ETH zürich

Institute of Geodesy and Photogrammetry

GNSS Earth System Monitoring: Present Examples and New Developments

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Double Jubilee, AIUB/Uraniae, 25.11.2022

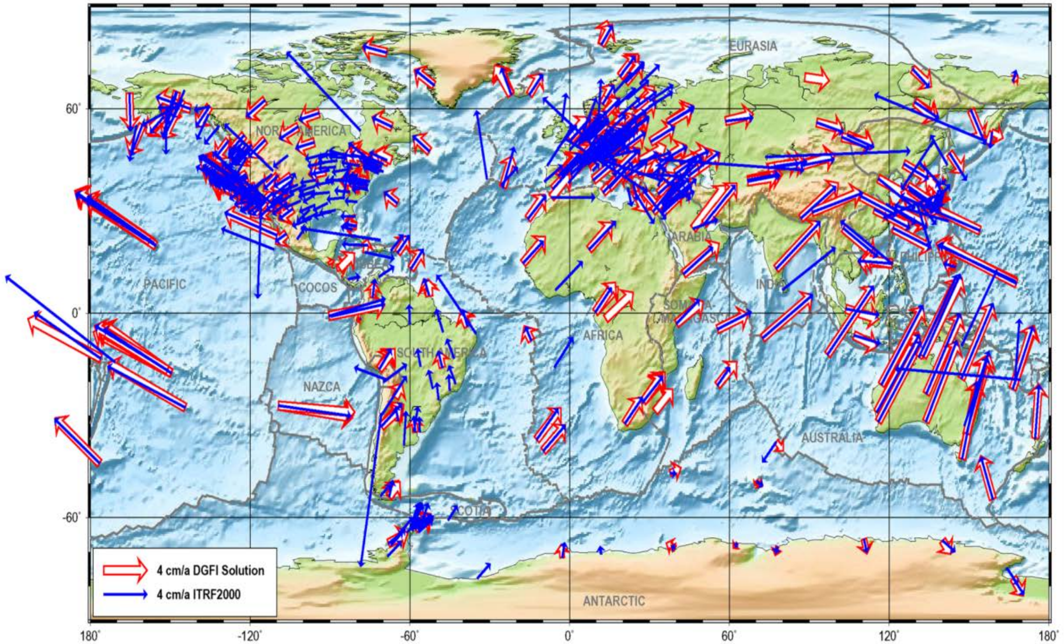
Overview

- Motivation: Monitoring of the Earth's System
- A few Examples of GNSS Earth Monitoring
- Three Ways to Overcome Limitations:
  - Turn Nuisance into Signal
  - Make Use of Low-Cost and Miniaturization
  - New Technologies
- Conclusions

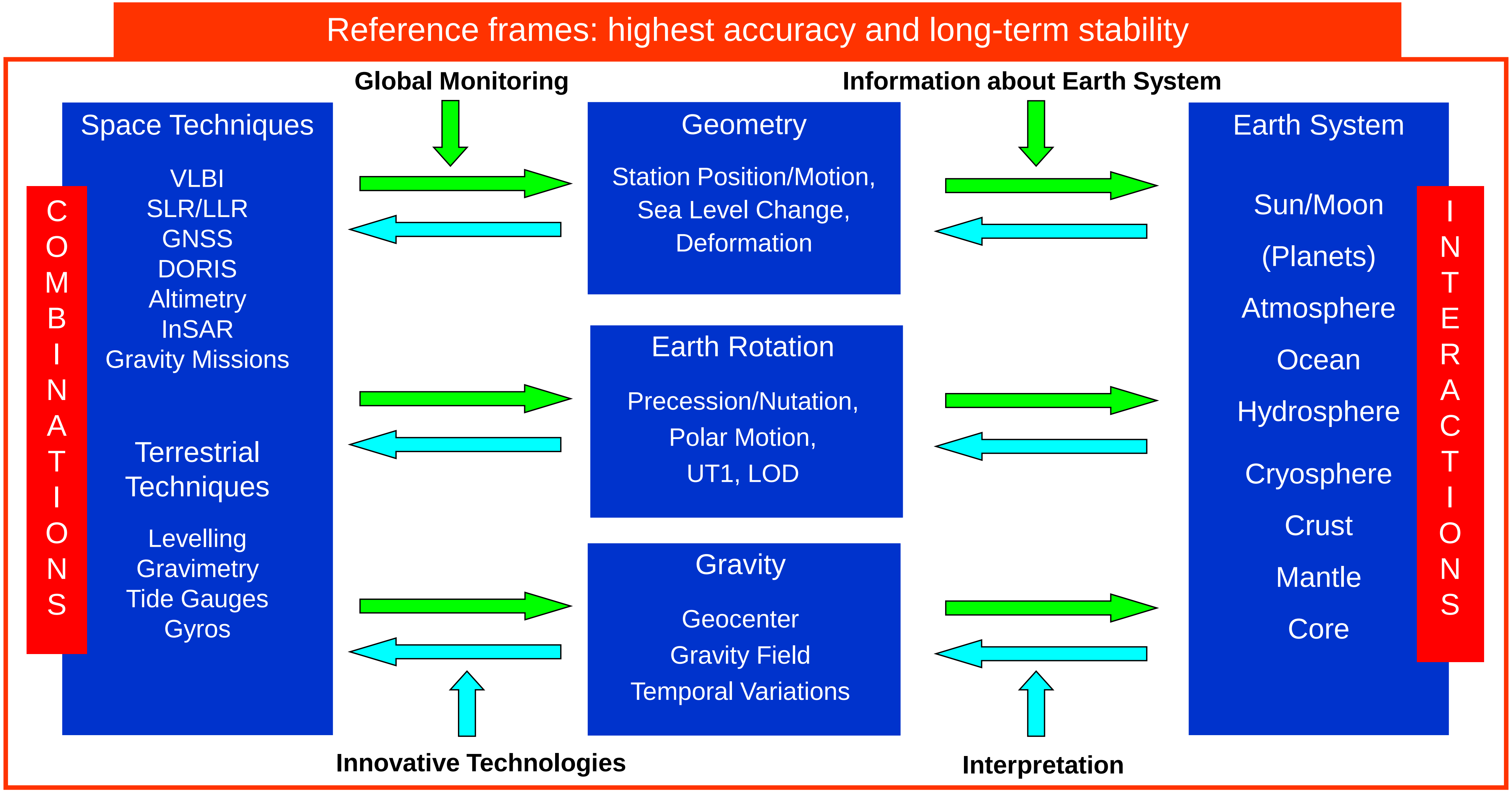
Motivation:

Monitoring the Earth's System

Processes: Millions of Years ↔ Fractions of Seconds

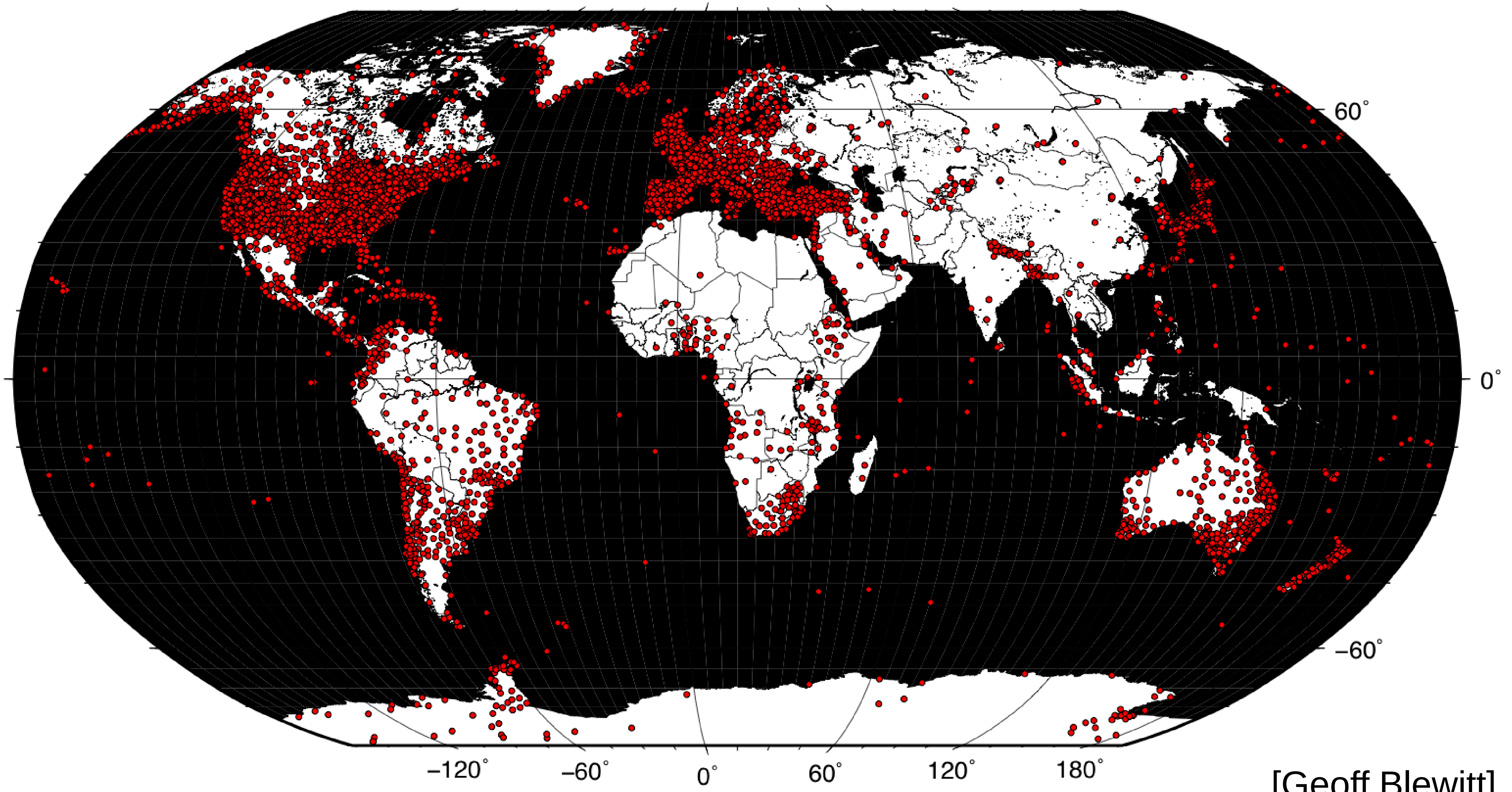


Monitoring and Modelling of System Earth



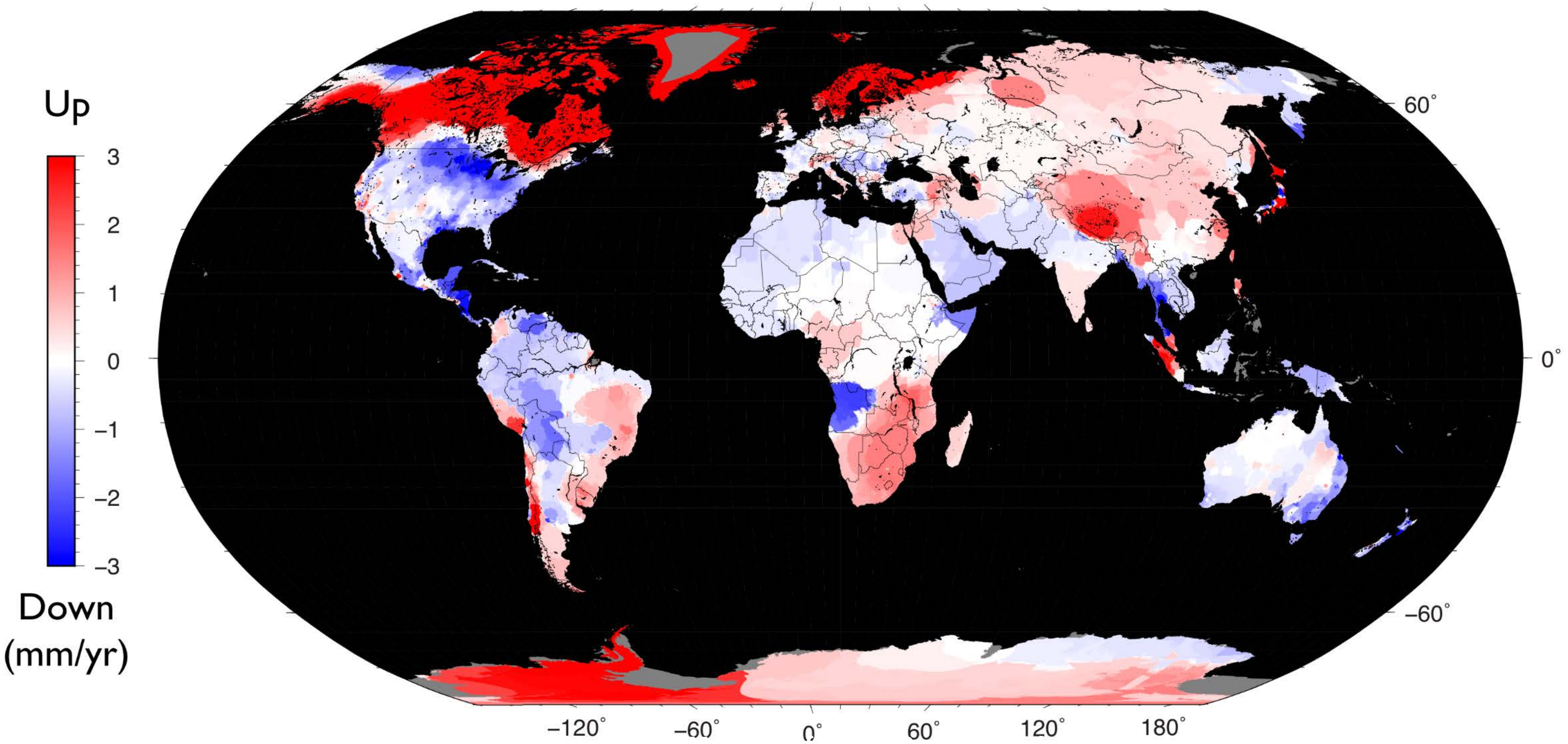
Examples of GNSS Earth Monitoring:
Small Long-Term Trends and Fast Events

The Global Picture: >18'000 permanent GNSS Stations



[Geoff Blewitt]

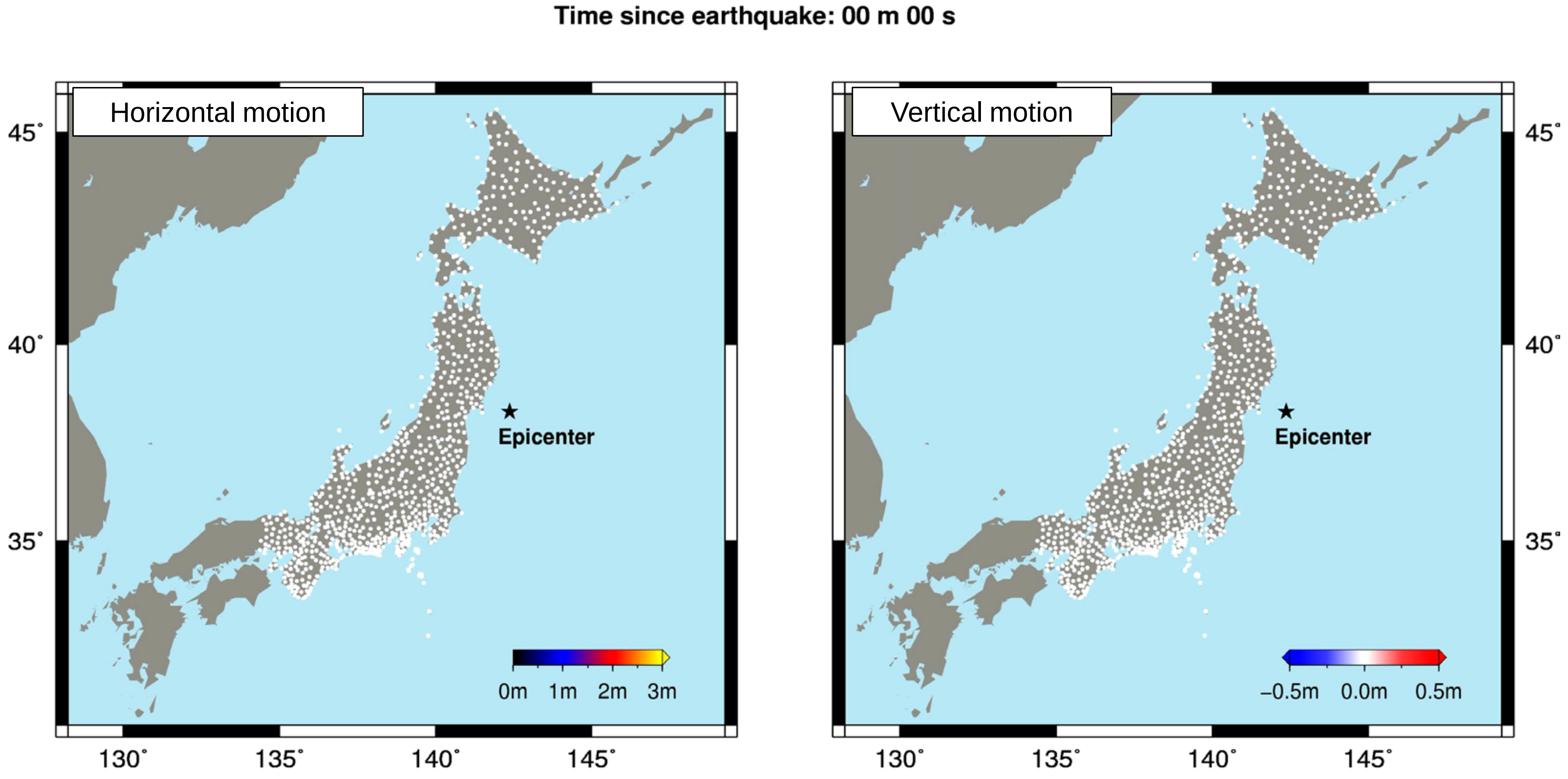
Global Vertical Land Movement from GNSS



Hammond, W. . and G. Blewitt (2019): Annual Meeting of NASA Sea Level Change Team, March 11-13, 2019, Annapolis, Maryland

Fast Event Detection: Closer and Closer to Real-Time

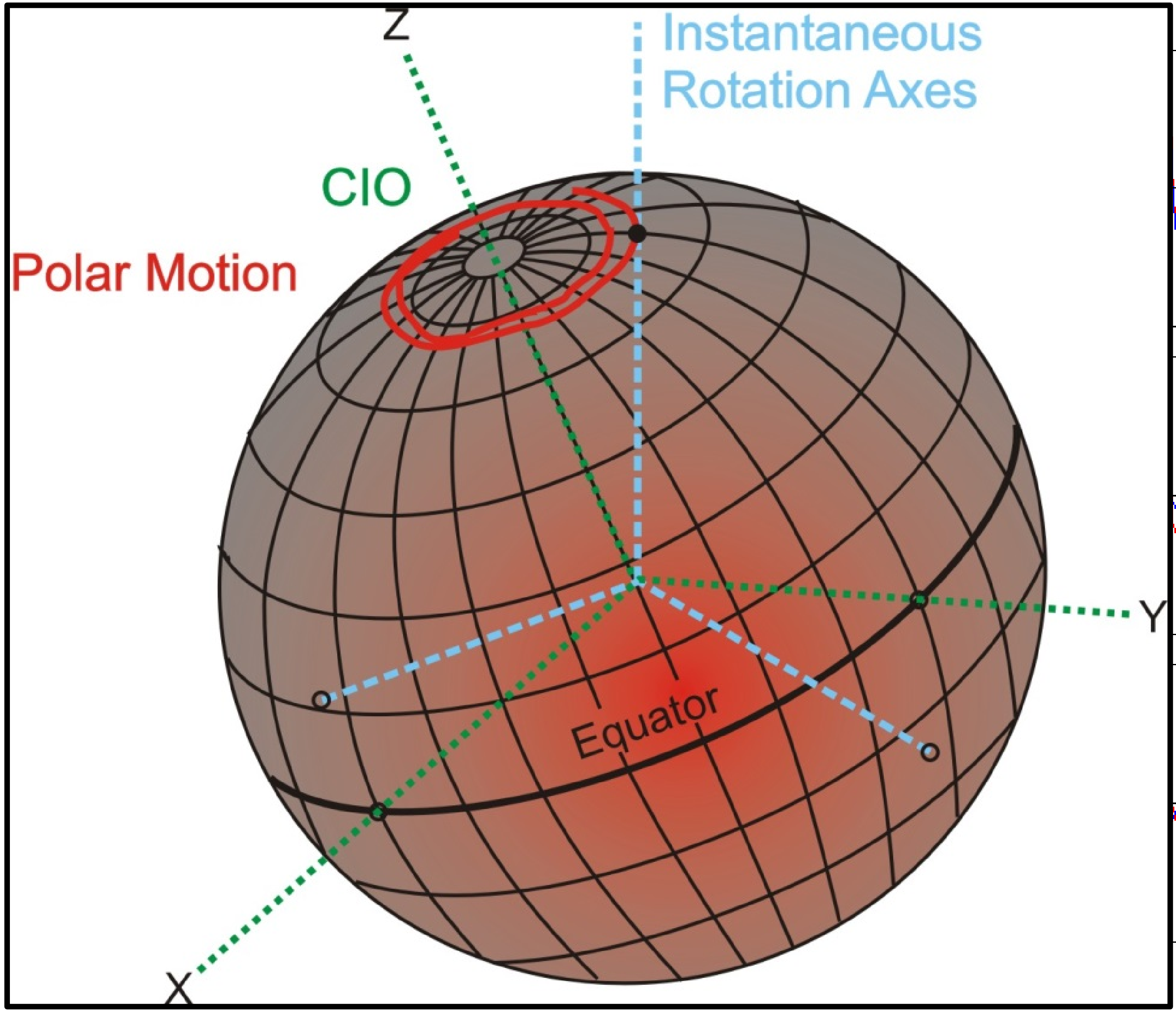
Earthquake ground displacements with GNSS, early warning

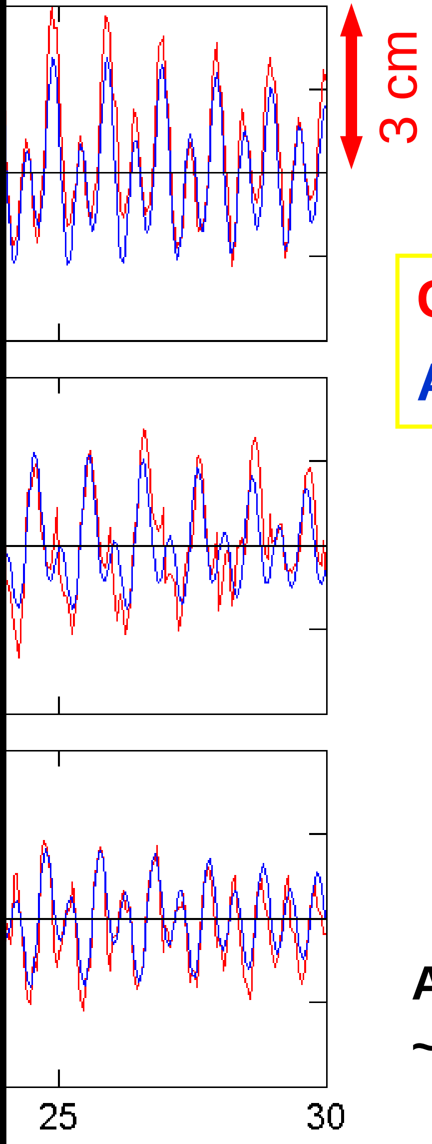


GPS 1-Hz, Tohoku-Oki earthquake

→ **rapid magnitude determination etc.**

Earth Rotation: GNSS Sub-Daily Variations (pioneered by AIUB in the 90s)



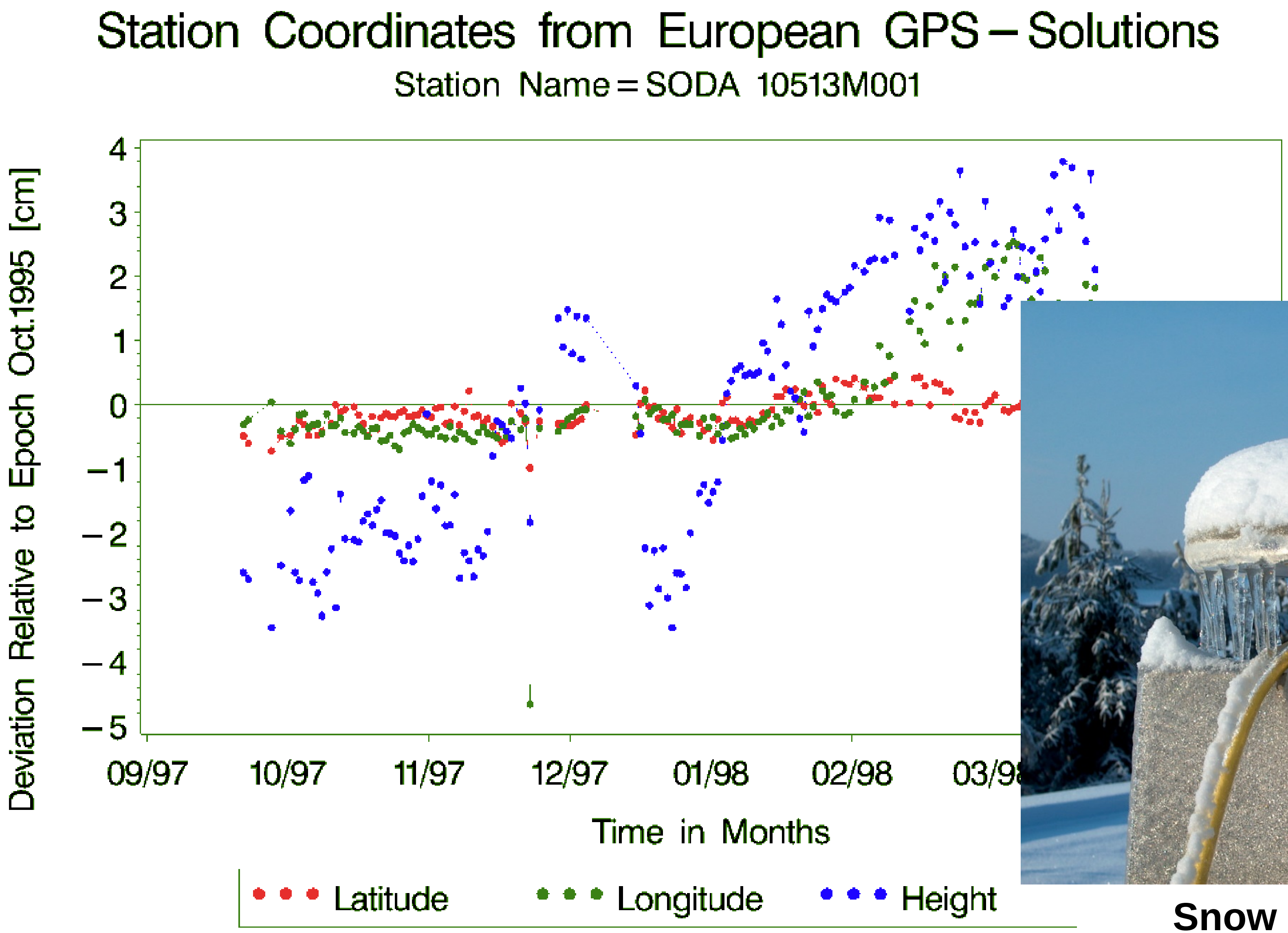


GPS (1h)
Altimetry

Accuracy:
~4 mm

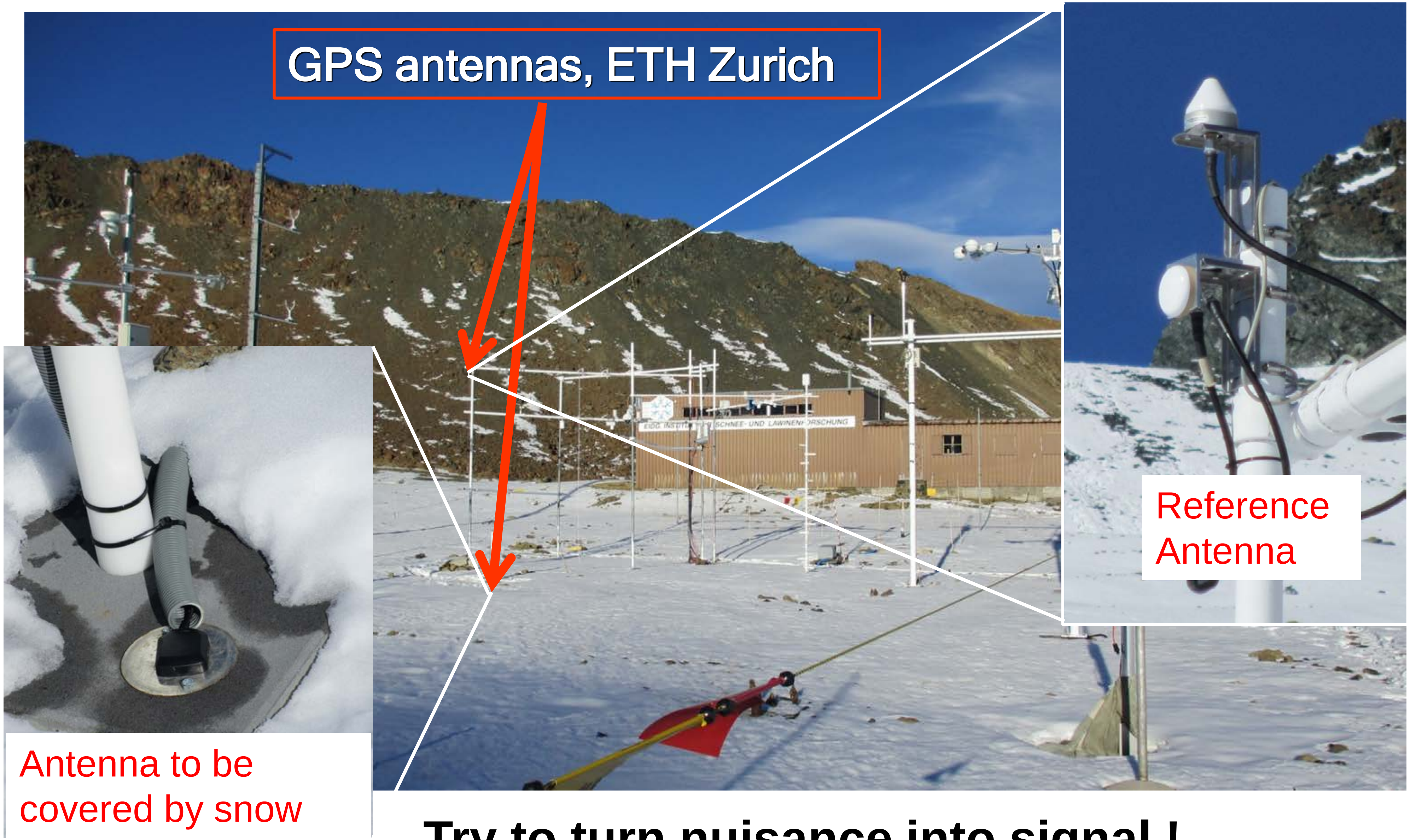

Overcome Limitations:
→ Nuisance to Signal

Nuisance/Limitation: Environmental Effects



Snow on the GNSS antenna

Snow Monitoring at SLF Weissfluhjoch, Davos



Try to turn nuisance into signal !

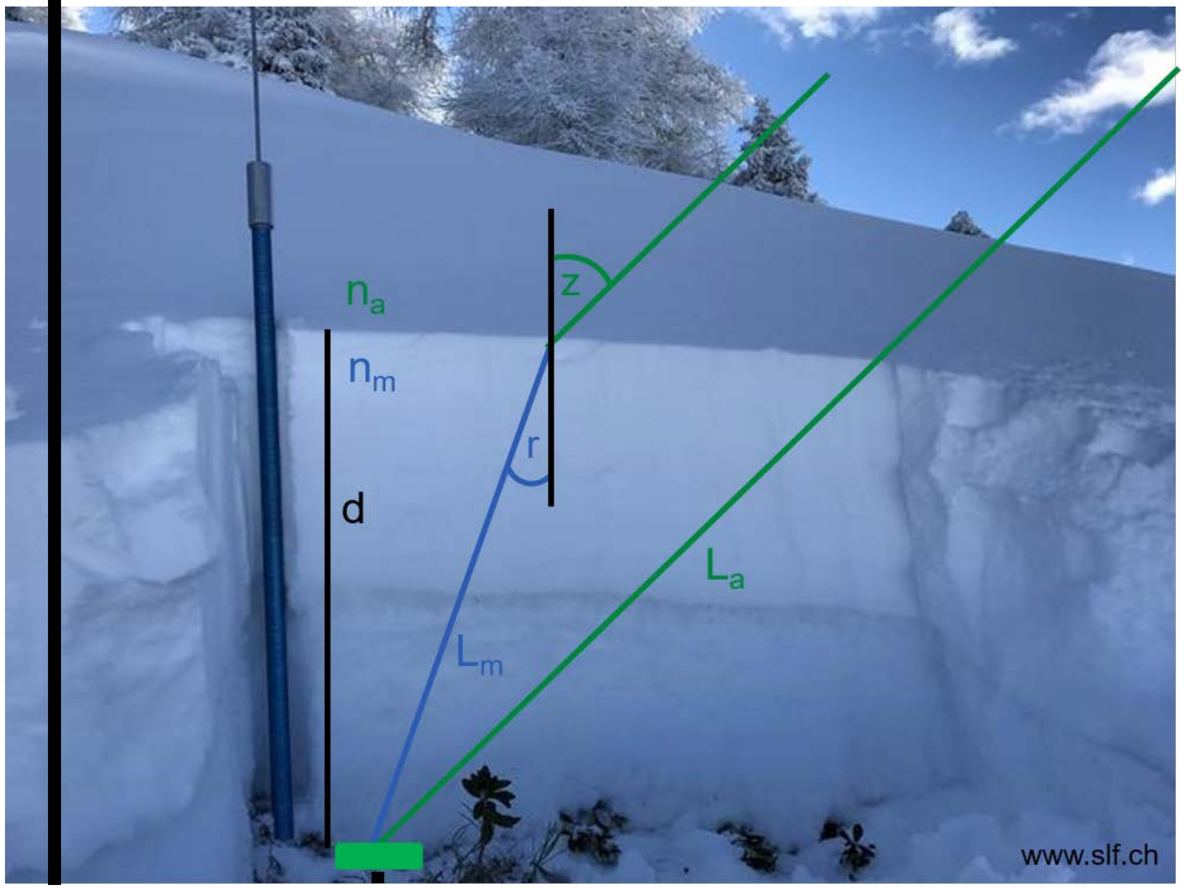
Estimation of Snow Water Equivalent (Single Layer Model)

Electrical path length in:

- Air: $L_a = c_0 * \Delta t_a$
- Water: $L_w = c_0 * \Delta t_m$

Excess path length δL:

$$\delta L_w = L_w - L_a = d * \underbrace{\left(\sqrt{n_w^2 - \sin^2 z} - \cos z\right)}_{\text{Mapping function}}$$

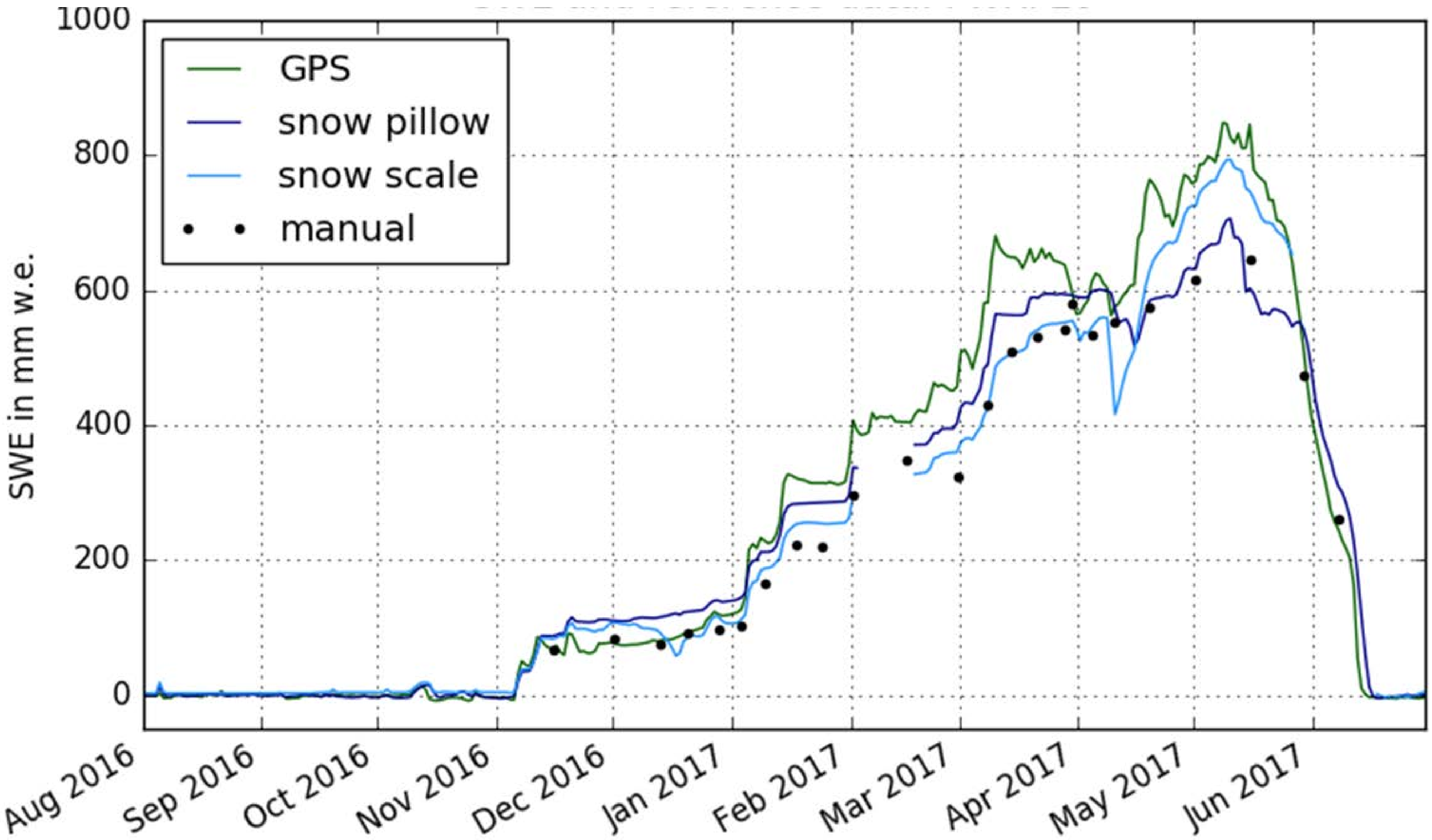


- Introduce additional parameter in GPS observation equation and estimate (SWE):

$$L = \rho + \delta\rho + \boxed{\delta L_w}$$
$$+\lambda N + \varepsilon$$

[Ladina Steiner]

Snow Water Equivalent Estimation with GPS



[Ladina Steiner]

Progress in GNSS / Overcome GNSS Limitations: Turn Nuisance into Signal

- **Basis for all high-accuracy GNSS applications: extreme accuracy of the phase measurements (1-2 mm)**
- **More and more applications by turning nuisance into signal:**
  - **Ionospheric refraction** → **Space weather assessment, ionosphere physics**
  - **Tropospheric refraction** → **Water vapor for weather predictions and climatology**
  - **Clocks** → **Time and frequency transfer, relativity tests**
  - **Multipath** → **Reflectometry and scatterometry, soil moisture, biomass mapping**
  - **Snow on antennas** → **Snow water equivalent, snow height**

Overcome Limitations:

→ Miniaturization and Low-Cost

MPGNET: Multi-Purpose low-cost GNSS NETwork

Motivation: → **GNSS: a very versatile sensor for monitoring**

- ❑ Environmental processes
- ❑ Natural hazards
- ❑ Climate change

Especially in remote/alpine areas!

Several applications/products:

- ❑ Ground movements (for landslide or seismic monitoring)
- ❑ Tropospheric delays (ZTD, ZWD) and integrated water vapor (IWV)
- ❑ Soil moisture and snow (snow-water-equivalent (SWE))

Pilot study in cooperation with MeteoSwiss: **Collocation of GNSS payload at SwissMetNet (SMN) sites**

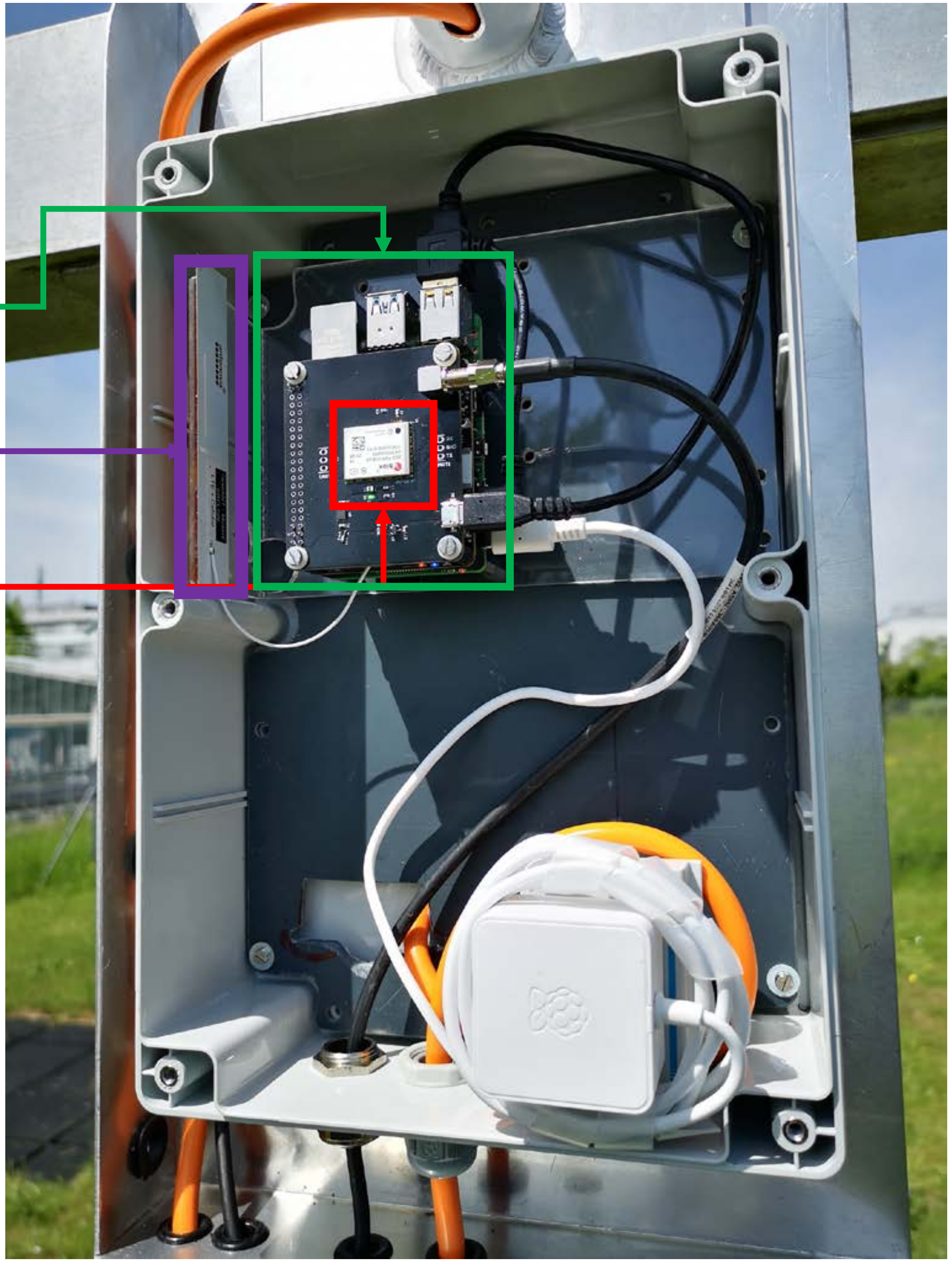
- ❑ Pilot project with 10 dedicated sites (5 stations already deployed)
- ❑ Test setup at prototype site
- ❑ Long-term vision: collocation **at > 200 sites in Switzerland**

Build-up of a low-cost, sustainable GNSS network, providing a variety of high-quality products for environmental monitoring

MPGET: Instrumentation

Data logging system:

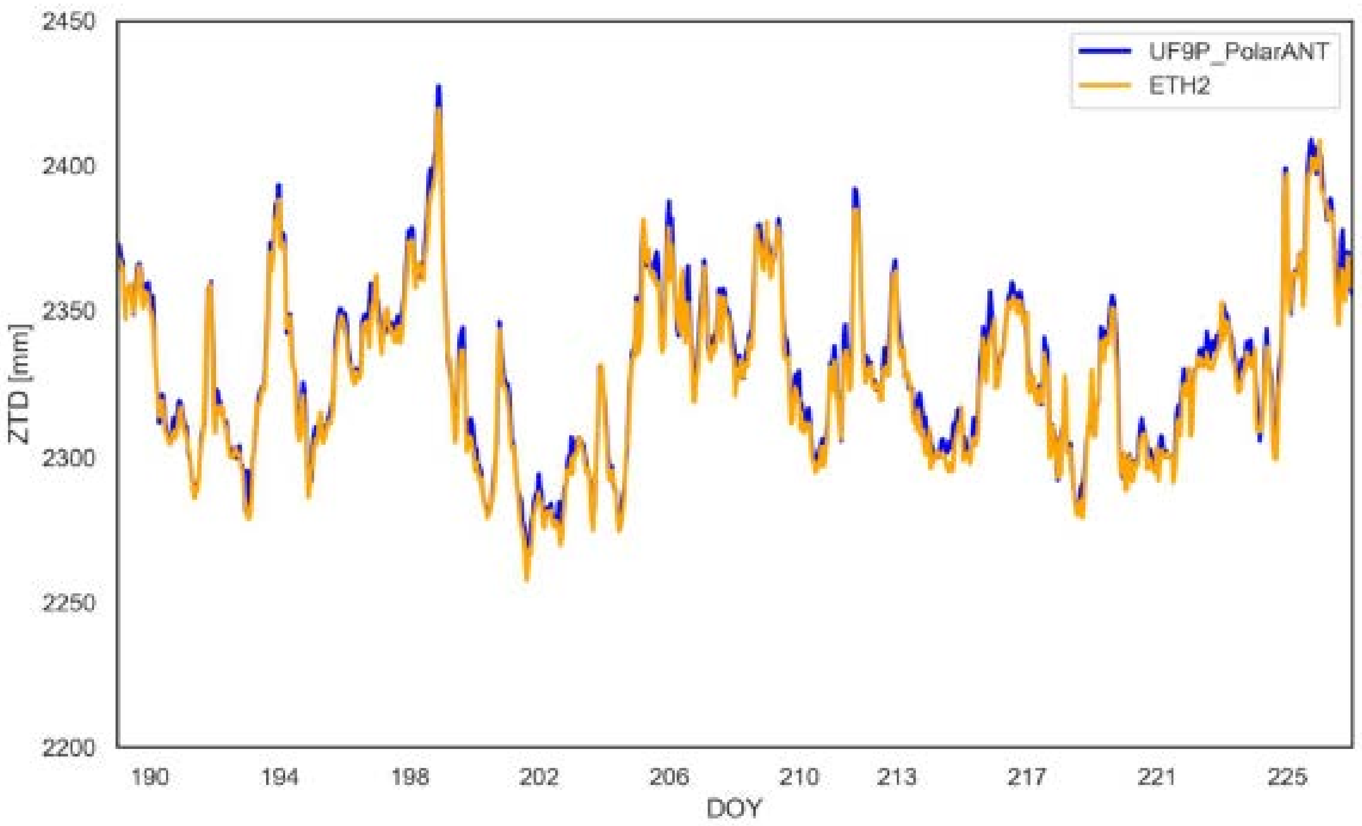
- **Raspberry Pi 4**: for data logging/transfer and basic scripting
- **LTE modem and antenna** for data transfer
- **u-blox ZED-F9P** dual-frequency, multi-GNSS board (GPS, GLONASS, Galileo, BeiDou, QZSS)
- **Septentrio PolaNt* MC** multi-frequency, multi-GNSS antenna



[Matthias Aichinger]

Quality of Water Vapor Determination with Low-Cost GNSS

Comparison of troposphere parameters from low-cost and geodetic-grade equipment



Bias [cm]	SD [cm]	RMS [cm]	R
0.29	0.34	0.44	0.99

[Matthias Aichinger]

Low-Cost GNSS Receivers on CubeSats: Vision

- **GNSS (Global Navigation Satellite Systems) have become a very important tool for satellite missions**
  1. GNSS **precise positioning** in space is essential to most Earth observation and science missions
  2. GNSS for **time synchronization** in space (e.g. ACES)
  3. **Earth observation** directly based on GNSS sensors in space: Water vapor, electron content in ionosphere, gravity field, ocean surface, tsunami early warning
- **Vision:** perform these GNSS measurements with **very efficient, small, low-cost, low-power GNSS receivers** (miniaturization, small is smart)

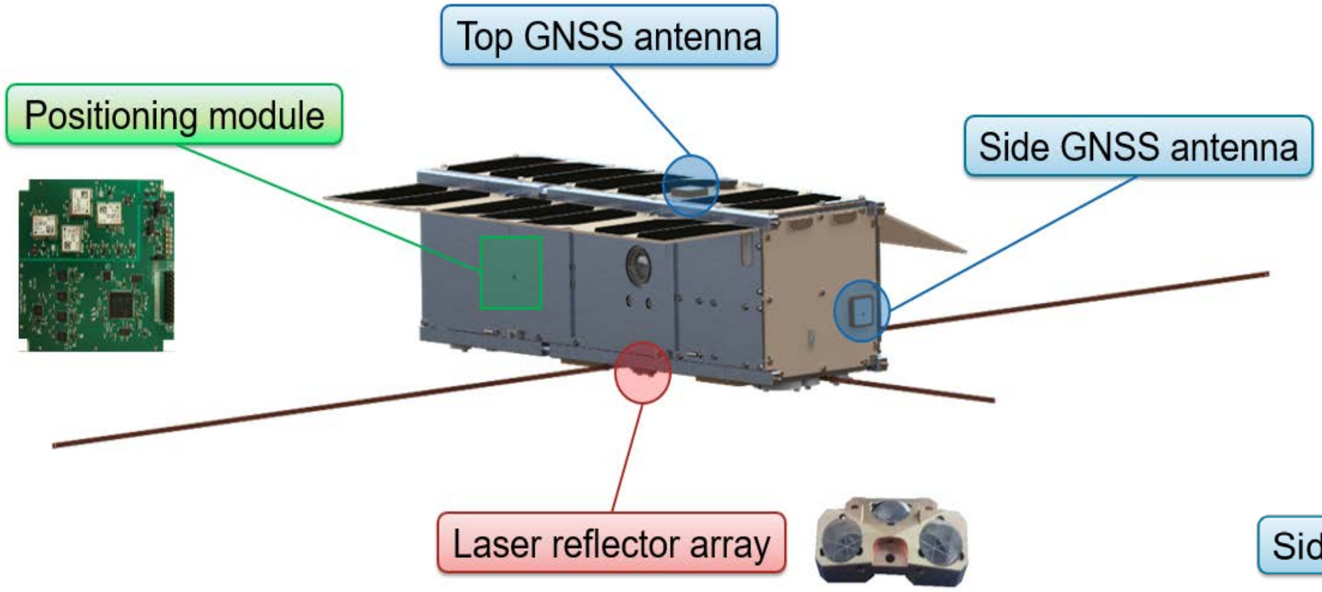
Geodetic type space receiver	**~ € 300'000,**	**3000 g,**	**15 W,**	**30 cm**
u-blox low-cost receiver	**~ € 100,**	**8 g,**	**0.16 W,**	**1.5 cm**

- Is it possible to do **state-of-the-art science** with low-cost GNSS sensors in space?
- Small satellites/sensors are a must for **future formation flying / large constellations**

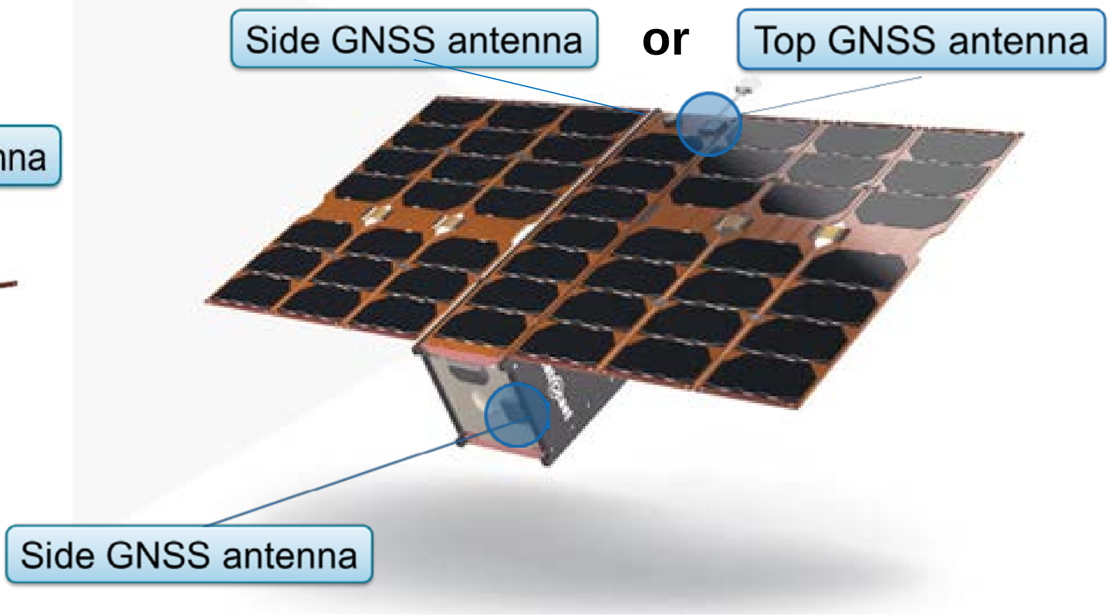
Astrocast Cubesats and COTS GNSS Payload

Collaboration with Swiss company **Astrocast**

Prototype Cubesats (2x)



Constellation Cubesats (10x)



- 4 NEO-M8T u-blox **multi-GNSS single-frequency** receivers (**redundancy**)
- 2 taoglas **GNSS antennas**
- 1 **retro-reflector** with 3 corner cubes for Satellite Laser Ranging (SLR)

→ **GNSS payload: 100 g, 160 mW, € 500**

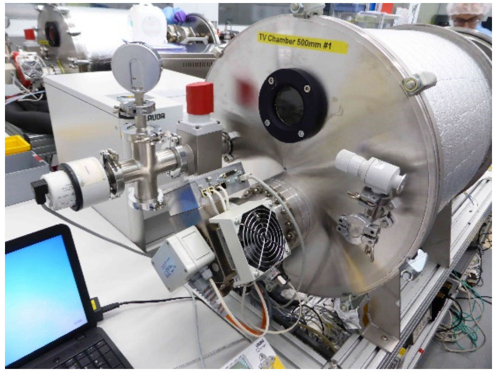
GNSS Payload Board Development and Testing

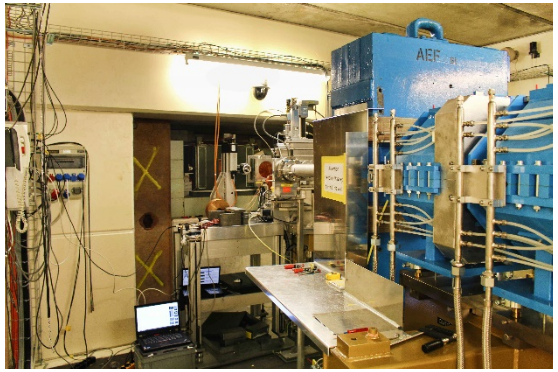
Receivers need a modified firmware

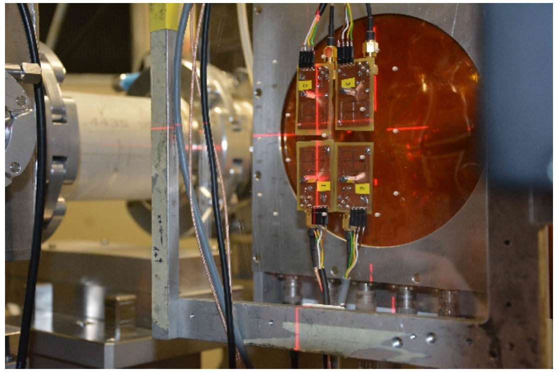
- Altitude and speed limits removed
- Tracking below horizon enabled
- Dynamic model and tracking adapted
- Increased Doppler search range for acquisition

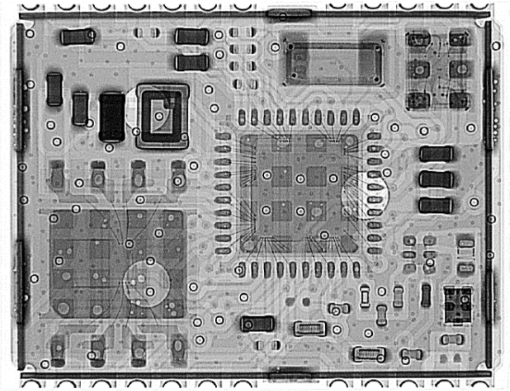
Receivers tested for space capability

- Performance tests based on simulated GNSS signals in a Low Earth Orbit (DLR)
- Vacuum and temperature tests (RUAG)
- Proton irradiation tests (PSI)
- Destructive physical analysis (ESTEC)

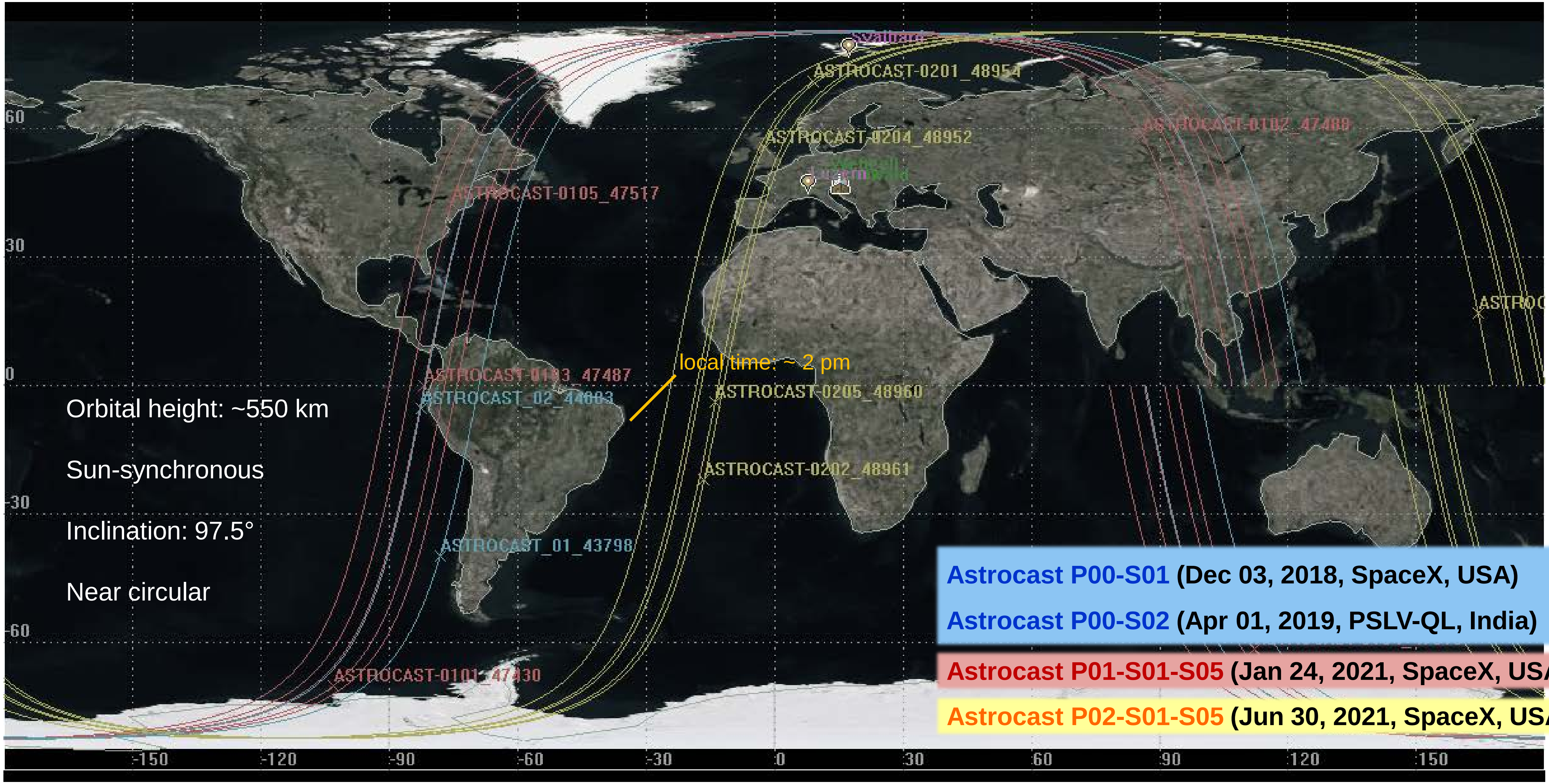








Present Astrocast Cubesat Constellation (12 Cubesats)



Orbital height: ~550 km

Sun-synchronous

Inclination: 97.5°

Near circular

Astrocast P00-S01 (Dec 03, 2018, SpaceX, USA)

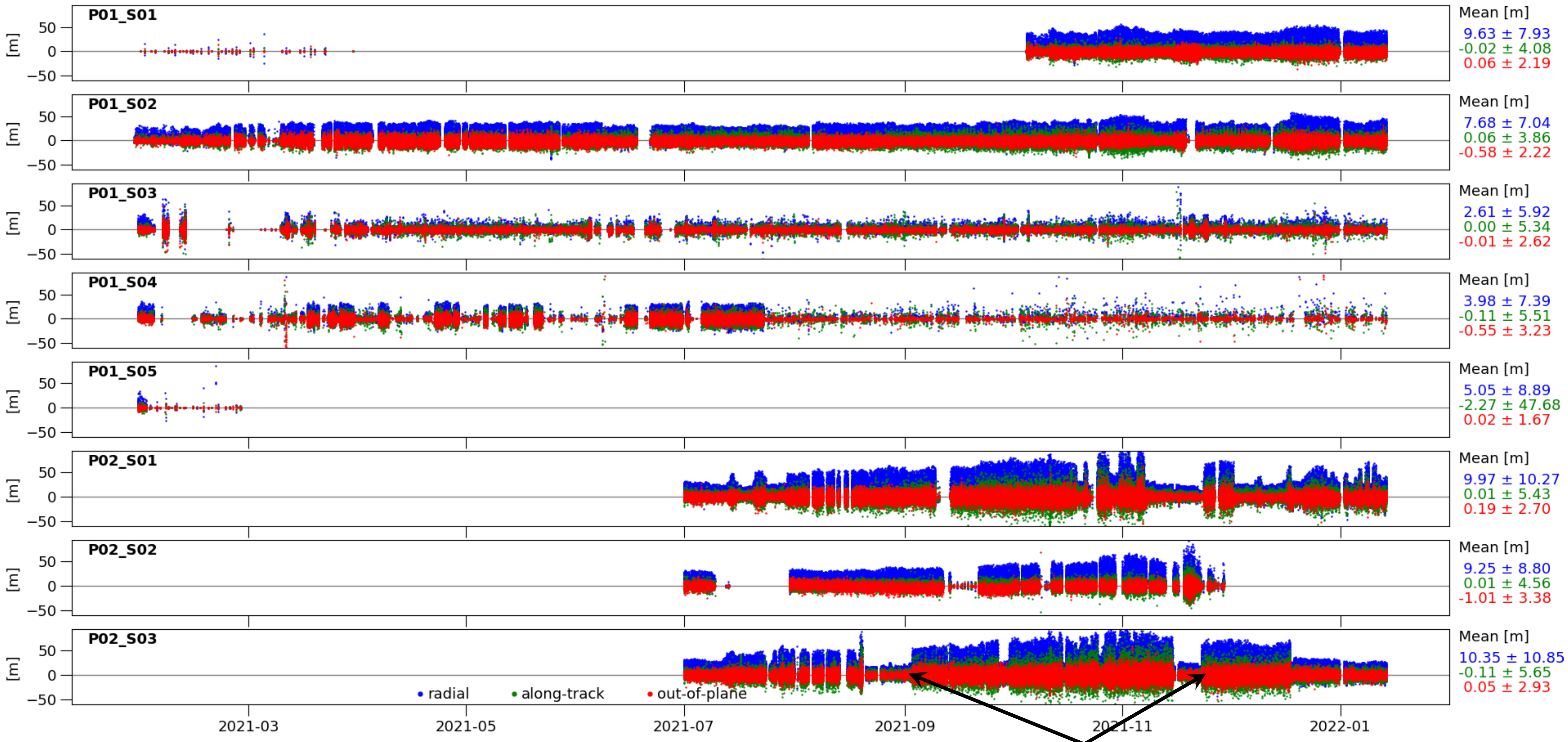
Astrocast P00-S02 (Apr 01, 2019, PSLV-QL, India)

Astrocast P01-S01-S05 (Jan 24, 2021, SpaceX, USA)

Astrocast P02-S01-S05 (Jun 30, 2021, SpaceX, USA)

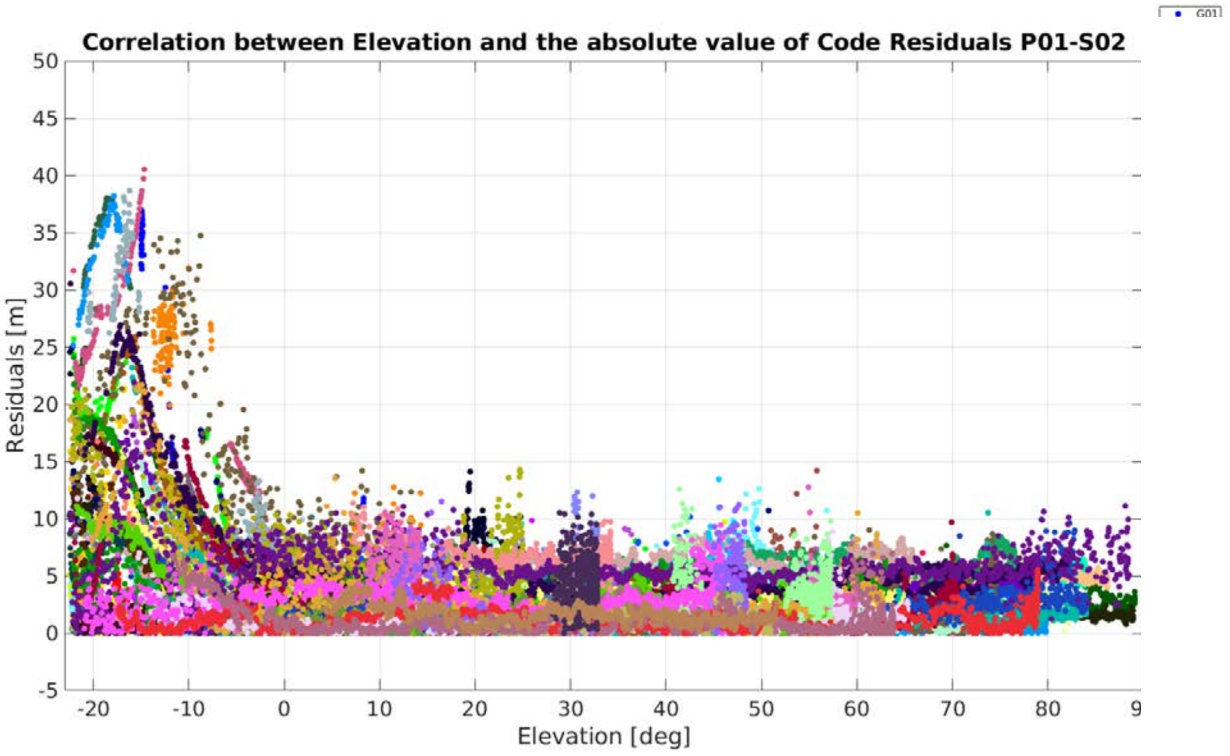
Constellation CubeSats: Navigation Solutions in Real-Time

Validation with a reduced-dynamic orbit fit over 1 day

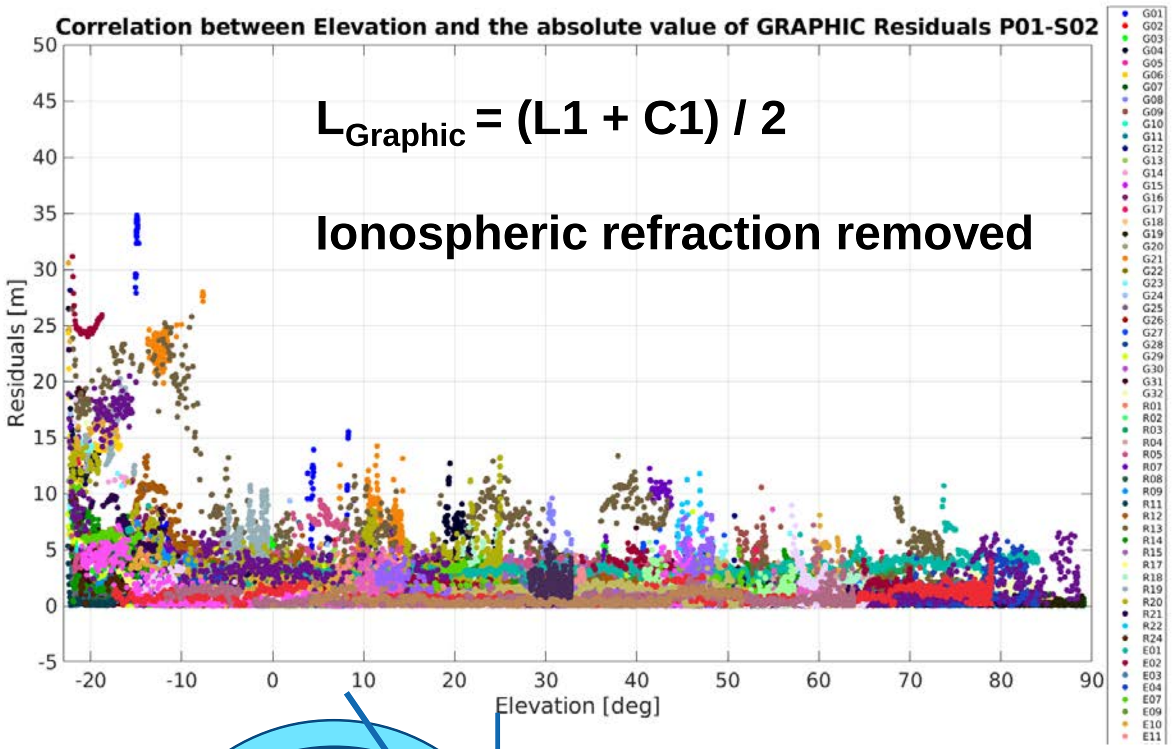


GNSS Raw Data Analysis: 100 minutes, 1Hz GPS + GLONASS + Galileo

Code residuals



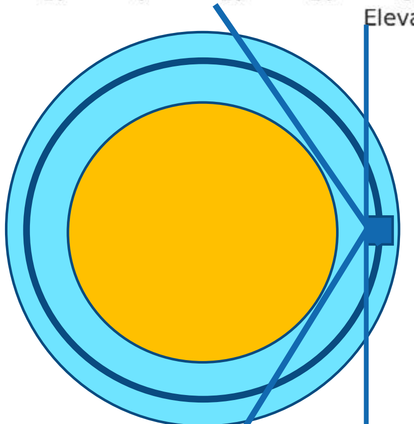
Graphic residuals



$L_{Graphic} = (L1 + C1) / 2$

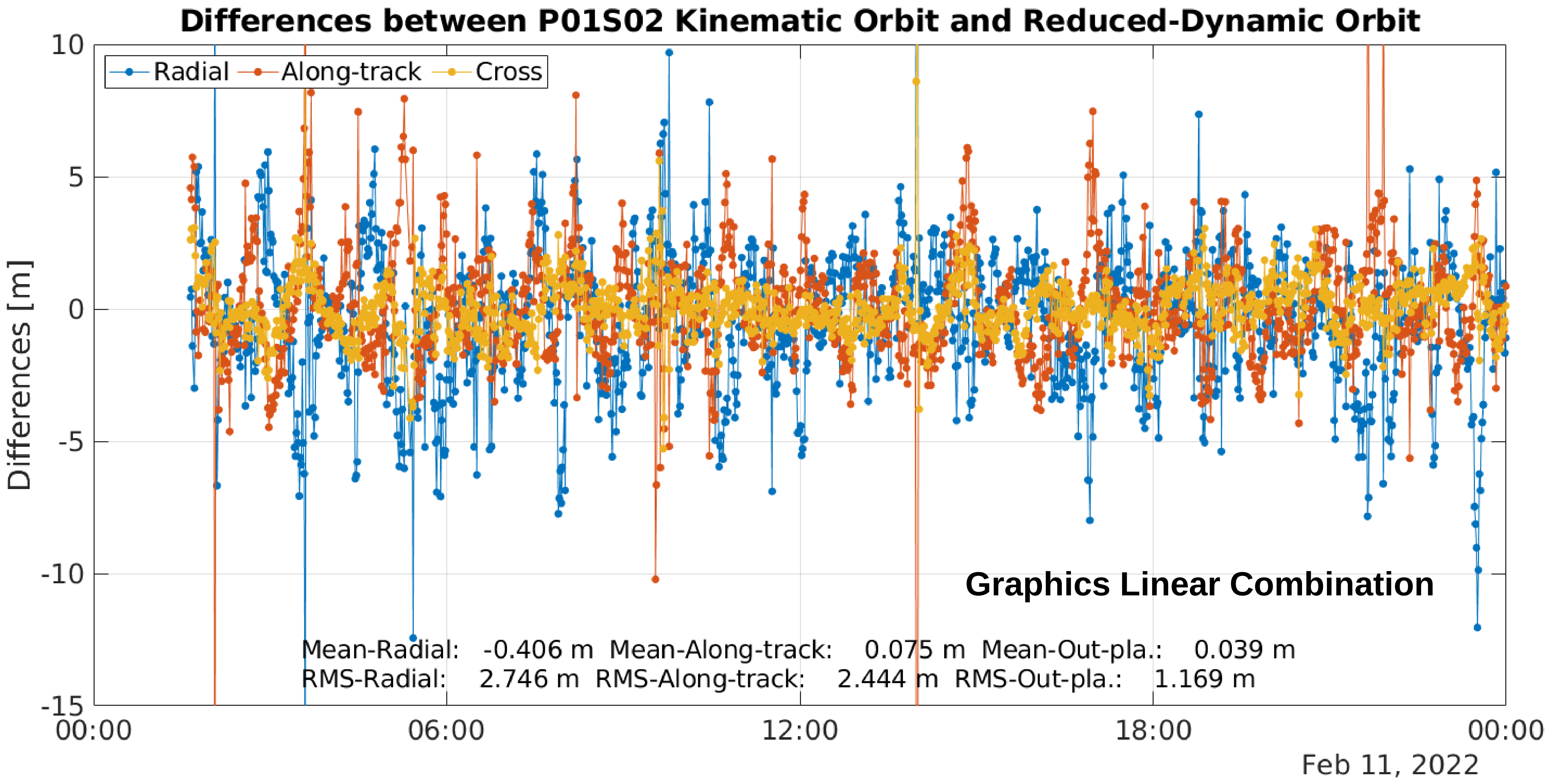
Ionospheric refraction removed

→ **Atmospheric sounding possible (radio occultations)**



LEO satellite

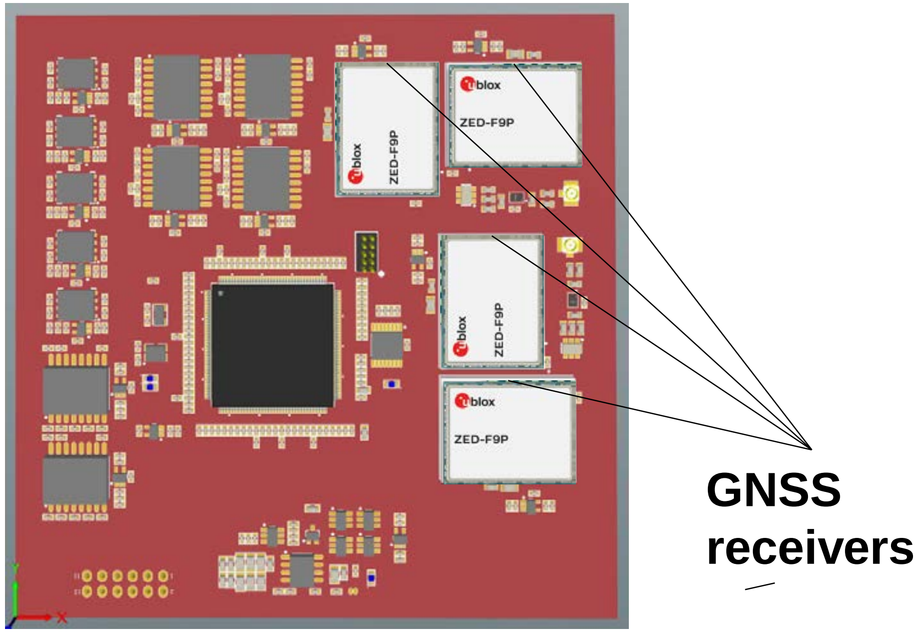
GNSS Raw Data Analysis: 23 hours, 1 min, GPS + GLONASS



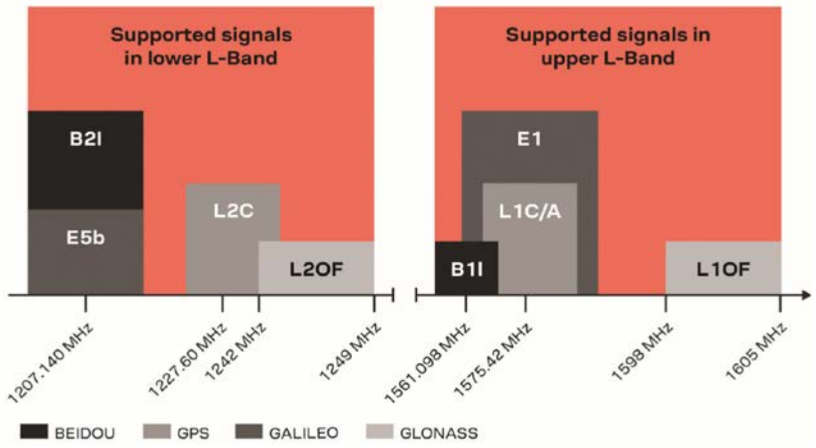
Next Generation: Dual-frequency multi-GNSS Payload (COTS)

Selected COTS hardware components

- 4 u-blox ZED-F9P receivers
  - Dual-frequency, multi-GNSS
  - Dimensions: 17.0 x 22.0 x 2.4 mm
  - Power consumption: 110 mA @ 3.0V
  - Sampling: up to 20 Hz
- Passive GNSS antenna
- Bandpass filters, LNA and signal splitter



Environmental tests have already successfully been performed: vacuum, temperature, radiation, GNSS signal generator tests

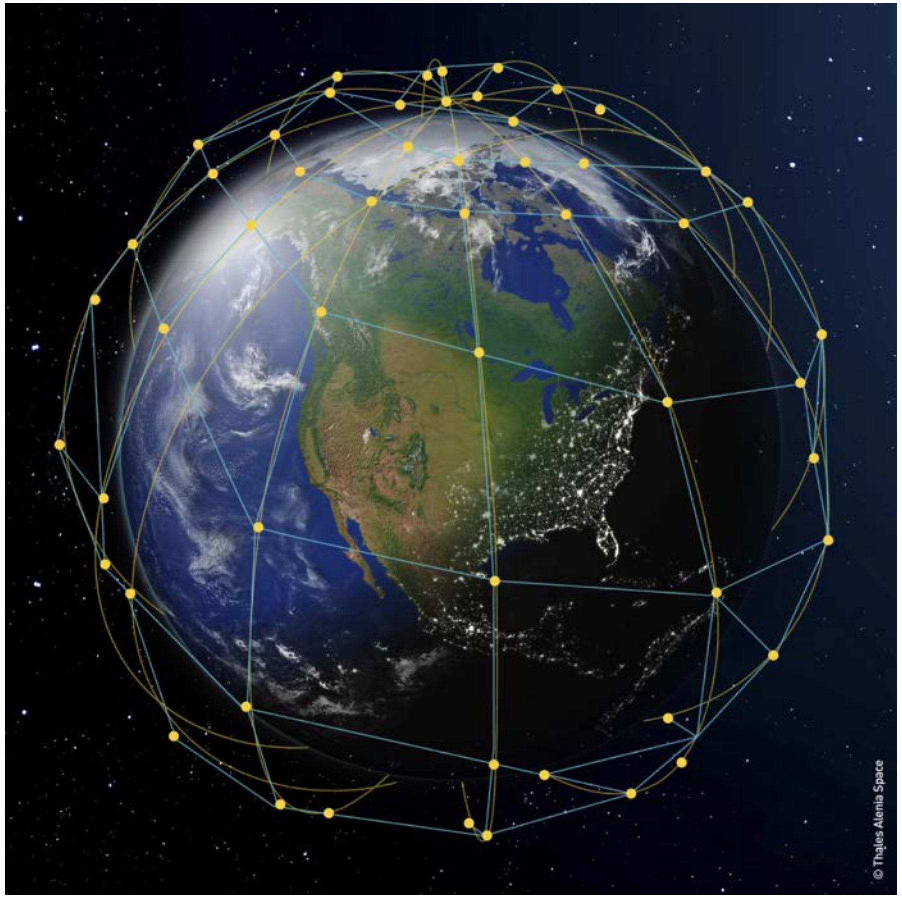


Future: Cubesat Constellation

- **First dual-frequency GNSS payload:**
  - Launch Q1/2023

- **Constellation** of ~100 Astrocast satellites → network in space

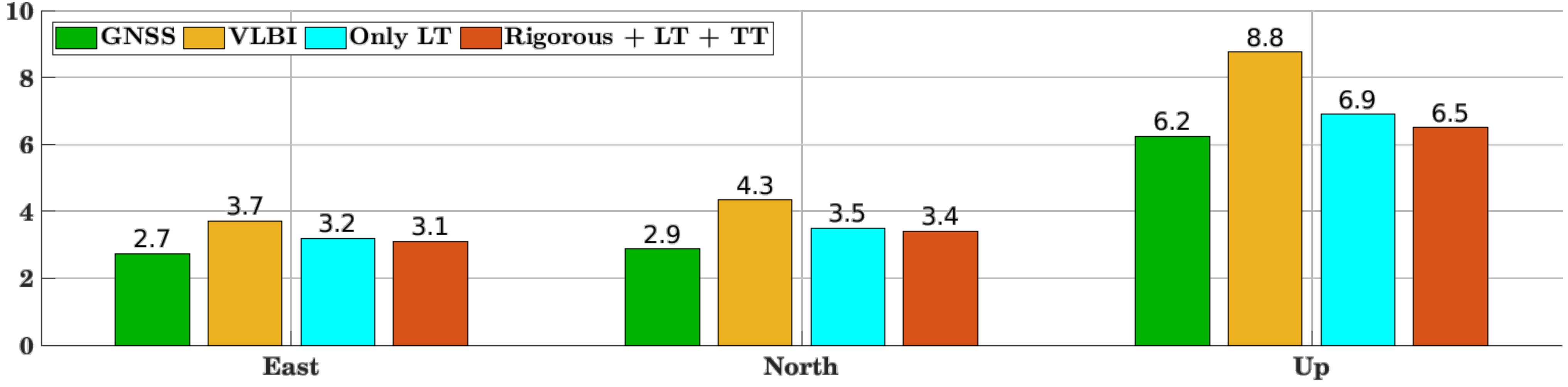
- **Earth observation applications foreseen:**
  - Tomography of the ionosphere
  - Radio occultation measurements
  - Air density from air drag
  - Gravity field of the Earth
  - Antenna phase center variations of GNSS satellites

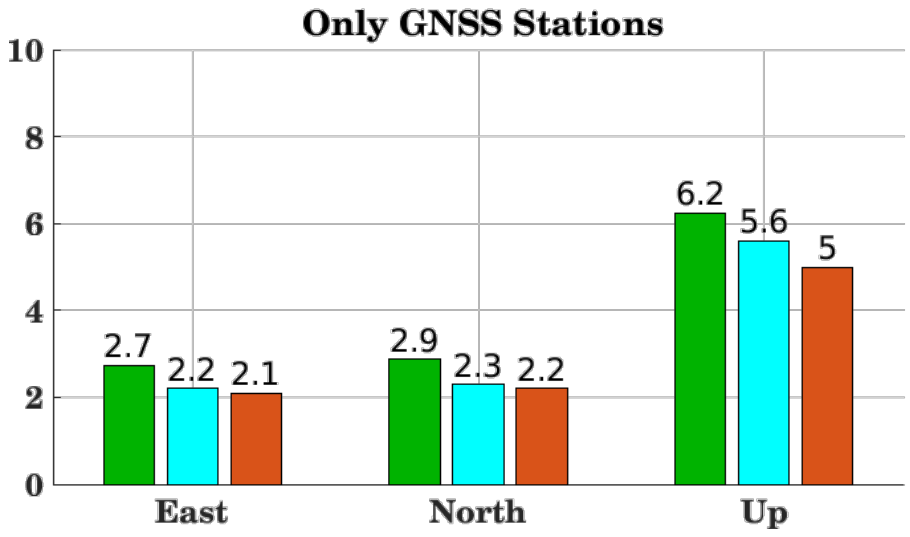


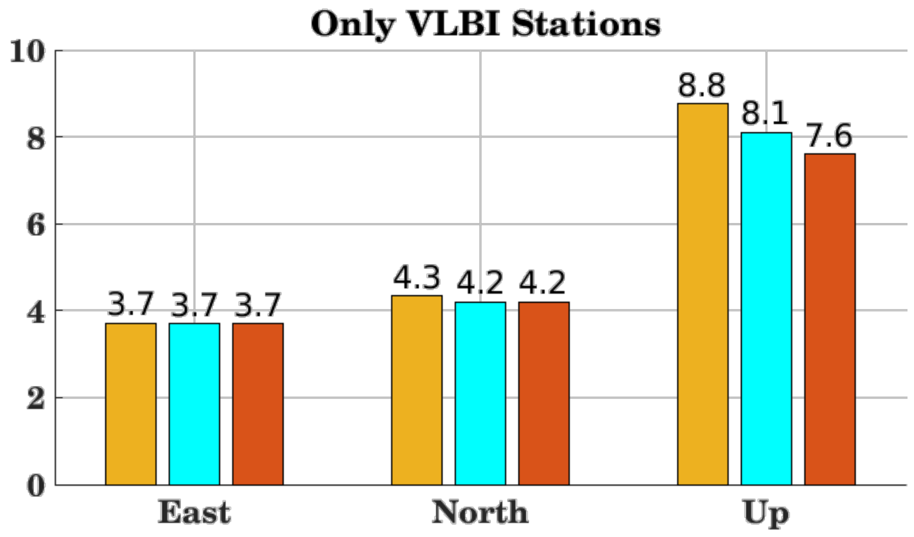
In the near future low-cost COTS GNSS equipment will be sufficiently accurate to perform state-of-the-art science that is nowadays performed with geodetic-type receivers and antennas


Overcome Limitations:
→ New Technologies

Rigorous Combination of GNSS and VLBI with Local Ties (LT) and Tropospheric Ties (TT): Site Coordinate Repeatabilities for CONT'17



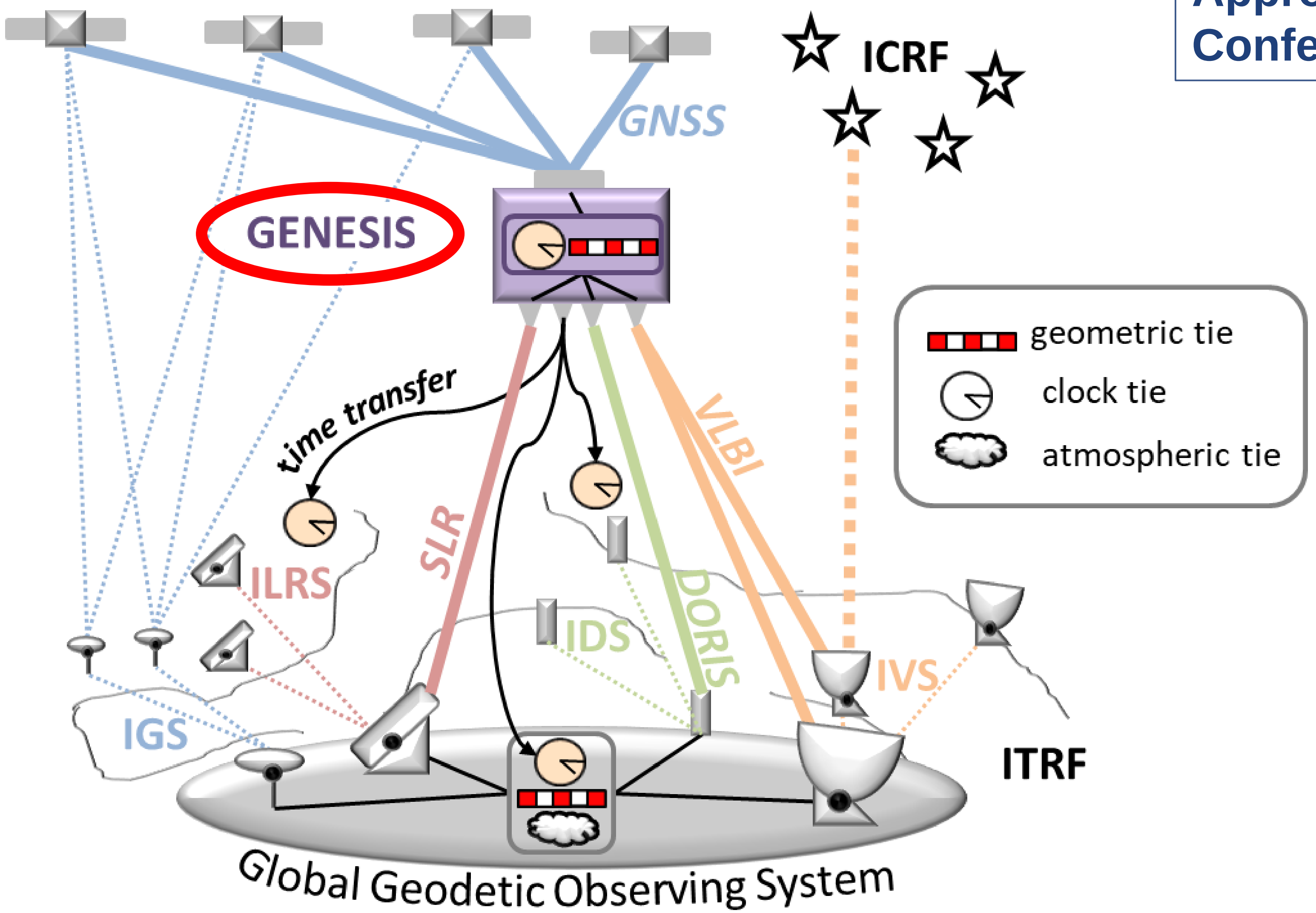




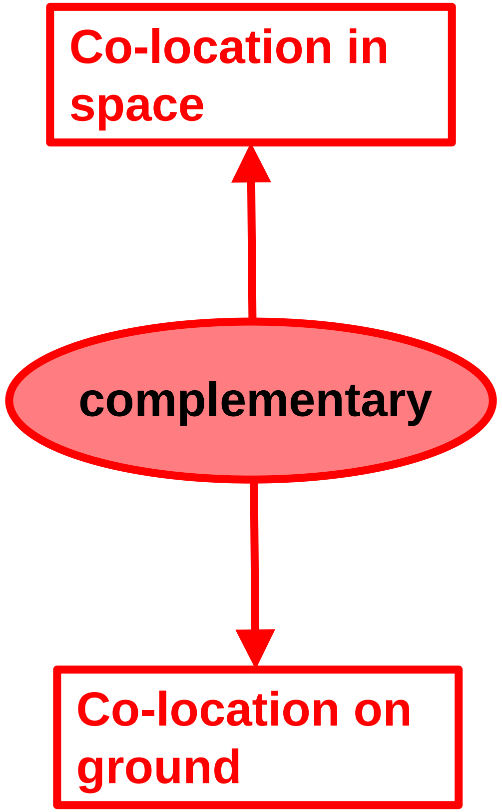
→ Still far from the GGOS goal of 1 mm

[Iván Herrera Pinzón]

Future Technologies: GENESIS, Unification of Space and Time Reference Systems

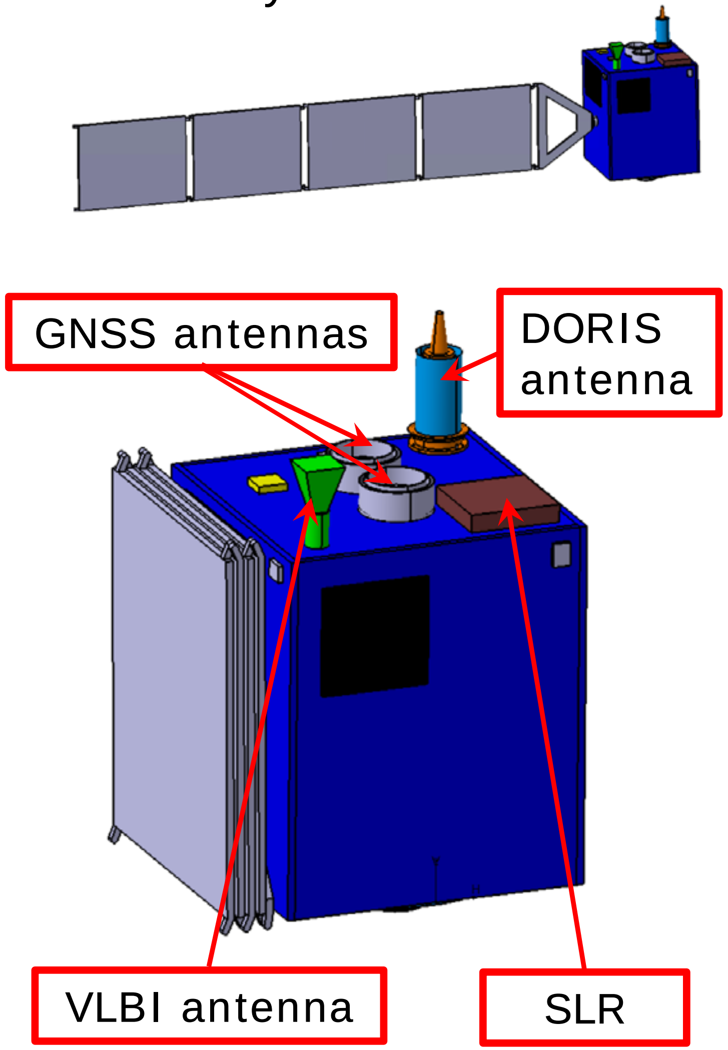


Approved by ESA Ministerial Conference, 23.11.2022 !



Future Technologies: GENESIS Characteristics and Orbit Injection

(ESA CDF Study confirmed mission feasibility)



Orbit	6000km circular 95.5° inclination Direct injection Harsh radiation environment	
Wet Mass with system margin	**220 kg incl. adapter**	
Power with system margin	**190 W** during nominal mode	
Dimensions Stowed	Max Height	1460mm
	Max Width	950mm
	Max Depth	1015mm
Payloads Mass & power with maturity margin **(~ 40 Kg and 75 W)**	GNSS 12.2kg, 21W VLBI 2.4kg, 17.4W SLR 1.6kg, passive DORIS 21kg, 26.3W USO 1.8kg, 12W	
Communication/GSO	S-Band used for TT&C LGA Ground station: ESTRACK Station	

Future Technologies: GENESIS Science Objectives (White Paper)

Reference Frames and Earth Rotation

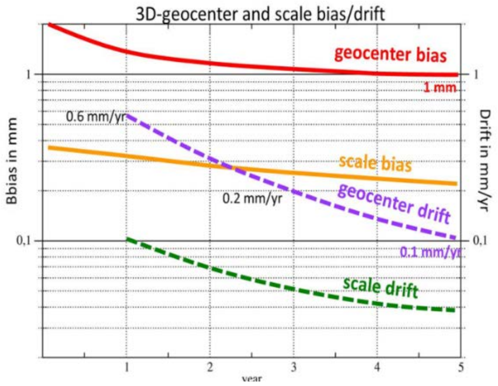
- Unification of reference frames and Earth rotation
- Geocenter and scale (factor 5-10)

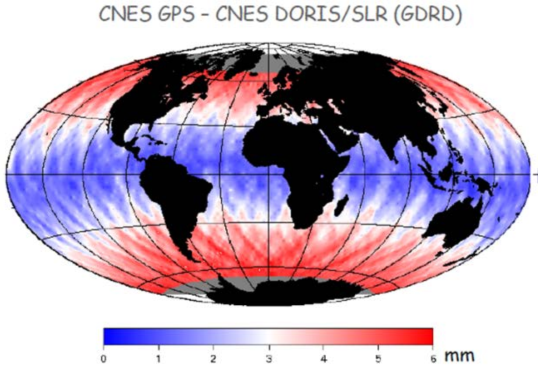
Earth Sciences

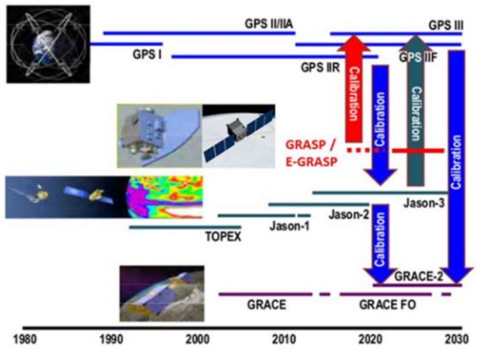
- Long-wavelength gravity field
- Altimetry and sea level rise
- Determination of ice mass loss
- Geodynamics, geophysics, natural hazards
- Thermospheric density measurements, improvements in the Earth radiation budget

Positioning and Navigation

- Improvement in global positioning
- GNSS antenna phase center calibration
- Positioning of satellites and space probes
- Time transfer over intercont. distances

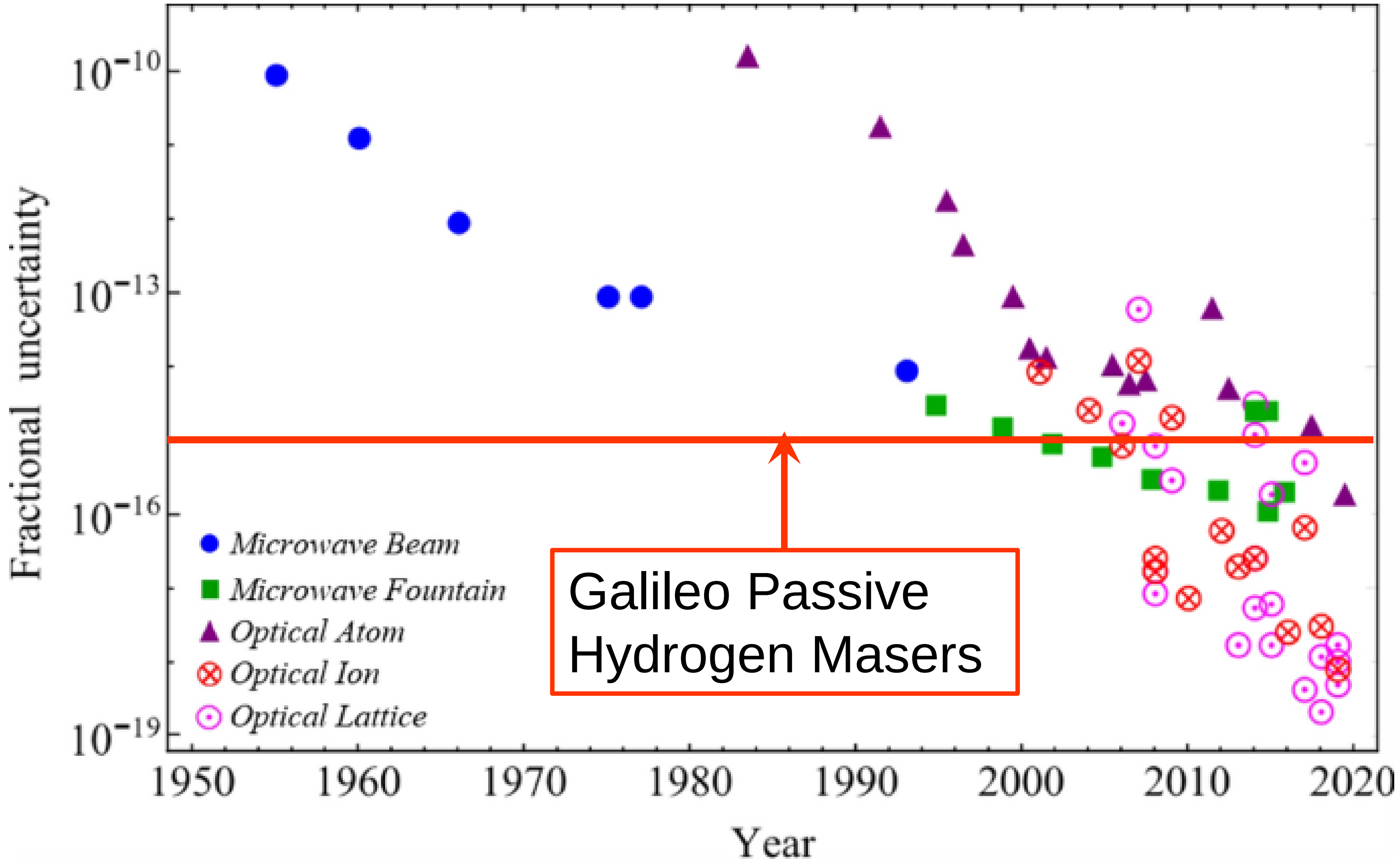






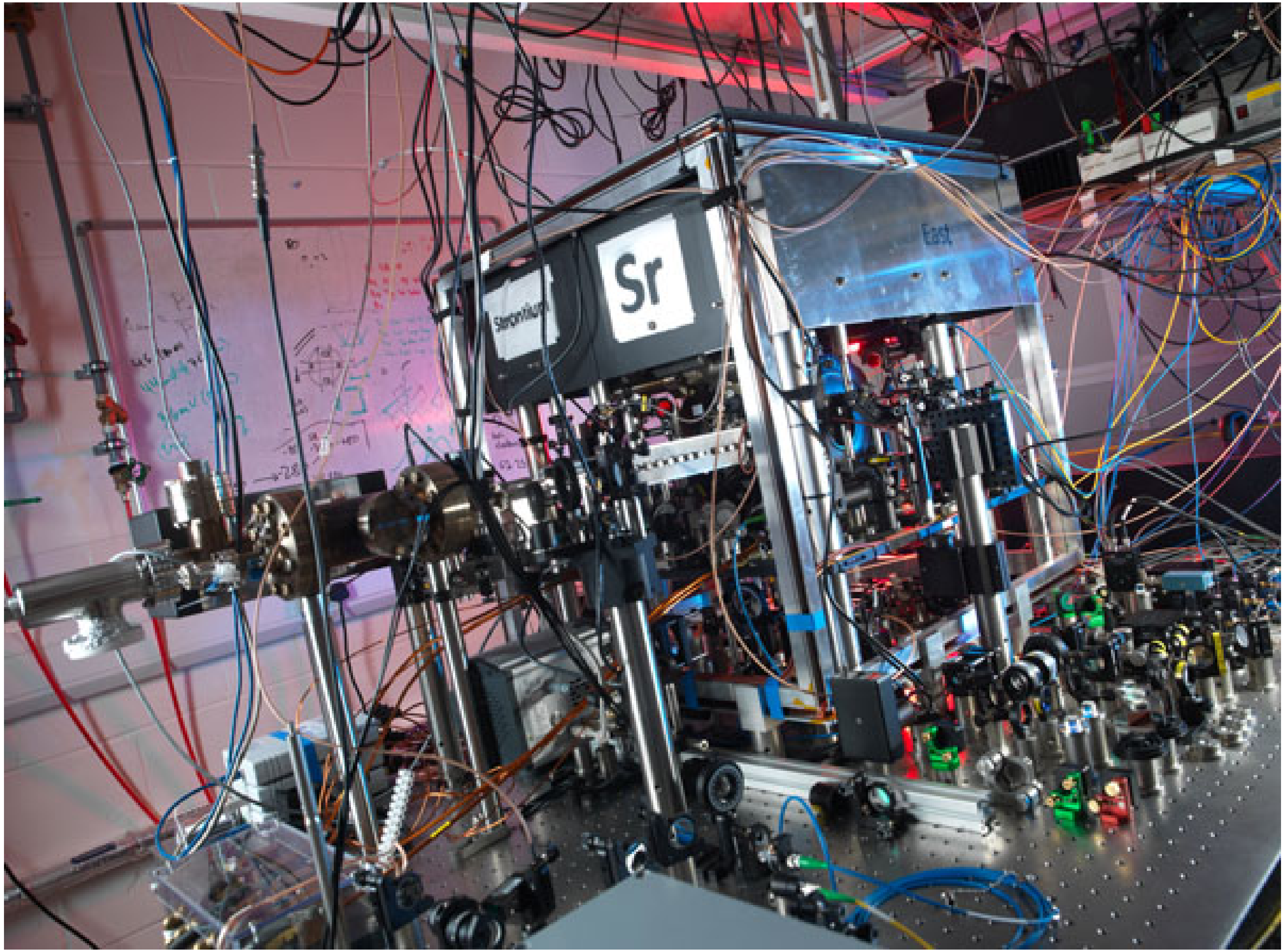
Future Technologies: Optical Clocks

Clocks are at the heart of GNSS



Still 3-4 orders of magnitude to exploit for GNSS !

Future Technologies: NPL Strontium-Lattice Optical Clock



- Not yet portable and not yet ready for space
- Improvements in navigation signals
- Direct measure-ment of the gravitational potential (10^{-18} ~ 1 cm in height)
- Clock ties (optical fibers), clock modeling
- Time transfer

Conclusions

- GNSS can contribute in fascinating ways to a multitude of Earth Sciences (small trends as well as fast events)
- Three ways to overcome limitations: turn nuisance into signal, use miniaturization and low-cost ("small is beautiful"), new technologies
- Small efficient and low-cost GNSS receivers/antennas will largely replace the older legacy instrumentation (in space and on ground)
- GENESIS and optical clocks with 3-4 orders of magnitude to go: Thrilling challenges for young scientists !

Thanks for your attention !

Congratulations to AIUB and Uraniae !