Le système de référence terrestre, une histoire de satellites

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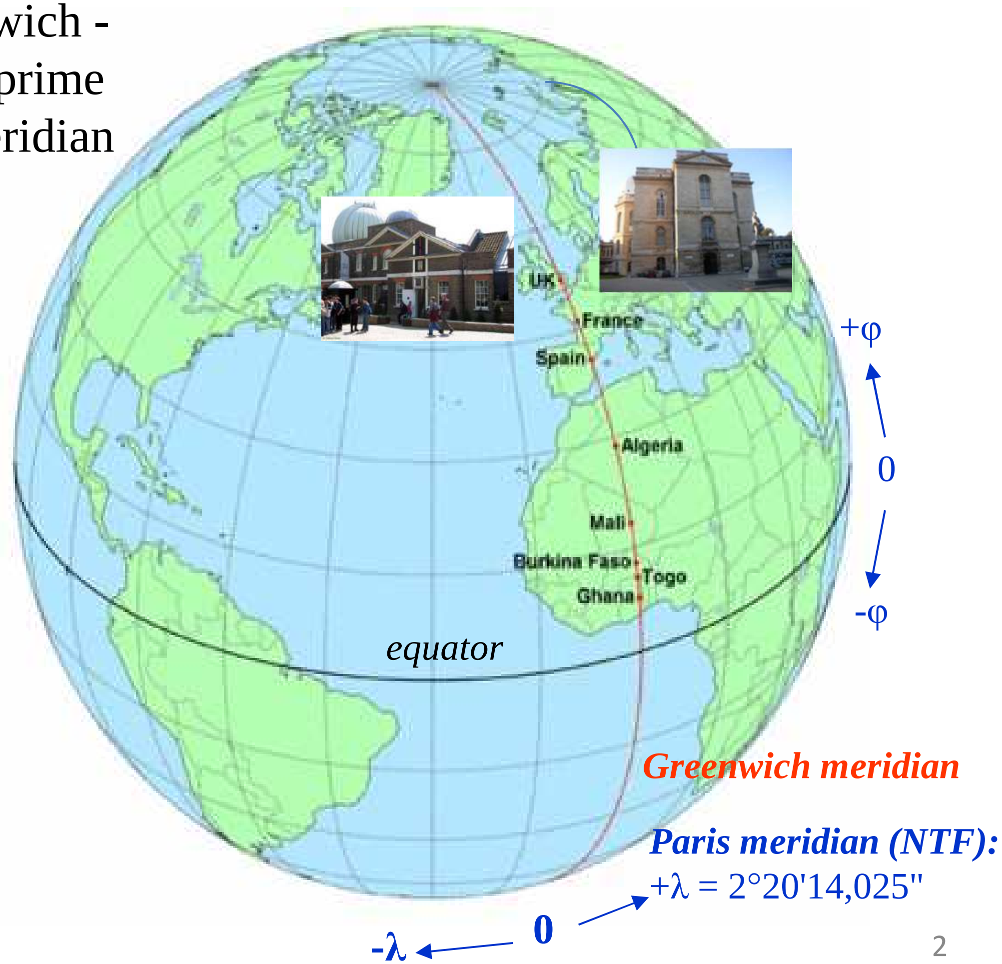
The beginning

The prime meridian on English maps was defined at the Meridian of Royal Observatory of Greenwich set by Sir George Airy in 1851 at the location of the Airy Transit Circle.

In October, 1884, the Meridian of Greenwich - widely used in shipping - was chosen as prime official meridian at the "International Meridian Conference“ held in Washington through the adoption of Greenwich Mean Time as Universal Time.

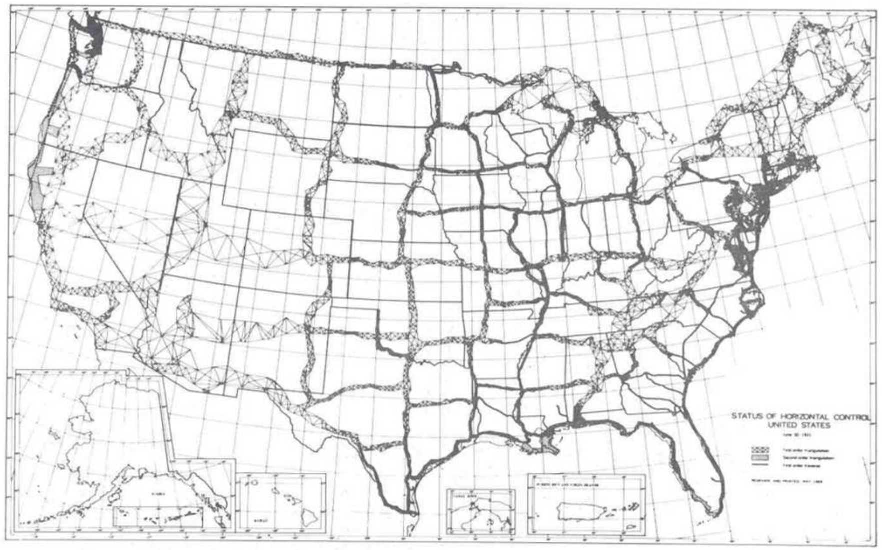
However France abstained from voting and French maps continued to use the Paris Meridian during a few decades.

Longitude is virtually described on the surface of the Earth by meridians, positive eastward; latitude is described by parallels, positive northward.

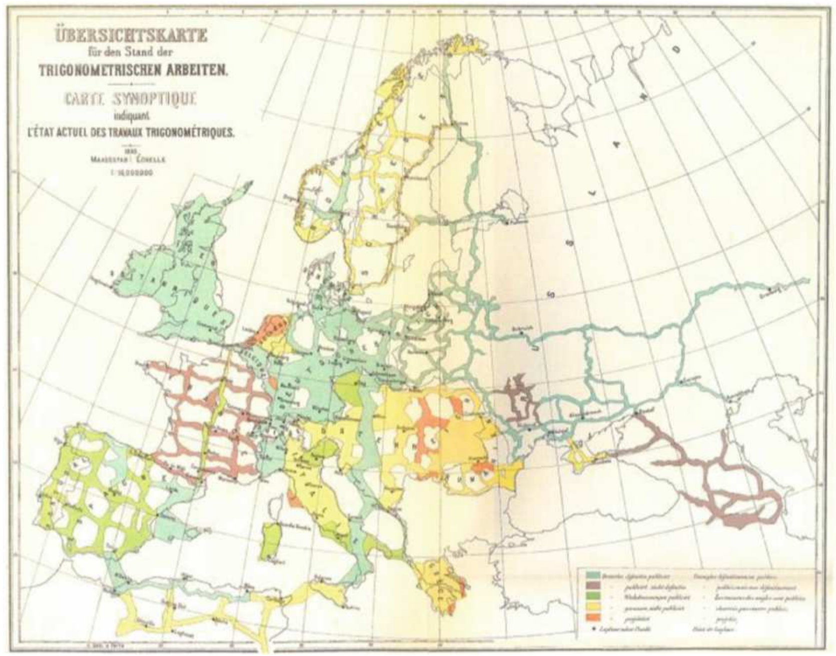


The pre-satellite era

Horizontal control network of the United States, 1931. Developing a network of areas based on manual surveys using triangulation was a precursor to today's modern National Spatial Reference System.

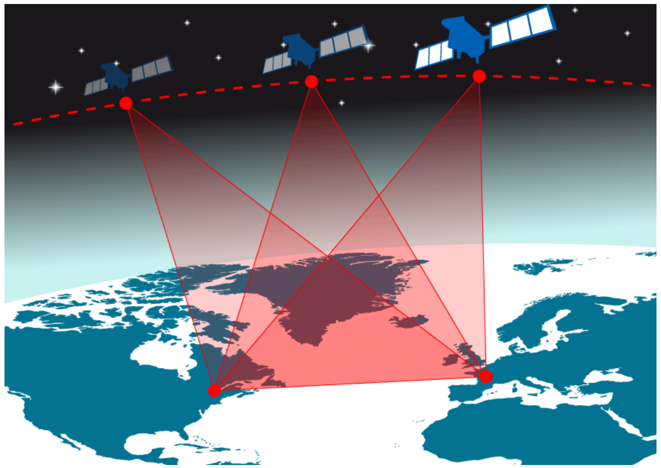


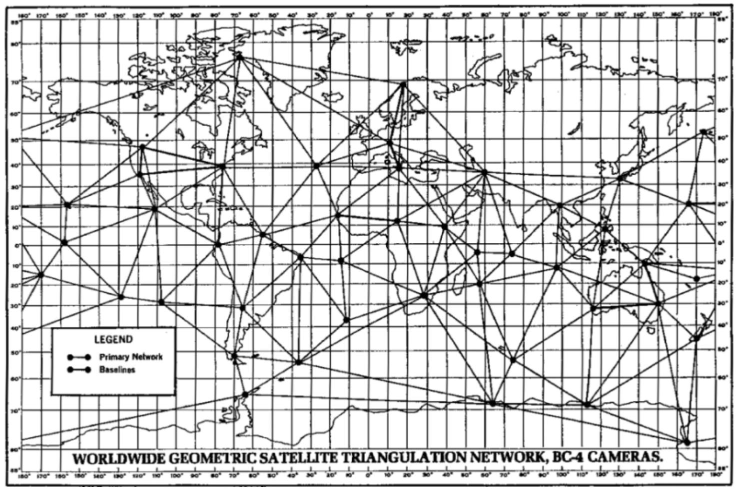
State of the triangulation in Europe, 1911, Verhandlungen der 17. Allgemeinen Conferenz der Internationalen Erdmessung, Berlin 1914



The satellite era

In January 1966, a **World Geodetic System Committee** composed of representatives from the United States Army, Navy and Air Force was charged with developing an improved WGS, needed to satisfy mapping, charting and geodetic requirements. Additional surface gravity observations, results from the extension of triangulation and trilateration networks, and large amounts of Doppler and optical satellite data (WGS66, WGS72) had become available since the development of WGS 60.





The **World Geodetic System WGS84** (revised in 2004) of the US Department of Defence is the reference system used le for the **Global Positioning System (GPS)**.
The zero meridian of the WGS-84 is 102.5 m east of the historic Meridian of Greenwich.
It is geocentric and globally consistent to ±1 m with the realizations of the International Terrestrial Reference System (ITRS) of the International Earth Rotation and Reference Systems Service (IERS).

The international terrestrial reference frame (ITRF)

BTS84-87: yearly TRF precursors worked out in the framework of BIH (Boucher & Altamimi, 1985) from VLBI, SLR, LLR, and Doppler/TRANSIT data

1987: creation of IERS (International Earth rotation - and reference systems - service)

ITRF88-89 : positions of ~100 sites. Velocities from AMO2 tectonic model (Minster & Jordan, 1978)

ITRF91-92-93: GPS introduced; position aligned on EOP/IERS, velocities estimated and aligned to NNR-NUVEL-1 (Argus & al., 1991)

ITRF94: DORIS introduced; use of variance matrices of coordinate series

ITRF96, ITRF1997, ITRF2000 (~500 sites)

1997: first international celestial reference frame (ICRF)

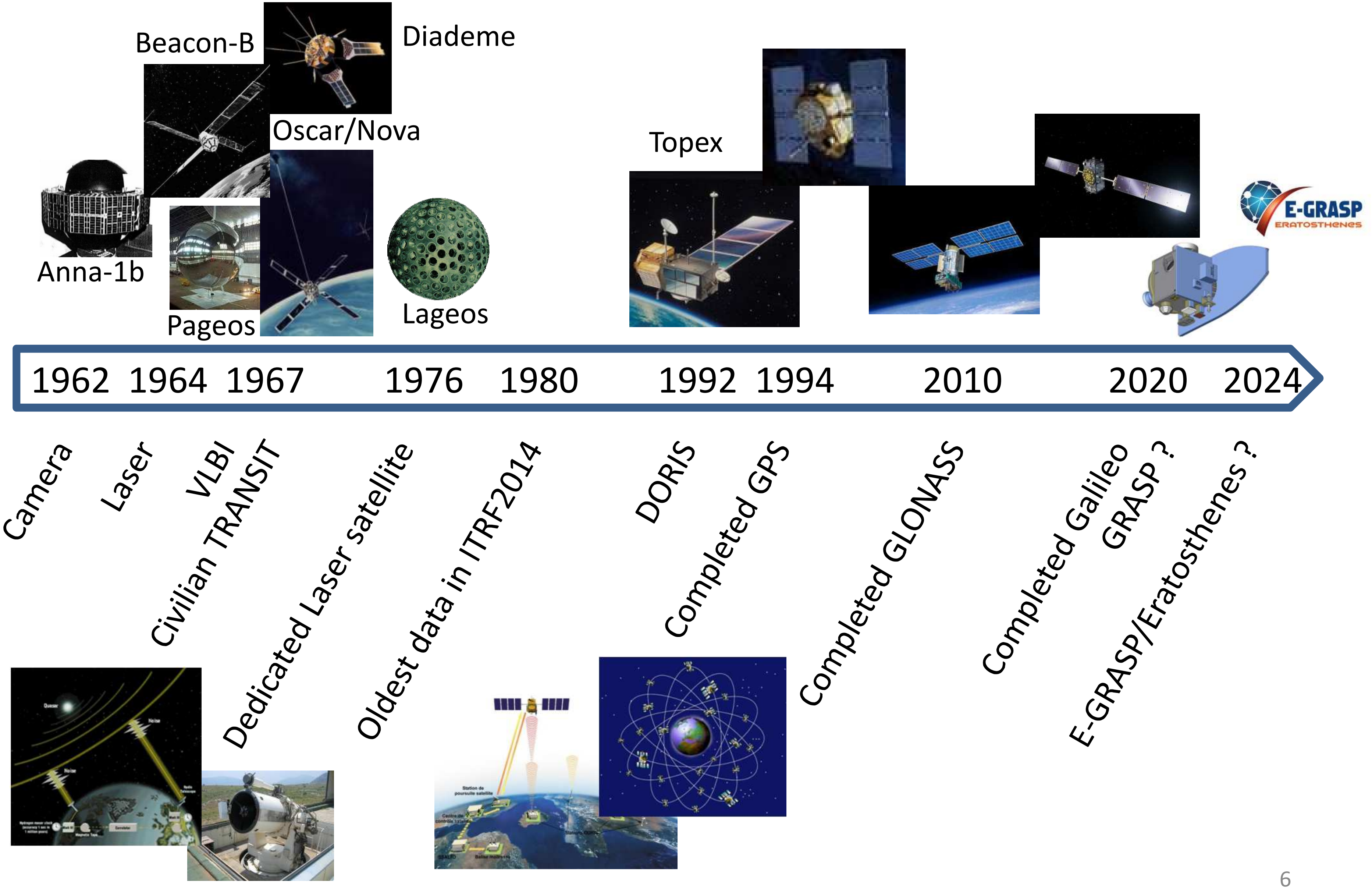
ITRF2005: jointly determined time series of TRF and EOP

ITRF2008: merging normal equations instead of time series

2009: ICRF2

ITRF2014: last realization of positions + velocities of ~1500 stations over 1980-2014; adjustment of periodical annual and semi-annual terms and post-seismic effects

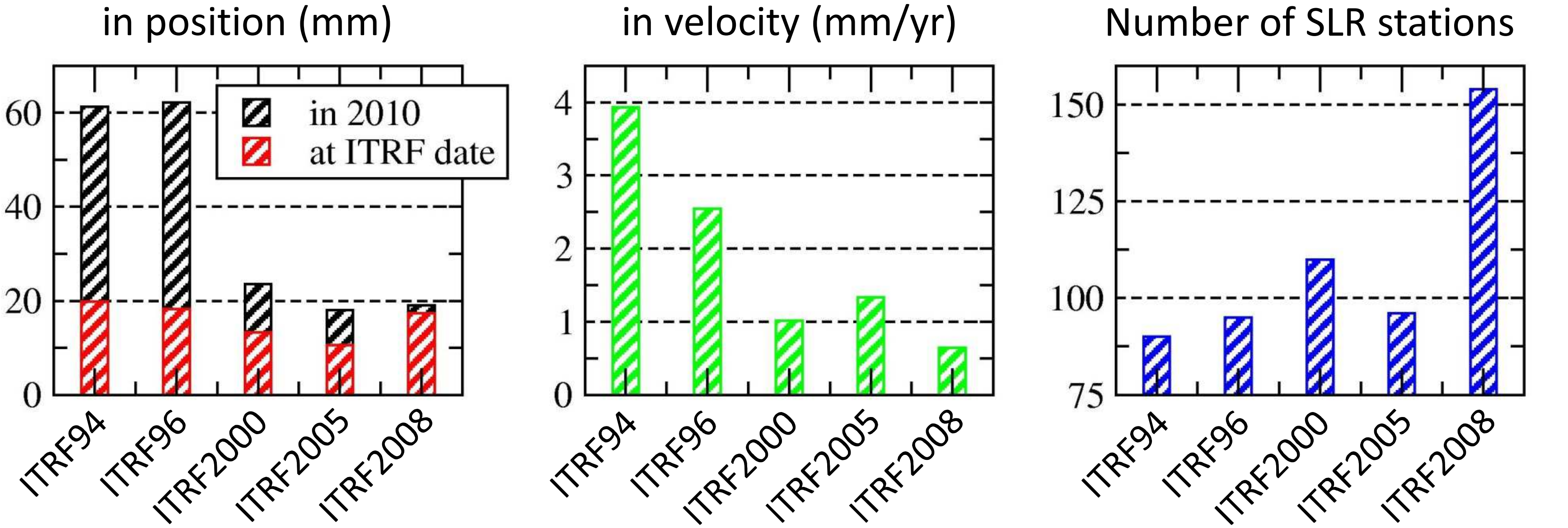
Review of techniques used and satellites



ITRF comparisons on SLR stations

Evolution of some ITRF realizations in terms of SLR station positions and velocities

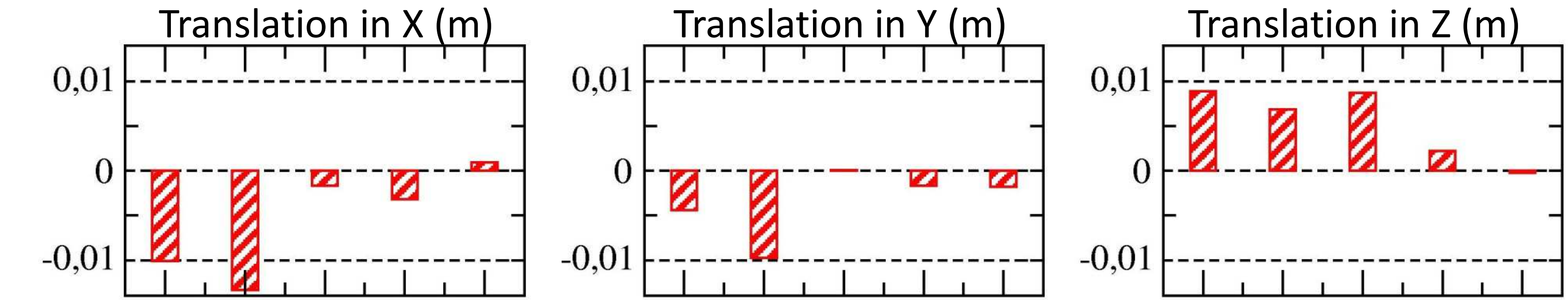
SLR station position comparisons with ITRF2014



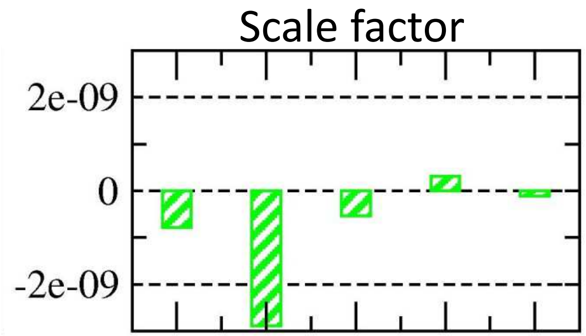
Comparisons of station positions are more consistent when using ITRF2014 velocities. The global standard deviation on coordinate differences remains within 1 to 2 cm.

Velocity standard deviations improve by a factor of ~6 over 20 years (1994-2014) up to ~.6 mm/yr.

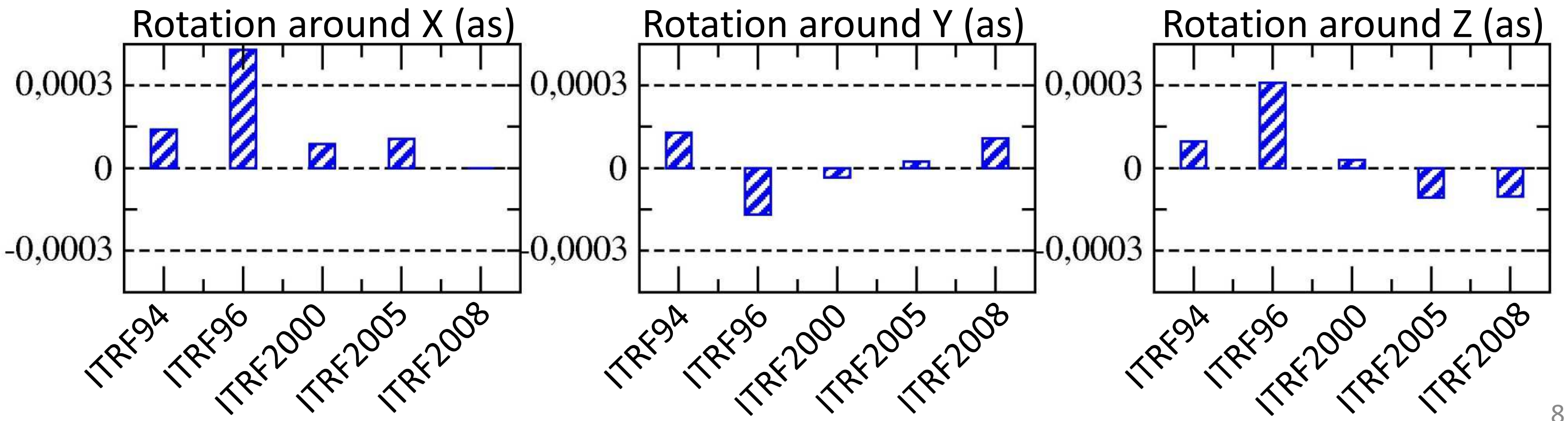
Transformation parameters wrt ITRF2014



ITRFs are aligned within the cm level in translation, scale and rotation, even much better for last realizations.

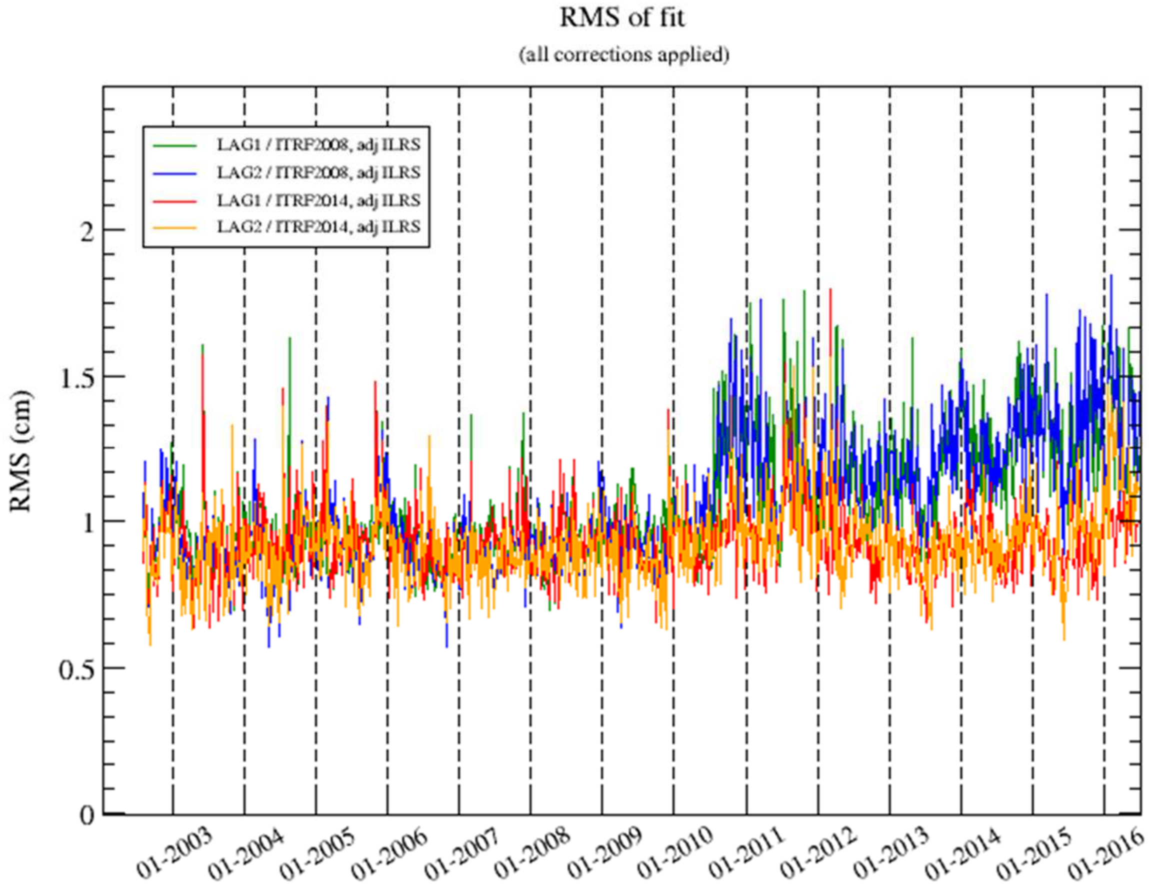


3 ppb ⇔ ~2 cm
.3 mas ⇔ ~1 cm



TRF validity on the long term

Lageos and Lageos2 SLR residuals with ITRF2008 and ITRF2014 over the 2002-2016 period



Source CNES/GRGS

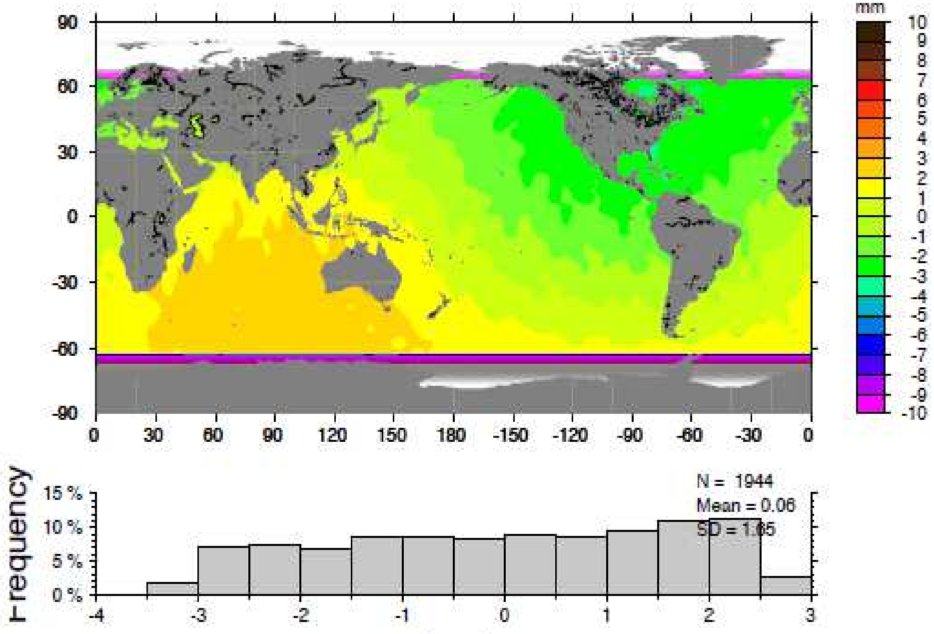
Lageos-Lageos2 residuals tend to increase after 2010 with ITRF2008

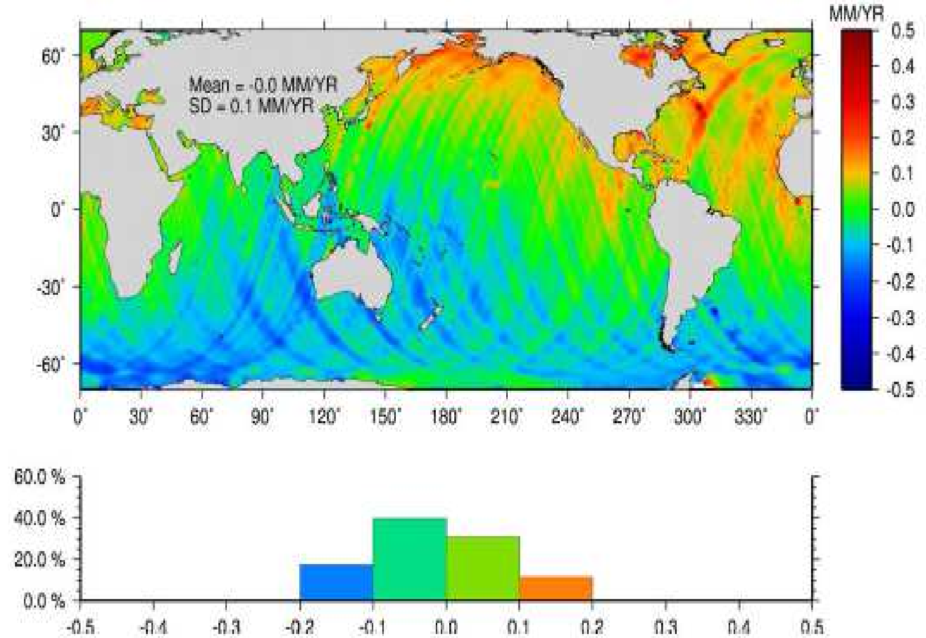
Impact on altimetric applications

Effect of the reference frame difference between ITRF2014 and ITRF2008 on:

Jason-3 radial orbit difference, (cycle 1-22)

Jason-2 regional sea level trend (whole Jason-2 period)





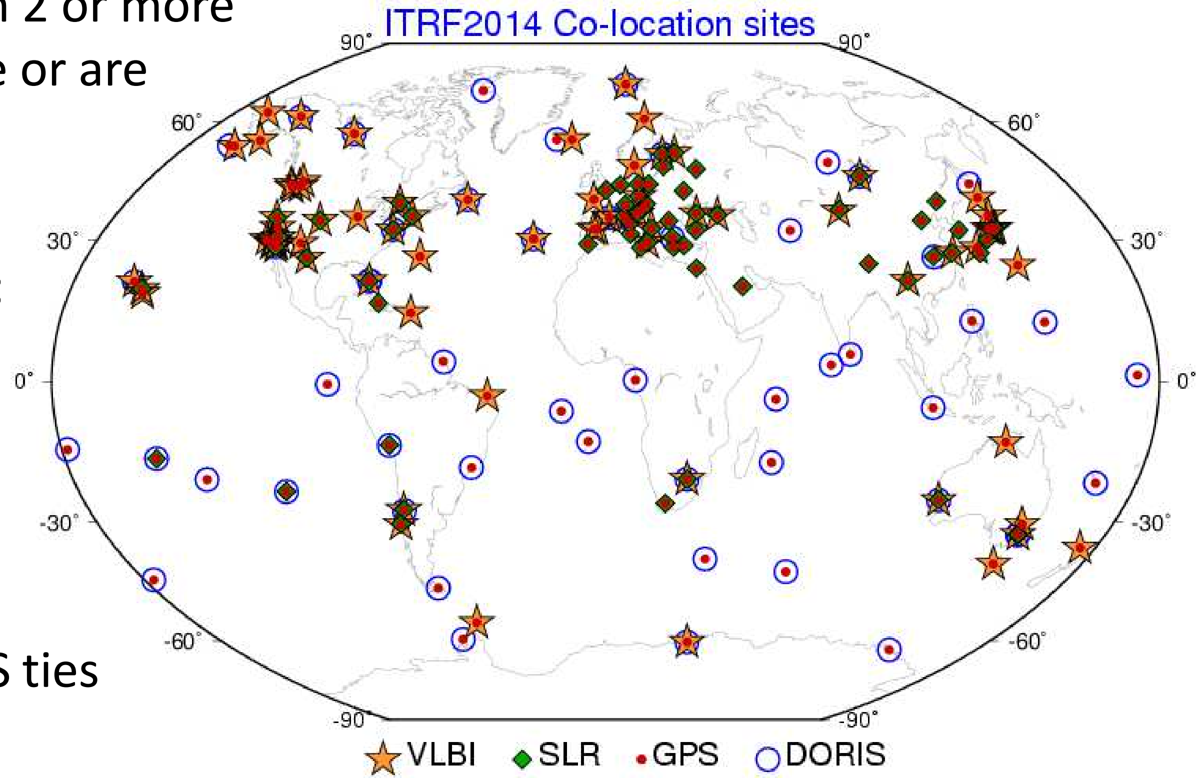
Radial orbit differences exhibit a degree 1 pattern with a 3 mm amplitude

Zonal bias and peak differences reach .2 mm/yr at high latitudes

Lemoine et al., Status of POD for Altimeter Satellites at GSFC, OSTST, Nov. 2, 2016

ITRF2014 co-locations

- 1499 stations located in 975 sites
- 91 co-location sites with 2 or more instruments which were or are currently operating
- Co-locations with GNSS:
  - 33 SLR
  - 40 VLBI
  - 46 DORIS
- 59 pairs of DORIS-DORIS ties



Altamimi et al., Review of IDS contribution to ITRF2014, *OSTST, IDS workshop, Oct. 31,2016*

Tie Discrepancies

- "Tie Discrepancies" means differences between terrestrial ties and space geodesy estimates

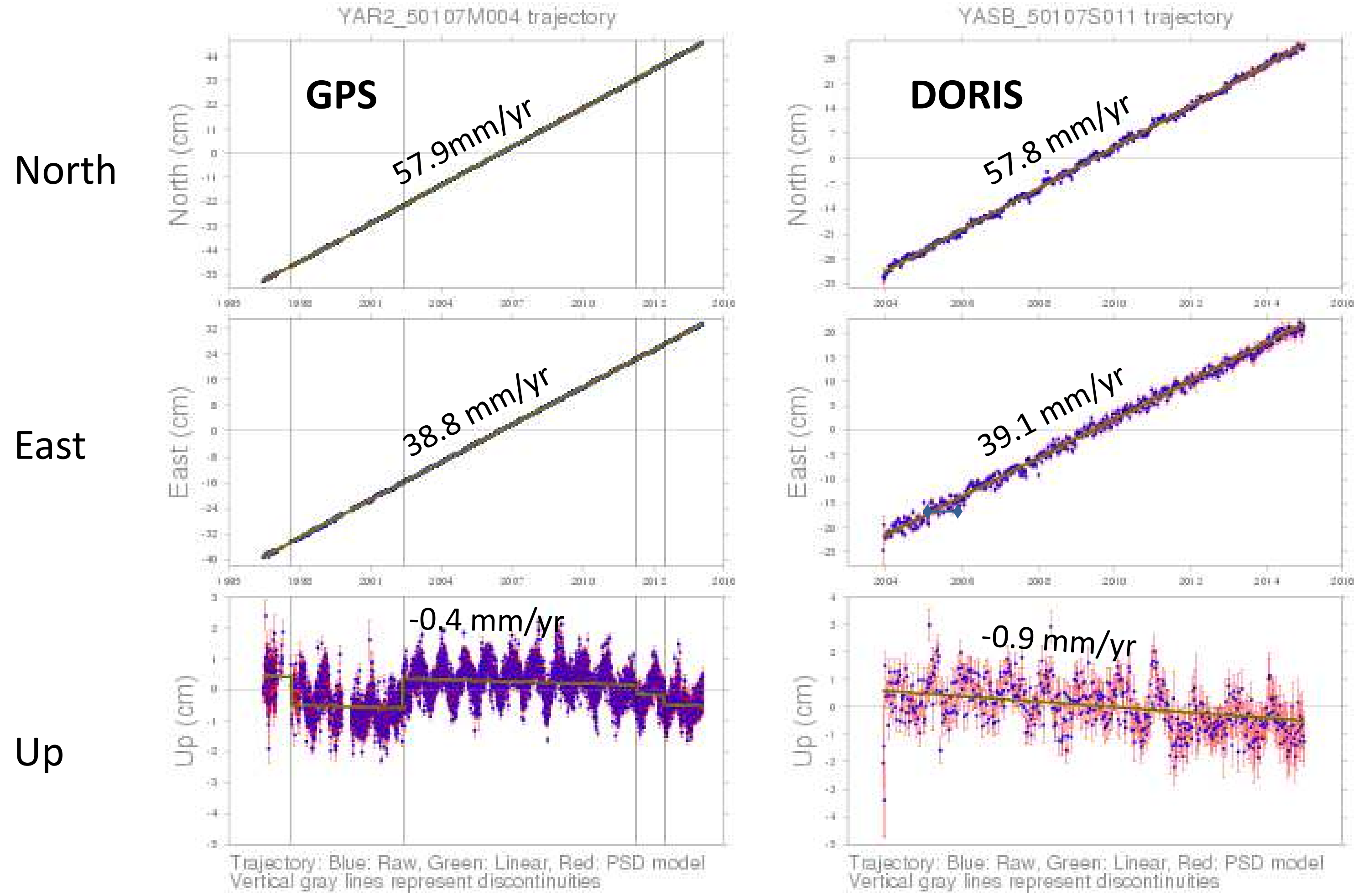
- Percentage of tie discrepancies

wrt GNSS :	< 5 mm	> 5 mm
– VLBI:	42 %	58 %
– SLR:	29 %	71 %
– DORIS:	23 %	77 %
DORIS – DORIS	34 %	66 %

Altamimi et al., Review of IDS contribution to ITRF2014, *OSTST, IDS workshop, Oct. 31,2016*

GNSS – DORIS velocity agreements

As example, agreement between GNSS/IGS and DORIS/IDS velocities at Yarragadee (West Australia) from 1995 to 2016: ~1 mm/yr



SLR (mm/yr)

N: 58.0
E: 38.7
U: -.6

VLBI (mm/yr)

N: 57.2
E: 40.1
U: 5.1

Altamimi et al., Review of IDS contribution to ITRF2014, *OSTST, IDS workshop, Oct. 31,2016*

How to go further?

Estimated precision of the last ITRF2014 realization:

Improvement will go through better:

- Loading effect modeling
- Propagation delays
- Instrument bias determination
- Satellite eccentricity vectors
- Orbit modeling
- Time synchronization

→ same platform

GGOS requirements for 2020:

- 1 mm position precision
- .1 mm/yr velocity precision

Table 2. WRMS Averages of Postfit Residuals, in mm, as Result of Three Stacking Tests: Standard Stacking (STD), Stacking With NTAL Applied, and Stacking Where the Annual and Semiannual Frequencies (FREQ2) Are Estimated With No NTAL Model Corrections Applied

Solution		East	North	Up
		IVS/VLBI, Session-Wise Sampling		
STD		3.79	3.97	11.00
NTAL	VLBI	3.75	3.93	10.81
FREQ2		3.74	3.91	10.81
		ILRS/SLR, Weekly Sampling		
STD		8.91	10.91	8.18
NTAL	SLR	8.90	10.76	8.14
FREQ2		8.83	10.54	8.03
		IDS/DORIS, Weekly Sampling		
STD		13.34	10.21	11.84
NTAL	DORIS	13.32	10.18	11.89
FREQ2		13.17	9.90	11.49
		IGS/GNSS, Daily Sampling		
STD		1.90	1.89	5.61
NTAL	GNSS	1.85	1.84	5.07
FREQ2		1.74	1.71	5.04

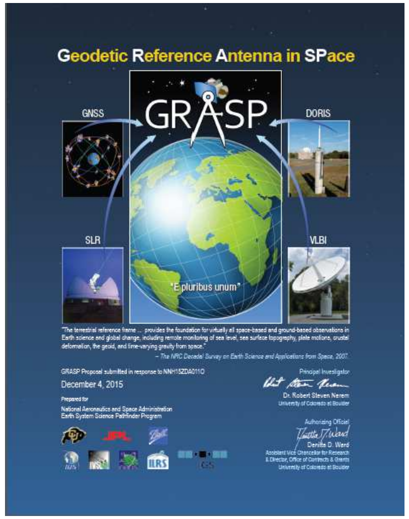
NTAL: non-tidal atmospheric loading *Altamimi et al., 2016*

Multi-technique mission projects

aiming at improving TRF to a precision of 1 mm and a stability of .1 mm/yr (GGOS requirements for 2020) and homogenizing TRF/CRF/EOP

❑ GRASP

- NASA Earth Venture Mission-2 (2020)
- Payload: GNSS/SLR/VT (+ DORIS in TriG?)
- Orbit: 925 – 1400 km, 100.2 deg. (sun-synchronous)
- Submitted on December 4, 2015



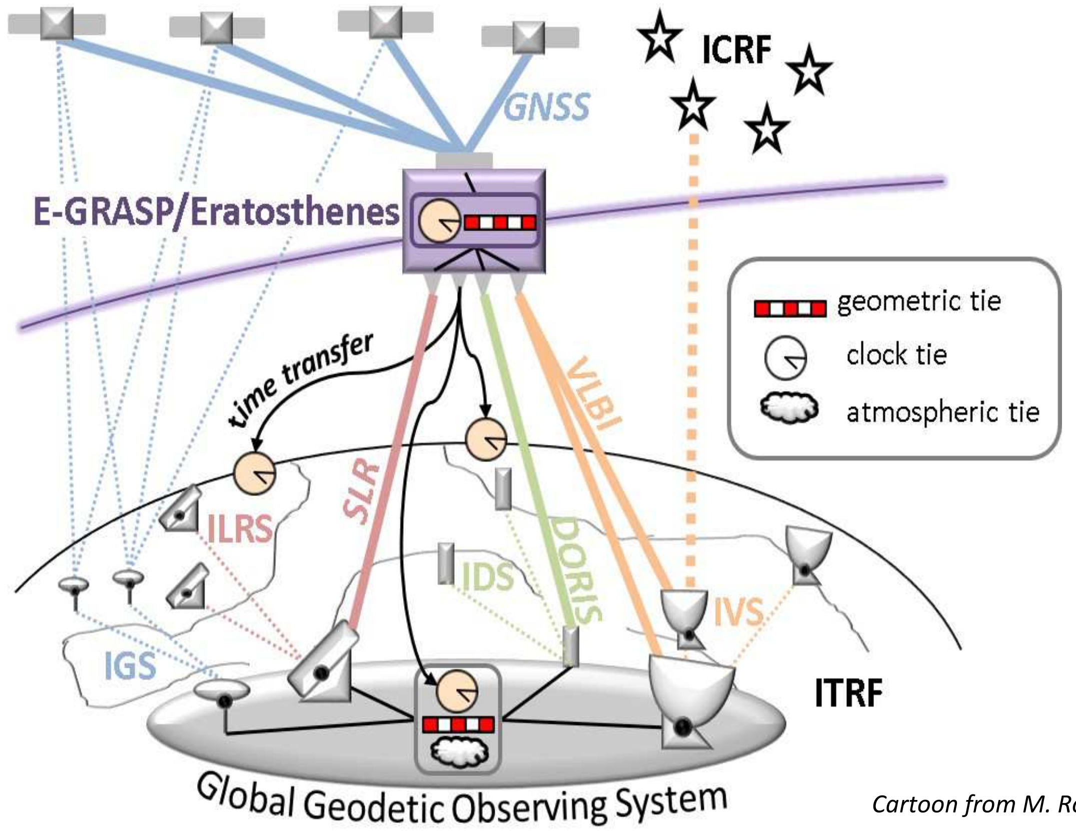
❑ E-GRASP/Eratosthenes

- ESA Earth Explorer-9 mission (2024)
- Payload: GNSS/DORIS/SLR/VT/T2L2 (+ µSTAR?)
- Orbit: 762 – 7472 km, 63.4 deg.
- Submitted on June 24, 2016

E-GRASP overview

- **GRASP heritage**
  - proposal to NASA's Earth Venture mission-2 in September 2011 and December 2015
  - Selection of CYGNSS in 2012 and ? in 2016
- **ESA Framework**
  - proposal to ESA's Earth Explorer Opportunity mission in June 2016
  - selection of 2 missions first in phase A (among 17) in December 2016
  - launch by VEGA-C around 2024
- **Payload**
  - as for GRASP (DORIS, GNSS, SLR, VLBI)
  - precise passive H-maser clock synchronized by T2L2
  - accelerometer ?
- **Orbit optimization**
  - "performance" eccentric orbit (762-7472 km)
  - "continuity" low orbit (⬄GRASP: 925-1400 km)
- **Science enhancing**
  - Geodesy (Earth reference system and applications)
  - Physics

Unification of space and time references

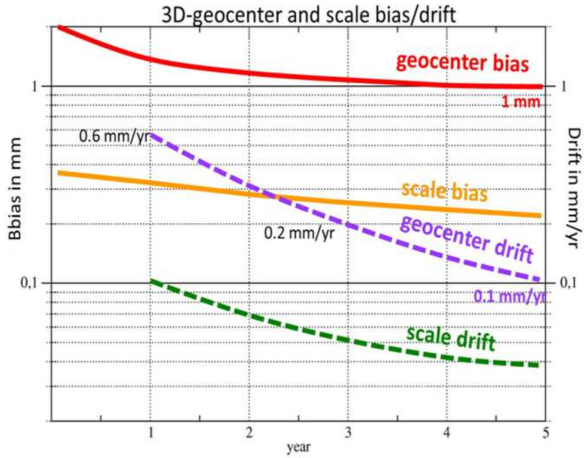


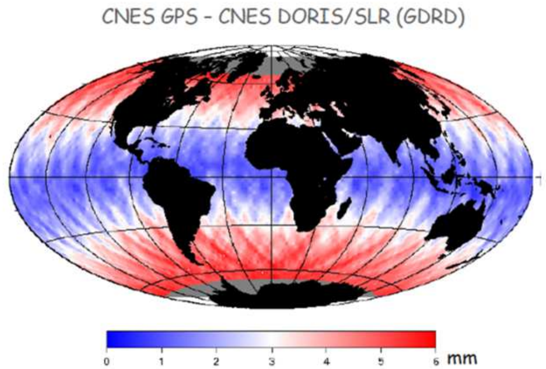
Cartoon from M. Rothacher, ETH

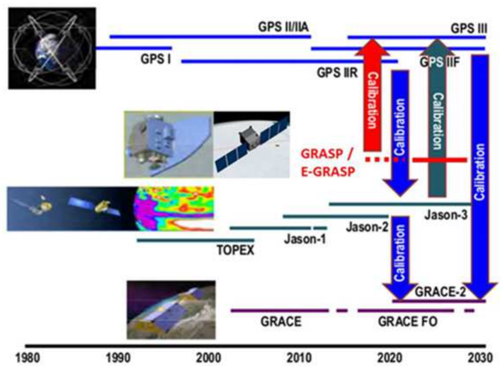
Science concept of E-GRASP/Eratosthenes including the space geodetic techniques and the corresponding co-location concepts

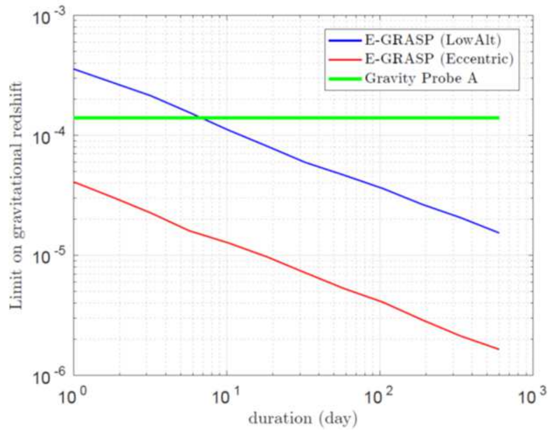
Science Objectives

- Unification of reference frames and Earth rotation
- Geocenter and scale
- Long-wavelength gravity field
- Altimetry and sea level rise
- Determination of ice mass loss
- Geodynamics, geophysics, natural hazards
- Improvement in global positioning
- GNSS antenna phase center calibration
- Positioning of satellites
- Relativistic physics









Parameters to be retrieved

Classification	Type	Parameter	VLBI	GNSS	SLR	DORIS	LLR
common, global	Satellite orbits	GNSS orbits	(√)	√	√		
		LEO orbit		√	√	√	
		LEO clock		√	(√)		
		E-GRASP orbit	√	√	√	√	
		E-GRASP clock	√	√	√	√	
	EOP	Pole coordinates	√	√	√	√	√
		UT1	√				
		LOD (Length of Day)	(√)	√	√	√	√
		Nutation	√				√
		Nutation rates	√	√	√	√	√
	Gravity field	Earth's center of mass		(√)	√	(√)	
		Low-degree coefficients		√	√	√	(√)
	TRF	Scale	√	(√)	√	(√)	√
common, local	Atmosphere	Ionospheric parameters	√	√	(√)	√	(√)
		Tropospheric parameters	√	√		√	
	TRF	Station positions	√	√	√	√	√
		Station velocities	√	√	√	√	√
	Time & Frequency	Station clocks	√	√	√	√	√
technique-specific	CRF	Quasar positions	√				
		Moon orbit					√
	Instrumental	GNSS clock		√			
		Range biases			√		√

co-location in space

co-location on ground

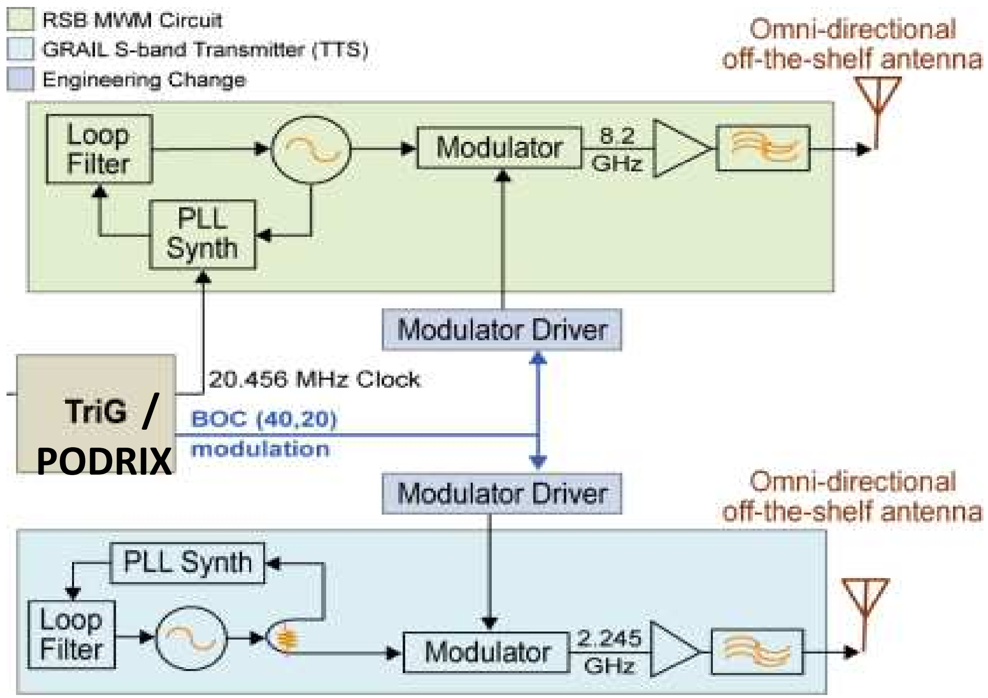
Orbits (continuity and performance scenarios)

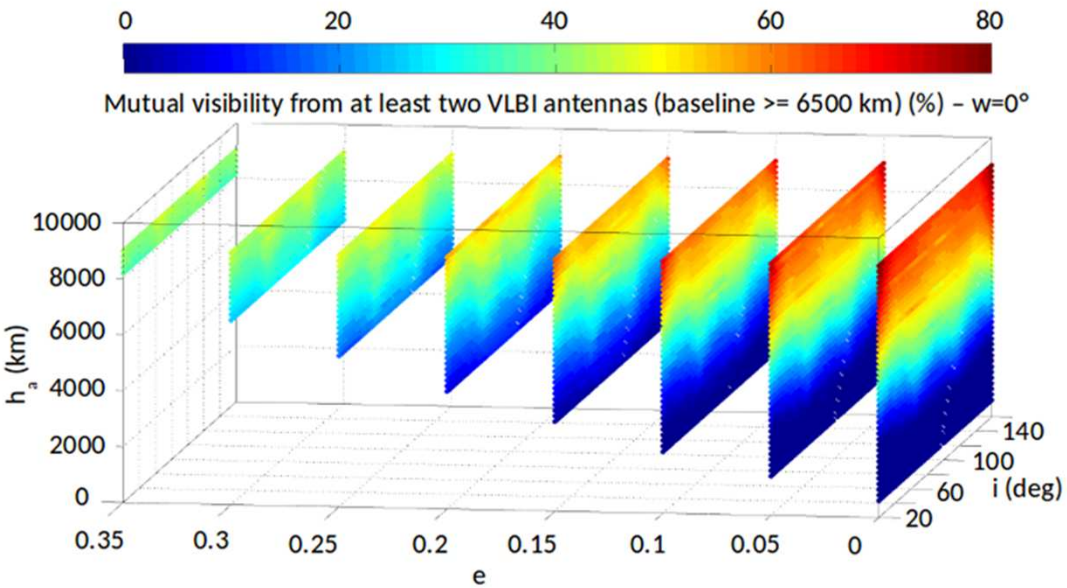
	GRASP scenario	E-GRASP scenario
Perigee altitude	925 km	762 km
Apogee altitude	1400 km	7472 km
Inclination	100.2°	63.4°
Node velocity	.98 deg./day (SSO)	-.97 deg./day
Perigee velocity	-2.35 deg./day	Frozen at equator
Orbit period	109 mn	178 mn

Criterion	GRASP	E-GRASP
Multi-technique visibility (% of seven days)	36.3 %	79.3 %
Mutual visibility for VLBI (baseline ≥ 6500 km - % of seven days)	0.0 %	58.4 %
Number of passes per day for all stations	2	3
Mutual visibility for GPS (% of seven days)	100.0 %	99.4 %
Empty sectors over four weeks (mean value)	71.1 %	5.1 %
Total radiation dose over three years (with 1cm Al shielding)	5.9 krad	5.3 krad

VLBI-transmitter (JPL)

Key microwave circuitry in the VT is inherited from the GRAIL RSB (green shading) and the GRAIL TTS transmitter (blue shading). The antennas (no shading) are existing flight hardware available to E-GRASP.



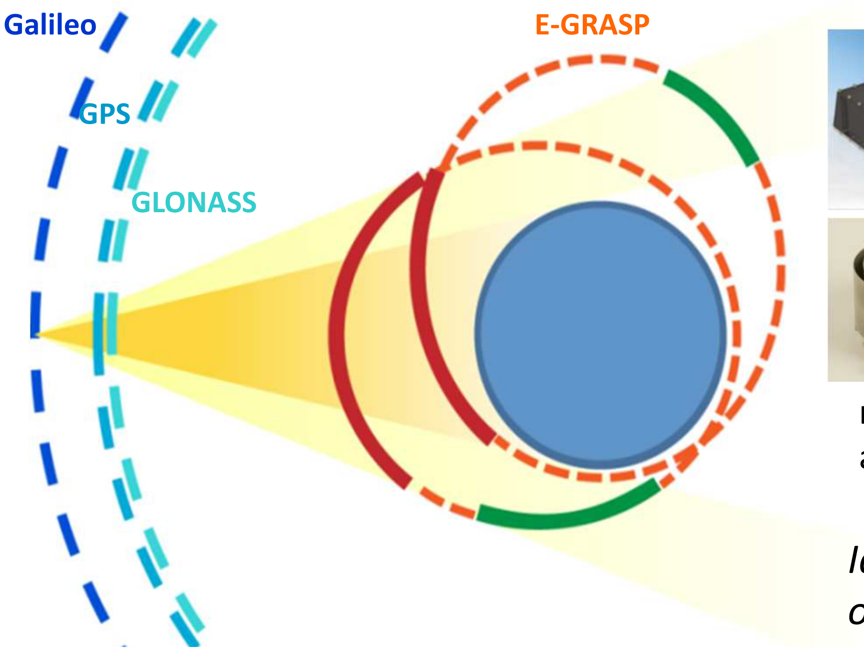


D. Coulot et al., 2015

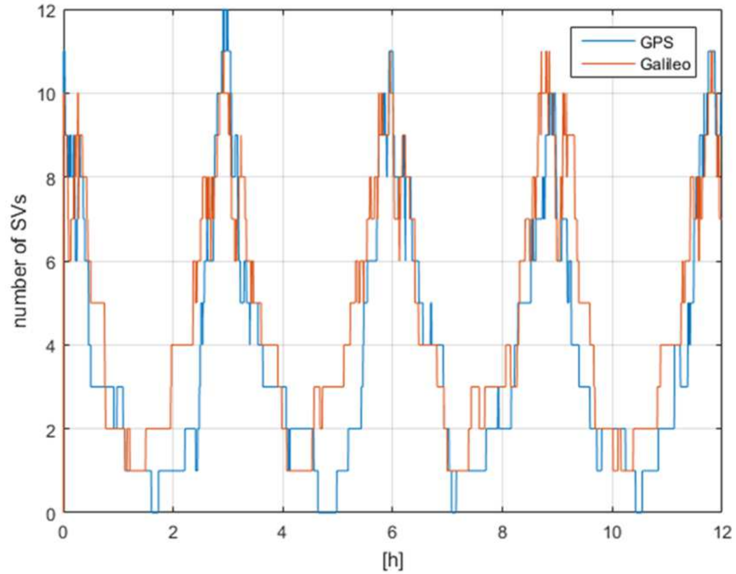
58%: percentage of mutual visibility of E-GRASP over one week from at least two VLBI antennas, with a baseline greater than 6500 km.

GNSS (RUAG Space)

PODRIX is a multi-constellation (GPS & Galileo) multi-frequency (L1/E1, L2 and L5/E5a) GNSS receiver platform from RUAG Space GmbH which is currently under development to be qualified in 2016. PODRIX is a direct continuation of the RUAG Space GPSR-G2 legacy GPS-receivers for Precise Orbit determination (POD), which are used on many European missions such as SWARM, SENTINEL 1,2,3 A/B, EARTHCARE



receiver box and antenna

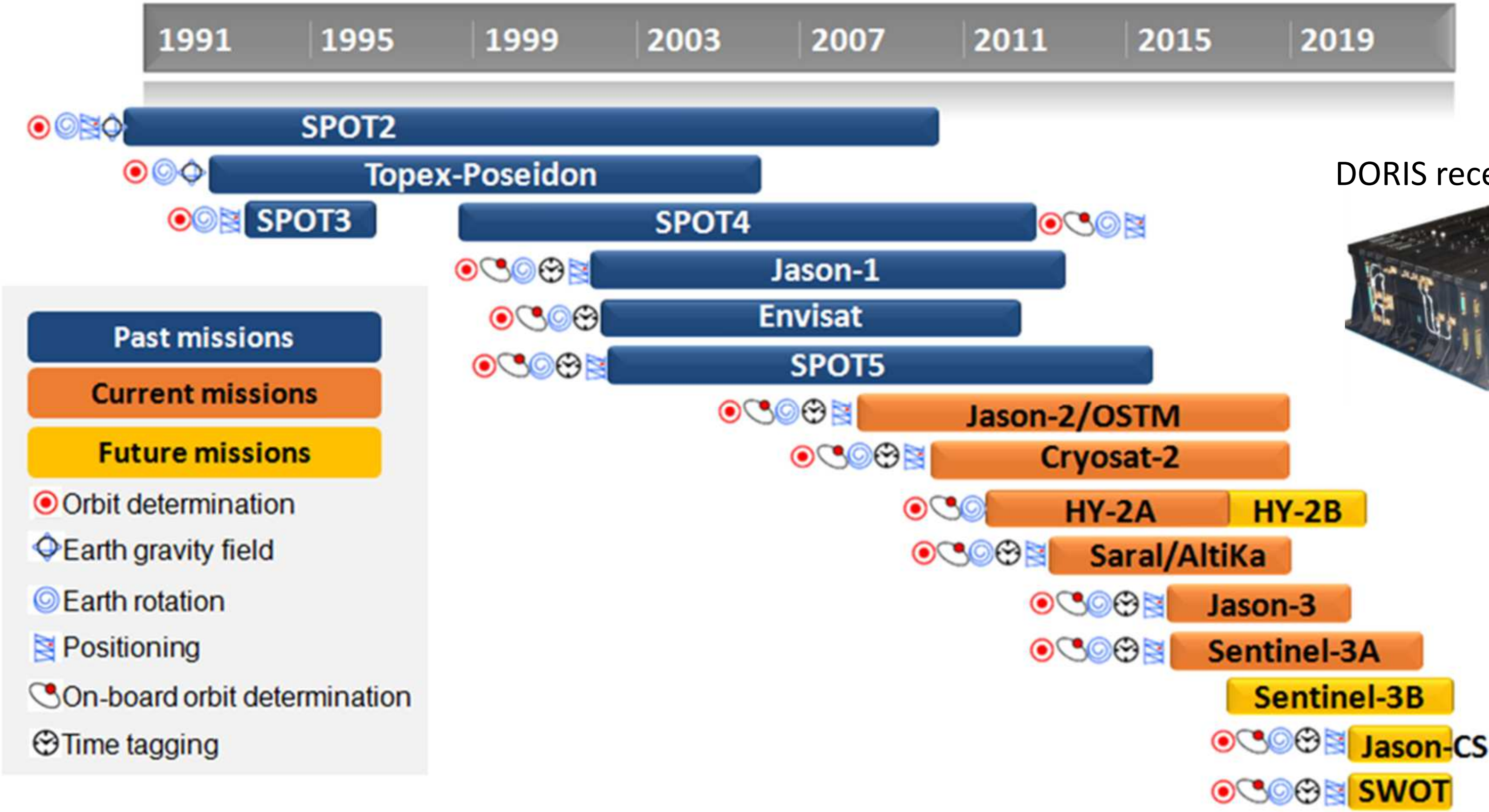


Portions of E-GRASP orbits which can be tracked by GNSS, in red with the top antenna, in green with the nadir antenna.

Identifier number of the visible space vehicles along the orbit with one zenith antenna over 12 hrs. A GNSS space vehicle is considered as visible in case the received carrier to noise ratio on L1/E1 exceeded the 27dBHz, which corresponds to the acquisition threshold of the RUAG GNSS receiver (credits RUAG).

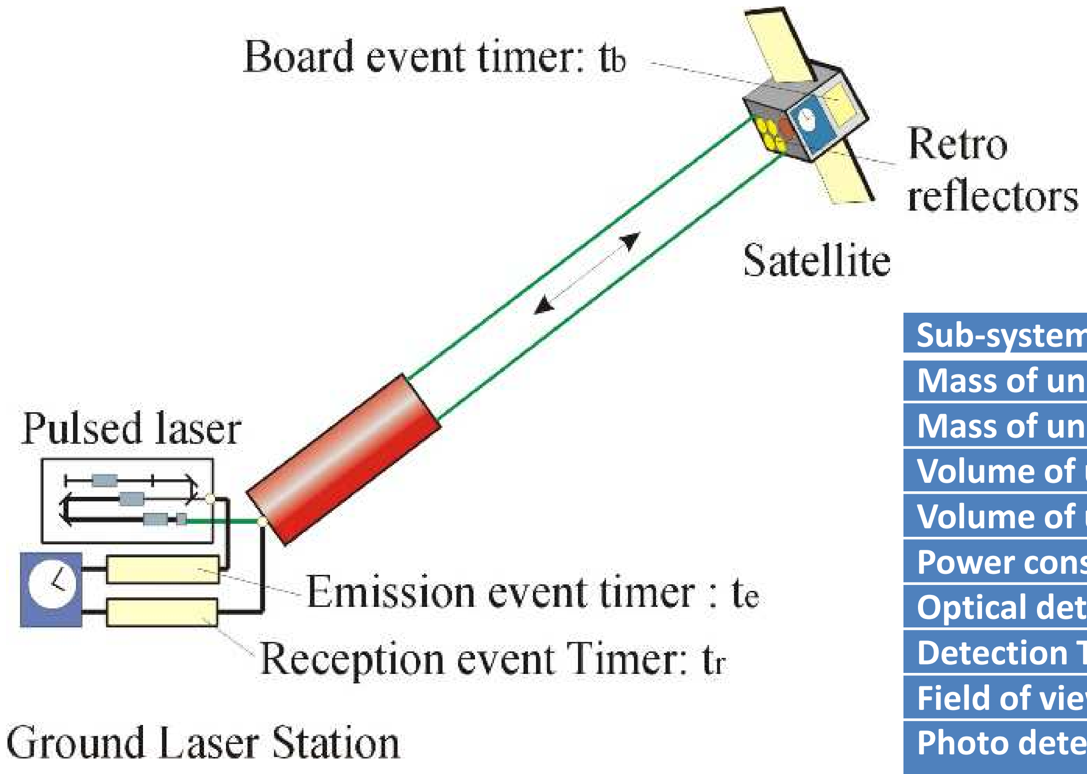
DORIS (CNES)

- High precision CNES Doppler measurement system (accuracy < 0.3 mm/s)
- Up to 7 dual frequency channels
- Routine high precision measurement mode reached autonomously.
- Direct impact on next altimetric missions tracked with DORIS



DORIS receiver box and antenna

SLR (GFZ) and T2L2 (OCA)



11 rings with a total of 245 cubes radius of the array about 10 cm because of different velocity aberrations between apogee (30 µrad) and perigee (60 µrad) as proposed by GFZ

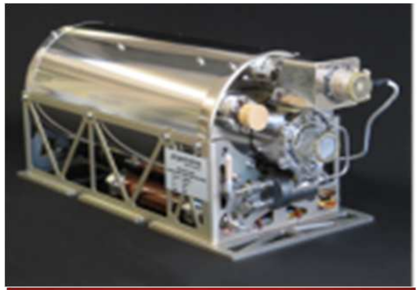
Sub-system	Characteristics
Mass of unit A	0.5 kg
Mass of unit B	4 kg
Volume of unit A	50x50x100 mm^3
Volume of unit B	150x150x150 mm^3
Power consumption	30 W
Optical detection wavelength	532.1 nm
Detection Threshold	Single photon
Field of view @ perigee	28°
Photo detection Standard deviation	20 ps RMS @ single photon
Event timer Standard Deviation	1 ps RMS

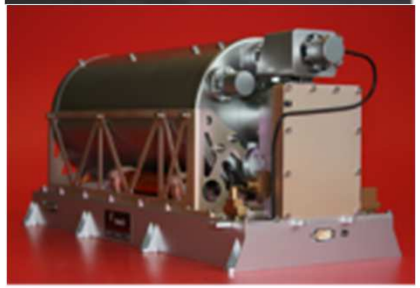
Principle: for every laser pulse, the laser station measures the start epoch t_e and the return epoch t_r after reflection on the satellite retroreflectors. The Time Transfer by Laser Link (T2L2) payload records the arrival epoch on-board t_b

T2L2 flight model (part B) designed for Jason-2 mission

Mini PHM (Leonardo-Finmeccanica)

Mini-PHM derives from PHM (Passive Hydrogen Maser) technology already in flight in the frame of Galileo Global Navigation System.





Leonardo-Finmeccanica

Specification	Mini-PHM
Output Frequency	10.00285741 MHz (fH/142)
Output Level	+ 7dBm (Main and Auxiliary outputs)
Frequency Drift (/Day)	≤ $1x10^{-14}$ after 1 week < $1x10^{--15}$ after 30 days
Allan deviation (1s<τ<10^4s)	< $1x10^{-12}$ x $\tau^{-1/2}$ max < $7x10^{-13}$ x $\tau^{-1/2}$ typical
Freq. sensitivity to temperature	< 1 $x10^{-15}$/°C
Freq. sensitivity to Main Bus Voltage	≤ $3x10^{-15}$/V
Dimensions	210 x 485 x 218 mm
Mass	12 Kg
Main Bus Voltage	50V ± 1V
Power consumption (W)	≤ 54 W at -5°C baseplate ≤ 47 W at +10°C baseplate
Qualification Temp. Range	- 15°C to +20°C
Lifetime (MEO Orbit)	>12 years
Allan deviation (s)	
1	$6.5x10^{-13}$
10	$1.4x10^{-13}$
100	$6.3x10^{-14}$
1000	$2.2x10^{-14}$

Instruments characteristics and TRL

Unit	Manufac-turer	Volume [mm^3]	Mass [kg]	Power [W]	Key Performance	Flight Heritage	TRL
Laser Retro-Reflector	GFZ / ASI / INFN	Ø 200, h 100	1	-	1 mm	PN-1A	7
GNSS receiver **GNSS antenna**	RUAG	280x240x81 Ø 200, h 87	3 .8	15	1 mm	Swarm, Sentinel, Earthcare	8
DORIS receiver **DORIS antenna**	TSA	388x366x173 Ø 160, h 427	18 2	22	.3 mm/s	Sentinel3, Jason	8
VLBI-Transmitter **S-band antenna** **X-band antenna**	JPL	190x210x60 100x100x6 Ø 44, h 200	3 .3 .4	10	1 mm	GRASP	6
T2L2	OCA	50x50x100 150x150x150	0.5 4.5	30	100 ps	Jason-2	4
OUS (with redundancy)	Leonardo/ Spectratime	210x485x218	24	≤ 56	10^{-14}	Galileo	6
Σ			**54.8**	**133**			
Micro-STAR (optional)	ONERA		12	12	10^{-11} m/s/√Hz	GRACE, GOCE	4

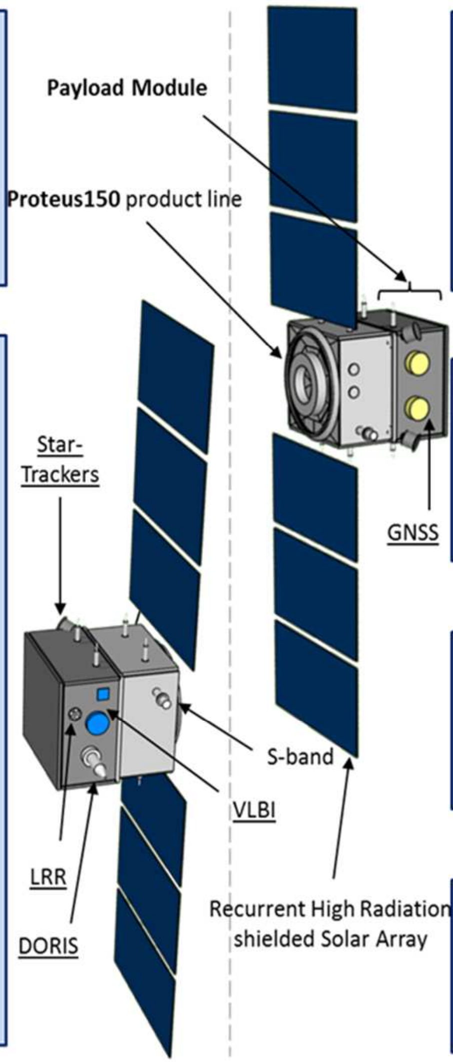
Mission architecture (Thales Alenia Space)

Mission requirements

- High elliptical orbit with enhanced observations opportunities.
- Multiple payload to drastically improve TRF knowledge with multiple application

Satellite

- Instruments & Star-Trackers on a dedicated Payload Module
- Recurrent radiation-shielded Solar Array (SA)
- Platform Proteus150 with structure adaptation to support the Solar Array
- Satellite dry mass < 500 kg
- Attitude Control : reaction wheels
- Uncontrolled reentry : lowering perigee with chemical propulsion
- TMI & TTC : S-band
- Scientific data 220 Mbit/day
- Yaw Steering to optimize power along the orbit



Mission

- High elliptical orbit : 762 - 7472 km
- Inclination 63°
- 5 years lifetime
- Launch in 2024

Launcher

- VEGA-C main and only passenger
- Compatible with VEGA Fairing
- Direct injection

Ground Segment

- Flight Operation Segment in ESOC
- Payload Data Ground Segment

Instruments

- DORIS
- VLBI
- LRR/SLR
- GNSS

E-GRASP challenges and recommendations

- Improving the TRF precision by a unique system, integrating all space geodetic techniques on one platform, with orbit and calibration optimized, in order to meet the present-day science requirements. The TRF available today needs an improvement by a factor of 5, as a minimum (recent ITRF2014 results).

- The accuracy of the Terrestrial Reference Frame (TRF) impacts directly the orbit determination of altimetric satellites and land motion estimation at tide gauges and consequently the quantification of the sea level variations in space and time.

- More generally, global studies on the mass budget of the earth-ocean-atmosphere system and on global tectonics require an accurate TRF.

- “Earth observations must become more precise. We require information about current trends at a scale measured in millimeters to detect changes of the Earth system with sufficient precision, to meet society’s future needs”, *Report of the UN expert committee on "Global Geospatial Information Management“, 2014.*

The end