ESOC Galileo Precise Orbit Determination

Prof. Dr.-Ing. Werner Enderle

ESA /ESOC – Navigation Support Office

02/09/2022

Overview

- ESA’s Navigation Support Office
- Basic Concept of Satellite Orbit Determination
- ESA/ESOC’s approach for Galileo Precise Orbits and Clocks Determination
- Galileo Precise Orbit Determination Results

ESA's Navigation Support Office – General Overview

ESA's Navigation Support Office is responsible for providing an independent reference in Europe for precise navigation.

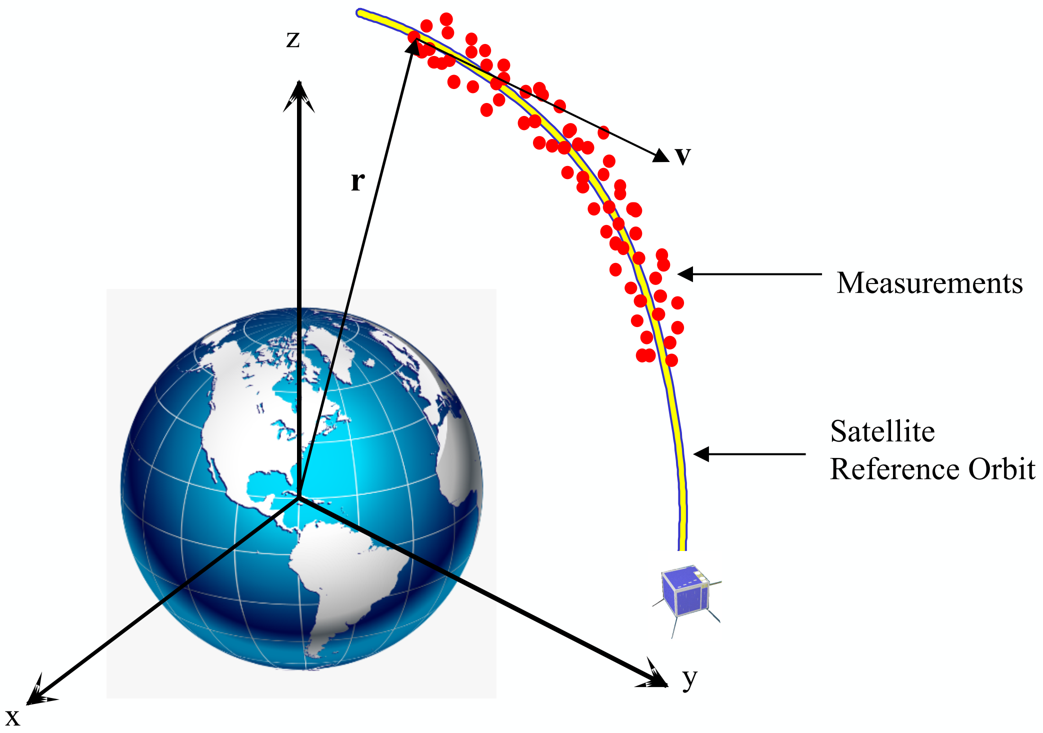
- Providing precise orbits and clocks for all GNSS spacecraft with focus on Galileo
- Providing precise orbits for User spacecrafts in different orbital regimes
    - LEO, GTO, GEO, HEO and Earth-Moon transfer orbit
- Providing the geodetic reference for ESA missions
- Contributing to UTC and providing the operational reference time for ESA's missions
- Operating a global real-time network (EGON) of GNSS sensor stations
- Analysis Center for:
    - GNSS (IGS)
    - SLR (ILRS)
    - DORIS (IDS)
    - VLBI (IVS) [associated]

ESA’s Navigation Support Office – Galileo POD

For more than 20 years, ESA’s Navigation Support Office is involved in a variety of Precise Orbit Determination (POD) activities for GIOVE and Galileo

- Galileo Orbit Dynamic Model development:
    - Solar Radiation Pressure (SRP), Albedo, attitude models, …
- Clock modelling, clock characterisation
- Meta data validation - PCV, PCO, DCB, Box-Wing parameter
- Anomaly investigations to ensure system performance
- Analysis of Galileo Sensor Station (GSS) RINEX data
- Galileo signal and service monitoring
- Research activities (EOP studies, clock modelling, Ambiguity Resolution, GREAT)
- Operational provision of Galileo orbit predictions for ILRS
- Coordinator of a European Consortium (GGSP) that provides the Galileo Geodetic Reference Frame

Basics of Satellite Orbit Determination



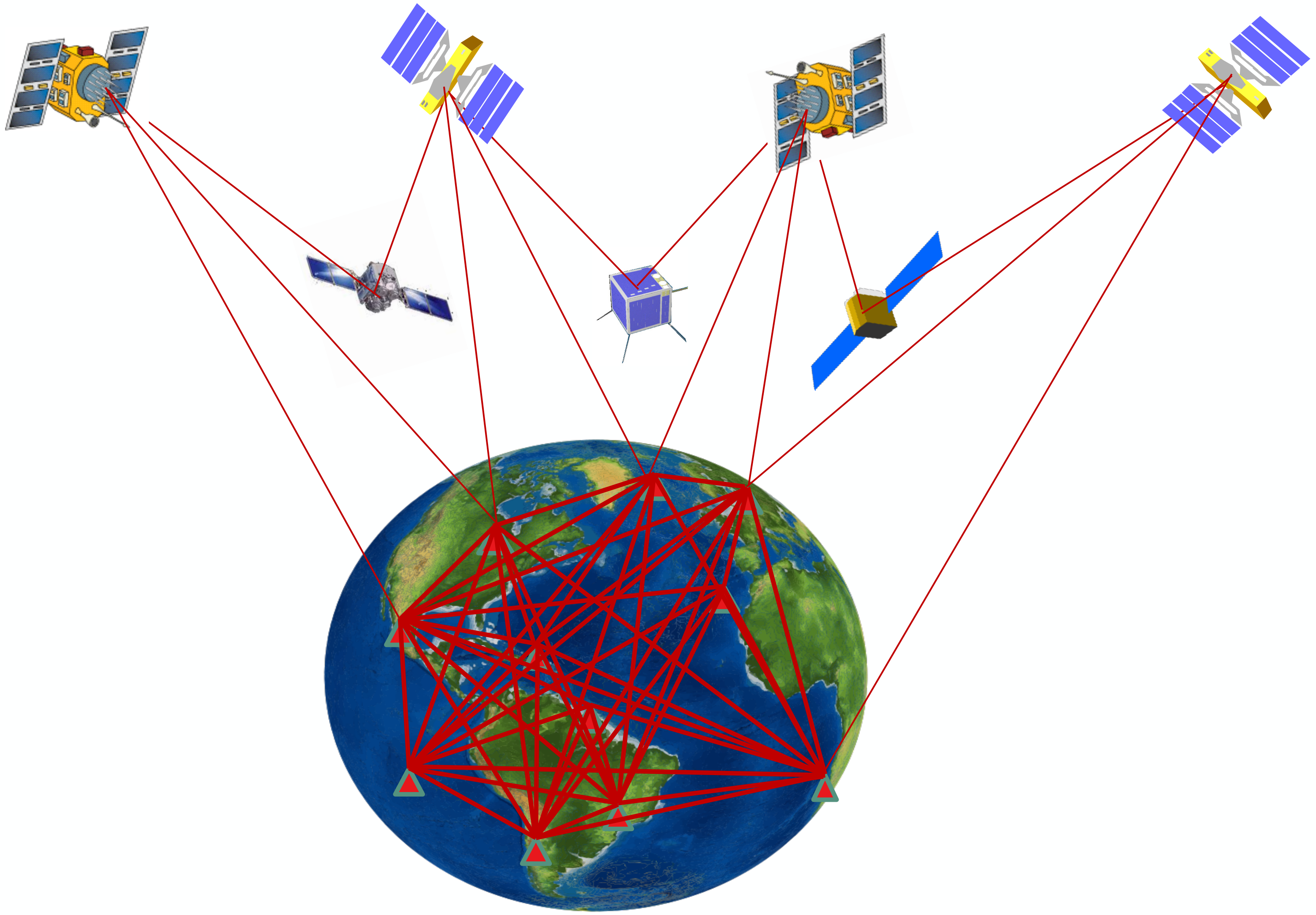
Basic Concepts for Satellite Orbit Determination

- Dynamic Orbit Determination
  - Modelling of forces acting on the satellite
  - Numerical integration of equations of motion
  - Re-construction of measurements
  - Combination of measurements and re-cosntructed measurements via applying of a suitable concept, e.g. Least Squares (LSQ) Method
  - Processing of data arc post-facto (batch processing)

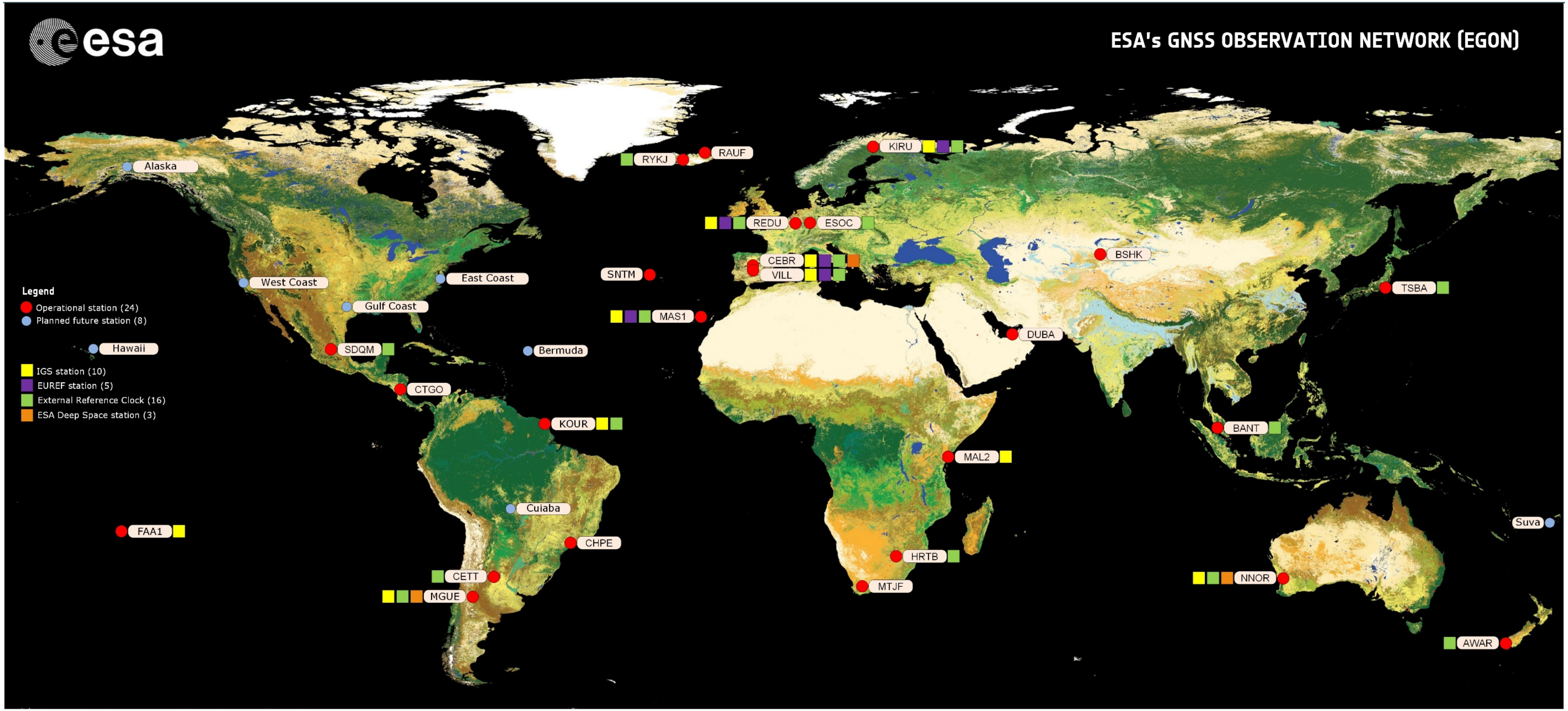
- Kinematic Orbit Determination
  - Only measurements are used for orbit determination
  - NO modelling of forces acting on the satellite
  - Can be used for real-time and also post-facto processing

- Reduced Dynamic Orbit Determination
  - Combination of Dynamic –and Kinematic Orbit Determination

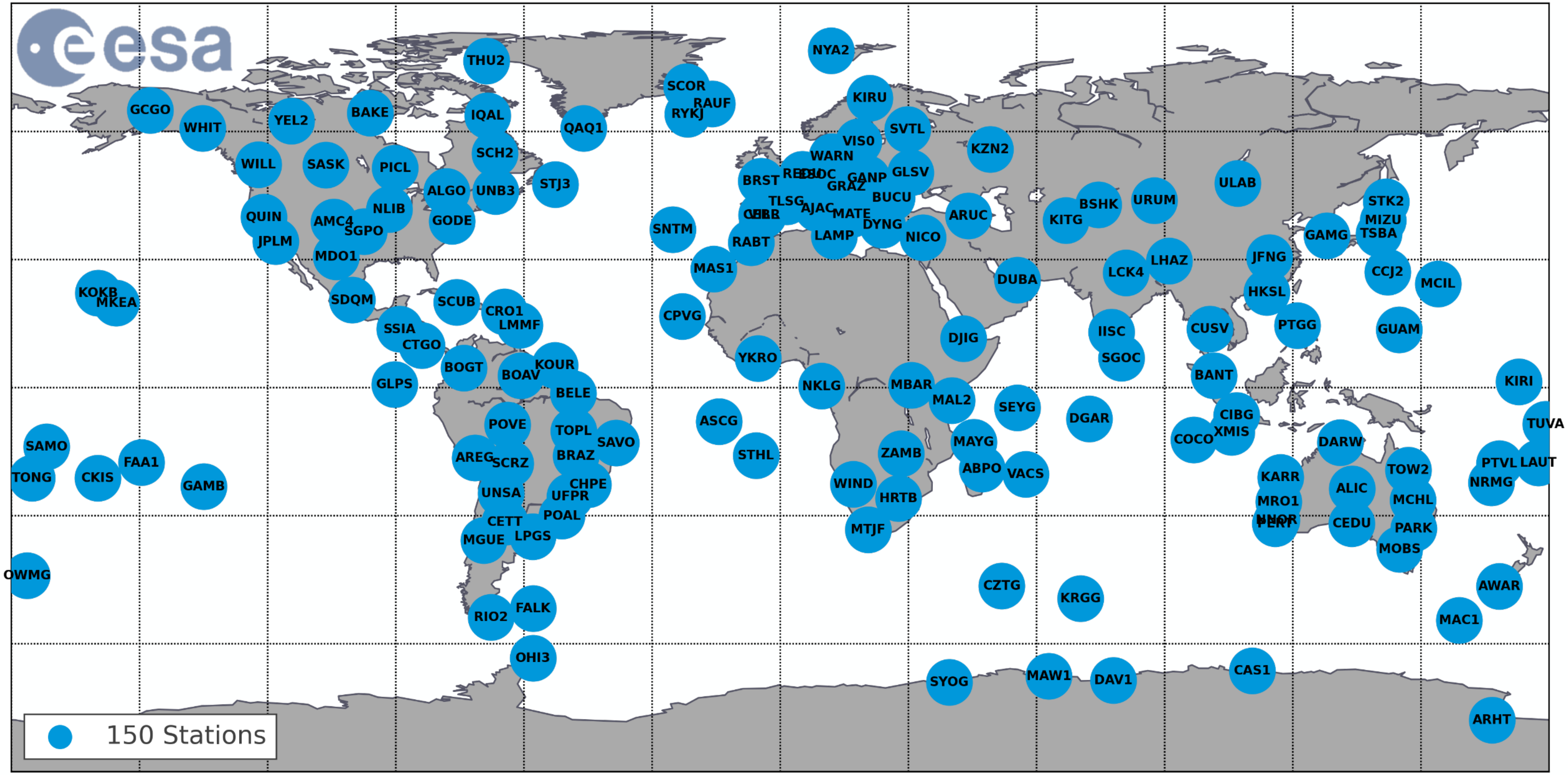
Satellite Orbit Determination - Network Proccessing



ESA's GNSS Observation Network (EGON)



ESOC MGNSS: Optimized Global Station Selection

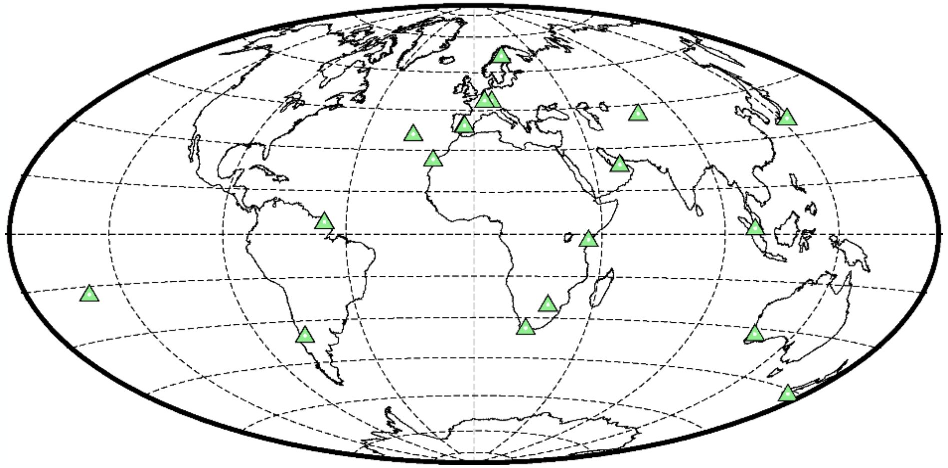


ESOC MGNSS station selection on 2022/07/01

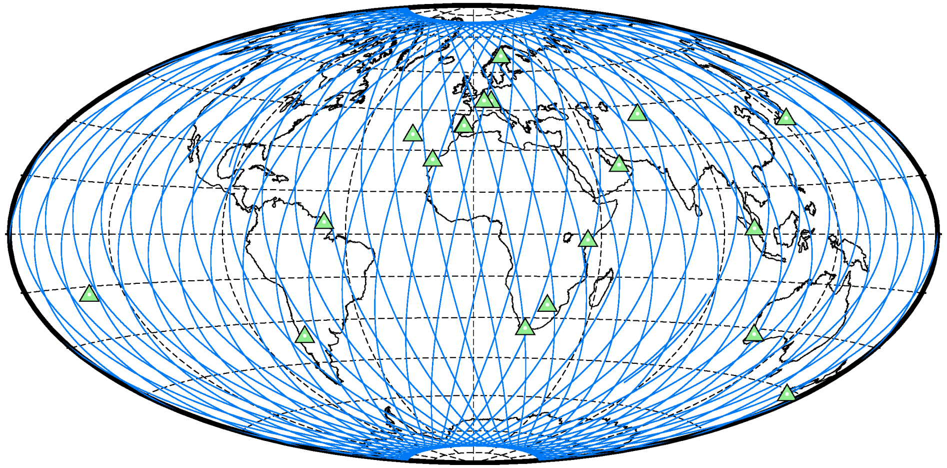
Network Processing including Sentinel Satellites

Polar-orbiting Sentinel constellation providing homogenous global coverage over both hemispheres

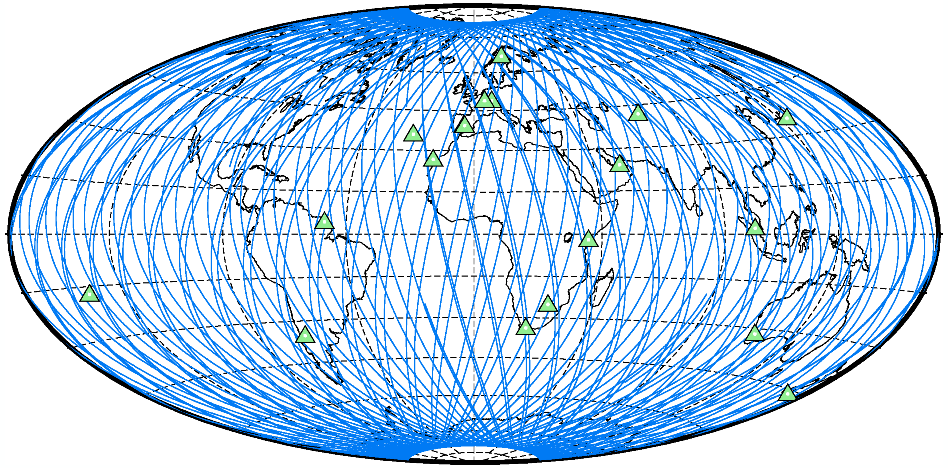
ESOC ground network as of July 2018 (# 19 stations)



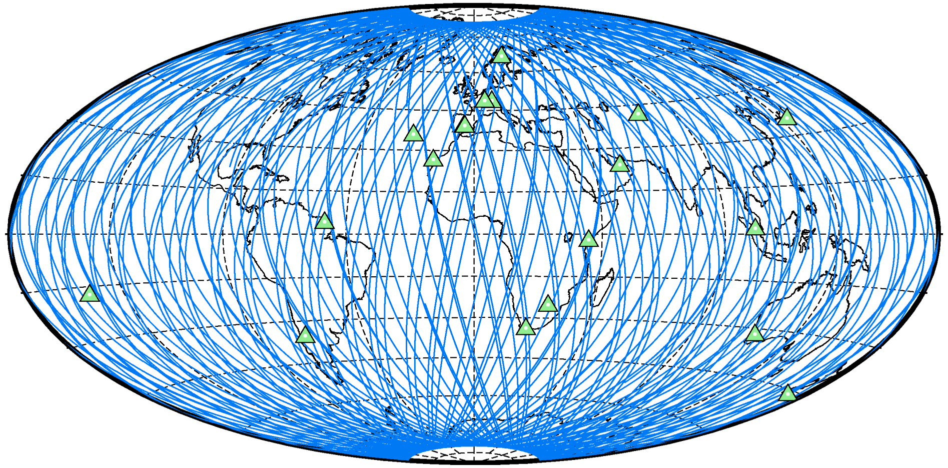
ESOC stations together with one–day ground tracks of Sentinel–1AB (# 2 SVs)



ESOC stations together with one–day ground tracks of Sentinel–1AB/2AB (# 4 SVs)



ESOC stations together with one–day ground tracks of Sentinel–1AB/2AB/3AB (# 6 SVs)



ESA/ESOC's Galileo Precise Orbit and Clocks Determination - Concepts

Batch processing systems - **NAPEOS**

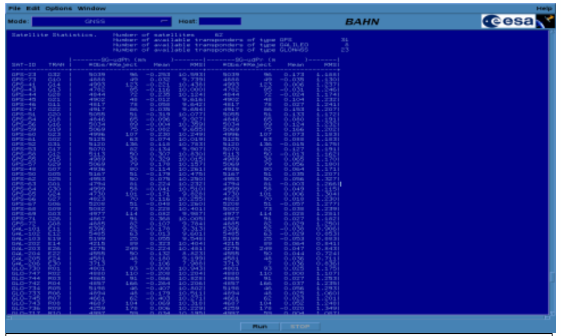
- High-precision orbit and clock determination and prediction
- Estimation of all relevant parameters and products
    - Station coordinates, Earth Orientation Parameters, …

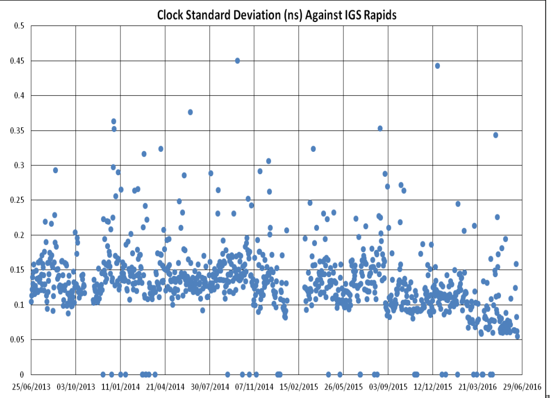
Batch processing systems (experimental status) - **EPODS** (ESOC Precise Orbit Determination System)

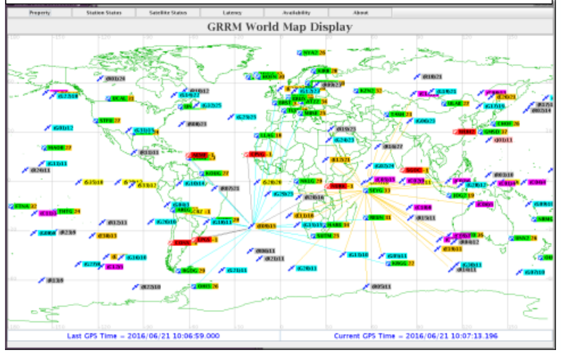
- Processing based on all available GNSS signals (RINEX) – undifferenced observations and no use of linear combinations
- Processing of GNSS, SLR, DORIS, ISL and VLBI observations
- High-precision orbit and clock determination and prediction
- Estimation of all relevant parameters and products
    - Station coordinates, Earth Orientation Parameters, …

Real Time GNSS processing system - **RETINA**

- Real Time Kalman filter for GNSS clock estimation
- Highly flexible infrastructure for visualisation, monitoring, control and for handling Real Time streams







ESA/ESOC's Galileo Precise Orbit and Clocks Determination

Dynamic POD Concept - Batch Processing

Galileo Dynamic Model

- Galileo dynamic modelling is considered as very good and stable
- Areas for further improvements have been identified, e.g. Radiation, clock models

Galileo Orbit Prediction

- Orbit prediction accuracy performance is considered as very good
- Galileo radial error is driven by the mass/area property – Galileo satellite is relatively light

Galileo Orbits and Clocks Estimation

- Important for the accuracy performance is the number of stations, geometry of the stations and also the quality of the observations
- Galileo orbit estimation is on the same level as GPS, despite the fact that for the Galileo network solution we have only the half of the number of satellites

GNSS Observation Equation – Code Phase

A GNSS code observation (in m) with frequency index i = 1,2,5,6,7,8,.. (carrier phase frequency
f_i and wavelength
λ_i) and signal index a = C,W,I,Q,.. generated by receiver
r from signals of GNSS satellite
s, measured at epoch
t_r in the receiver time scale and processed at epoch
t in the processing reference time scale is given by:

$$C^s_{r,ia}(t_r) = \rho^s_r(t) + corr_\tau(t) + corr_{geom}(t, dt_r(t)) + c[dt_r(t) - dt^s(t) + \delta dt^s_{rel}(t)] + \frac{40.28}{f_i^2}10^{16} \cdot STEC^s_r(t) + UCD_{r,ia}(t) + UCD^s_{ia}(t) + Corr^s_r(t) + \epsilon_{C^s_{r,ia}}(t)$$

where

- $\rho^s_r(t) = |\vec{X}^s_I(t) - \vec{X}_{I,r}(t)|$ is the geometric distance between receiver position (antenna reference point) and satellite position (centre of mass) both at reception epoch t and given in an inertial reference frame
- $corr_\tau(t)$ is the travel time correction which needs to be applied since the satellite position to derive the geometric distance is computed at reception epoch t instead of signal transmission time
- $corr_{geom}(t, dt_r(t))$ is the geometric correction which needs to be applied since the observations are measured in receiver time, but processed in the processing reference time scale
- $dt_r(t)$ and $dt^s(t)$ are the receiver and satellite clock offsets respectively with respect to the processing reference time scale
- $\delta dt^s_{rel}(t)$ is the periodic GNSS satellite clock relativistic effect due to time dilation, including the effect of the Earth's gravitational field J2 term
- $STEC^s_r(t)$ is the slant total electron content along the path of all signals between a GNSS satellite and receiver in TECU (= $10^{16} e^-/m^2$)
- $UCD_{r,ia}(t)$ and $UCD^s_{ia}(t)$ are the receiver and satellite uncalibrated code delays
- $Corr^s_r(t)$ includes all corrections selected in the "Measurement Correction Modelling" section of the Bahn - Observations panel. The optional correction terms are described in more detail below
- $\epsilon_{C^s_{r,ia}}(t)$ is the code observation noise including multipath

Orbit Determination – Parameter Estimation

State vector and a-priory Covariance matrix of parameters

$$X_0 = \begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ \dot{x}_0 \\ \dot{y}_0 \\ \dot{z}_0 \\ \alpha_1 \\ \vdots \\ \alpha_k \end{bmatrix}, \quad P_0 = \begin{bmatrix} \sigma_{11}^2 & \sigma_{12} & \cdots & \sigma_{1n} \\ \sigma_{21} & \sigma_{22}^2 & \cdots & \sigma_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{n1} & \sigma_{n2} & \cdots & \sigma_{nn}^2 \end{bmatrix}$$

Observation vector and a-priory Covariance matrix of observations

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}, \quad Q_0 = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_m^2 \end{bmatrix}$$

Observation residual (error) vector

$$\varepsilon = \begin{bmatrix} y_1 - f_1\left(\hat{X}(t_1)\right) \\ y_2 - f_2\left(\hat{X}(t_2)\right) \\ \vdots \\ y_m - f_m\left(\hat{X}(t_m)\right) \end{bmatrix}$$

Loss funtion

$$J(\hat{X}_0) = \varepsilon^T \cdot Q_0^{-1} \cdot \varepsilon + \Delta X_0^T \cdot P_0^{-1} \cdot \Delta X_0$$

Minimum!

Normal Equations – Iterative Process for Parameter Estimation

$$X_0^{k+1} = \hat{X}_0^k + (P_0^{-1} + F^T \cdot Q_0^{-1} \cdot F)^{-1} \cdot (\Delta Y_k + P_0^{-1} \cdot (X_0 - \hat{X}_0^k))$$

Design Matrix

$$F = \begin{bmatrix} \frac{\partial f_1}{\partial x_0} & \frac{\partial f_1}{\partial y_0} & \frac{\partial f_1}{\partial z_0} & \frac{\partial f_1}{\partial \dot{x}_0} & \frac{\partial f_1}{\partial \dot{y}_0} & \frac{\partial f_1}{\partial \dot{z}_0} & \frac{\partial f_1}{\partial \alpha_1} & \cdots & \frac{\partial f_1}{\partial \alpha_k} \\ \frac{\partial f_2}{\partial x_0} & \frac{\partial f_2}{\partial y_0} & \frac{\partial f_2}{\partial z_0} & \frac{\partial f_2}{\partial \dot{x}_0} & \frac{\partial f_2}{\partial \dot{y}_0} & \frac{\partial f_2}{\partial \dot{z}_0} & \frac{\partial f_2}{\partial \alpha_1} & \cdots & \frac{\partial f_2}{\partial \alpha_k} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial f_m}{\partial x_0} & \frac{\partial f_m}{\partial y_0} & \frac{\partial f_m}{\partial z_0} & \frac{\partial f_m}{\partial \dot{x}_0} & \frac{\partial f_m}{\partial \dot{y}_0} & \frac{\partial f_m}{\partial \dot{z}_0} & \frac{\partial f_m}{\partial \alpha_1} & \cdots & \frac{\partial f_m}{\partial \alpha_k} \end{bmatrix}$$

Residual Matrix

$$\Delta Y_k = \begin{bmatrix} y_1 - f_1(\hat{X}_0, t_1) \\ y_2 - f_2(\hat{X}_0, t_2) \\ \vdots \\ y_m - f_m(\hat{X}_0, t_m) \end{bmatrix}$$

ESA/ESOC's Galileo Precise Orbit and Clocks Determination

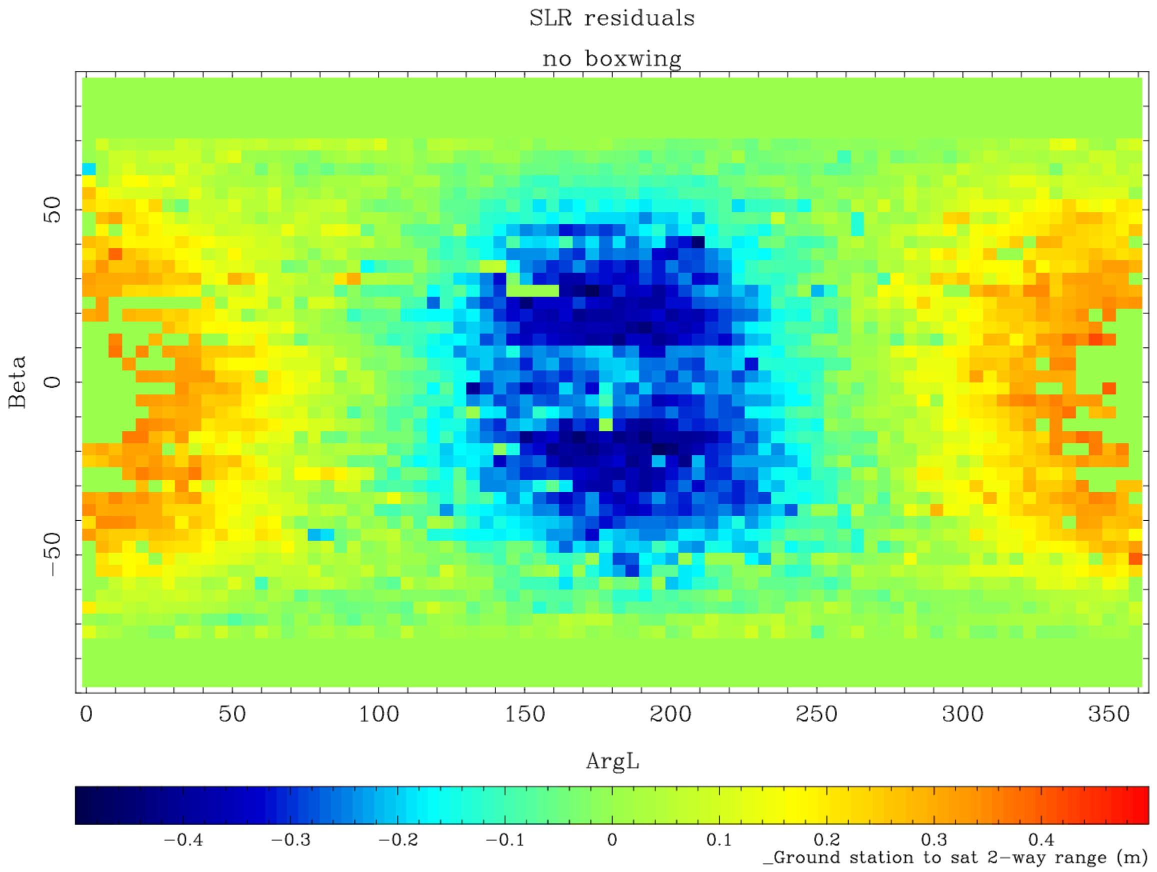
POD Concepts - Batch Processing

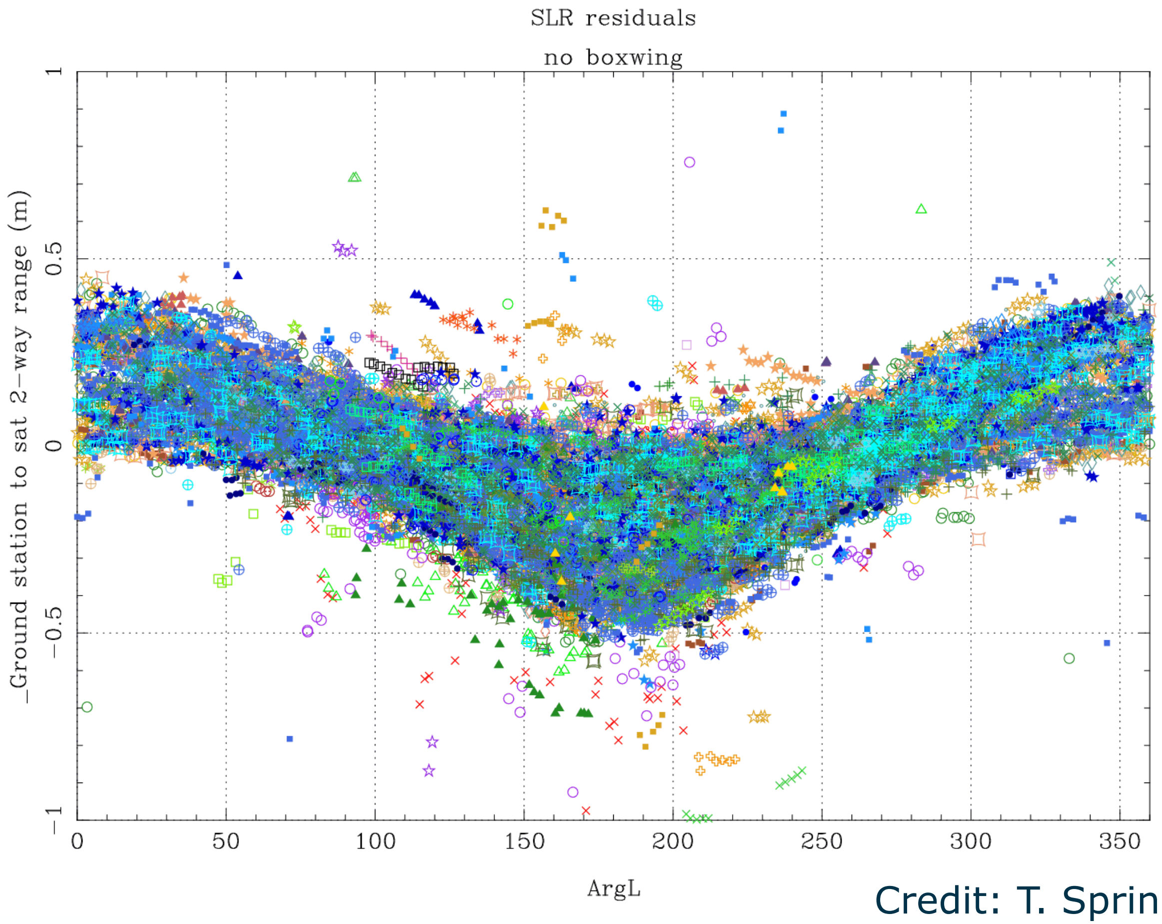
- POD based on dual-freq. Iono-Free Galileo observations provides very good results and is currently the standard approach
- POD based on multi-freq., multi-signal undifferenced and no linear combinations are applied to the observations (Raw Method) is closer to physical reality and will improve the POD accuracy even further this will be the standard concept in the near future
- For multi-GNSS the Raw Method has the potential to change the approach for POD, by allowing to take advantage of the strength of the individual GNSS (e.g. clocks of Galileo)
- Ambiguity fixing is implemented and improves the GNSS orbit accuracy estimation significantly

GALILEO Radiation Pressure Modelling

SLR Residuals with only ECOM (empirical model)

2016



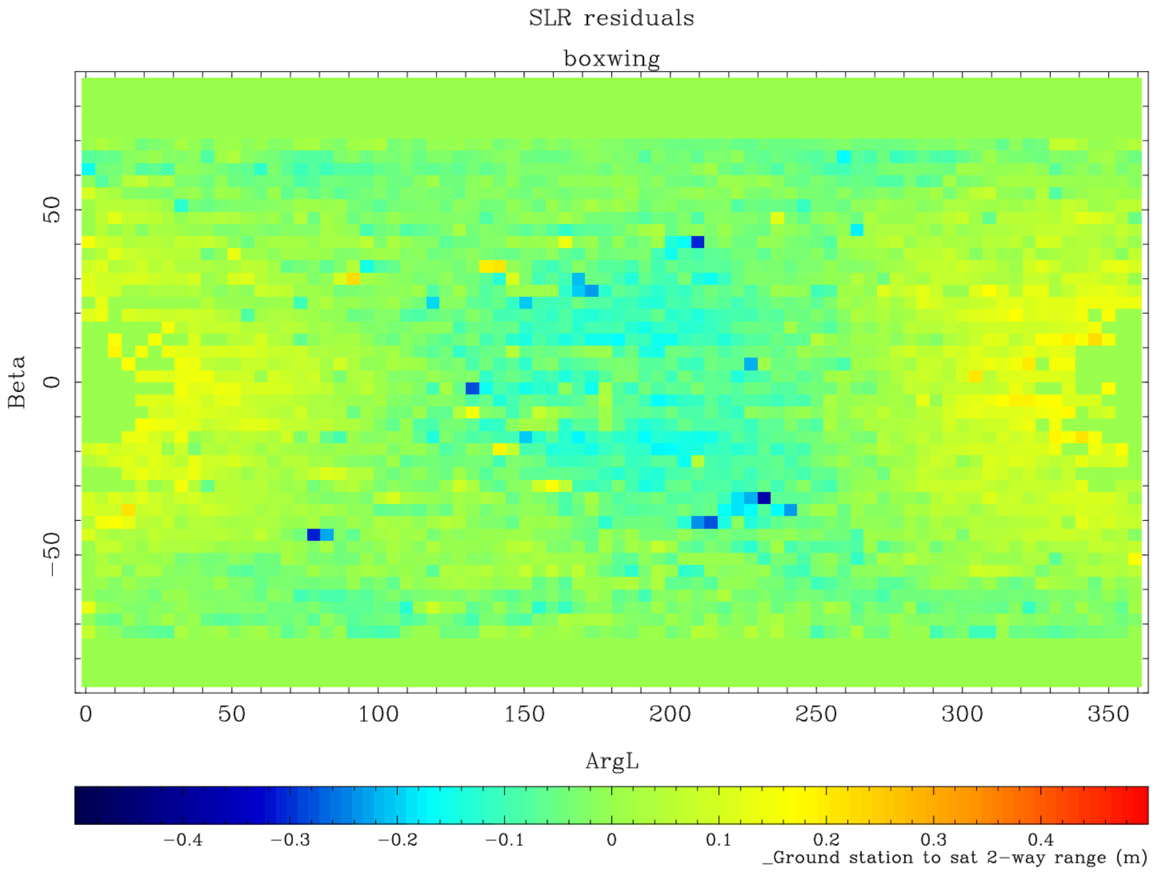


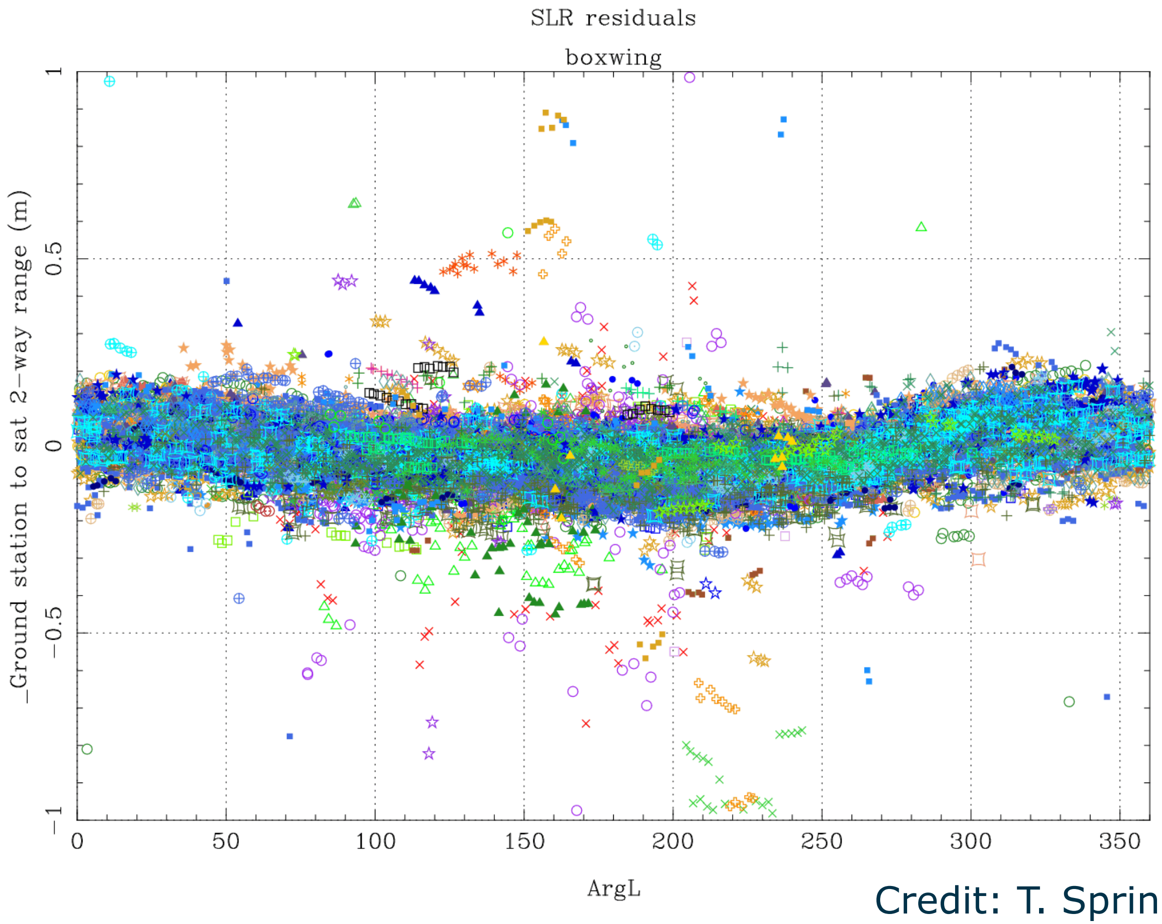
Credit: T. Springer

GALILEO Radiation Pressure Modelling

SLR Residuals with Box-Wing model (physical model)

2016



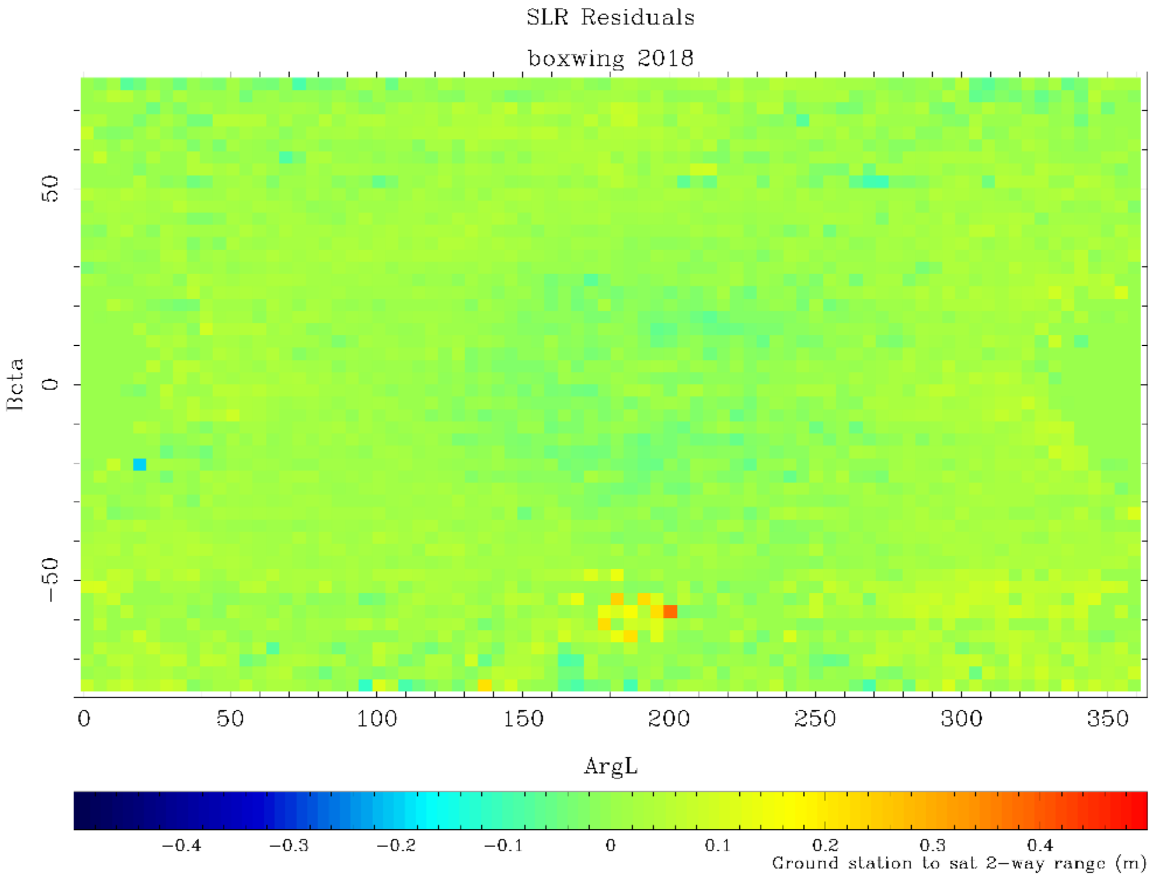


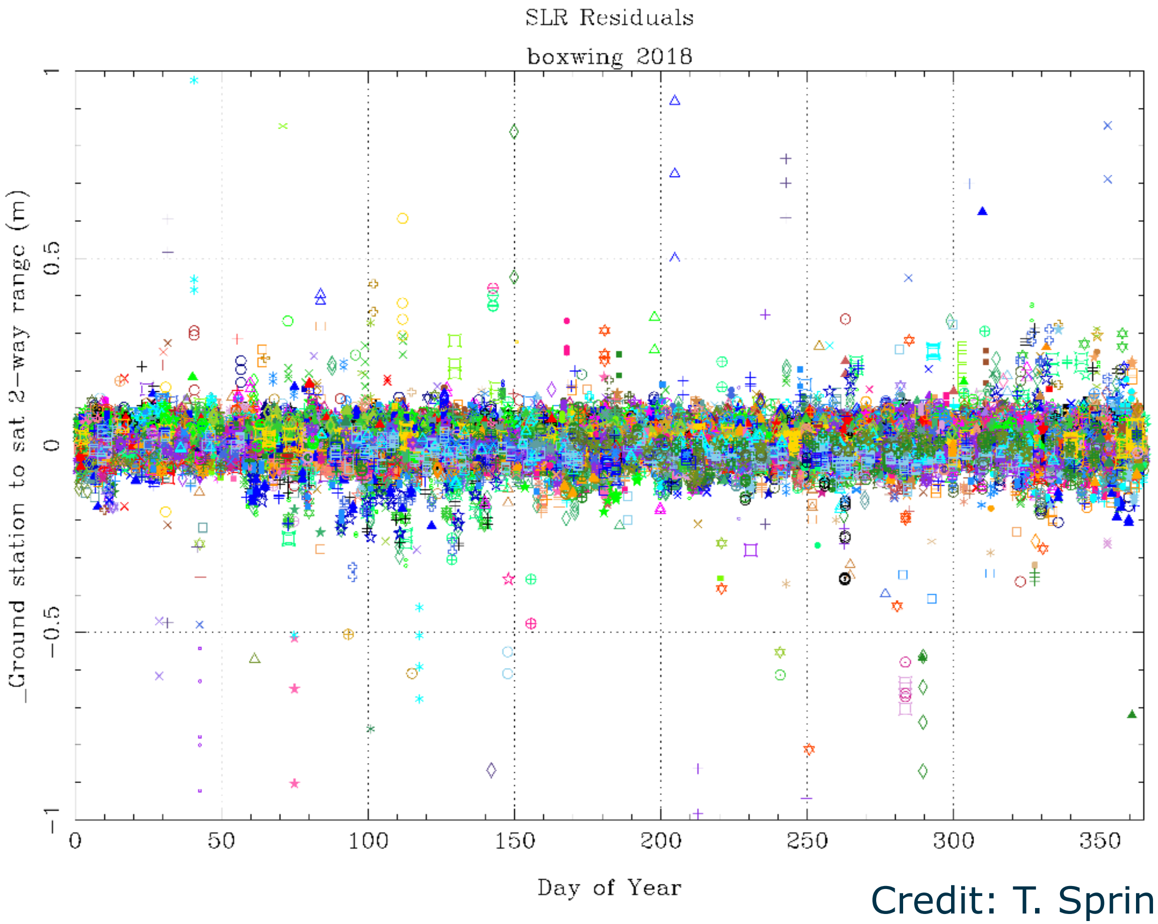
Credit: T. Springer

GALILEO Radiation Pressure Modelling

SLR Residuals with Box-Wing model (physical model)

2018





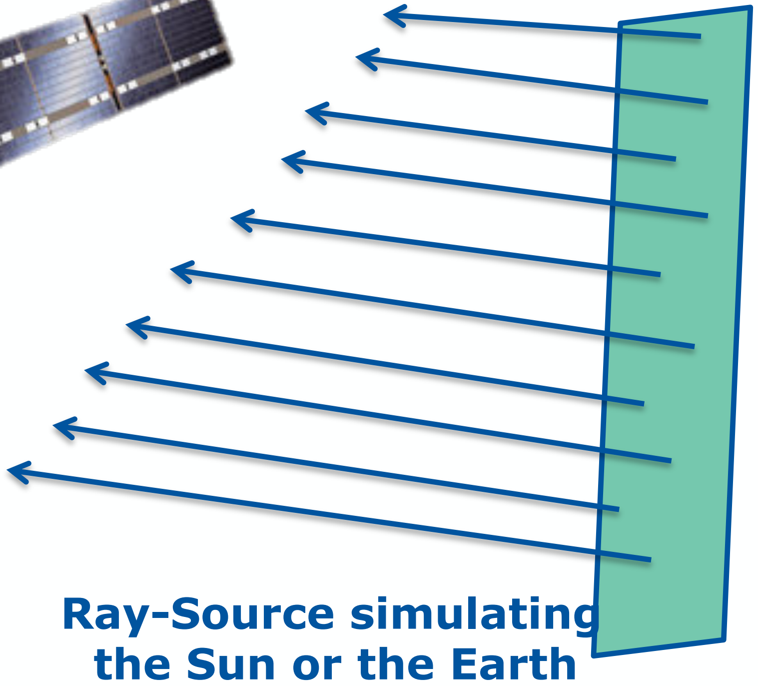
Credit: T. Springer

Next Generation Radiation Pressure Model

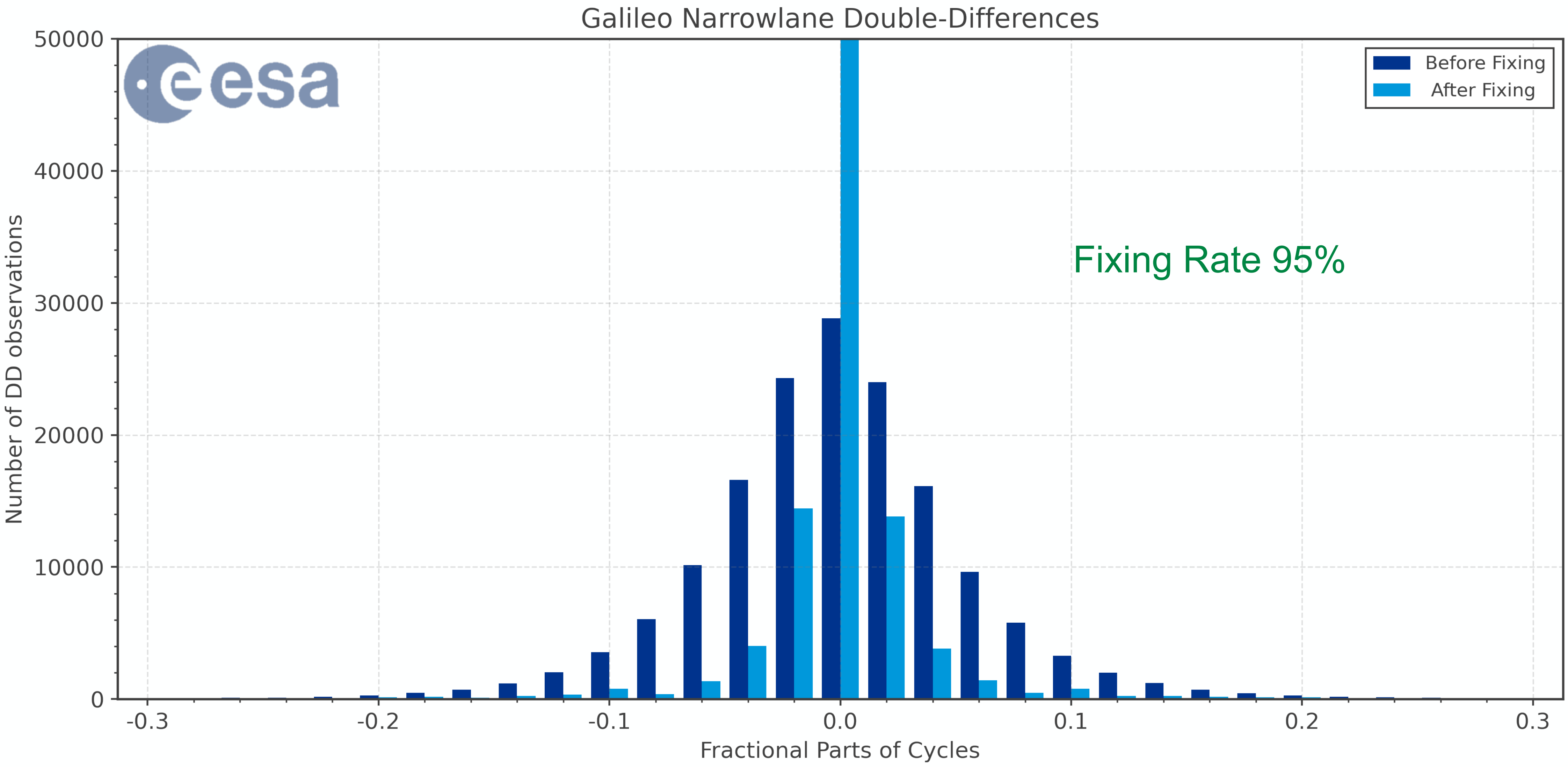
ARPA (Aerodynamics and Radiation Pressure Analysis)

- Replacement of Box-Wing model by **Raytracing** Procedure
- Detailed information about satellite geometry and surface properties allows improved modelling of **Radiation Pressure** and **Air Drag** (LEO)

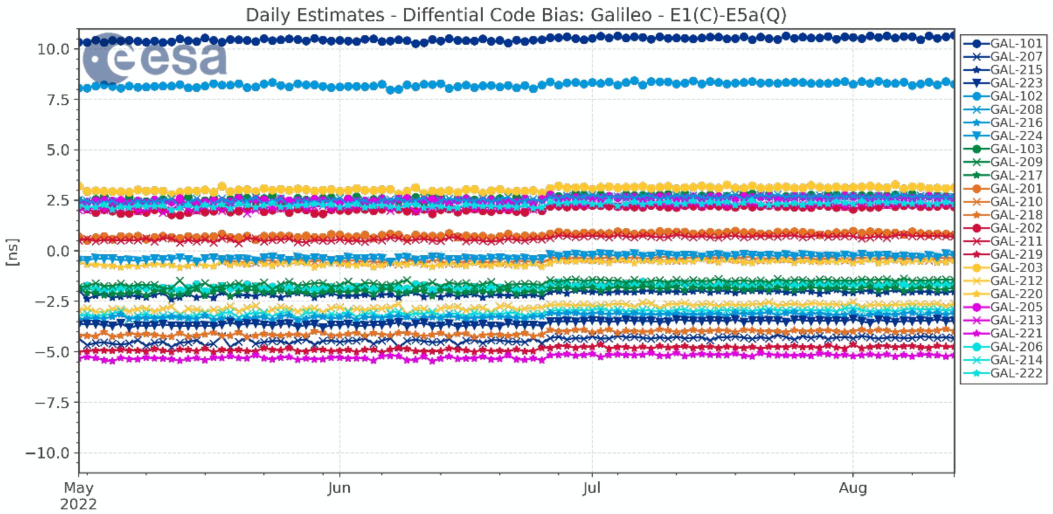
Galileo FOC.
Credit: ESA-P. Carril

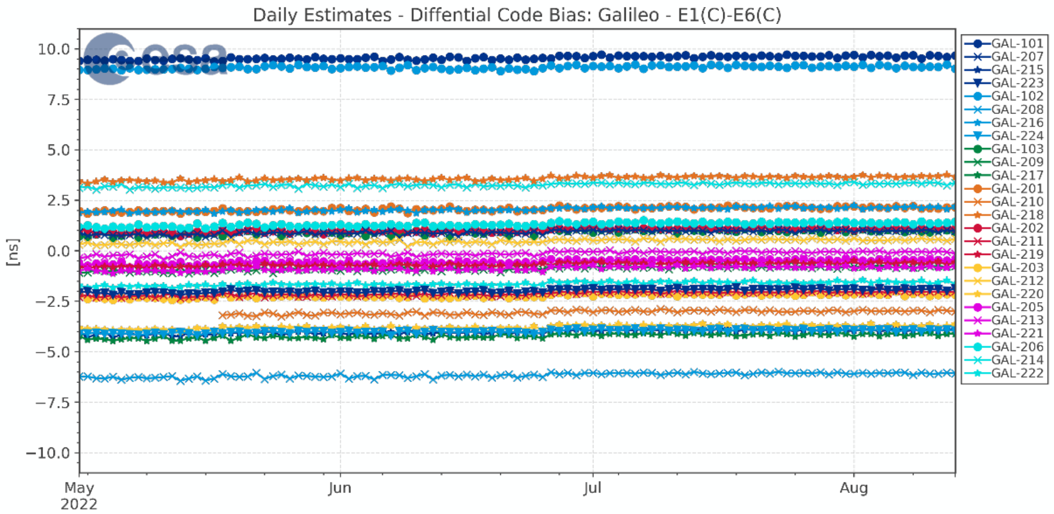


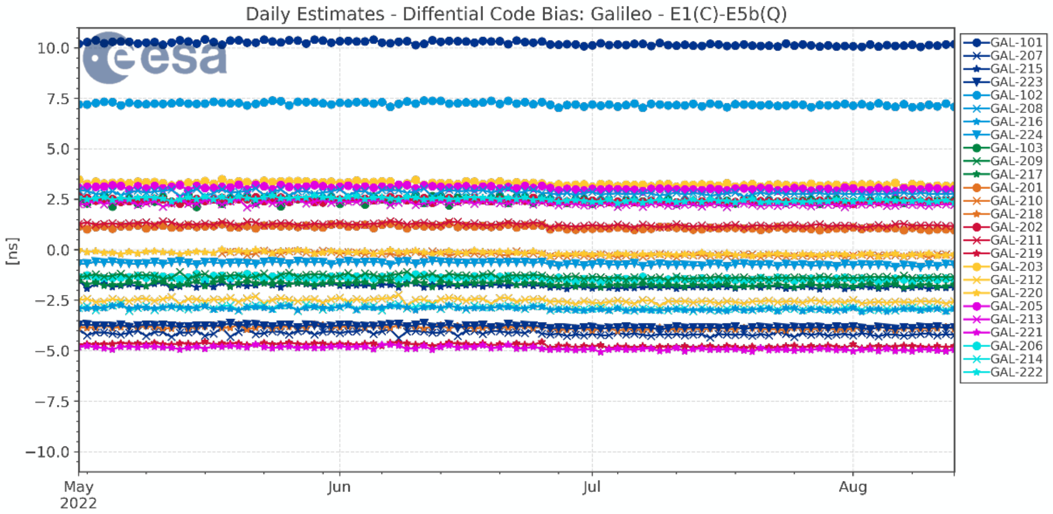
Galileo Ambiguity Fixing

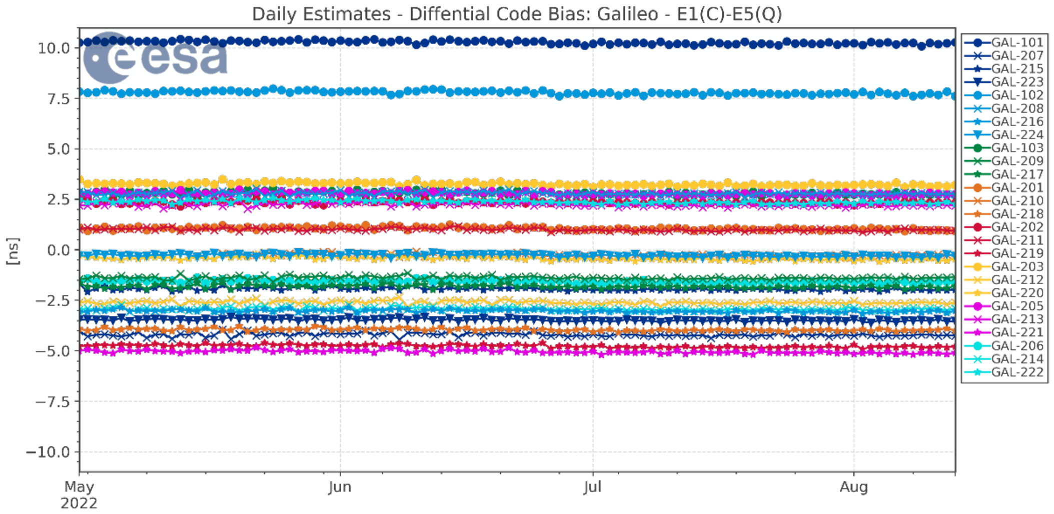


Galileo Differential Code Bias Estimation

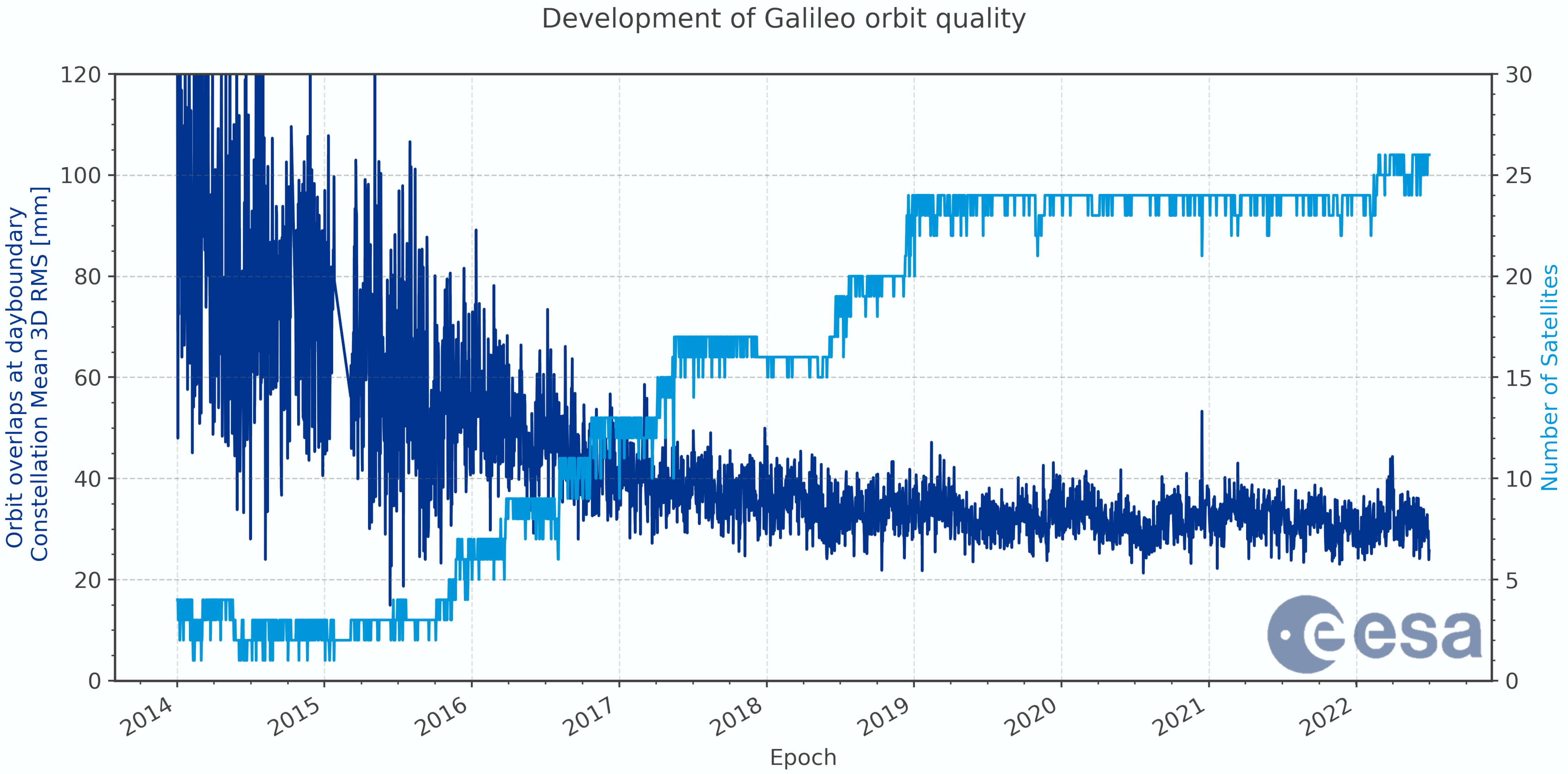








Continuous improvement of Galileo orbits



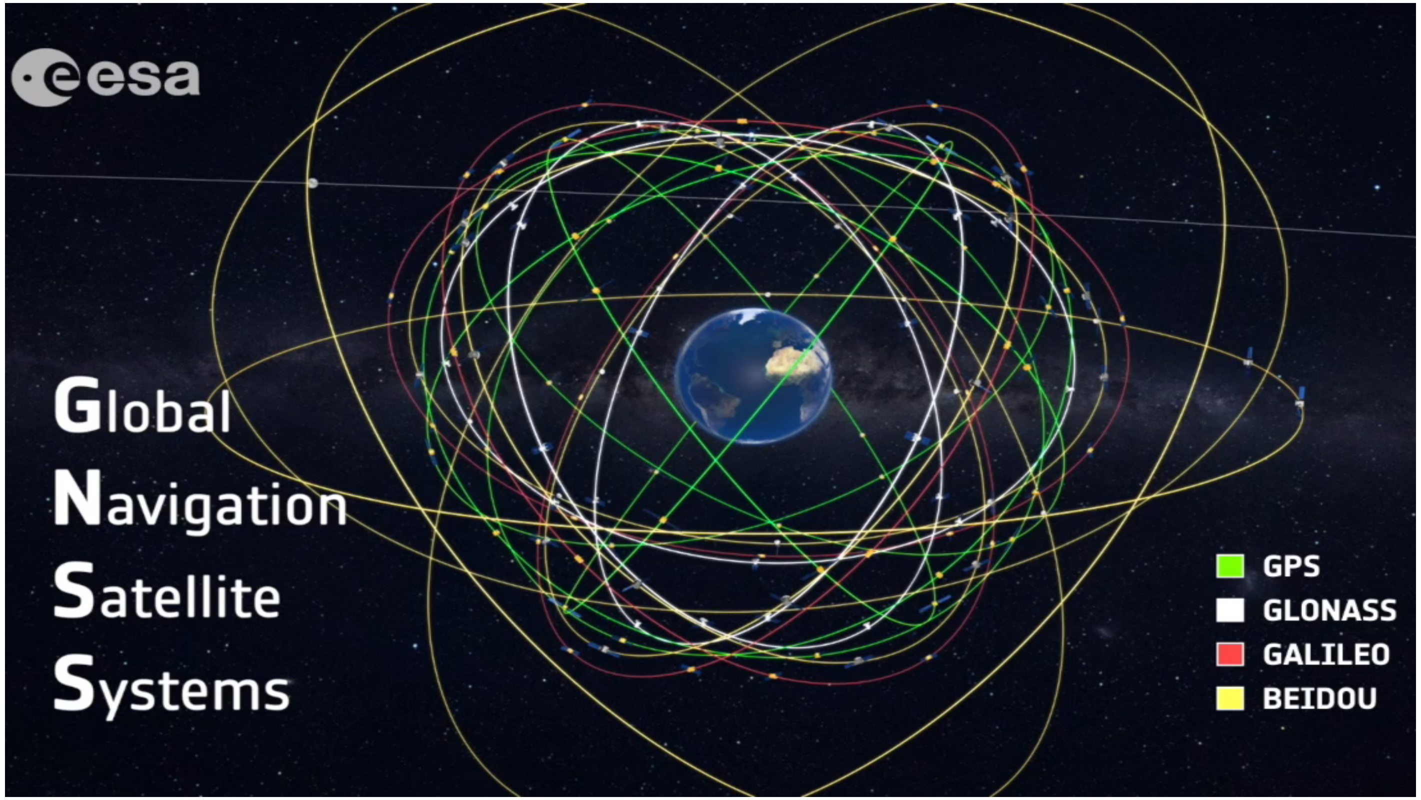
Galileo orbit quality (2017–present)

[mm]		Day-boundary overlap RMS				Satellite Laser Ranging Residuals		
System	Type	Radial	Along	Cross	3D	Sigma	Mean	RMS
Galileo	**IOV**	**24**	**29**	**20**	**42**	**23**	**11**	**26**
	FOC	**22**	**25**	**18**	**38**	**24**	**33**	**41**
GPS	IIR	21	23	18	36	-	-	-
	IIF	18	22	16	33	-	-	-
	III	23	28	23	43	-	-	-

Multi-GNSS processing at ESOC

- Combined GNSS processing
- Exploit interoperability of the systems

	Processed	In Orbit
GPS	32	32
GLONASS	18	26
Galileo	26	28
BeiDou	43	49
QZSS	4	4
Total	123	139



Advanced Processing Features

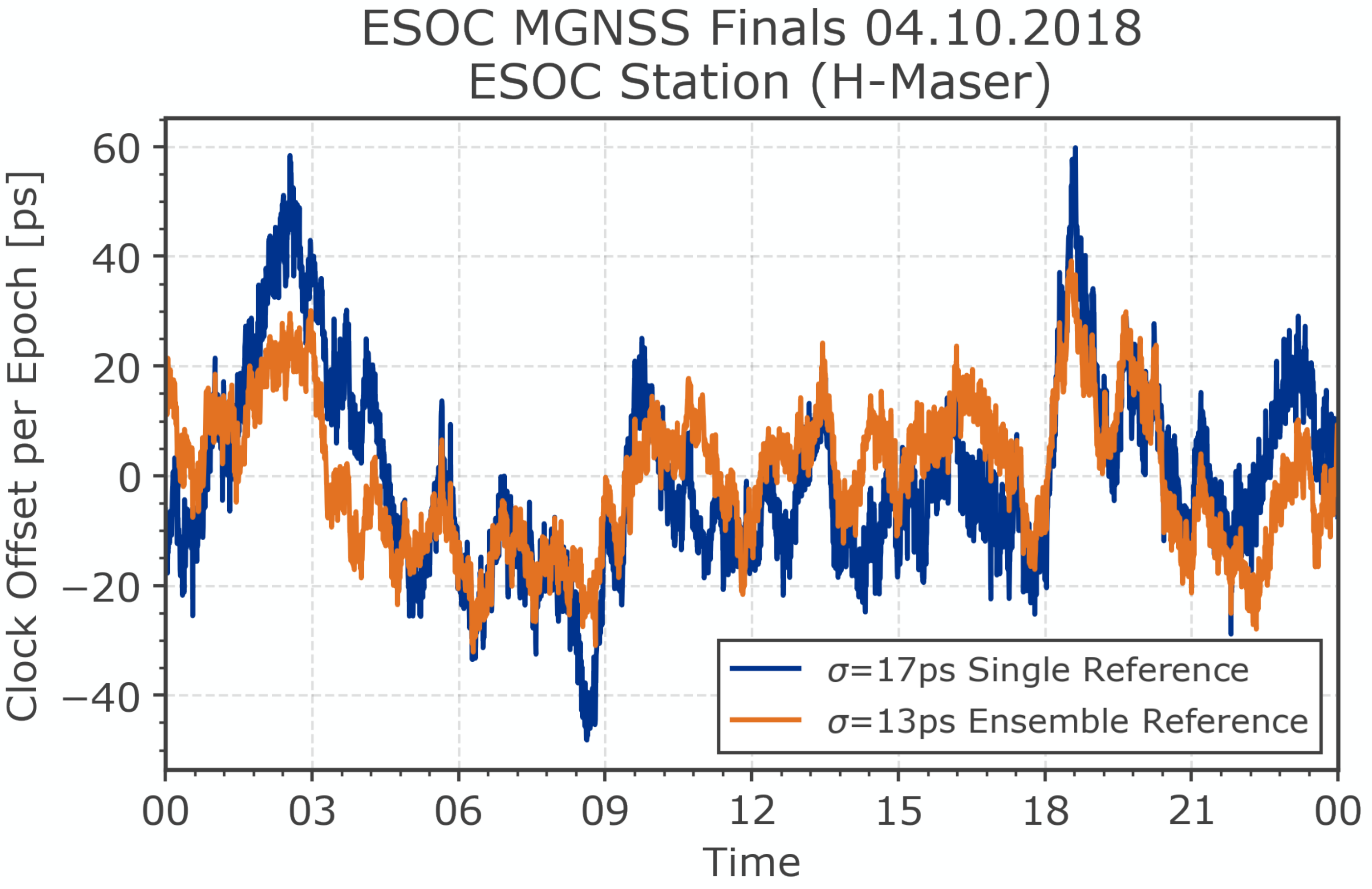
Advanced logic to overcome clock datum defect

Old:

Fix **Station clock** with best linear fit as Reference clock

New: Ensemble Clock

Zero-mean constraint on the stations with best linear fit to reduce systematics

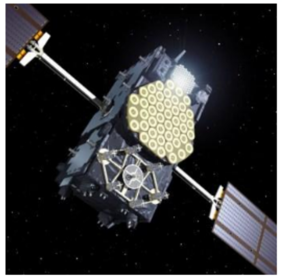


Multi-GNSS processing at ESOC

- Operational multi-GNSS processing at ESOC's Navigation Support Office
  - Routine analysis of ~30 Mio. observables/day from 120+ GNSS satellites
  - Ambiguity-fixed one-day arc solutions with unsurpassed accuracy at the 0.02 to 0.05 m level
  - Constellations – GPS, GLONASS, Galileo, BeiDou, QZSS
- Data products:
  - 5-min orbits, 30-sec "white-noise" clocks, 1-day EOPs, and 1-day ISBs
  - Available in IGS format for 2014-01-01 onwards at http://navigation-office.esa.int


GPS

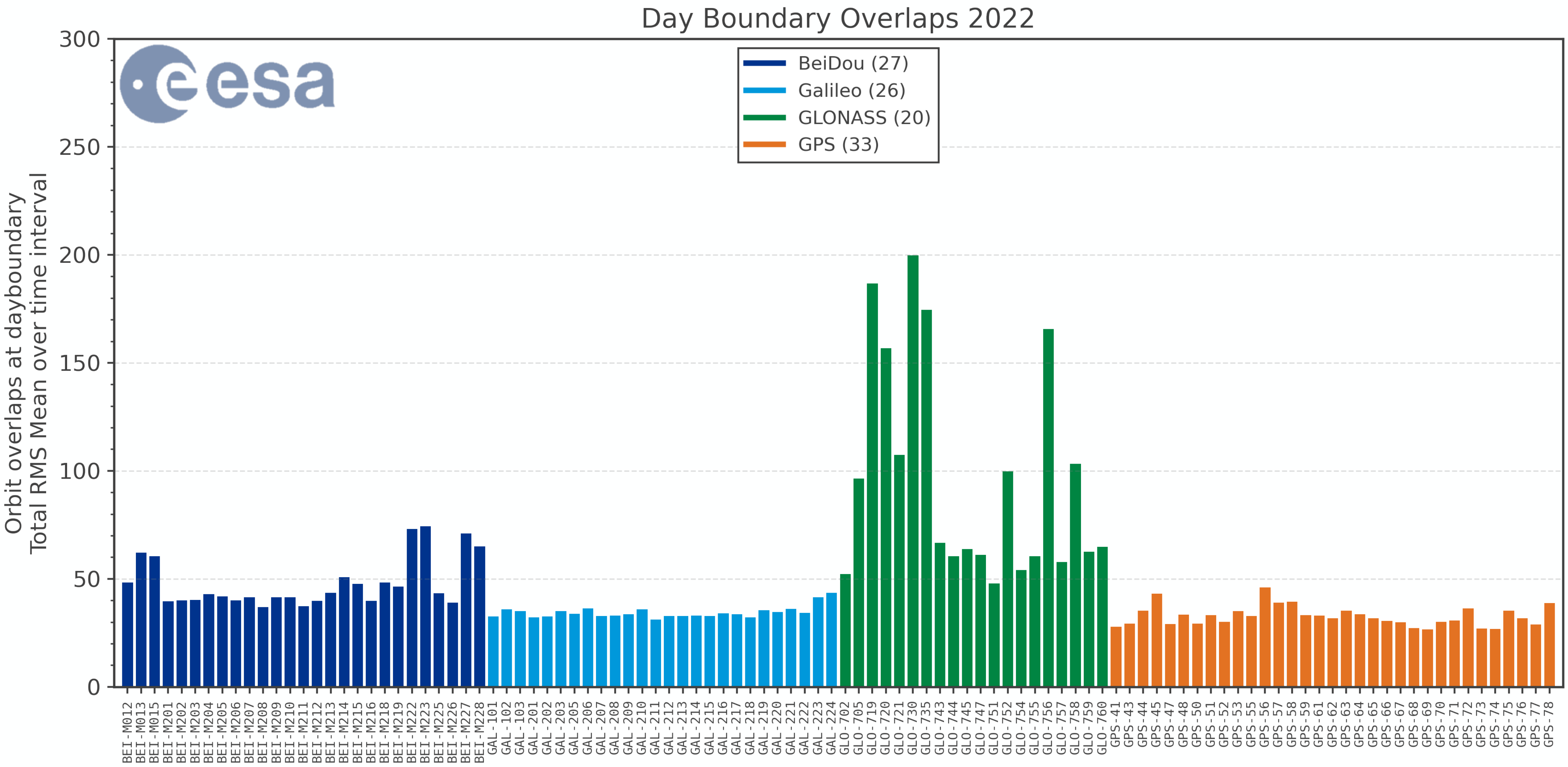

GLONASS


Galileo


BeiDou


QZSS

ESOC MGNSS Final Products



ESOC MGNSS Final Products

- Final products with 12 – 5 days delay (ESA0MGNFIN)

Products	Format	Ext.	Interval	Period
Ephemeris	SP3	.sp3	300 s	24 h
Clocks	CLK RINEX	.clk	30 s	24 h
Inter-System Bias	SINEX	.bias	24 h	24 h
Earth Rotation Parameter	ASCII	.erp	24 h	24 h
Summary file	ASCII	.sum		168 h

- Publicly available at: http://navigation-office.esa.int

Processing Standards and Models

EOP	Precession-nutation	IAU 2006/2000A
	Celestial pole offsets	IAU 2006/2000A, daily dx and dy corrections from IERS Bulletin-A applied
	Celestial pole rates	interpolating between given offsets
	Subdaily nutation	prograde diurnal and semi-diurnal nutations in polar motion applied using IERS routine PMSDNUT2.F
	UT1-UTC	interpolated from IERS Bulletin A (IERS rapids)
	UT1 libration	semi-diurnal UT1 libration applied using IERS routine UT1LIBR.F
	Subdaily pole/UT1	diurnal and semi-diurnal variations in pole coordinates and UT1 (caused by oceanic tidal effects) applied using according to IERS routine ORTHO_EOP.F
	Mean pole	IERS 2010 mean pole model (quadratic trend until 2010, linear trend from 2010
	Terrestrial pole offsets	interpolated from IERS Bulletin A (IERS rapids)
Terrestrial reference frame	A priori frame	ITRF2014
	Solid Earth tides	anelastic Earth model, IERS 2010 Conventions (dehanttideinel.f routine)
	Permanent tide	zero-frequency contribution left in tide model, NOT in site coordinates (conventional tide-free)
	Solid Earth pole tide	IERS 2010 conventions, mean pole removed by IERS 2010 mean pole model
	Ocean tides	IERS 2010 conventions, site-dependent amps/phases from free ocean tide loading provider (Bos and Scherneck, 2017) for EOT11A tide model including centre of mass correction, NEU site displacements computed using HARDISP.F from D.Agnew
Gravitational perturbations	Gravity field (static)	EIGEN-GRGS.RL03-v2, C21 and S21 computed according to IERS 2010 conventions
	Gravity field (time varying)	annual/semi-annual terms of the low coefficients (up to degree and order 50)
	Solid Earth tides	applied, see above
	Permanent tide (tidal system)	applied, see above
	Solid Earth pole tide	applied, see above
	Ocean tides	applied, see above
	Ocean pole tide	applied, model by S. Desai for C21 and S21 terms only (IERS Conventions 2010)
	Lunar gravity	applied, only J2 effect considered
	Third bodies	JPL DE405: all planets, Sun and Moon
Relativistic model	Schwarzschild terms	applied
	Lense-Thirring precession	applied, IERS 2010 conventions
	Geodesic (de Sitter) precession	applied, IERS 2010 conventions
	Relativistic clock effects	2nd order relativistic correction for non-zero orbit ellipticity
	Gravitational time delay	applied, IERS 2010 conventions

GNSS Modelling and Parametrisation

Observations	Sampling	30s
	Elevation cutoff angle	10degrees
	Weighting of observations	elevation-dependent
	Observation type	ionosphere-free linear combination of dual-frequency: Galileo E1-E5a, GPS L1-L2, GLONASS L1-L2, BeiDou B1-B3
Troposphere	Hydrostatic a priori model	Saastamoinen, pressure and temperature from GPT model
	Hydrostatic mapping function	GMF dry (Boehm et. al, 2006)
	Wet mapping function	GMF wet (Boehm et. al, 2006)
	Gradient mapping functions	1/(sin(e) * tan(e) + 0.0032)
Ionosphere	First order effect	accounted for by dual-frequency obs. in linear combination
Gravity field	Degree and order	12
Non-gravitational perturbations	Solar radiation	Box-wing model
	Earth radiation (albedo + IR)	Box-wing model (monthly files based on CERES mission)
	Antenna thrust	applied
Satellite reference	Satellite mass	constant
	Satellite attitude model	GNSS nominal attitude
Antenna	GNSS satellite antenna	igs14.atx (SV-specific z-offsets, block-specific xy-offsets and block-specific nadir- and azimuth dependent PCVs applied from IGS based on ITRF2014)
	GNSS receiving antenna	igs14.atx (offsets from ARP and elevation- and azimuth dependent PCVs applied)
	Phase wind up	applied according to Wu et al. (1993)
Orbit integration	Integrator details	Adams-Bashforth/Adams-Moulton 8th order prediction-correction (multistep) method initialization: 8th order Runge Kutta (RKF)
	Integrator step size	120 steps per revolution
Parametrisation	Earth orientation	daily X-pole, Y-pole, pole rates, LOD
	Clock sampling	30s
	Transmitter & Receiver clocks	at each epoch
	Satellite orbits	deterministic positions and velocities (300s sampling)
	Arc length	24h
	Troposphere	zenith delay estimated as linear parameters every 1 hrs, North and East gradients as linear parameter per day
	Empirical accelerations	1 set per arc from the enhanced CODE orbit model (Springer, 1999): D0, Y0, B0, Bcos, Bsin
	1/rev empiricals (CPR)	1 set per arc in along-track: A0, Acos, Asin
	Phase cycle ambiguities	adjusted except when double difference ambiguities can be resolved confidently. Integer ambiguity resolution scheme from GFZ

Thank you very much for your attention

Navigation Support Office ESA/ESOC
www.navigation-office.esa.int
Werner.Enderle@esa.int