ESA/ESOC's activities and contributions to the Geodetic Reference
- The importance of Inter-Technique consistency

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Outline

- Introduction
  - Importance of accurate Terrestrial Reference Frames
  - Importance of Inter-Technique consistency
- ESA/ESOC's activities and contributions to the Terrestrial Reference Frame
  - Overview
  - Examples
- Future ESA Activities
- Take aways

Introduction

It is worth to highlight that, any kind of positioning and navigation on Earth, in Air and in Space relies on an accurate reference. On a global scale this reference is realised by International Terrestrial Reference Frame (ITRF).

UN Resolution 69/266. A global geodetic reference frame for sustainable development

Recognised “the economic and scientific importance of and the growing demand for an accurate and stable global geodetic reference frame for the Earth that allows the interrelationship of measurements taken anywhere on the Earth and in space”

The importance of this resolution for ESA, EU and Commercial Mission is acknowledged by the European Space Agency by making significant contributions for a sustainable development of the geodetic reference.

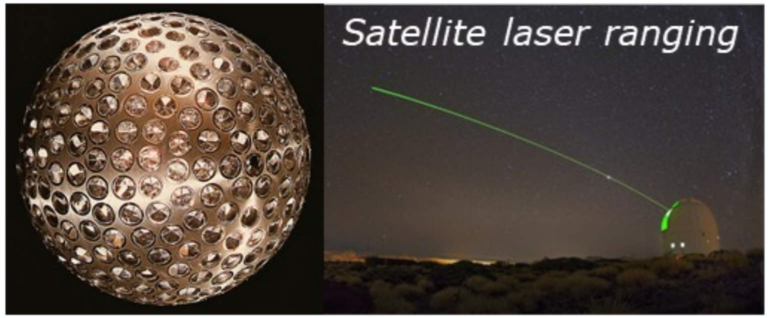
International Terrestrial Reference Frame (ITRF)

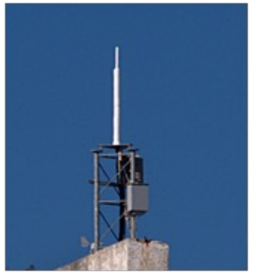
Contributing Space Geodetic Techniques

Different geodetic techniques are used for the realisation of the ITRF.

According to their peculiar observing principle and systematic errors, each technique plays a distinct role in the realization of the ITRF:

• Satellite Laser Ranging (SLR)	contribution to ITRF Origin and Scale
• Very Long Baseline Interferometry (VLBI)	contribution to ITRF Scale
• Global Navigation Satellite Systems (GNSS)	dissemination of ITRF - provides link between techniques
• Doppler Orbitography Integrated by Satellite (DORIS)	dissemination of ITRF for Altimetry missions





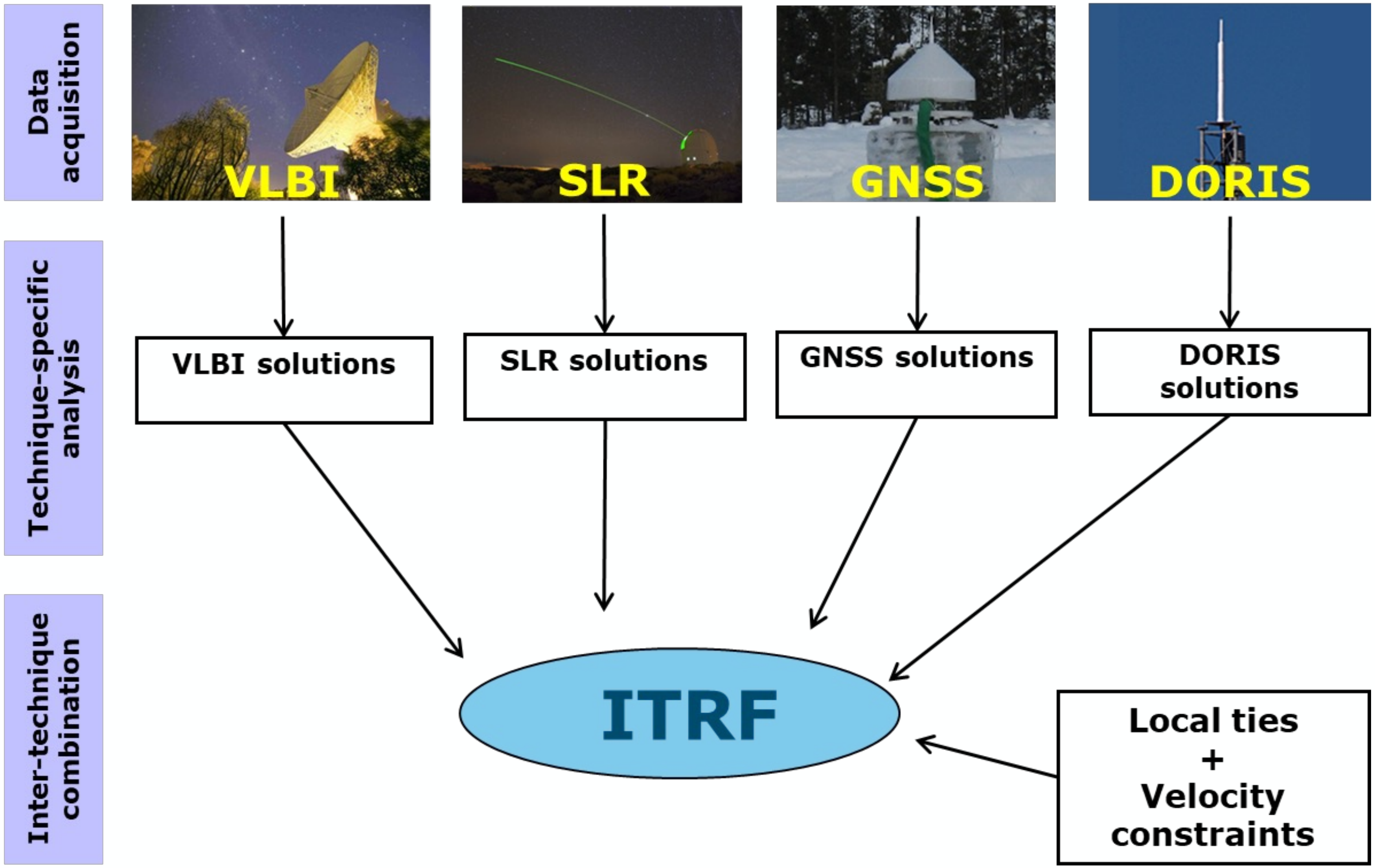
Doppler Orbitography Radiopositioning Integrated by Satellite

Technique Specific contributions to Reference Frames

Different space geodetic techniques are required to observe different reference frame parameters

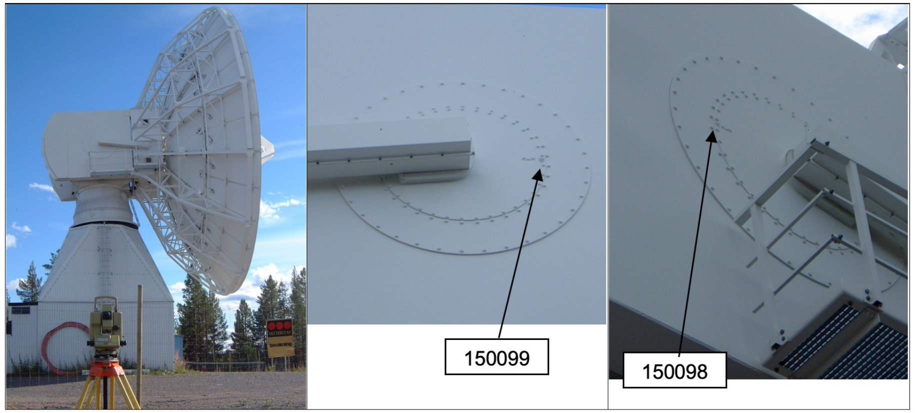
	Parameter	GNSS	SLR	DORIS	VLBI
Celestial Reference Frame (CRF)	Quasar positions				x
	Satellite orbits	x	x	x	
Earth Orientation Parameters (EOP)	Nutation				x
	UT1-UTC				x
	LOD	x	x	x	x
	Polar motion	x	x	x	x
	Polar motion rates	x		x	x
Terrestrial Reference Frame (TRF)	Station positions	x	x	x	x
	Scale	(x)	x		x
	Geocenter		x		
Nuisance parameters	Troposphere	x		x	x
	Ionosphere	x		x	x
	Clock biases	x		x	x
	Range biases		x		

Generation of ITRF

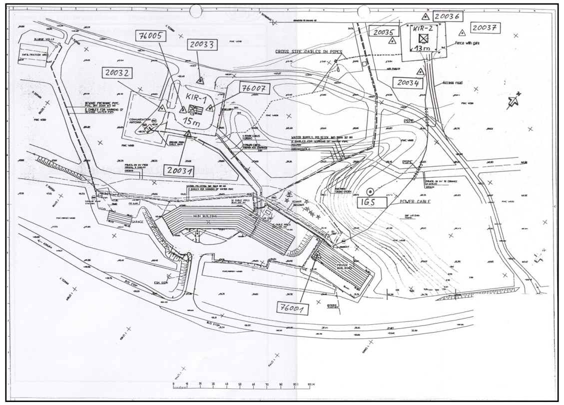


Generation of ITRF - Challenges
Inter-technique inconsistencies

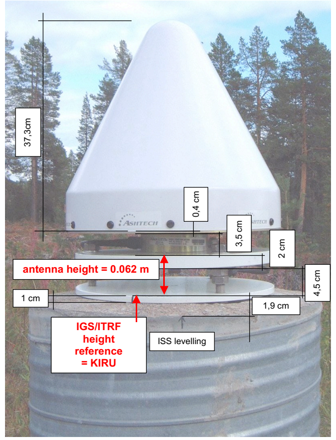
- Importance of consistency of models
- Importance of considering the correlation of estimated parameter
- Accuracy of Local Ties
  - The knowledge on the relative orientation of the technique specific reception points is mandatory to link the observations and as a result the estimated products (e.g. Orbits, Coordinates, …) of the different techniques.



Kiruna ESTRACK deep Space antenna



Sketch of Kiruna PCN in Local Survey 2003



Kiruna GNSS antenna

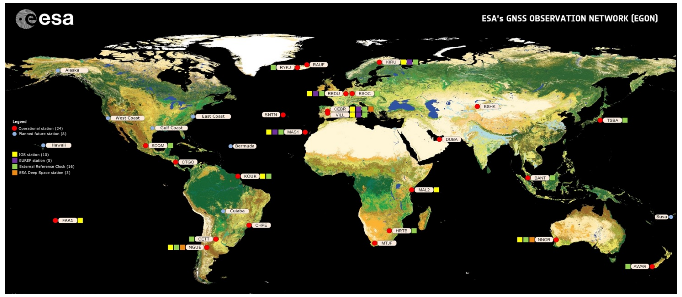
ESA/ESOC's activities and contributions to the Terrestrial Reference

ESA/ESOC's

Activities on Terrestrial Reference Frames and Earth Orientation Parameters

ESA/ESOC operates Ground Infrastructure – Data Acquisition – Local Ties

- ESA's GNSS Observation Network (EGON) – contributing to the IGS
- ESA/Europe is building up / operating SLR stations – contributing to the ILRS
- European Space Tracking network (ESTRACK)
- ESA's Tracking Site Directory (TSD)



ESA's GNSS Observation Network (EGON)

ESA/ESOC's Navigation Support Office processes all space geodetic techniques - Technique Specific Analysis

- Contribution to the International Association of Geodesy (IAG) as Analysis Centre (AC) to the:
  - International GNSS Service (IGS)
  - International Laser Ranging Service (ILRS)
  - International Doris Service (IDS)
- And as associated AC to the:
  - International VLBI Service (IVS)
- Responsible for the generation of the Galileo Terrestrial Reference Frame (GTRF) – GGSP Consortium leader

ESA/ESOC is an AC for 3 out of 4 Space Geodetic Techniques fourth, VLBI in preparation

IZN-1: Teide Observatory

ESA/ESOC's Navigation Support Office combines all space geodetic observations - Inter Technique Combination

- Combination on Observation Level (CoOL)
- Generation on Earth Rotation Parameters – new ESA/ESOC service

ESA/ESOC's activities – Combination on Observation Level

Improving Inter-Technique consistency

ESA/ESOC's **NA**vigation **P**ackage for **E**arth **O**rbiting **S**atellites (NAPEOS) is a software used for all tasks in the Navigation Support Office requiring highest accuracy.

NAPEOS software package is:

- Developed and maintained at ESA/ESOC – Navigation Support Office
- Using the latest models – enabling highest possible POD in all orbit regimes of the Space Service Volume
- Capable to process all space geodetic observations
- Capable to perform Combination on Observation Level (CoOL) including all four space geodetic techniques

*The CoOL - **C**ombination **o**n the **O**bservation **L**evel approach is the combination of multiple Space Geodetic Techniques in a single process, in the case of NAPEOS a single Least Squares Process. This approach ensures highest consistency and the proper consideration of correlations and variances.*

Therewith NAPEOS is perfectly suited to generate consistent inter-technique solutions and to analyse inconsistencies.

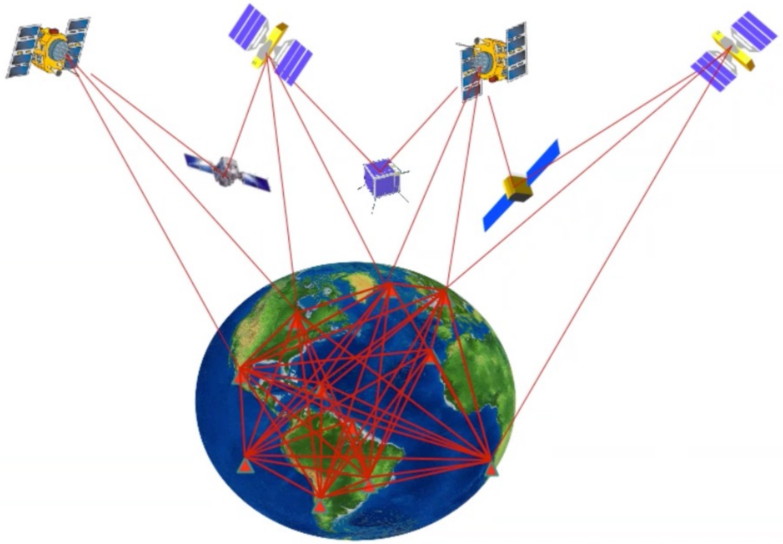
CoOL processing

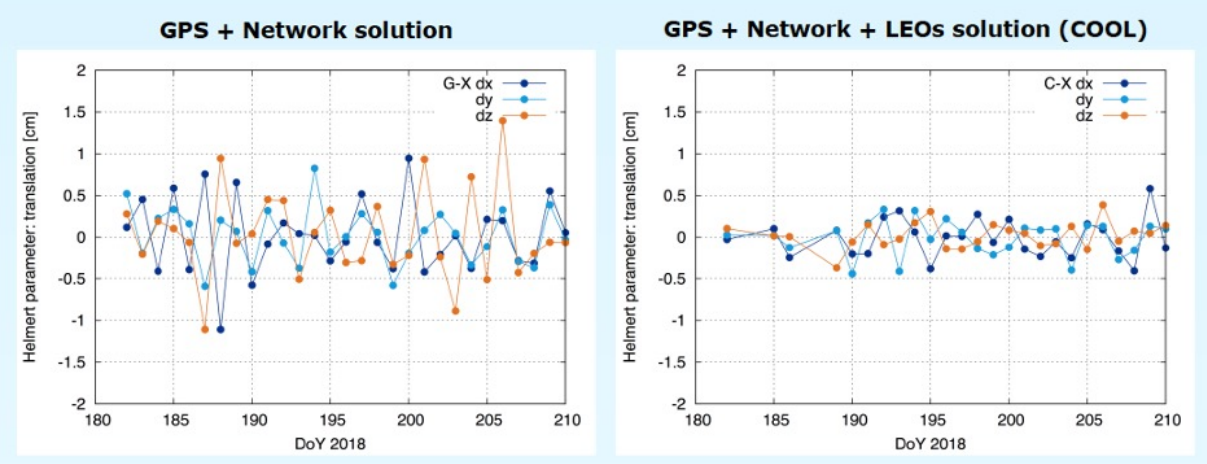
Example Sentinel-3A & 3B analysis

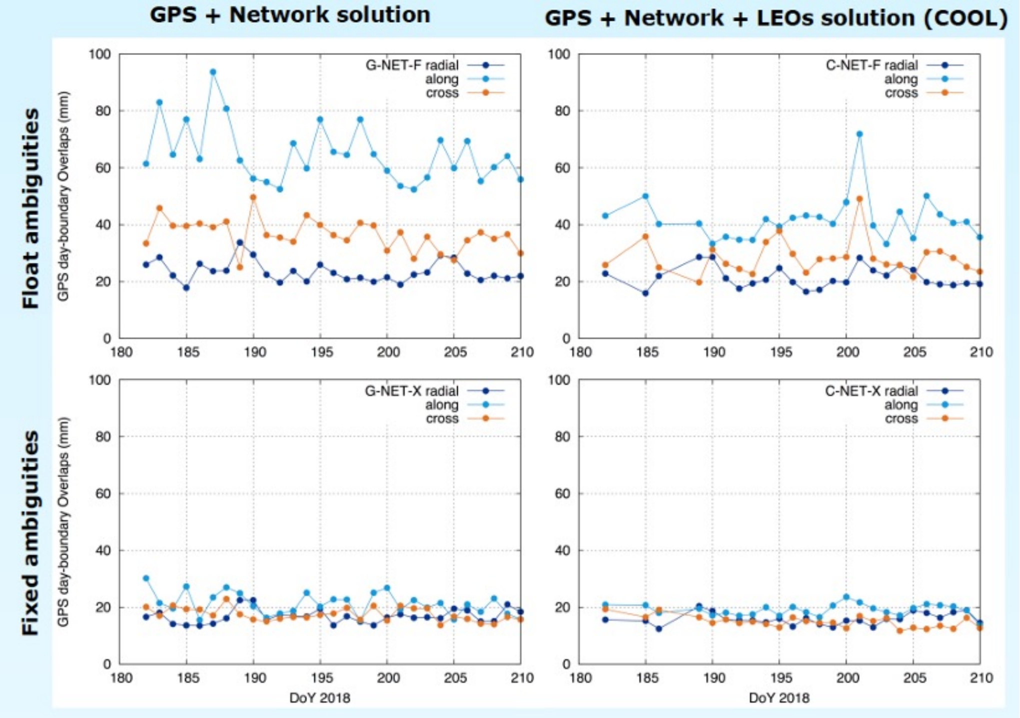
Combined processing of GNSS satellites,

Static Network (Stations) and Dynamic Network (LEOs)

In this case including Sentinel-3A & 3B into the GNSS Network approach*







Clear benefit for the station coordinate repeatability and GNSS day to day orbit consistency

*Gini et al., **Integer ambiguity resolved orbits and the benefits of combined Sentinel and GPS processing.** EGU 2019*

ESA/ESOC's activities – CoOL Analysis

Benefits of analysing observations from different techniques

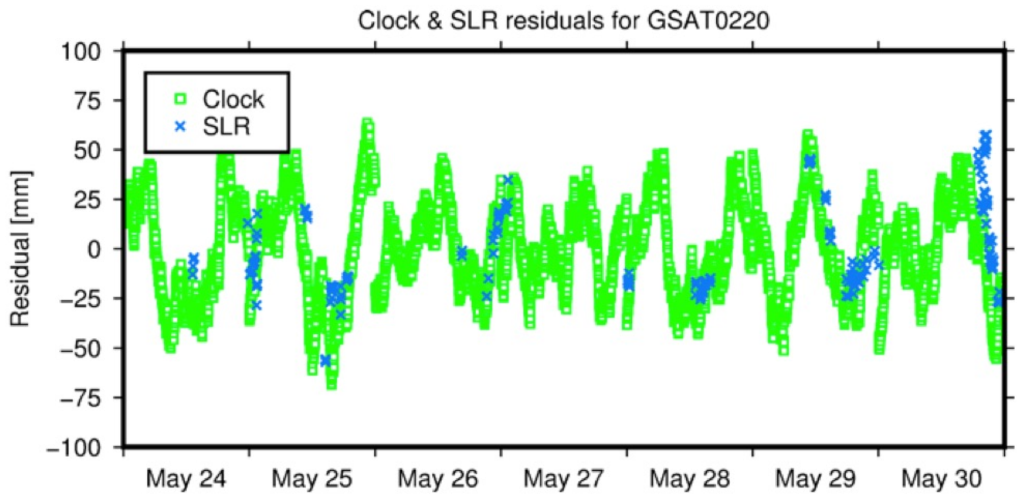
Satellite Laser Ranging high-rate measurements can be used to identified satellite model errors.

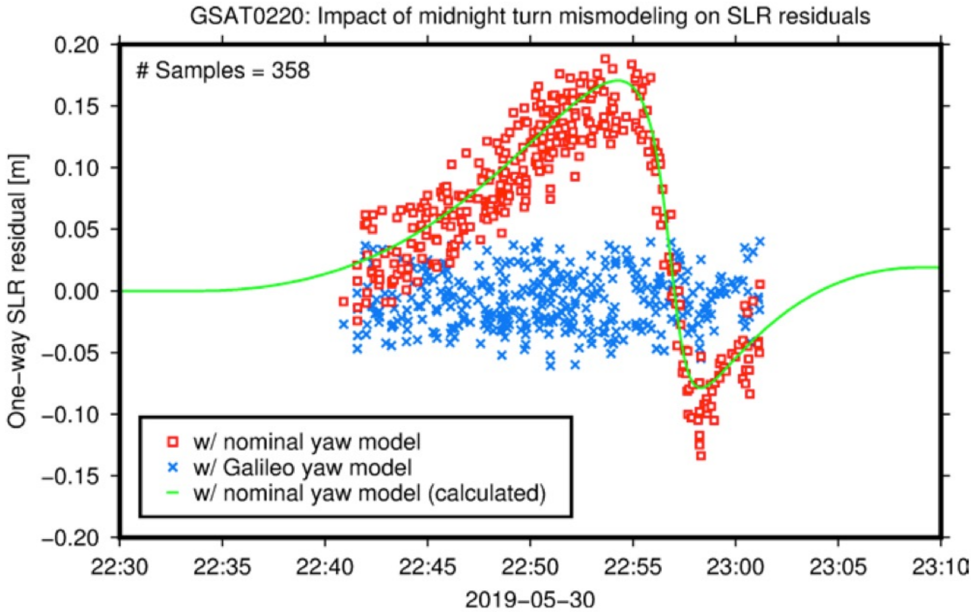
Examples:

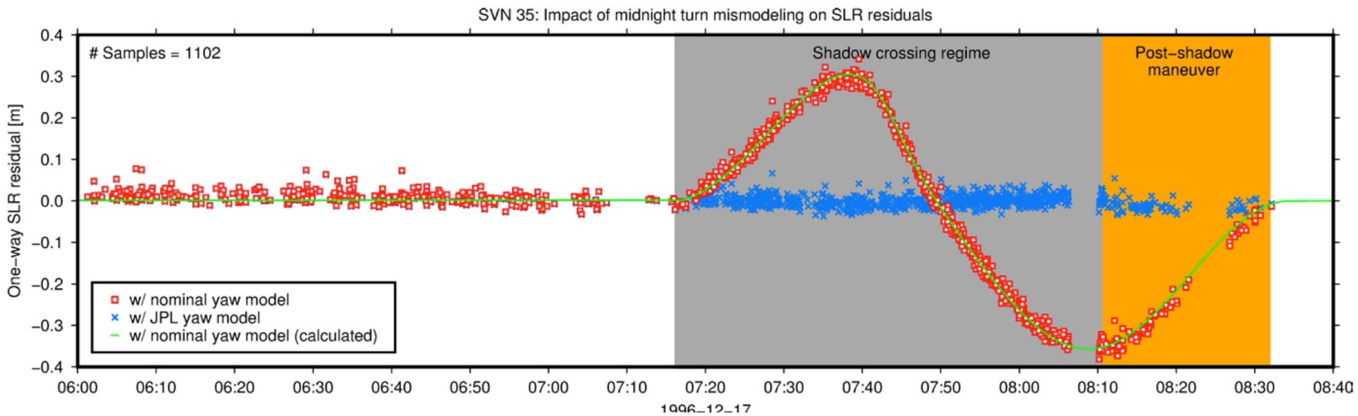
- Correlation of Galileo radial orbit error/ SLR residual and clock estimates

- GPS JPL yaw model (bottom left)

- Galileo midnight turn (bottom right)







ESA/ESOC's activities – Model improvements

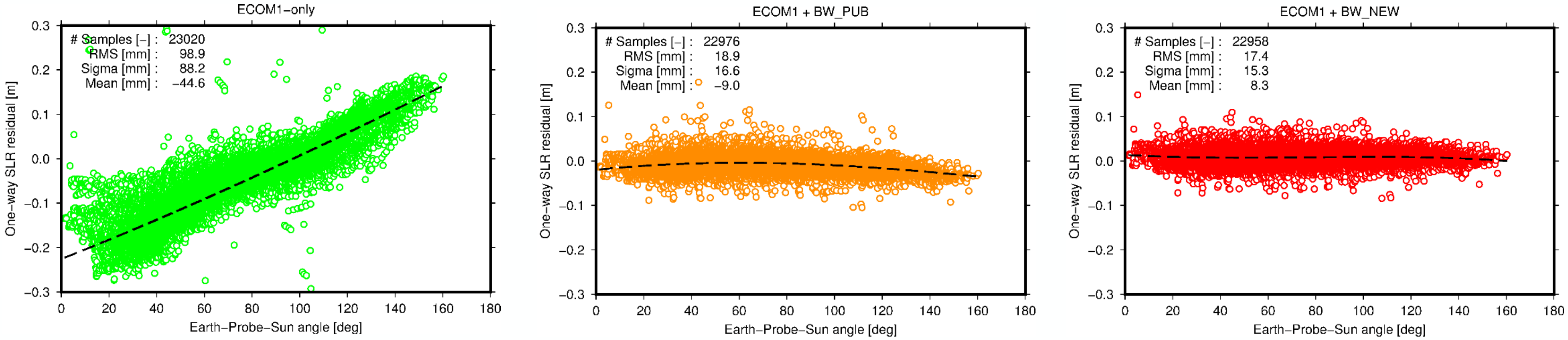
Improving Inter-Technique consistency

- Spacecraft models undergoing continuous refinements and improvements
- Recent upgrade of analytical radiation force model for Galileo FOC:
  - Separation into subgroups (SVN 201-213, SVN 214, SVN 215-223)
  - Additional structural details for antenna panel (NAVANT, SARANT, MISANT, LRR, IRES)
  - Addition of infrared properties for all surfaces
  - Addition of material properties for solar array back side
  - Update of optical properties of OSR material
  - Grid-based TRR force model for NAVANT
  - Ray-tracing model for Solar and Earth radiation pressure (ARPA)
  - TRR force model for +Y and -Y panel ("Y-bias")
  - TRR force model for clock radiator panel
  - TRR force model for solar array
  - Instant re-radiation for MLI-covered surfaces
  - …

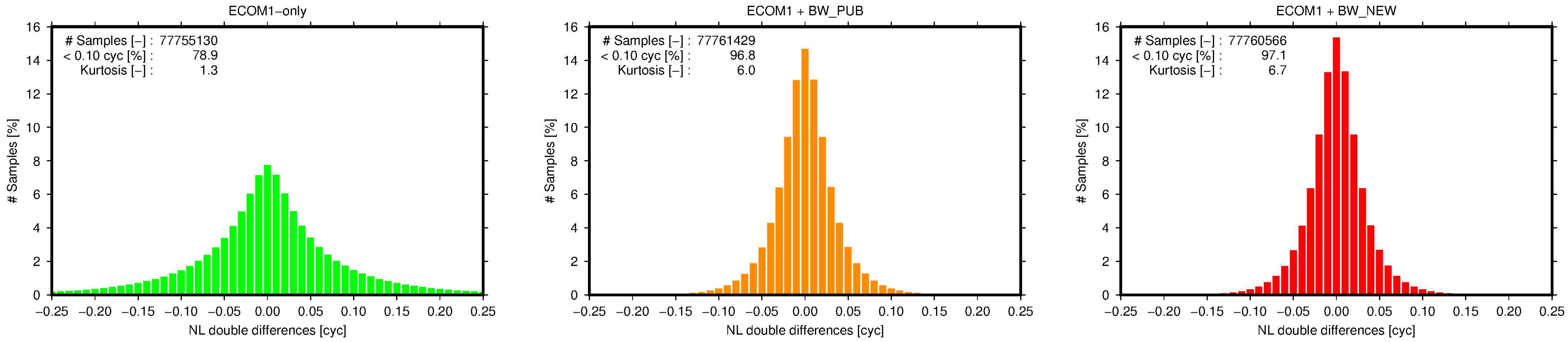
ESA/ESOC's activities – Model improvements

Improving Inter-Technique consistency

- Comparison between different Galileo force models: no box-wing, standard box-wing, advanced box-wing
- Significant reduction in Galileo SLR residuals, for certain ILRS core sites down to less than 1 cm:



- Improvement visible in other metrics as well such as NL ambiguity residuals clustering more tightly around zero:

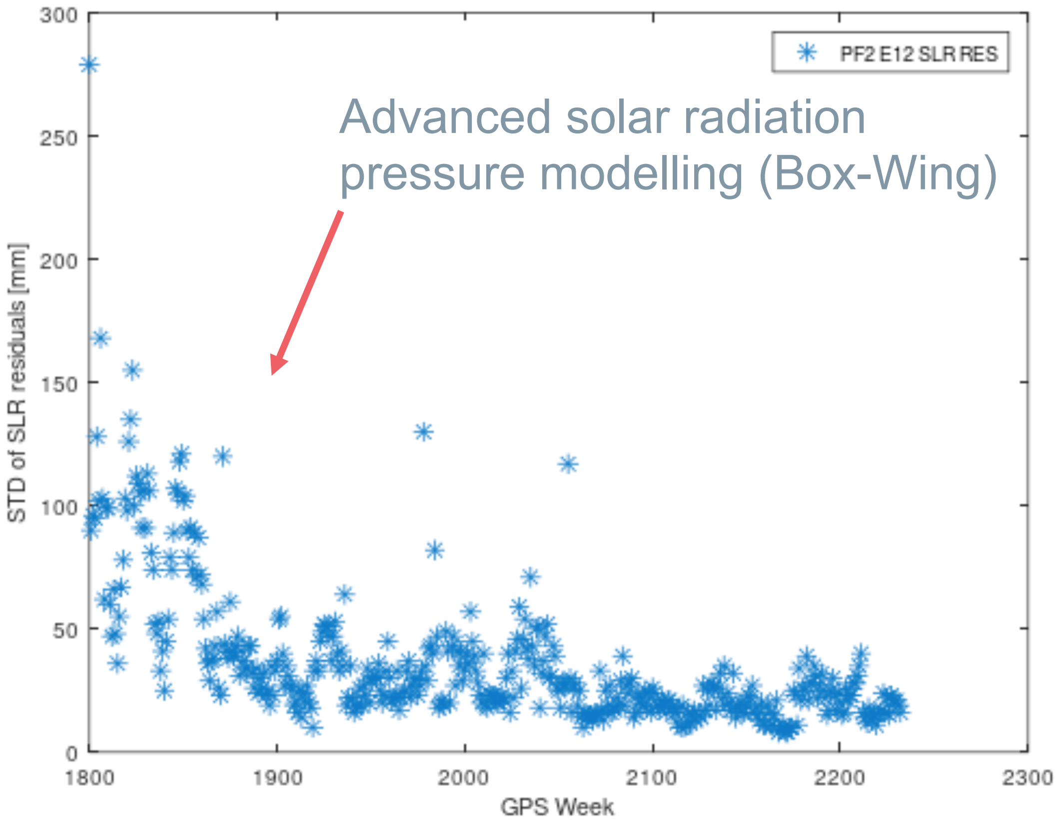


ESA/ESOC's activities – Model improvements

Inter-Technique consistency - evolution

Thanks to continuous model improvements the Inter-Technique consistency has continuously improved

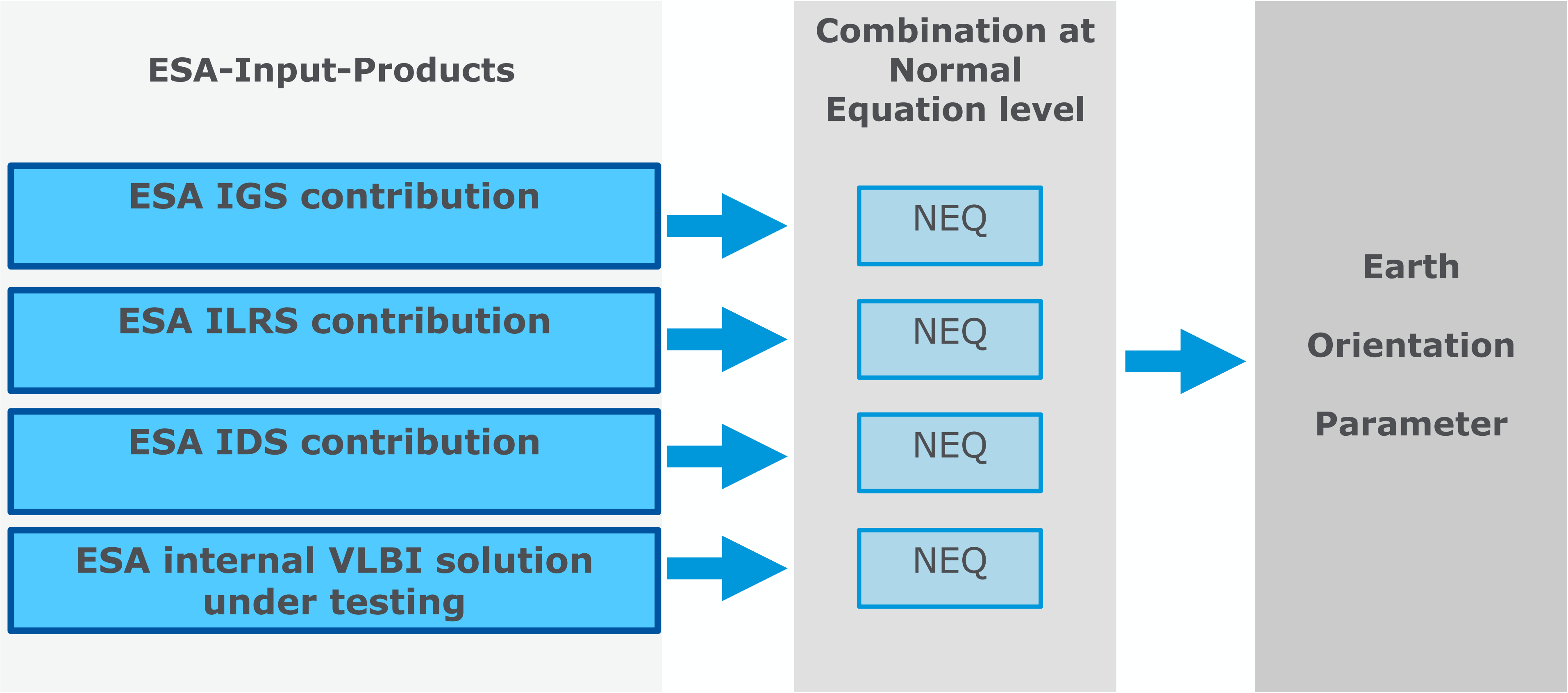
Example: Operational Galileo processing (Galileo E12 SLR residuals)



2014 - 2022

Operational CoOL implementation

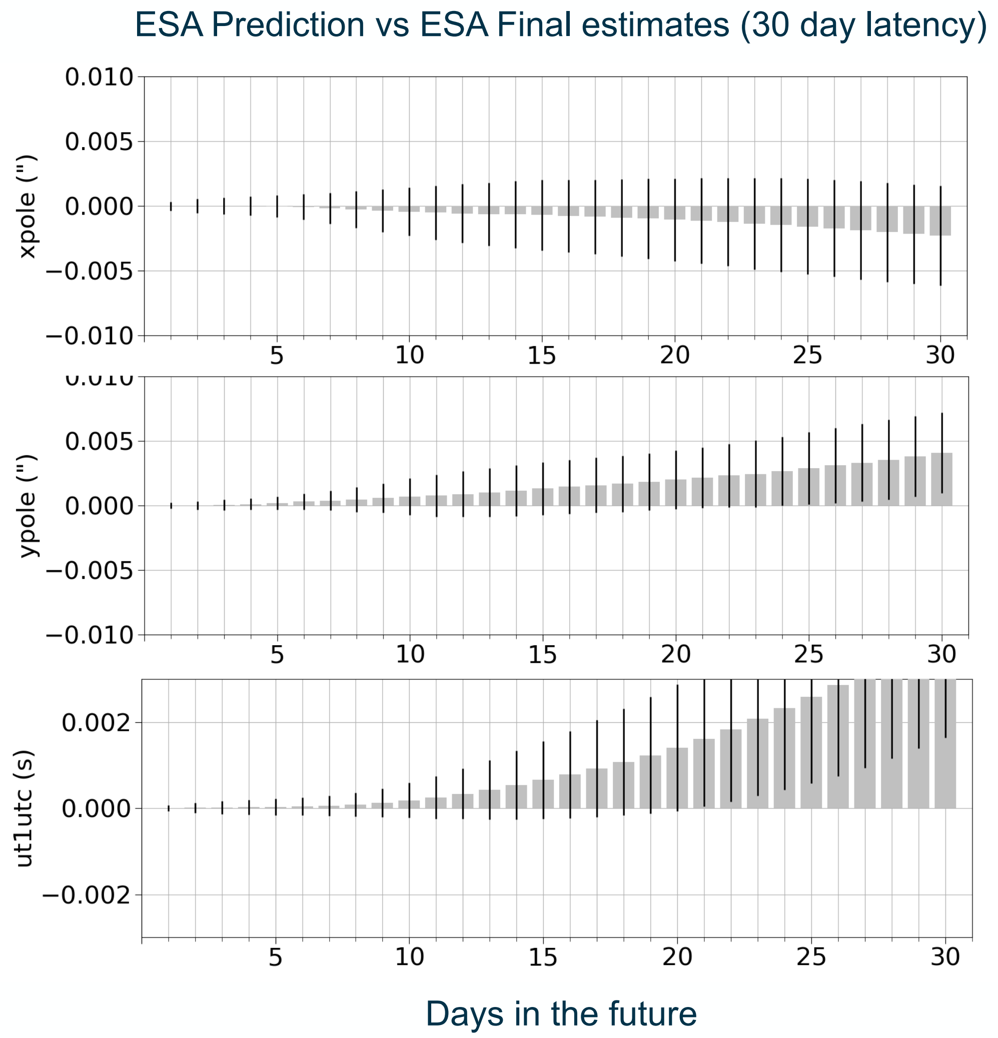
Example ESA/ESOC's ERP service



- Highest consistency: same software and models used in the data analysis
- A posteriori combination of **Normal Equation (NEQ)** equally allows to take parameter correlations and variances into account.

Combination on Normal Equation (NEQ) Level

ESA/ESOC’s ERP service - initial results



Histogram bars: average discrepancy between predicted and estimated values for predictions up to 30 days into the future
Whiskers: standard deviation of the discrepancies

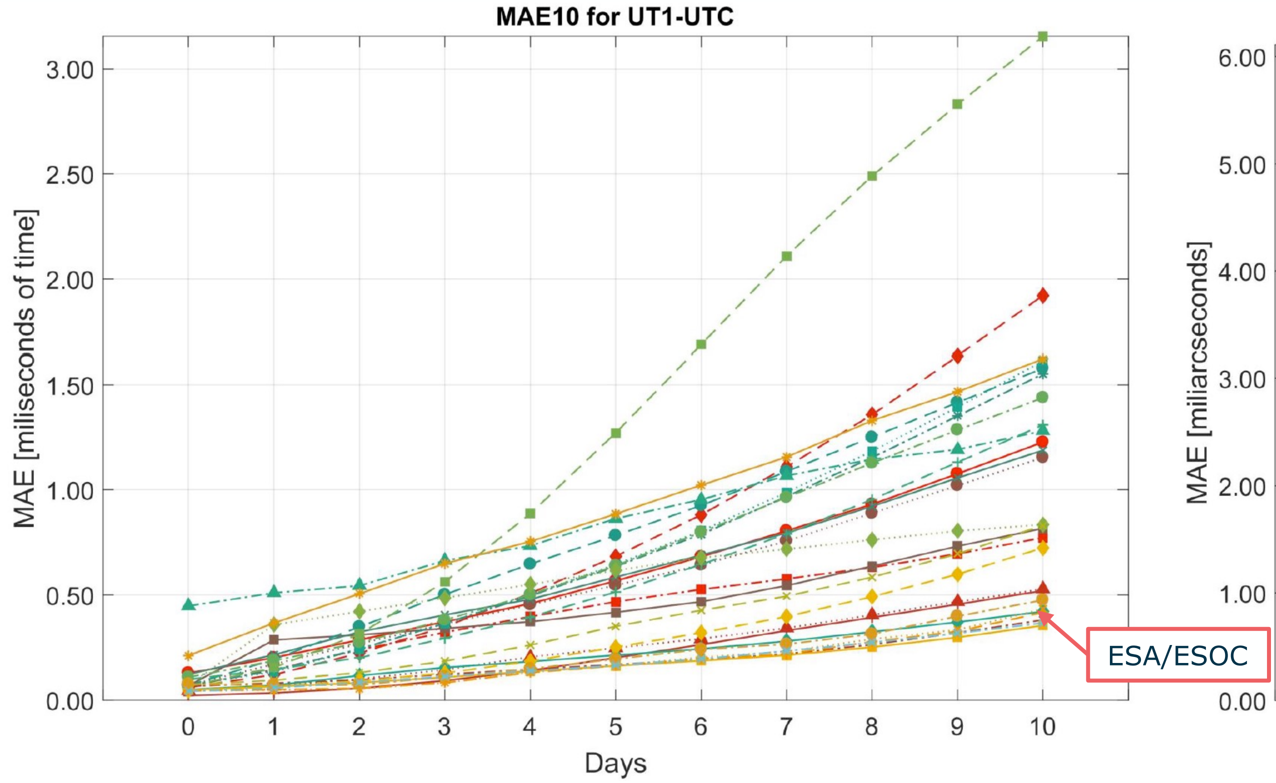
Statistics are based on the results generated up to Nov 01 2022. Results may vary over time.

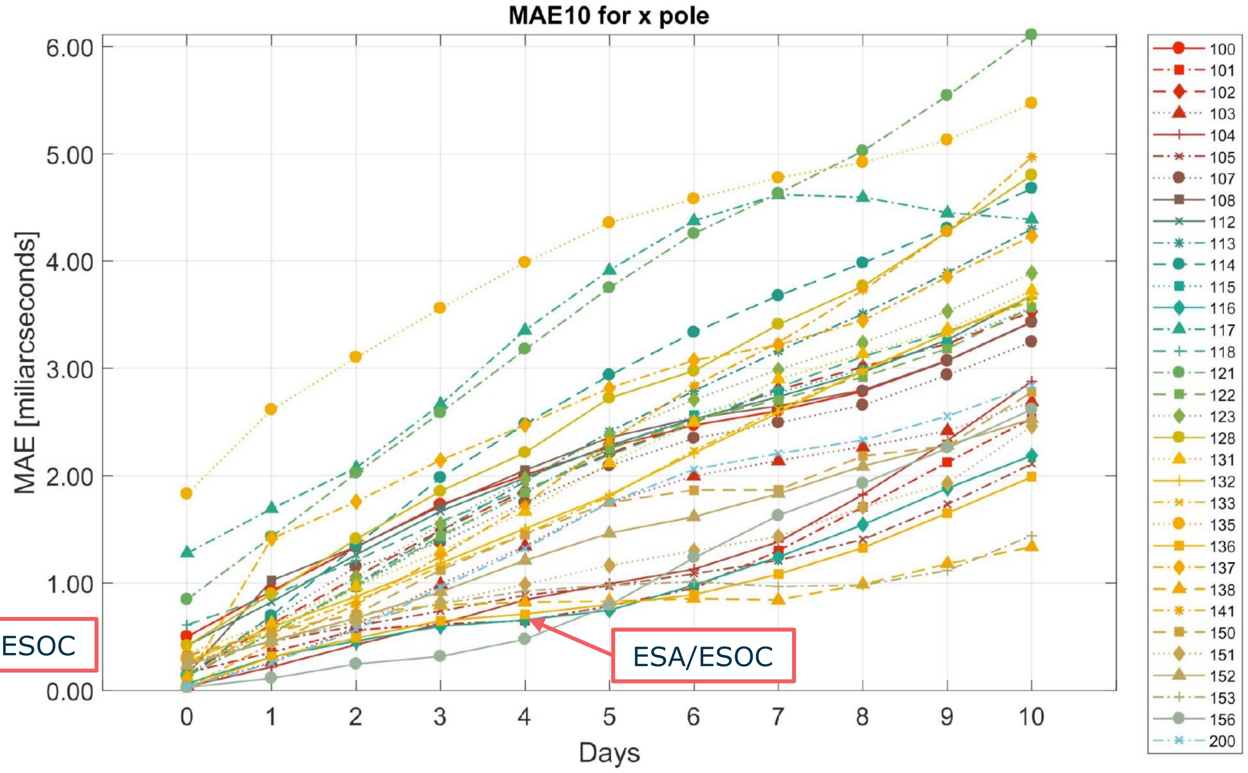
Earth Rotation Parameter Predicted vs. Final solution mean and std for n days into the future

		n=1	n=7	n=15	n=30	n=60	n=90
x pole (mas)	mean	0.01	-0.19	-0.75	-2.51	-9.31	-16.58
	std	0.35	1.20	2.73	3.88	5.62	5.67
y pole (mas)	mean	-0.01	0.39	1.32	3.94	11.41	17.57
	std	0.23	0.75	2.08	3.19	3.44	9.56
UT1-UTC (ms)	mean	0.00	0.06	0.65	4.08	12.46	20.89
	std	0.07	0.23	0.90	2.39	5.41	9.69

Combination on Normal Equation (NEQ) Level

ESA/ESOC's ERP service - initial results (2. EOP Prediction Comparison Campaign)





T. Kur, J. Śliwińska, J. Nastula, H. Dobslaw, M. Wińska, A. Partyka, Annual summary of the Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC), REFAG2022 Reference Frames For Applications in Geosciences,17 –20 October 2022,Thessaloniki, Greece

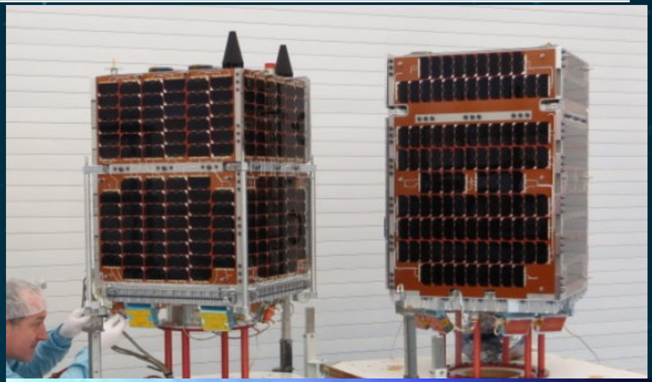
ESA's future activities improving Terrestrial Reference Frames

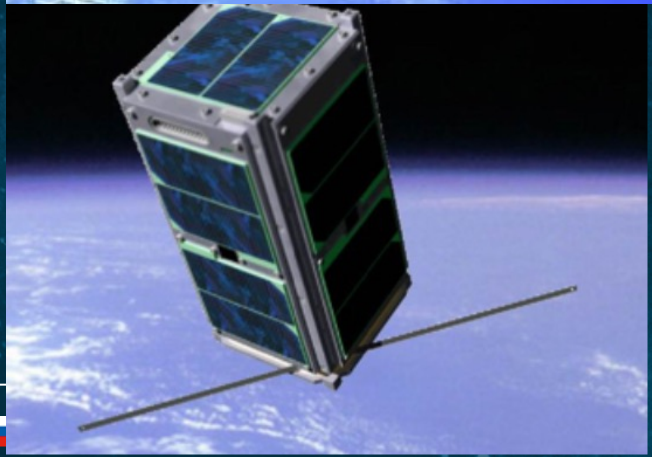
GNSS SCIENCE MISSIONS: BASED ON THE USE OF SMALL SATELLITES

Envisaged NAV Science missions could be implemented through small MEO and/or LEO satellites, typically in the range of 200-400 Kg (for MEO) and 50-200Kg (for LEO).

The use of standard, low-cost platforms and new-space approaches will be favoured to lower the cost of the missions.

For some scientific experiments, the deployment of small Cubesat dedicated constellations may also be considered

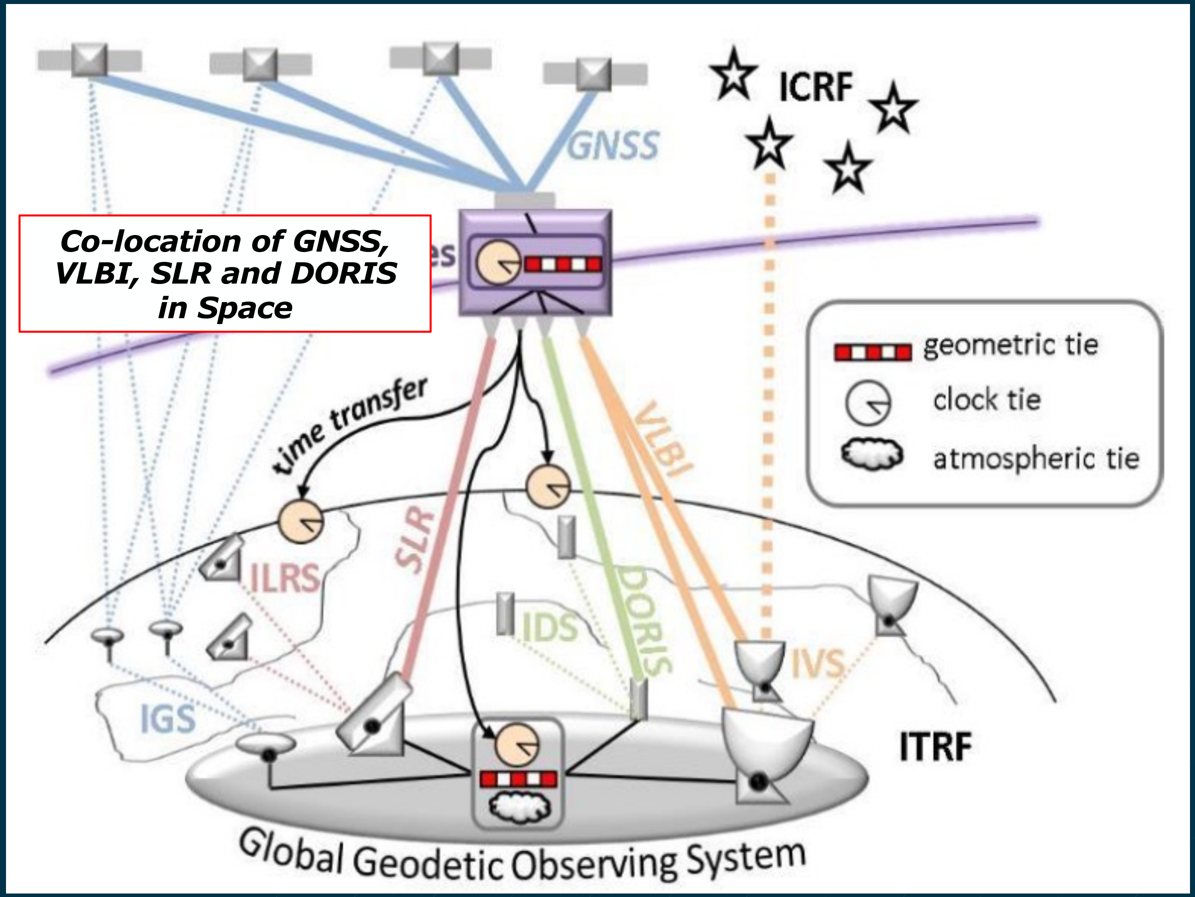




GENESIS Missions proposed to ESA Ministerial Council

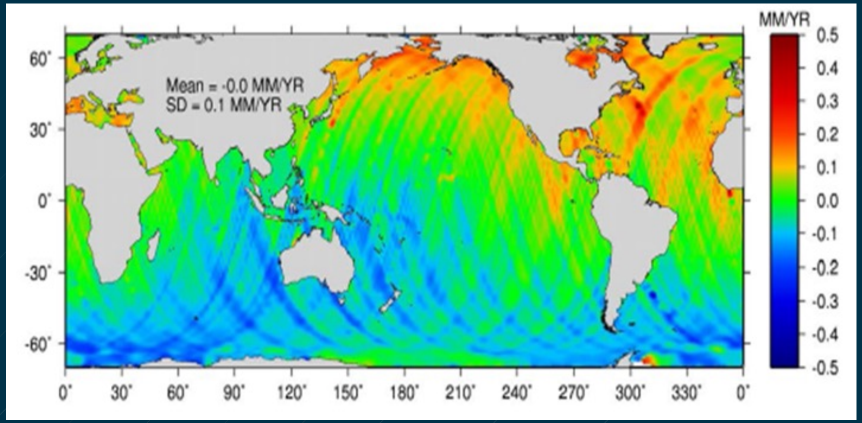
- **First ever space-colocation of all space-based geodetic techniques GNSS, VLBI, SLR and DORIS Complementing ground-based co-location**
- **Precise Optical Time Transfer in space**: Most precise optical time transfer demonstration over free-space supporting global-scale geodesy and high-accuracy time-frequency distribution. This could in turn become a major source of dedicated scientific tests (e.g. tests of fundamental Physics in general relativity, etc) and new applications.
- **PNT Missions in support to Fundamental Physics:** A large number of scientific breakthroughs (or pathfinders for future scientific tests) in the field of fundamental physics based on precise time and orbit determination and/or by setting up very accurate metrological inter-satellite relative positions with ultra stable on-board clocks via a dedicated NAV Science missions.
- **Advanced modelling of non-gravitational forces:** dedicated experiments and technologies for the accurate modelling of non gravitational forces (e.g. sun radiation pressure). This could in turn allow the development of enhanced orbitography techniques including dynamic models of high interest for science and future navigation missions

GENESIS: GEODESY AND GEOPHYSICS



First ever space-colocation of all space-based geodetic techniques GNSS, VLBI, SLR and DORIS Complementing ground-based co-location

- Coupled with high-precision time transfer (T2L2)
- Some major benefits:
  - ITRF major improvement
  - Improvement of EOP parameters
  - Altimetry and sea level rise
  - Ice mass loss
  - Improve geodetic datasets
  - Improvement of GNSS positioning
  - Improve the POD of all space missions



Jason-2 sea level trend difference between ITRF2014 and ITRF2008 (±0.5 mm/y)

Take aways

- An accurate and stable Terrestrial Reference Frame is the backbone of any kind of Positioning and Navigation on Earth, Sea, in Air and in Space.
- The International Terrestrial Reference Frame (ITRF) is generated using complementary Space Geodetic Observations (GNSS, SLR, DORIS, VLBI).
- Inter-Technique consistency is the key for an accurate ITRF
- Best Inter-Technique consistency is achieved for Combinations on Observation Level (CoOL).
- ESA/ESOC is continuously working on improving the Inter-Technique consistency – contributing to ITRF as analysis centre (AC)
- ESA's GENSIS mission under preparation - first ever space-colocation of all space-based geodetic techniques

Thank you very much for your attention!

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