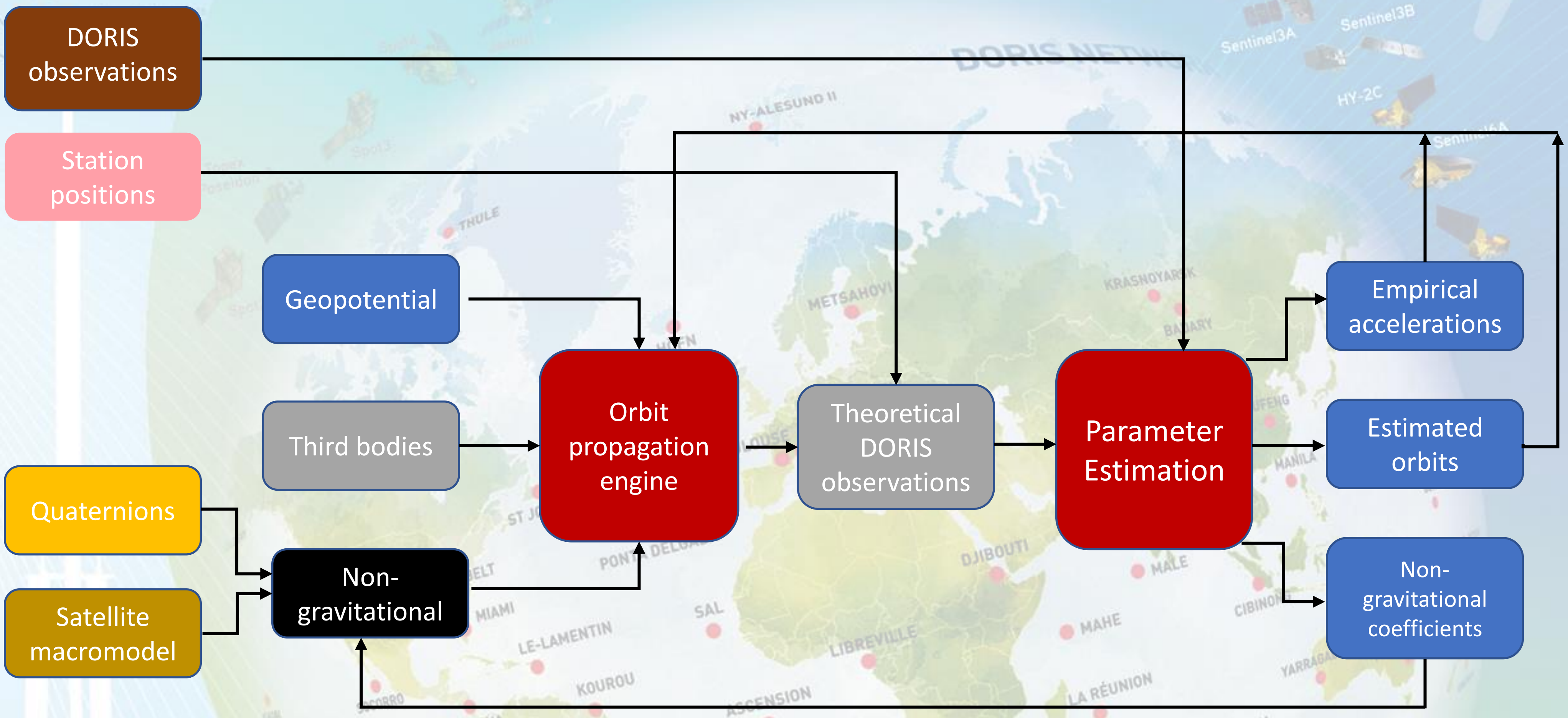
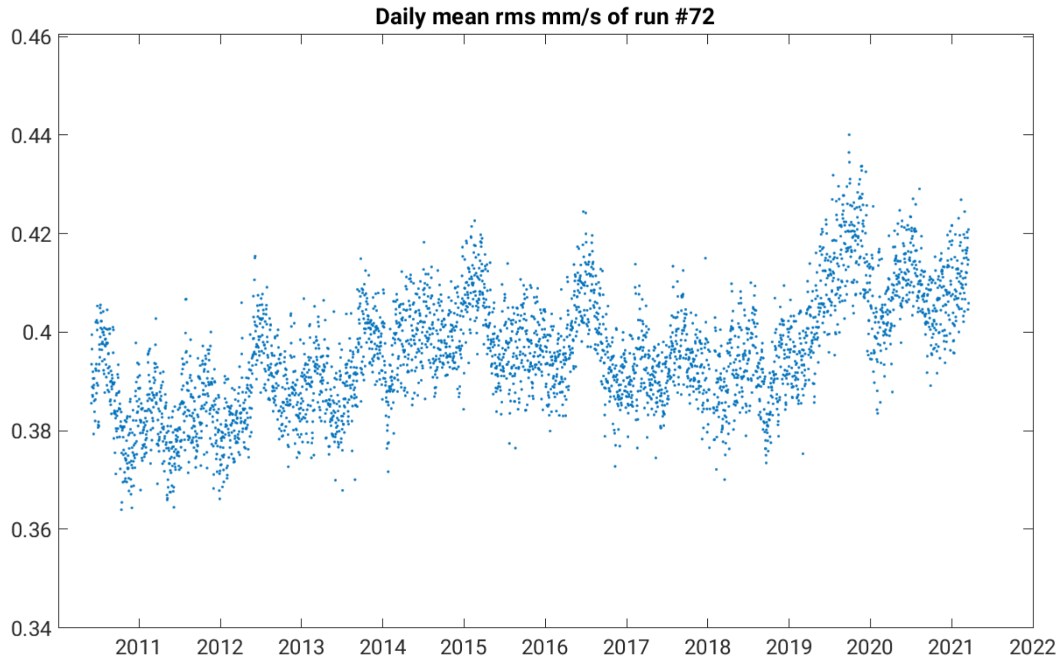
Schematic orbit processing

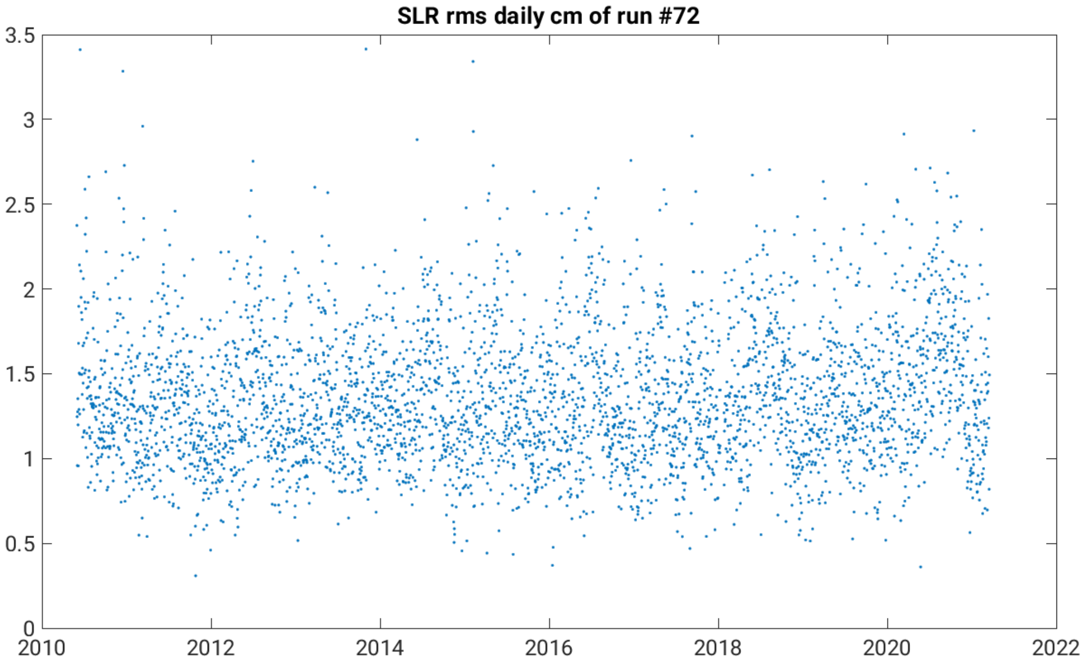


Observation data and availability

- Each DORIS beacon transmits on two configurable frequencies
  - ≅ 400 MHz
  - ≅ 2 GHZ
  - The phase centers of each frequencies depend on the antenna type
  - Transmitted: time synchronization pulses, meteo data, and there is a carrier
  - Analysis centers need to get a radio-permit license with the local authorities
- C1/C2 satellite clock synchronization relative to master beacons
  - This is a separate process that you solve in advance
- Meteorologic data is encoded for each beacon
- Two data types
  - Format 2.2 where 10 second integrated Doppler data is provided
  - Carrier phase data on 400 MHz and 2 GHz much like in GNSS

Typical residuals of 10s Doppler and SLR data



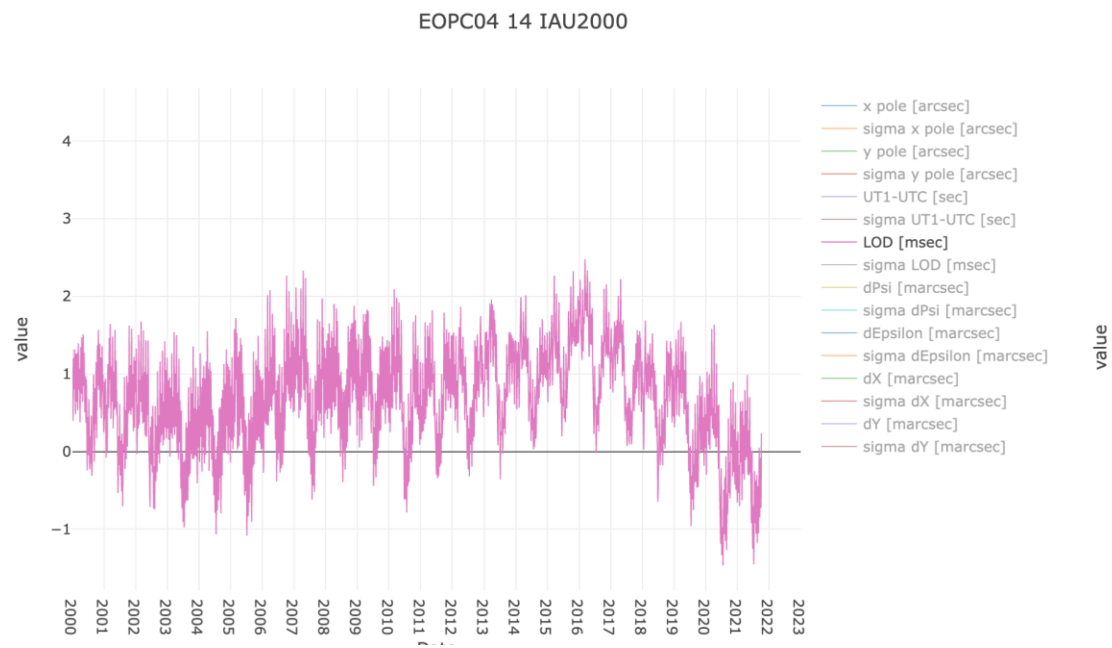


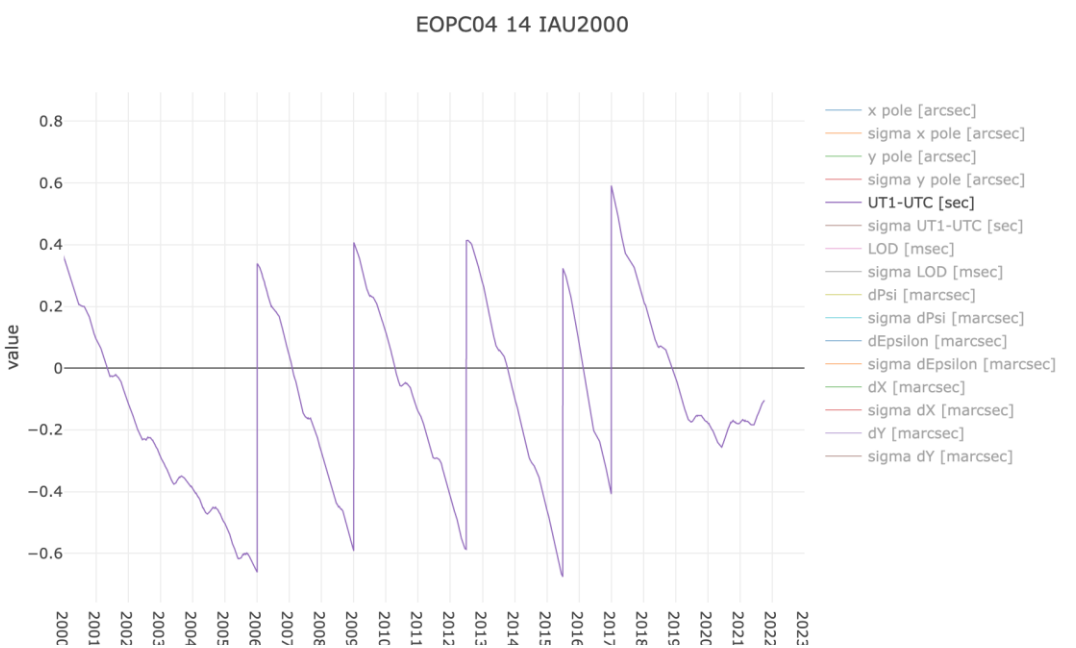
Daily mean data for CryoSat-2 between 2010/4 and 2021/3

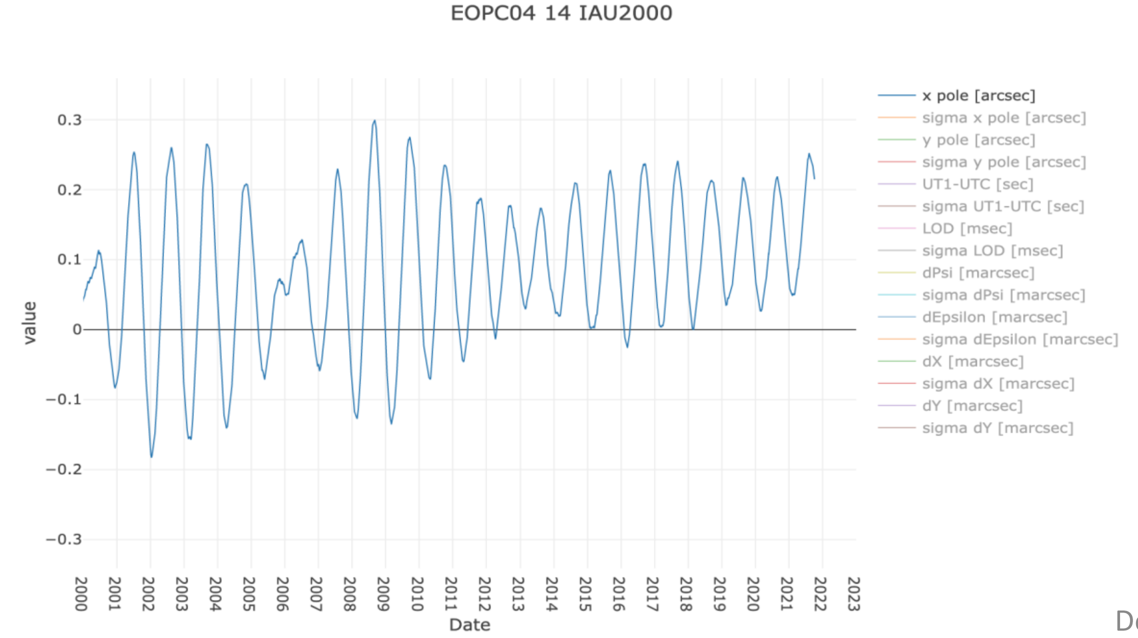
Reference models

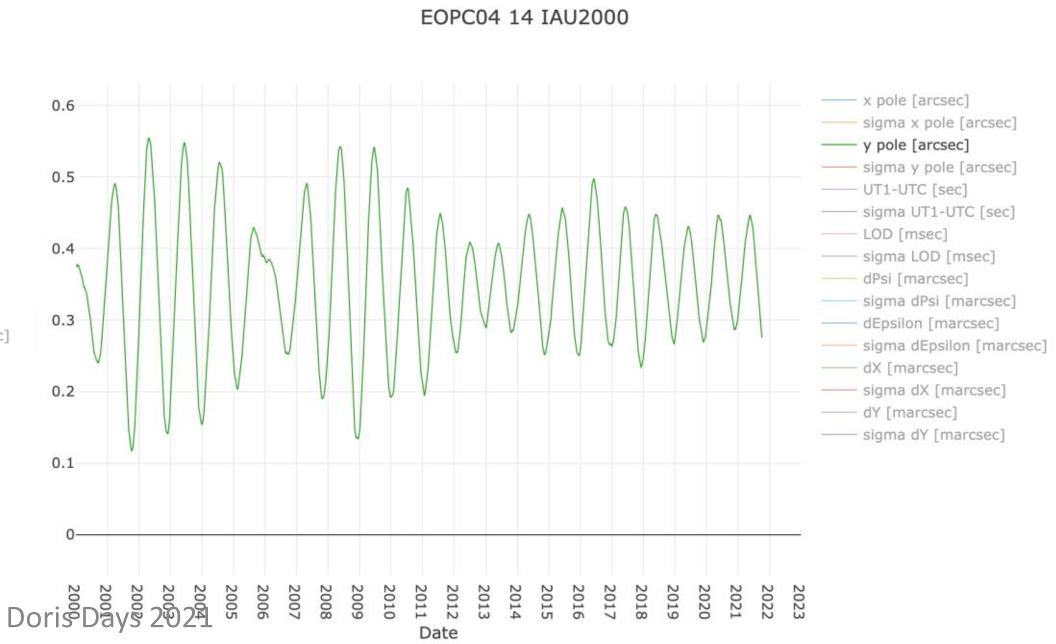
- Geopotential models
  - Heritage GRACE and many other satellite missions
  - SLR to LAGEOS etc for J2/J3 zonals in the gravity field model
- Other non-geopotential models
  - Drag, Radiation, Albedo, Third bodies, Tides
- Station coordinates
  - ITRF, DPOD or recently surveyed beacon data
- Earth Orientation parameters
  - Agreements on Earth Orientation models (precession/nutation etc)
- Other Physical and Planetary constants

Earth Orientation parameters









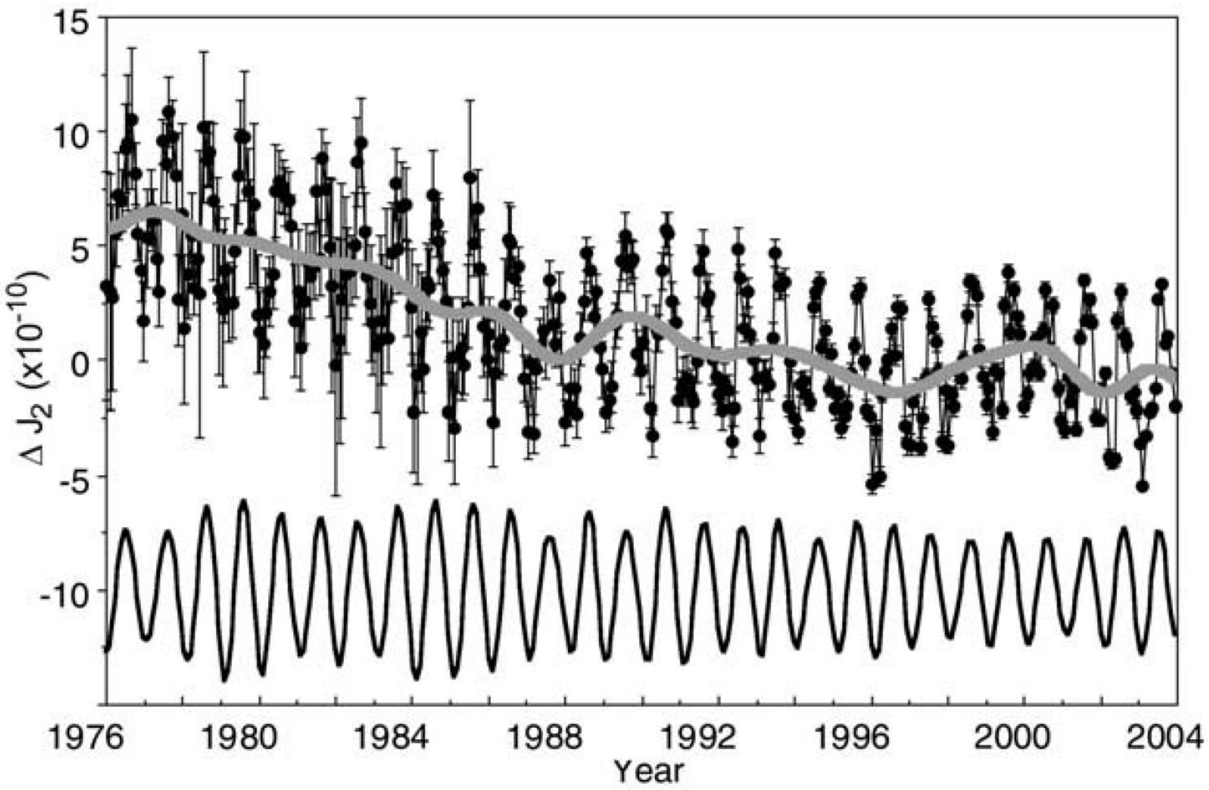


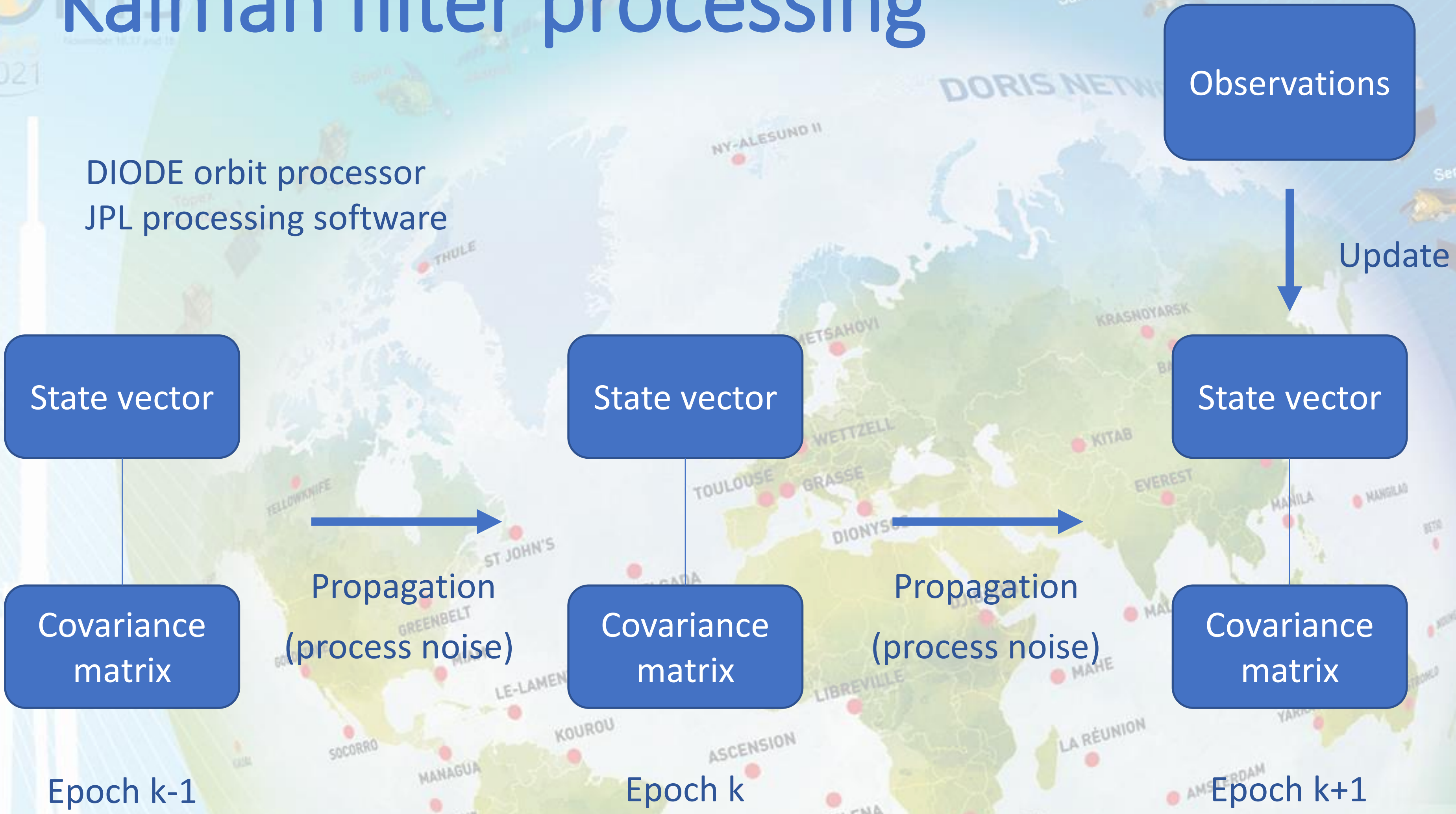
Figure 1. Variation in J_2 from this analysis of SLR data with 30-day sampling interval (dotted black line) and its long-wavelength signature (gray line). The seasonal variation (solid black line, biased by -1.0×10^{-10}) is separated from original time series by wavelet analysis.

Methods for parameter estimation

- Batch least squares
  - Collect all data for instance one week
  - Solve it in one run (one batch)
  - Deal with pass parameters (Beacon troposphere/frequency corrections)
  - Iterate because it is a non linear problem
- Kalman filtering
  - Progressively collect input data
  - Process it at the same time step during processing
  - Accumulate information for parameters that are solved later

Kalman filter processing

DIODE orbit processor
JPL processing software



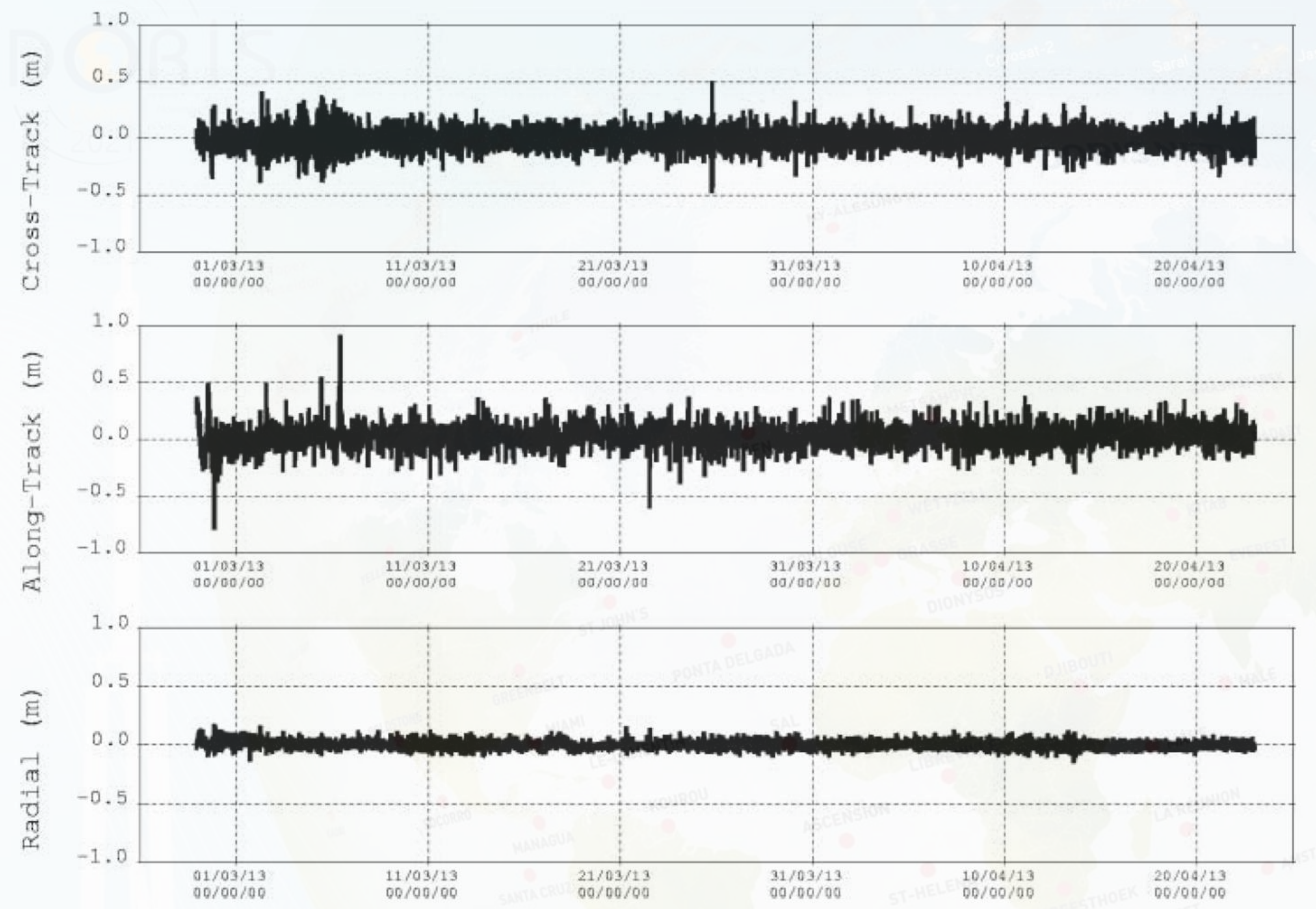


Figure 4. Comparison between on-board estimations and ground Medium Orbit Ephemerides (m); 1 m thresholds.

Performance of DIODE Kalman filter on SARAL Altika

C. Jayles et al 2015

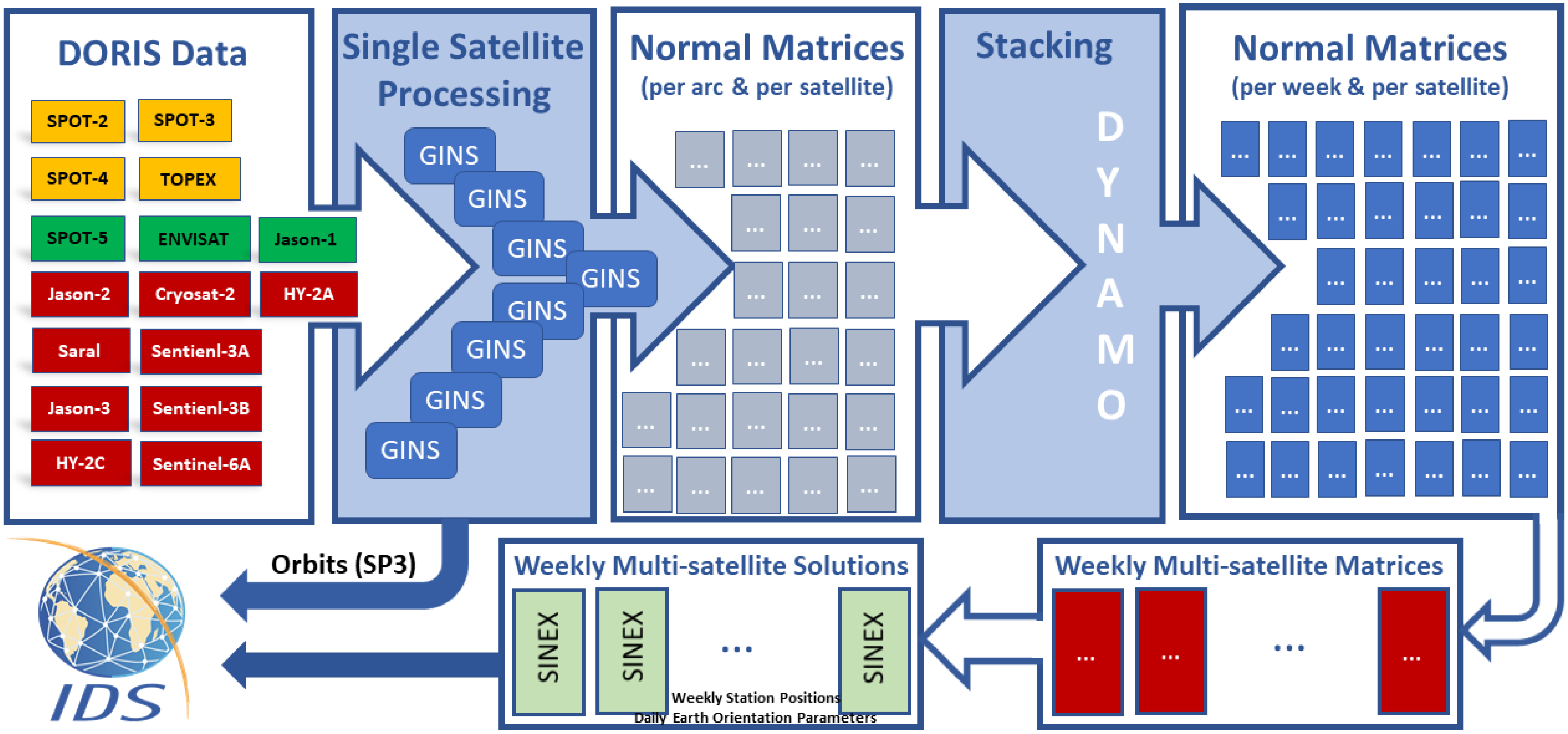
More recently approx. 3.5 cm radially is demonstrated on CryoSat-2.

Parameter estimation

- Orbit dynamics problem:
  - Initial state vector updates
  - Accelerations: geopotential, radiation, drag, empirical, etc
  - A-priori: Time-variable gravity, atmosphere model for drag,
  - A-priori: attitude model of satellite and solar panels
- Clock parameterization:
  - Time/Frequency reconstruction of the IDS receiver relative to TAI
- Beacon position parameterization:
  - Coordinates and plate velocity
  - Geo-center motion
  - Co-location with other geodetic results

Software	Techniques	DORIS		IDS AC	Language	Licence
Bernese software (mod)	(D)+G	Carrier Phase	Least-Squares	GOP	Fortran	Agreement with Bern (Commercial or Academic)
GEODYN	D+G+L+V	Carrier Phase, Doppler	Least-Squares	GSC	Fortran	Public (non-commercial)
GIPSY-X	D+G+(L)	Carrier phase	Kalman	IGN	C++ Python	Academic
GINS	D+G+L+V	Carrier Phase, Doppler	Least-Squares, Kalman	GRG	Fortran	Academic
NAPEOS	D+G+L	Carrier Phase, Doppler	Least-Squares	ESA	Fortran	Academic or Commercial
EPOS-OC	D+G+L+V	Integrated Doppler count	Least-Squares	GFZ	Fortran	Academic
DOGS-OC/RI/CS	(D)+G+L	Carrier Phase	Least-Squares	DGFI-TUM	Fortran	TBC
ZOOM	D+G+L	Carrier Phase, Doppler	Least-Squares	CNES	TBC	TBC

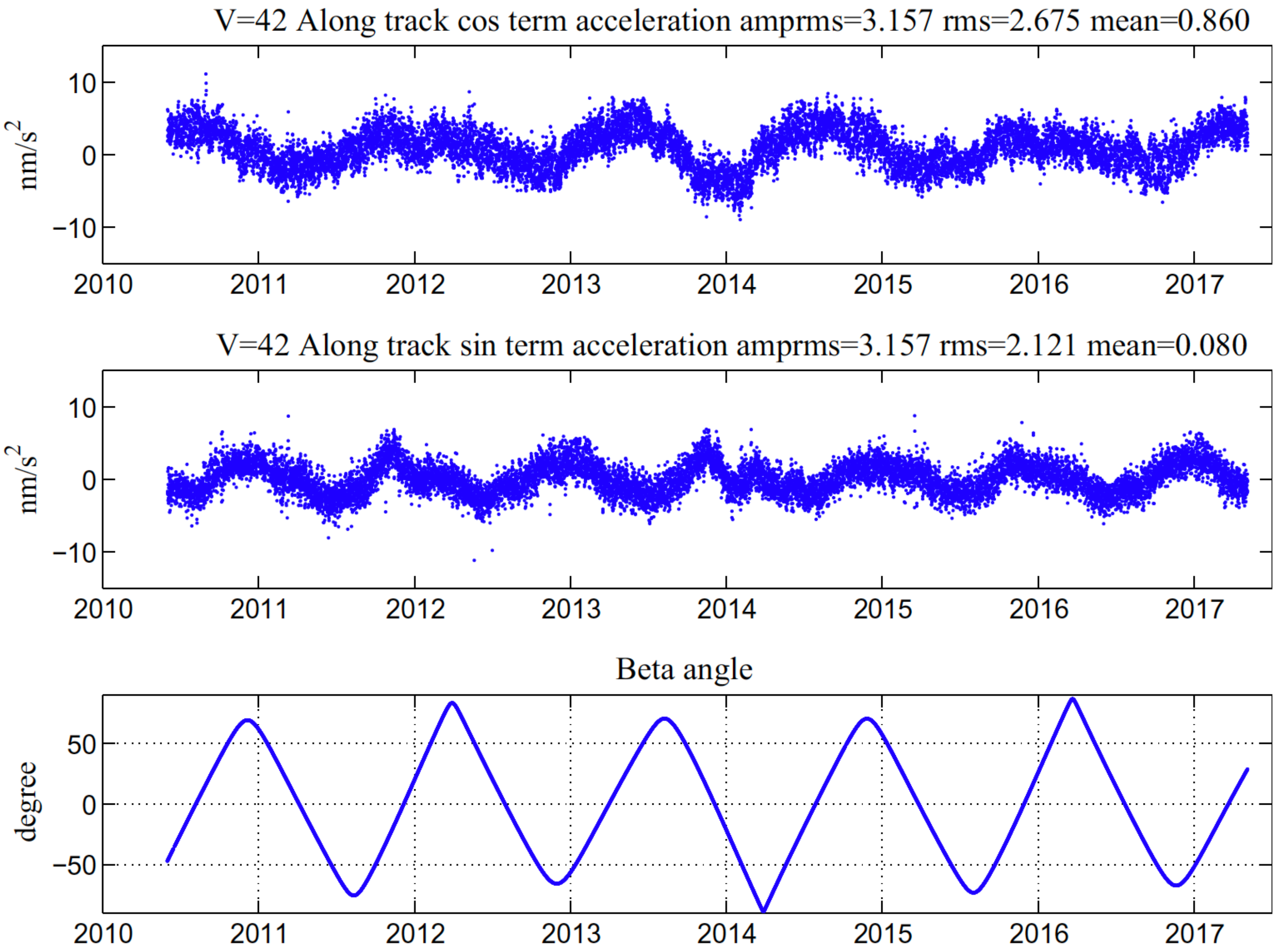
GINS DORIS Data Processing



Solar radiation pressure modelling

- For each satellite an a priori panel model is specified, it is based on a the construction of the satellite, and more importantly, the terminal housekeeping
- We do not expect that the a priori engineering models are perfect, and allow for two mechanisms to deal with deficiencies which we see because of the abundant tracking data
- Empirical acceleration modelling catches all unmodeled accelerations
- SRP scale factor adjustment specifically targets the SRP model

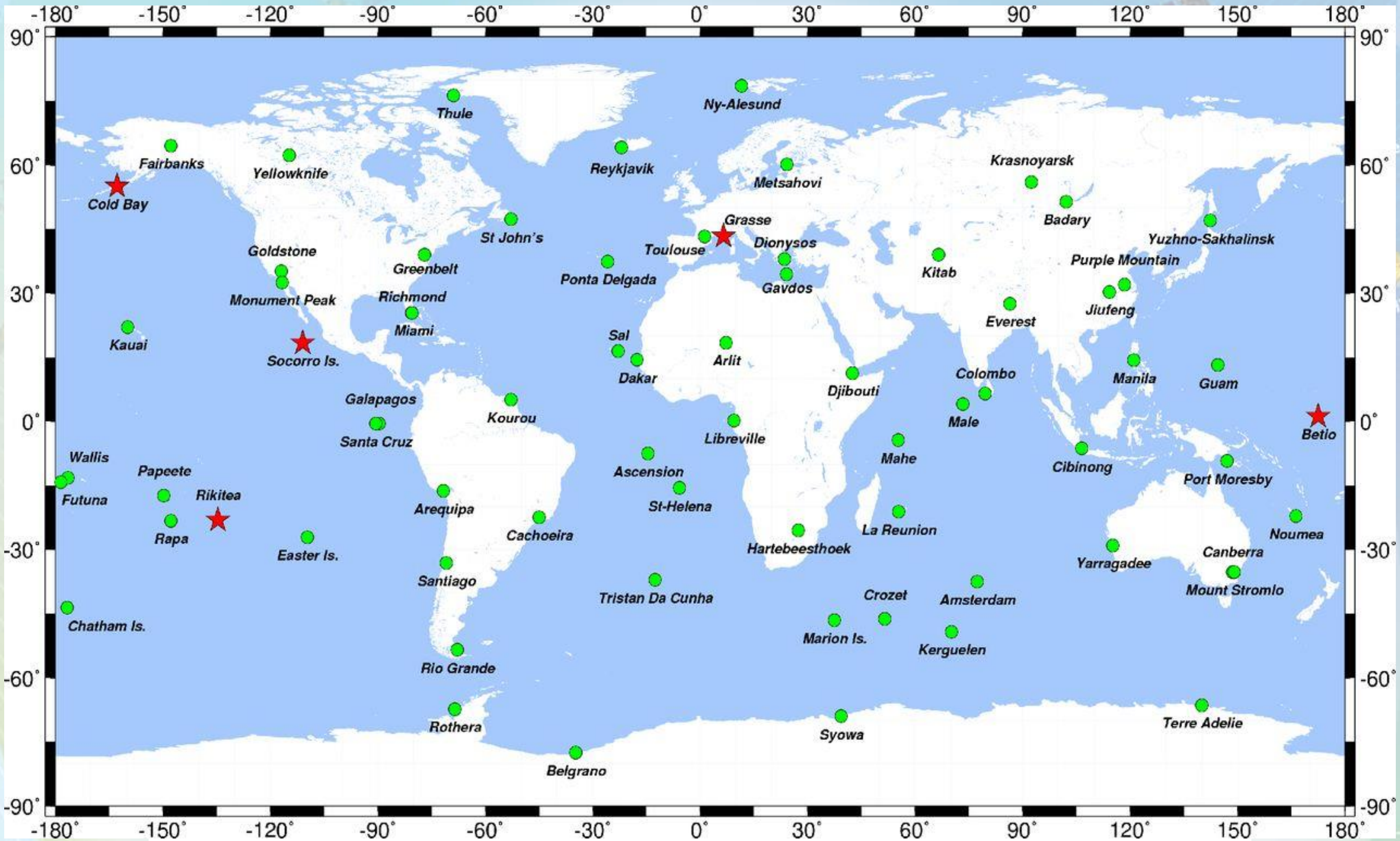
Along track sine and cosine empirical acceleration components CryoSat-2 orbits



Station positions and velocities

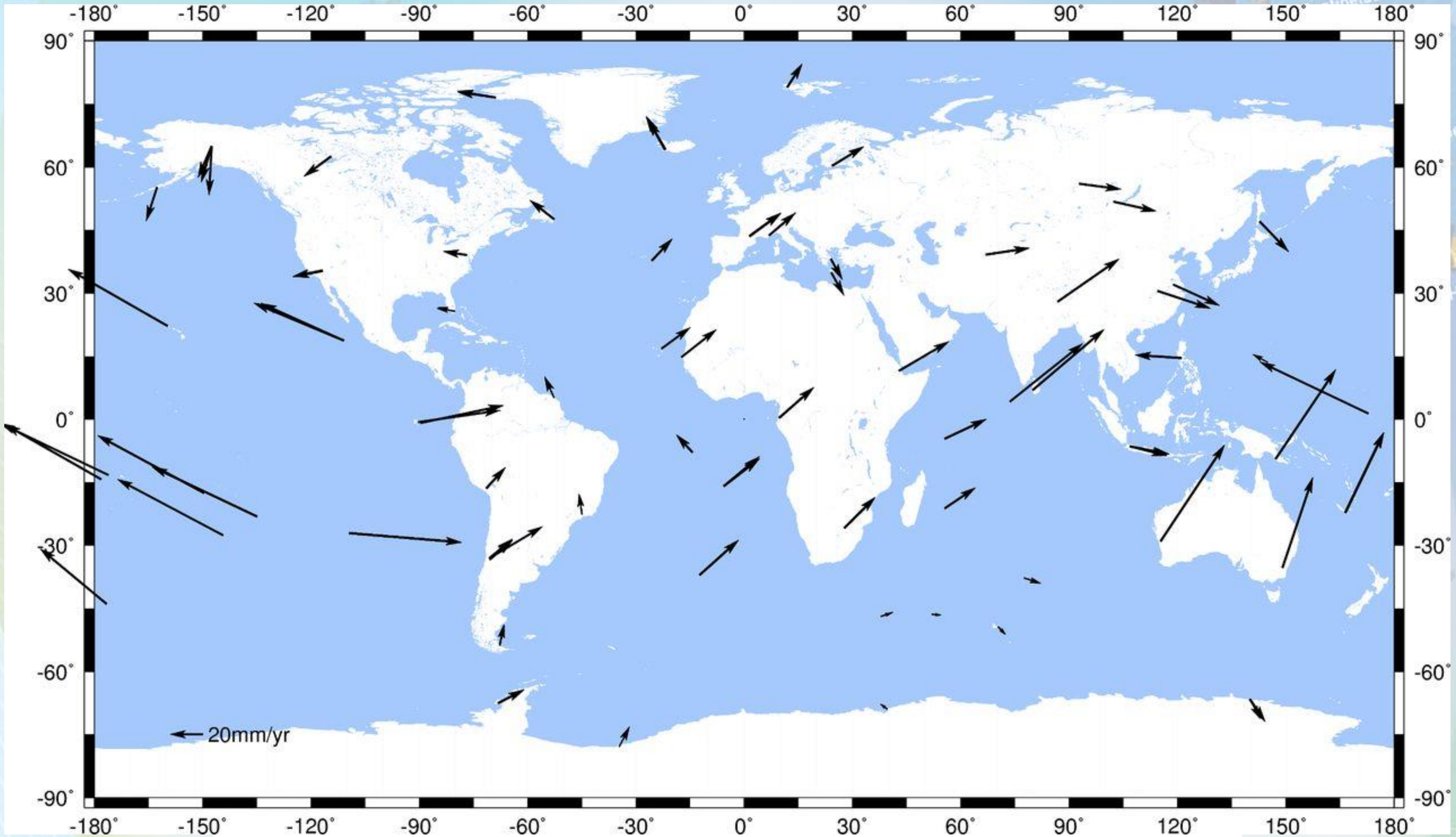
- There are reference models (like NUVEL-1 or others) we can use to start the analysis
- IDS is capable of determining stations positions and velocities, so it is also contributing.
- Station position and velocity parameter estimation is separate from parameter estimation that involves satellite arc parameters

Moreaux et al 2016, Geographical distribution of the 71 DORIS sites included in the IDS contribution to ITRF2014 (red stars are new sites relative to ITRF2008)



Geophys J Int, Volume 207, Issue 1, October 2016, Pages 209–227, https://doi.org/10.1093/gji/ggw265

Moreaux et at 2016: Horizontal velocities at the DORIS sites from the IDS 09 weekly files.



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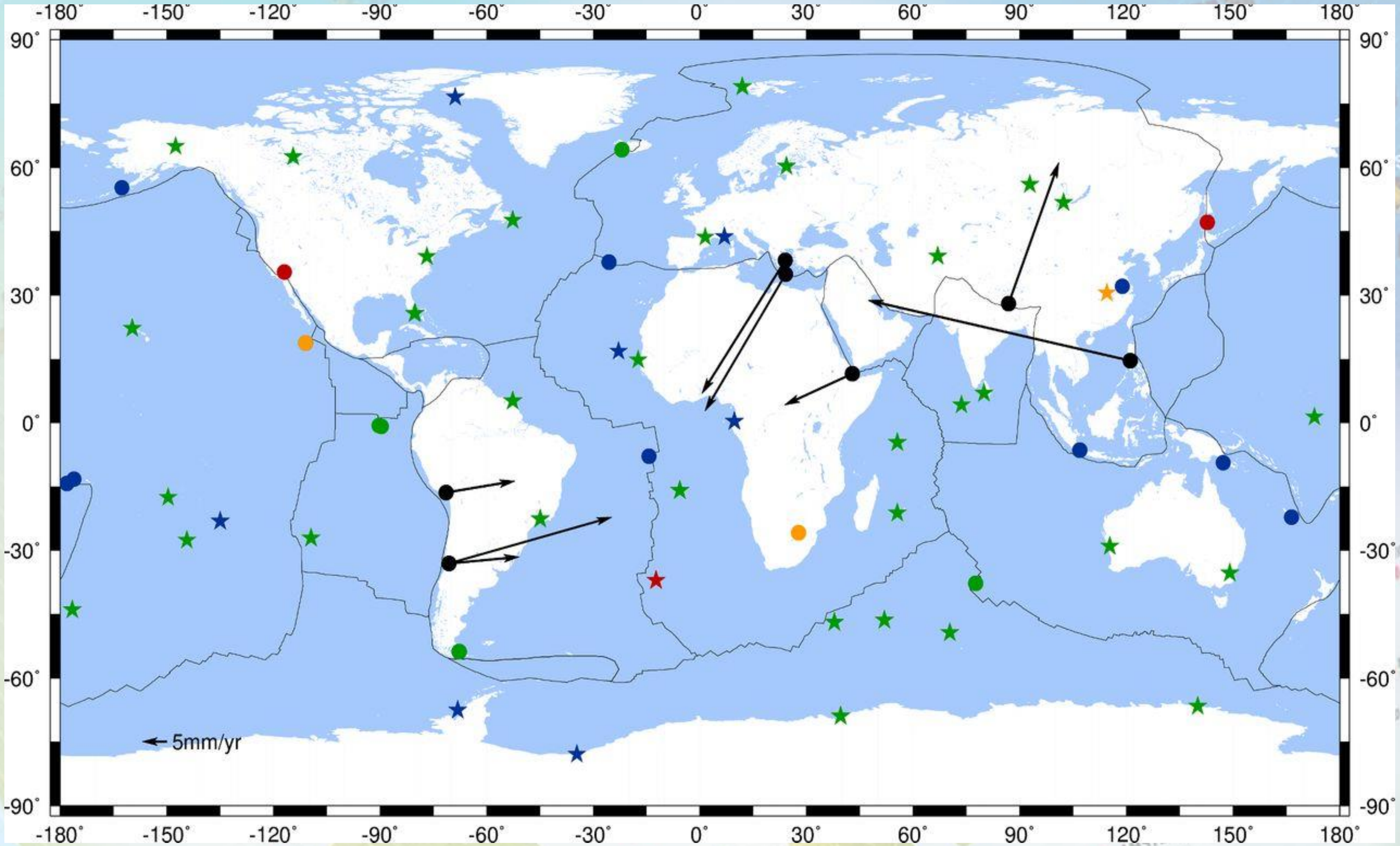
OXFORD UNIVERSITY PRESS

Moreaux et al 2016 Horizontal velocity differences between IDS 09 and GEODVEL (velocities of the latter are subtracted from the former)



GEODVEL: Argus et al 2010, it is based on a combination analysis of DORIS, GNSS, SLR and VLBI

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File formats

- Format 2.2 files, provided on a weekly basis up to the CryoSat mission
- Receiver independent exchange (RINEX), much like in GNSS where you need to solve the clock problem yourself and where the carrier phase becomes available to the users
- SINEX, a solution exchange format, various elements but typically contains a solved for parameter vector and an associated covariance matrix
- Ties (obtained by geodetic site surveys), between the beacon benchmark and a observation location can be part of the RINEX files.

Suggested reading

Tapley Schutz and Born, Statistical Orbit Determination, Elsevier Academic Press, ISBN 0-12-683630-2

Günter Seeber. Satellite Geodesy, Foundations, Methods and Applications, de Gruyter, ISBN 3-11-012753-9

Jayles, C., Chaveau JP, Auriol A (2015) DORIS/DIODE: Real-Time Orbit Determination Performance on Board SARAL/AltiKa Marine Geodesy, 38, 233-248, doi:10.1080/01490419.2015.1015695

"NAPEOS Mathematical Models and Algorithms" European Space Agency, Document DOPS-SYS-TN-0100-OPS-GN 1.0, 5-nov-2009, (https://hpiers.obspm.fr/combinaison/documentation/articles/NAPEOS_MathModels_Algorithms.pdf)

Marty, J.C., Loyer, S., Perosanz, F., et al., (2011) "GINS: the CNES/GRGS GNSS scientific software" In: 3rd International Colloquium Scientific and Fundamental Aspects of the Galileo Programme, ESA Proceedings WPP326, Copenhagen, Denmark, 31 August – 2 September, 2011, (http://ids-doris.org/images/documents/report/publications/GINS_ GRGSsoftware-Marty-2011.pdf)

Bertiger, William I., et al. (2020). GipxyX/RTGx: A software set and results for operations and Space Research, Adv. Space Res., 66(3), 469-489, doi:10.1016/j.asr.2020.04.015

Moreaux et al (2016) *Geophys J Int*, Volume 207, Issue 1, October 2016, Pages 209–227, https://doi.org/10.1093/gji/ggw265