Copernicus POD Service

DORIS processing with FOCUSPOD

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30YPRA – IDS meeting,
Montpellier, France, 2-7th September 2024

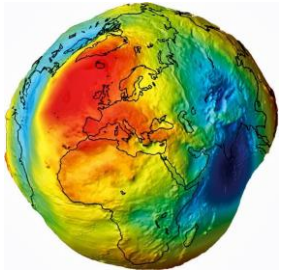
Agenda

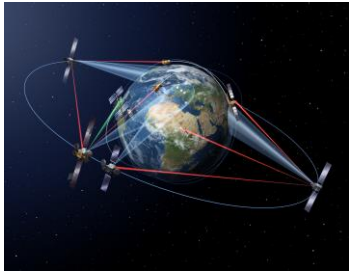
1. FocusPOD
2. DORIS observation modelling
3. POD results
4. Conclusions & future work

FocusPOD

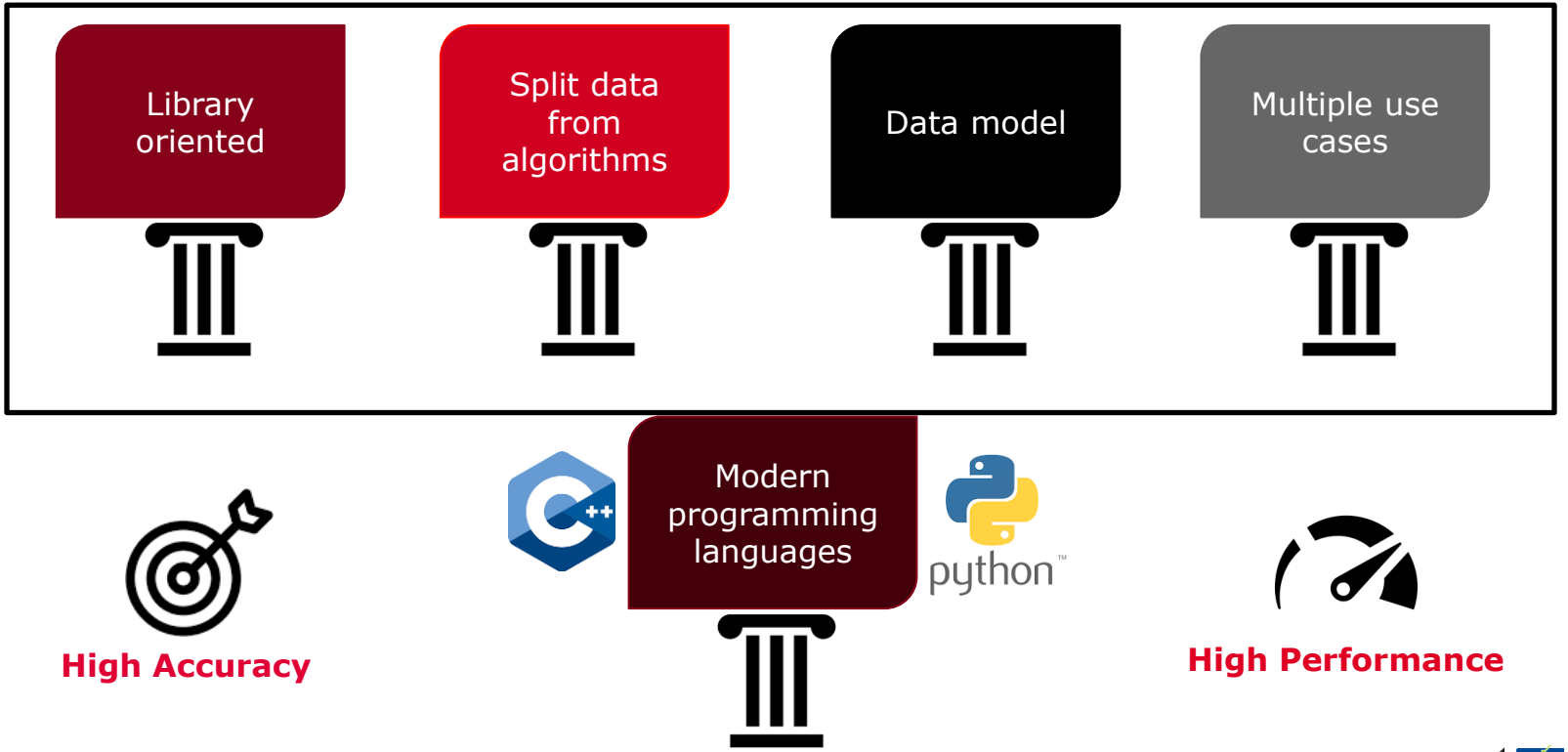
FOCUSPOD
What is it?

- ***FocusPOD*** (https://www.gmv.com/en-es/products/space/focuspod), is a GMV Flight Dynamics and Geodesy library, written in **C++** and **python** from scratch, using state-of-the-art software development paradigms and astrodynamics algorithms, allowing the development of **advanced applications** in the areas of:
  - Precise Orbit Determination (POD) and Geodesy
  - Space Surveillance and Tracking (SST) / Space Traffic Management
  - Space Flight Dynamics (FD) / Interplanetary
  - Mission Analysis and Simulation



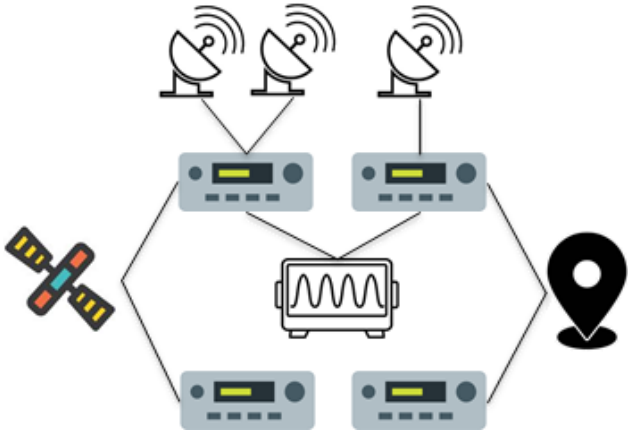


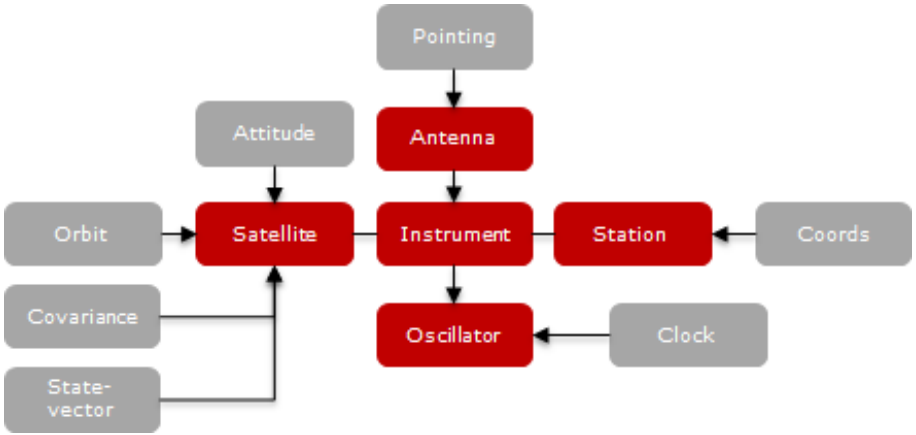
FOCUSPOD
Design pillars



FOCUSPOD
Data model

- … is the library **key pillar**
- … is a **rational and unique** representation of the physical reality
- … enforces **separation** of data and algorithm, to facilitate the reuse of data or algorithms
- … is **relational** – establishing links between elements
- … is **optimized for large volumes** of data, e.g., GNSS observations, mega-constellations…





FOCUSPOD
History

- Written from **scratch** starting in 2021
- **Agile** methodology: 2-week sprints, performance testing w.r.t. legacy SW (accuracy / performance)
- **Team size**: between ~3 to 7 developers in 2021-2023; then ~2 (maintenance, R&D…)
- **Operational** SW by 2023!

Start Jan 2021

Data model
High level architecture

Jan 2022

Perturbations
Numerical propagator
Manoeuvres

Observation reconstruction & pre-processing: GNSS, SLR
Estimation (WLS)
Events

Jan 2023

Operational readiness
(CPOD)
Integer ambiguity resolution

Coords & tropo
GNSS from ground
Simulation
Ext. Kalman Filter

Today

DORIS

2025+

VLBI

FOCUSPOD
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Jan 2022
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- Observation reconstruction & pre-processing: GNSS, SLR
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Jan 2023
- **Operational readiness** (CPOD)
- Integer ambiguity resolution
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- Ext. Kalman Filter

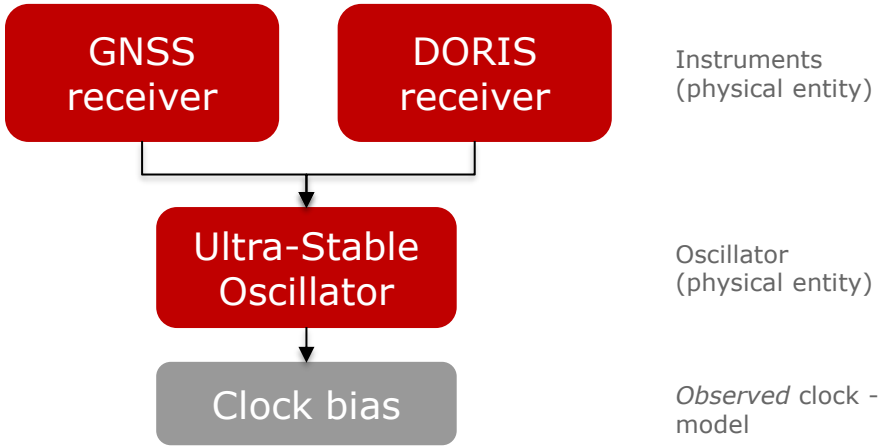
Today
- **DORIS**

2025+
- **VLBI**

DORIS observation modelling

DORIS processing
Highlights

- DORIS RINEX (v3) supported
- Existing data model entities reused: satellite, station, coords, instrument, oscillator…
- Carrier phase (*L*) used to form *range differences*
- No ad-hoc rcv clock bias treatment → values from RINEX



DORIS observation modelling

RINEX

```
     3.00           O                   D                   RINEX VERSION / TYPE
Expert              CNES                20240401 073022 UTC PGM / RUN BY / DATE
G = GPS R = GLONASS E = GALILEO S = GEO M = MIXED D = DORIS COMMENT
SENTINEL-3A                                                 SATELLITE NAME
2016-011A                                                   COSPAR NUMBER
SPA_BN1_5.8.0       CNES                                    OBSERVER / AGENCY
CHAIN1              DGXX-S              1.00                REC # / TYPE / VERS
DORIS               STAREC                                  ANT # / TYPE
        1.5700        0.0730        1.0760                  APPROX POSITION XYZ
        1.5000        0.2200        0.0100                  CENTER OF MASS: XYZ
D   10  L1  L2  C1  C2  W1  W2  F   P   T   H               SYS / # / OBS TYPES
  2024    03    31    00    00   18.8509872     DOR         TIME OF FIRST OBS
D  100   2  C1  C2                                          SYS / SCALE FACTOR
D          -0.100                                           L2 / L1 DATE OFFSET
    53                                                      # OF STATIONS
D01  MLAC MANGILAO                      82301S001  3   0    STATION REFERENCE
D02  NOXC NOUMEA                        92701S005  4   0    STATION REFERENCE
D03  MSPB MOUNT STROMLO                 50119S004  4   0    STATION REFERENCE
D04  YASB YARAGADEE                     50107S011  4   0    STATION REFERENCE
D05  ADHC TERRE ADELIE                  91501S005  3   0    STATION REFERENCE
      ⋮                                                                 ⋮
D51  BETB BETIO                         50305S001  3   0    STATION REFERENCE
D52  TSTC TEST-FERMAT                   10003S006  4 -22    STATION REFERENCE
D53  ASEB ASCENSION                     30602S005  3   0    STATION REFERENCE
     4                                                      # TIME REF STATIONS
D05          6.540          27.667                          TIME REF STATION
D10          2.364          23.148                          TIME REF STATION
D43          8.112          30.325                          TIME REF STATION
D44          0.305          39.031                          TIME REF STATION
  2024    03    31    00    00    0.0000000                 TIME REF STAT DATE
                                                            END OF HEADER
> 2024 03 31 00 00 22.159948900  0  1       -3.308961669 0
D01  -2022818.097    -1225034.253   100964582.24211 100964633.58911      -124.300 7
        -111.700 7      3722.794        1007.000 0       23.978 1        72.967 1
> 2024 03 31 00 00 25.159948900  0  1       -3.308961669 0
D01  -2138533.120    -1247833.987   100962878.59111 100962929.76411      -124.300 7
        -111.700 7      3722.794        1007.000 0       23.978 1        72.967 1
```

Power received (W) used to exclude high noise observations

Relative frequency offset (F) used for receiver clock handling

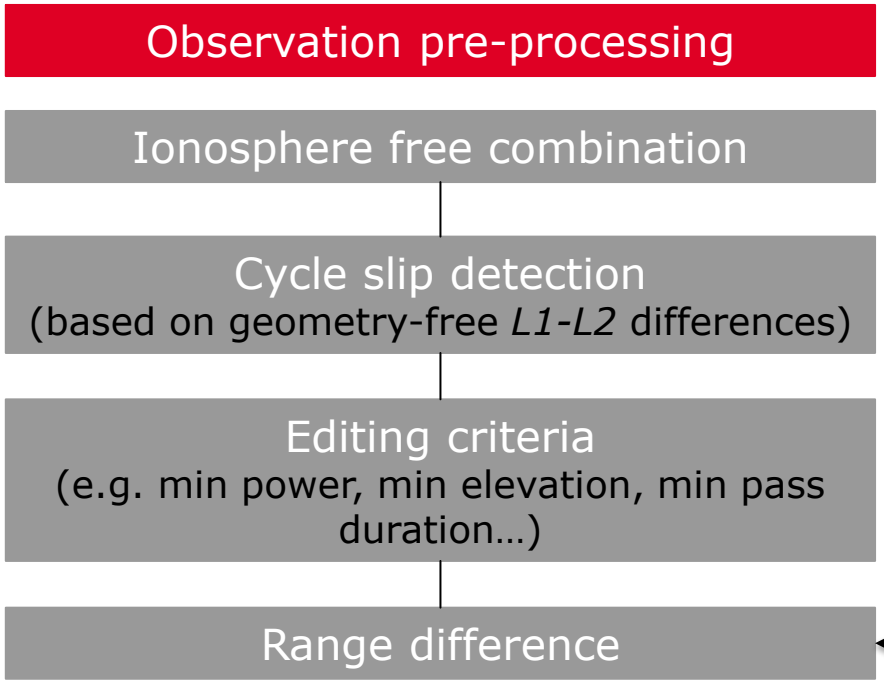
Pressure, temperature and humidity used for Tropospheric correction

Frequency shift factor (K) used for station frequency computation f_e

Receiver clock offset applied to observation epoch (DOR) to obtain TAI (epochwise)

DORIS observation modelling

Obs pre-processing



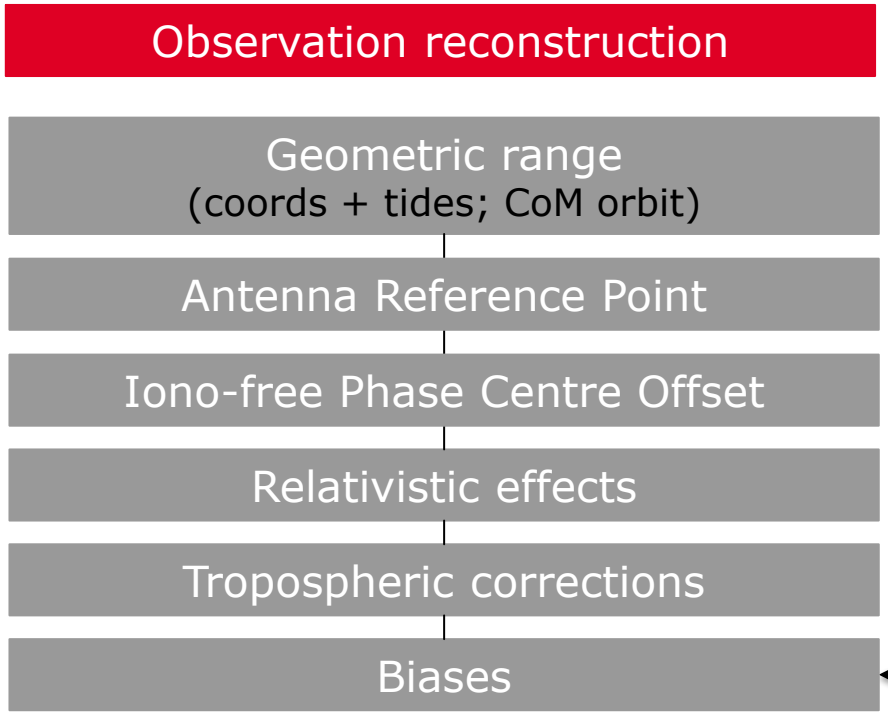
$$\Delta\rho^r = \frac{c}{f_e}\left(f_e - f_r - \frac{N_{\mathrm{DOP}}}{\Delta t_r}\right)\Delta t_r$$

$$N_{DOP} = \frac{L_{IF1} - L_{IF2}}{c/S_1}$$

- $\Delta\rho^r$: range difference (*real measurement*) based on 10-sec carrier phase differences
- c: velocity of light in the vacuum
- f_e: emitter frequency (nominal S1 freq. w/ RINEX frequency shift factor)
- f_r: receiver frequency at t_1 (from RINEX F record, epochwise)
- N_{DOP}: doppler count (iono-free carrier phase difference [m] as S1 cycles)
- Δt_r: receiver interval (TAI, receiver clock biases applied from RINEX epoch records)

DORIS observation modelling

Obs reconstruction



$$\Delta\rho^t = \rho_2 - \rho_1$$

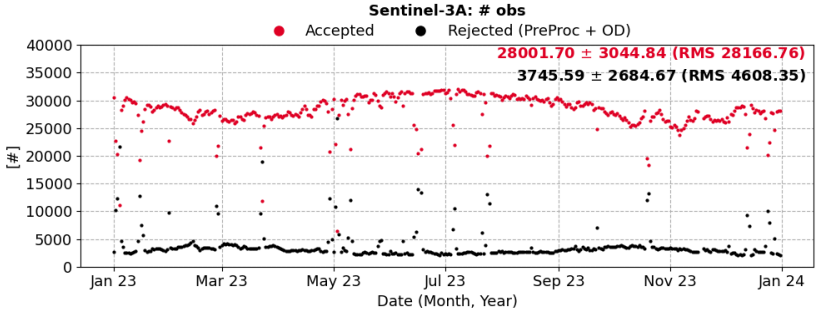
- $\Delta\rho^t$: range difference (*theoretical measurement*)
- ρ_1: range at t_1
- ρ_2: range at t_2

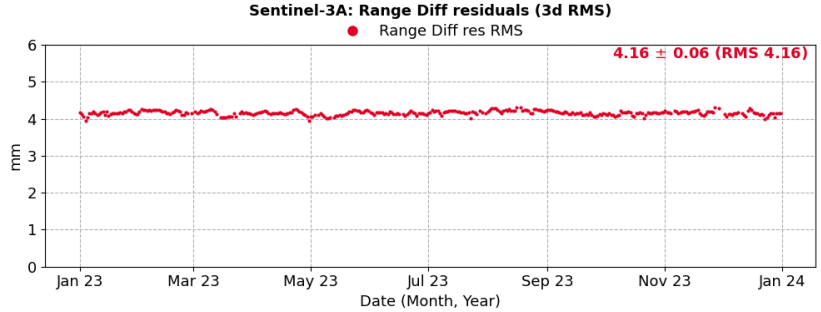
POD results

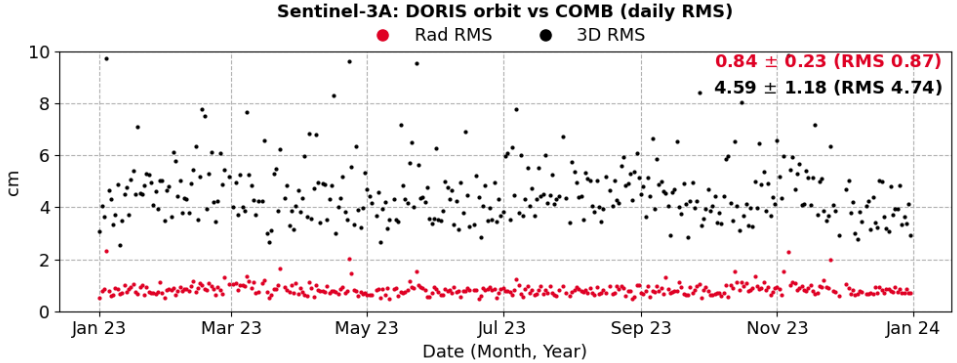
POD results
SENTINEL-3A parametrization

Determination arc	72h, of which only central 24h are compared
Measurements	DORIS only (RINEX v3); σ_{range_diff} = 6 mm
Orbit propagation	COST-G (time-varying terms) + AOD1B + ocean/solid tides Third-body (JPL DE421) SPR + IR + albedo + drag (NRLMSISE-00; based on CPOD macro-model)
Meas. reconstruction	Geometric delay + (iono-free) ARP + relativity + tides Tropo: Saastamoinen with estimated parameters (ZTD, TMF)
Attitude	Real quaternions
Stations	dpod2020_023.snx (modified for iono-free Z comp) ITRF2020-doris.psd
Parameters	Dynamic: 30 CDs, 1 CR, manoeuvre errors, 12 CPRs (along/cross sin/cos) Observation: 1 bias per station per pass, 1 ZTD+TMF per station per pass
Edit criteria	10º min elev 120 s min pass length

POD results
SENTINEL-3A results







Radial agreement
< 1 cm RMS

POD results
SENTINEL-6A parametrization

Determination arc	72h, of which only central 24h are compared
Measurements	DORIS only (RINEX v3); σ_{range_diff} = 8 mm
Orbit propagation	COST-G (time-varying terms) + AOD1B + ocean/solid tides Third-body (JPL DE421) SPR + IR + albedo + drag (NRLMSISE-00; based on CPOD macro-model)
Meas. reconstruction	Geometric delay + (iono-free) ARP + relativity + tides Tropo: Saastamoinen with estimated parameters (ZTD, TMF)
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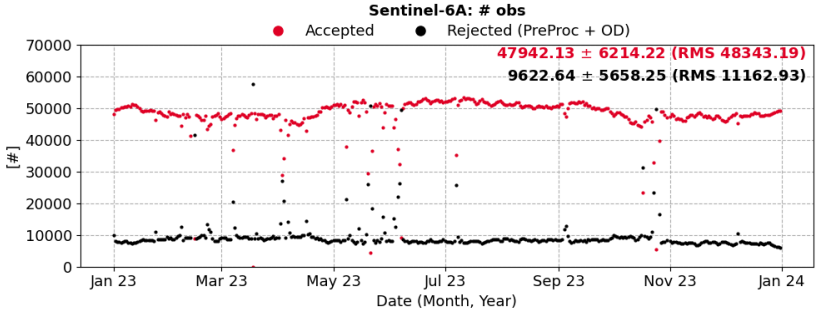
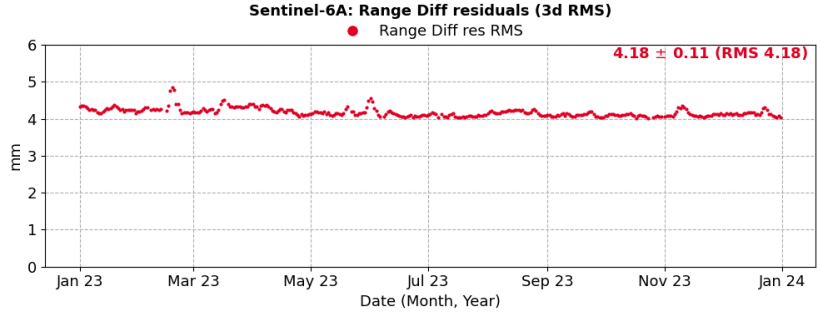
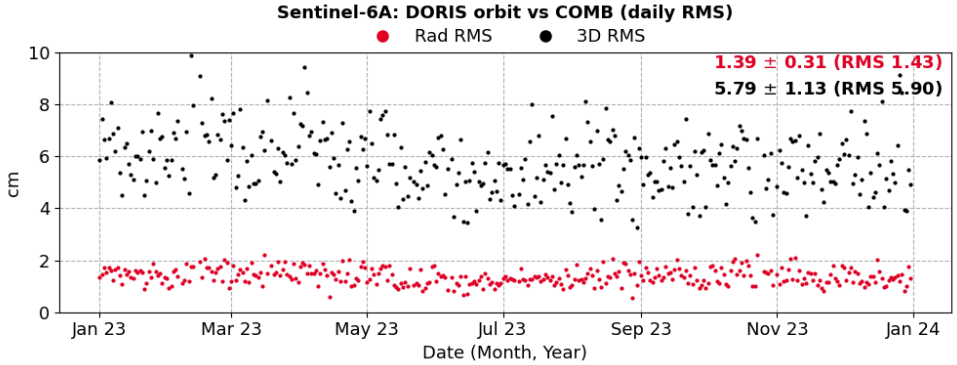
Parameters	Dynamic: 1 CDs, 1 CR, manoeuvre errors, 30 CPRs (along/cross sin/cos) Observation: 1 bias per station per pass, 1 ZTD+TMF per station per pass
Edit criteria	10º min elev 300 s min pass length

POD results
SENTINEL-6A results







Radial agreement
< 1.5 cm RMS

~worse than S3A

POD results
Future work

- Revisit satellite parametrization
- Improvement of LEO receiver clock bias:
  - Smoothing of "F" observable / receiver clock bias in epoch record from RINEX
  - Rcv clock bias estimation based on pseudo-ranges from reference stations
  - Rcv clock derived from GNSS measurements (WG in progress)
- Improvement of data screening (elevation weighting, revisit observation sigmas…)
- Improvement of troposphere modelling: GPT, VMF, estimated gradients
- Test impact of Seasonal Geocenter Motion (ITRF20)
- Replace "constant bias per station per pass" by estimates of station frequency bias and drift ?

Any recommendation from the IDS is more than welcome! ☺

Conclusions

Conclusions

- ***FocusPOD*** is capable of processing DORIS (RINEX), but still *"work in progress"*
- LEO POD based on DORIS for Sentinel-3 and -6 show radial agreement ~ 1 cm
- Roadmap to keep improving the SW towards state-of-the-art processing!

Thank you

Copernicus POD Service

Carlos Fernández (GMV)
Marc Fernández (GMV)
Jaime Fernández (GMV)
Heike Peter (POSITIM)
Pierre Féménias (ESA/ESRIN)
Carolina Nogueira-Loddo (EUMETSAT)

FOCUSPOD
Capabilities (I)

Category	Functionality
Time and frames	Handle transformation between multiple time scales (TAI, UTC, UT1, GNSS) and reference frames (ITRF, GCRF, TEME, etc.)
Measurements	Simulation and reconstruction. GNSS, SLR, DORIS, XYZ, Range, Doppler, Angles.
Orbit propagation	Numerical propagation (Adams-Bashforth, Runge-Kutta) with state-of-the-art orbit perturbations Keplerian, SGP4
Clocks	Simulation and estimation of clock biases.
Attitude	Quaternion-based; Simulation & SLERP interpolation.
Events	Orbital (eclipse, ascending node crossing…) Station (elevation, field of view…)

FOCUSPOD
Capabilities (II)

Category	Functionality
Parameter estimation method	Batch least square Extended Kalman Filter (EKF) Parameters: dynamic (SV, CD, RP, empirical), observation (clocks, ambiguities, biases, tropo), coords, manoeuvres.
Optimization	Consider parameters (aerodynamic/SRP error, biases…)
GNSS	Integer Ambiguity Resolution
SST	Initial Orbit Determination. Association (track-to-track, track-to-orbit, orbit-to-orbit). Manoeuvre detection, object size estimation, etc.
Quality control	Orbit, clock and attitude comparisons. GNSS sensor performance. Ground-track and tube control.

FOCUSPOD
Geophysical models (I)

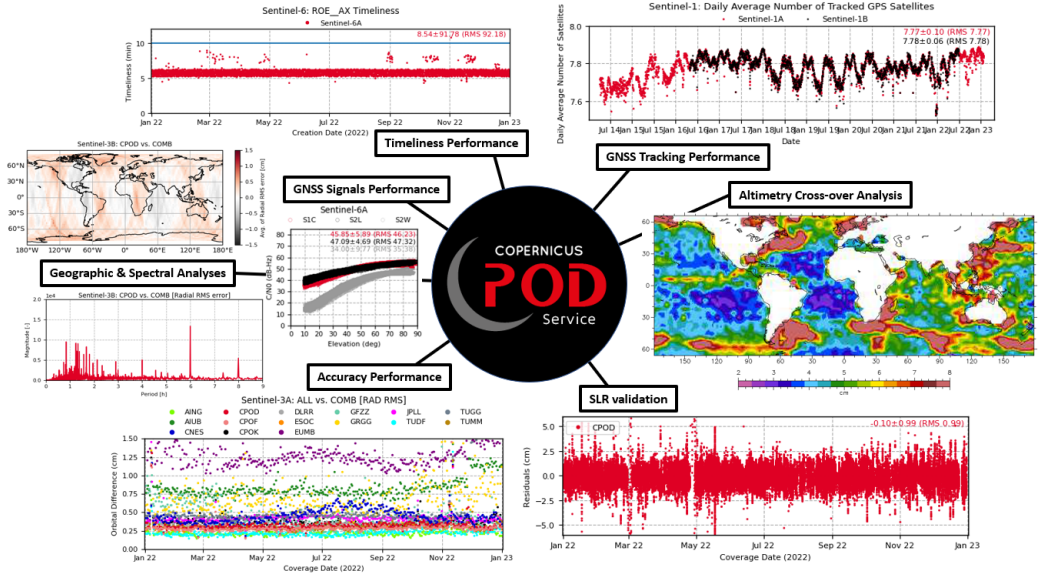
Category	Models
Frames	IERS 96 and 2010 conventions Linear mean pole Local frame converter (topocentric, QSW, TNW)
Gravity	COST-G, EIGEN, EGM (w/ support to time-varying terms) Ocean tides (OTIERS): FES2014 Solid tides (STIERS): IERS 2010 Atmospheric gravity (AOD1B) Seasonal geocenter motion: ITRF20
Third-body	JPL ephem. DE405, DE421
Density	MSISE00
Space weather	RSGA, Celestrak
Biases	Absolute and Differential signal biases

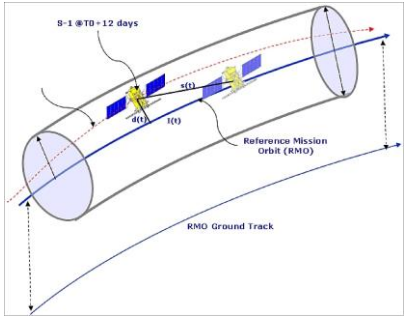
FOCUSPOD
Geophysical models (II)

Category	Models
Radiation	Solar Radiation Pressure (SRP), albedo, infra-red, antenna power thrust
Empiricals	Constant-Per-Revolution (CPR) ECOM, ECOM-2
Ionosphere	Iono-free, Nequick
Troposphere	Mendes-Pavlis, Niell, Saastamoinen
Satellite	Fixed area, macro-model Theoretical or real attitude laws Impulsive and long manoeuvres
Station	North-East-Up or ad-hoc pointing Post-Seismic Deformations ITRF20 seasonal geocenter motion

FOCUSPOD
Applications in geodesy

- **CPOD Service**: LEO POD based on GNSS + SLR validation
- **Galileo 2nd Generation System Test Bed** & **Integrity algorithms for Space Corridor**: GNSS measurement simulation





FOCUSPOD
Geodesy roadmap

- **GNSS**
  - Multi-GNSS constellation (GPS, GAL, GLONASS, BeiDou, QZSS…) orbits & clocks computation
  - Signal bias calibration
- **SLR**
  - Geodetic satellite processing (LAGEOS, LARES…)
- **DORIS**
  - LEO POD accuracy improvement: troposphere, long term frequency bias estimation…
  - LEO POD of more satellites: JASON-3, HY-2CD…
- **VLBI**
  - First implementation starting

CPOD Orbital Accuracy

CPOD RSR#30 2023 results