STE-QUEST – Space Geodesy Mission for Terrestrial and Celestial Reference Frame Realization

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- STE-QUEST and GAIA
- Survey of Extragalactic Sources at S/X/Ka/.../(W)-band (higher bands)
- Metrology link for operational relativistic geodesy

STE-QUEST – Twofold Mission

STE-QUEST

Fundamental Physics

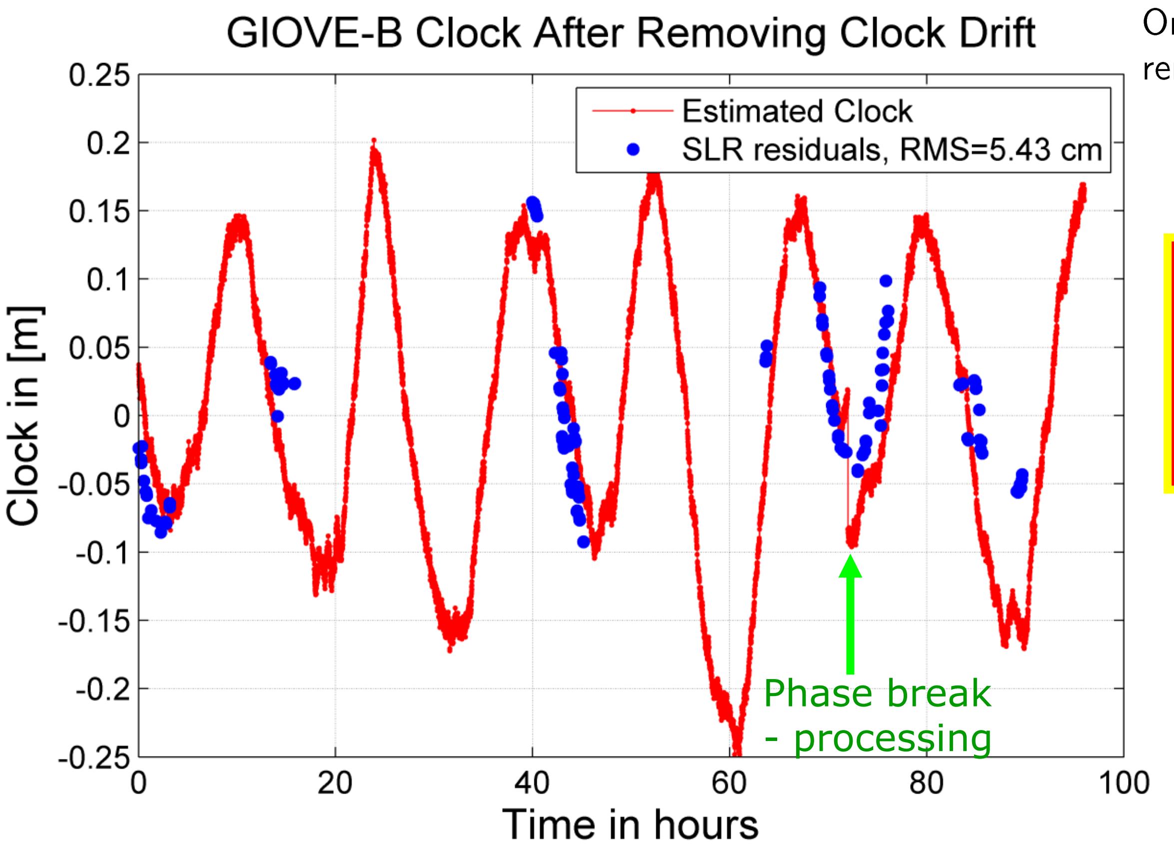
- High-accuracy Relativistic Geodesy

Space Geodesy

- **VLBI:** STE-QUEST μ-Metrology Link – (S,X,Ka)
- **Satellite Laser Ranging**
- **GNSS** - AGGA-4 chip: Galileo, GPS, GLONASS, Beidou
- **DORIS** (at higher altitudes)
    - GNSS receiver tracking both GNSS/DORIS signal
    - nadir flat phased-array antenna (GNSS/DORIS)
- **Space VLBI with STE-QUEST Clock (link to GAIA)**
    - with phased-array antenna – VLBI/GNSS (top)
    - possible optical data link

No-Additional Payload – just enhancing proposed payload

GIOVE-B Clock Against SLR-Satellite Laser Ranging



Only time bias and time drift removed!

First time: GNSS clock geometrically maps the radial orbit error!!!

Clock improves and stabilizes the orbit!

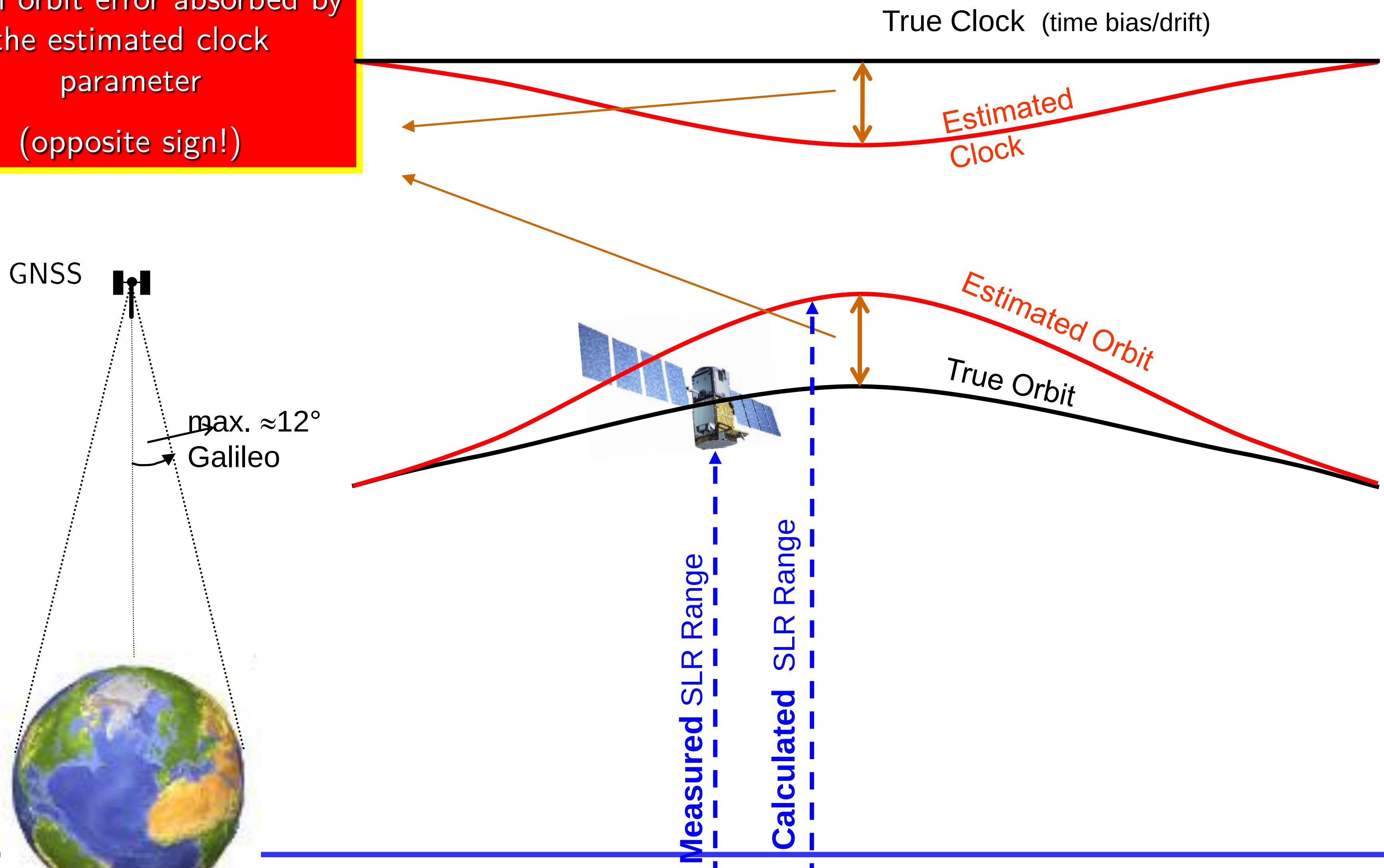
Agreement between GIOVE-B clock and SLR is fantastic **1-2 cm only!!!** (with limited ground network)

(Svehla et al., 2010)
Figure fully authorised for the publication by the Galileo Project

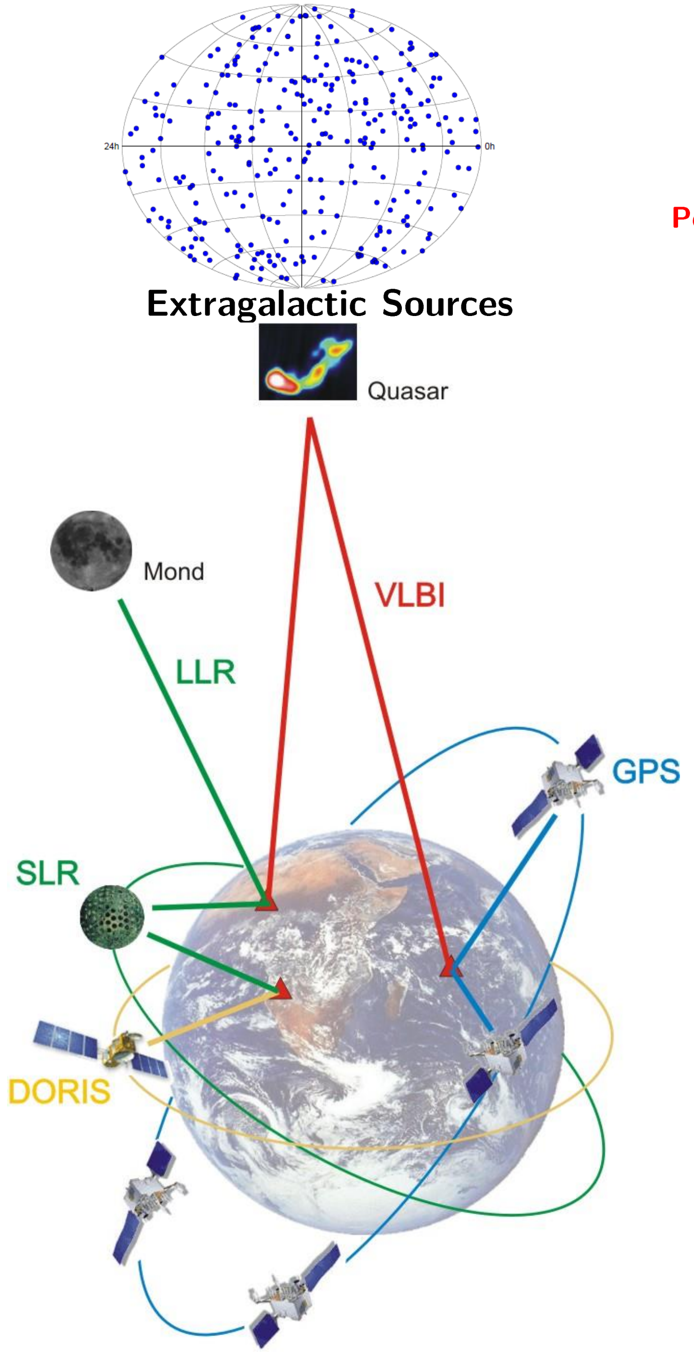
Orbit and Clock Dependency

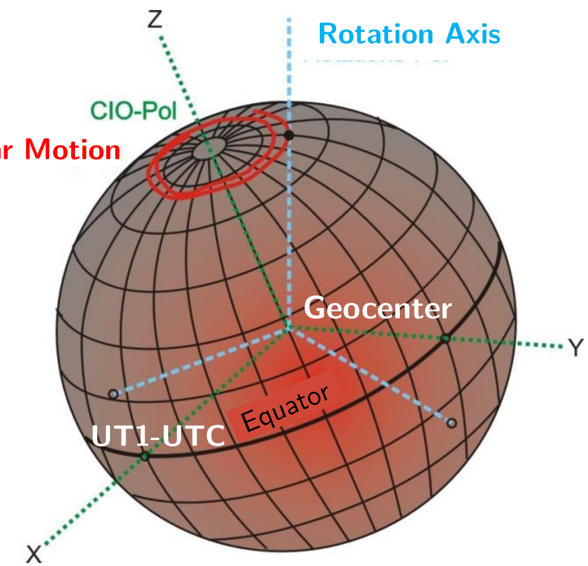
Radial orbit error absorbed by the estimated clock parameter

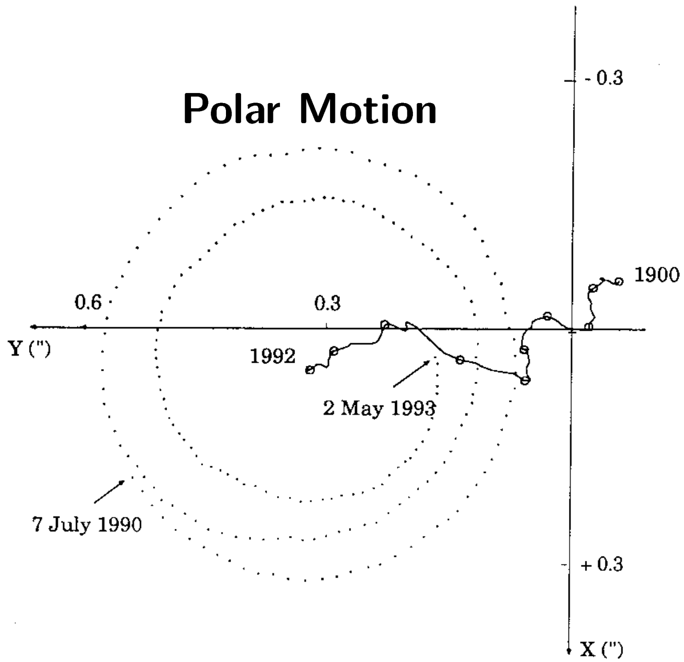
(opposite sign!)

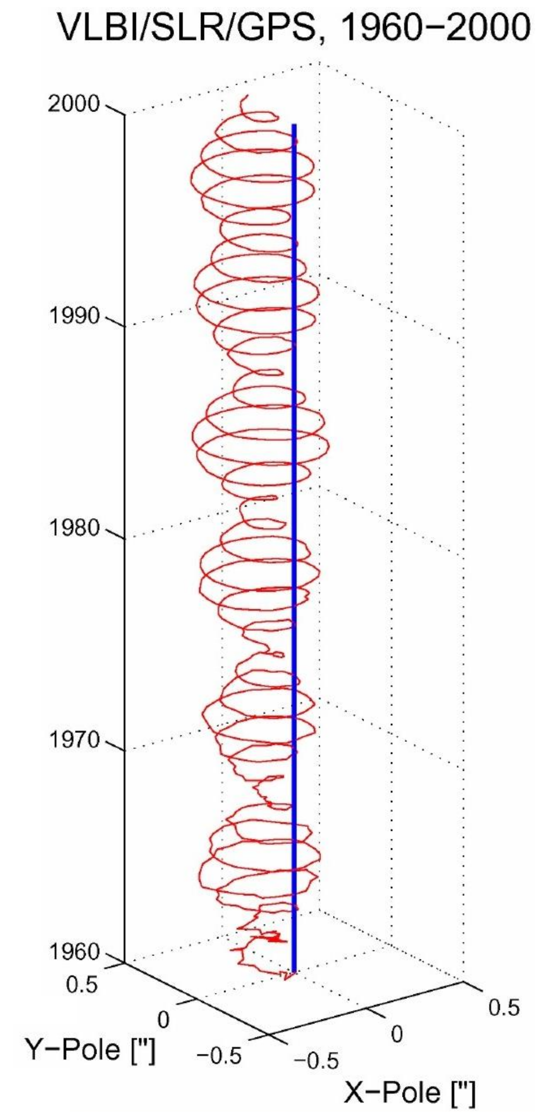


Terrestrial and Celestial Reference Frames









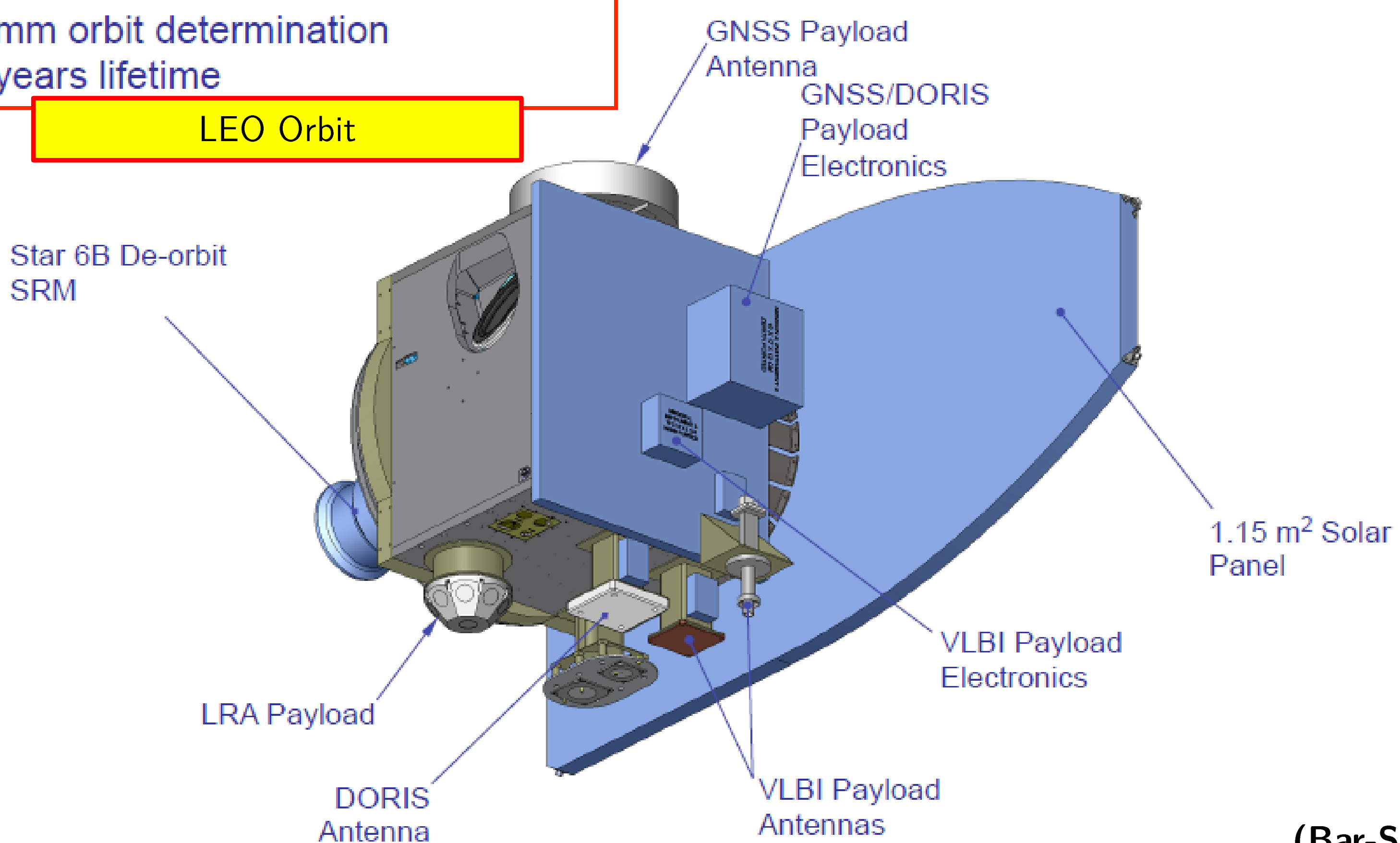
The Geodetic Reference Antenna in Space (GRASP): A Mission to Enhance the Terrestrial Reference Frame

STE-QUEST is GRASP mission in highly elliptic orbit + Space VLBI

The GRASP Spacecraft

Orbit: 850x1350 Sun-synch
Collocate sensors and CM to 1 mm
1 mm orbit determination
3 years lifetime

LEO Orbit



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Wahr
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(Bar-Sever et. al 2012)

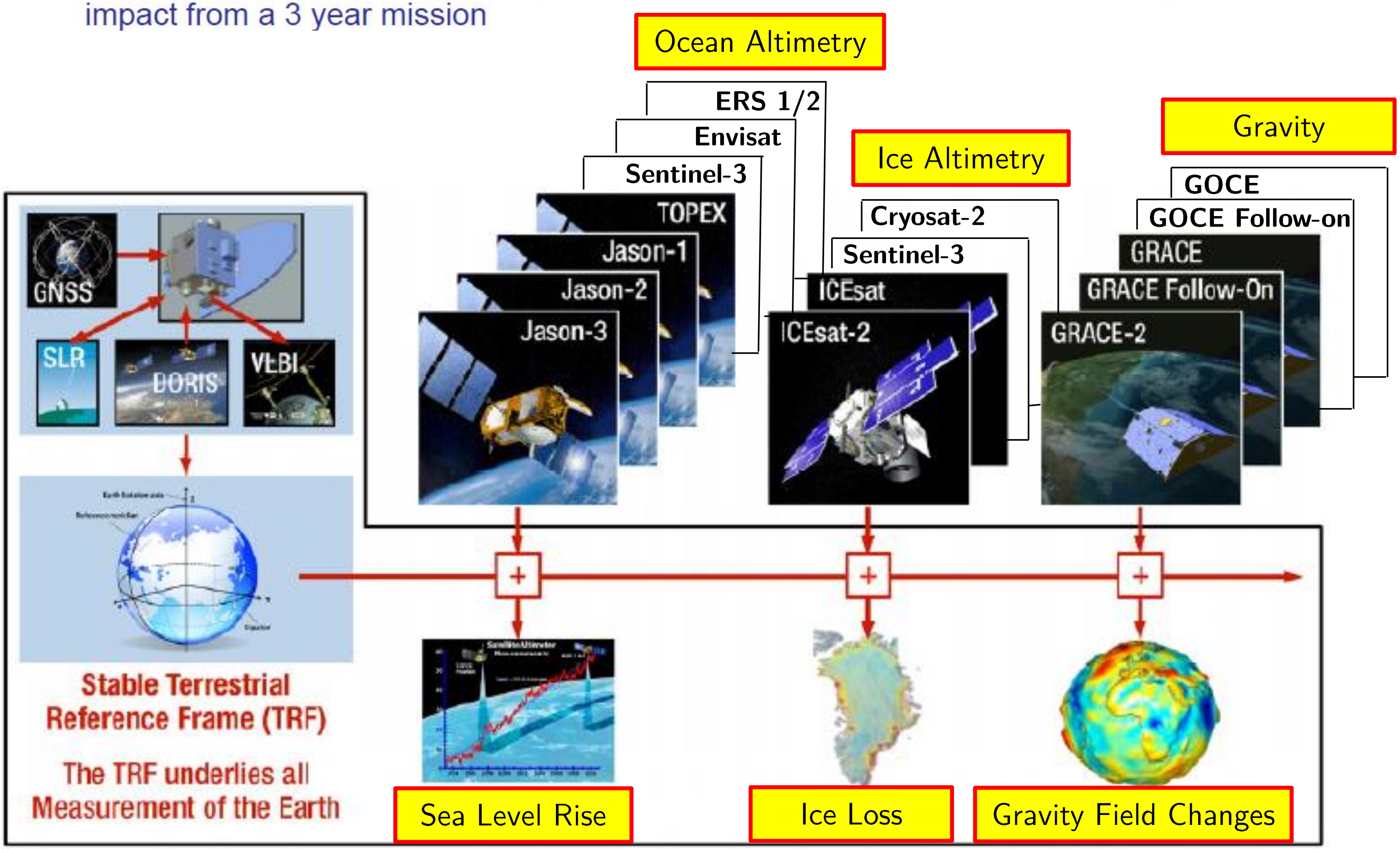
GRASP Mission - JPL

Collocate all the geodetic technique on a supremely calibrated satellite

- Use as reference for all GNSS antennas (space and ground)
- Determine ground collocation at arbitrary baselines

(Bar-Sever et al., 2012)

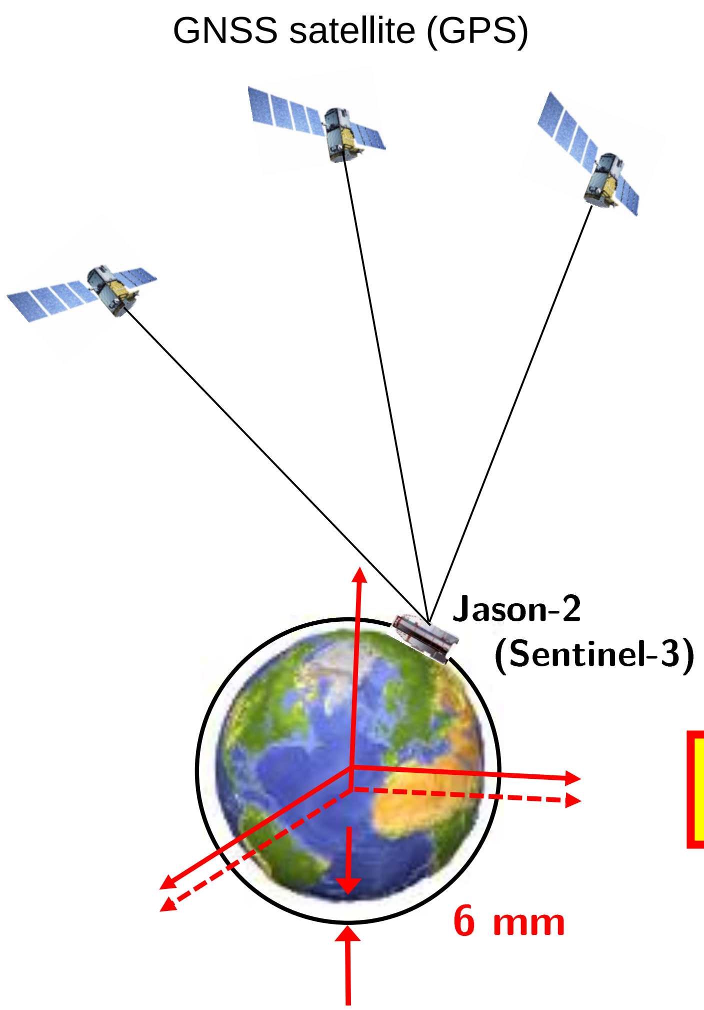
GRASP enhances science from past and future Earth science missions; ~30 year impact from a 3 year mission



STE-QUEST - Space Geodesy Mission

- **Terrestrial Reference Frame** Realization (STE-QUEST as GRASP Mission from JPL in highly elliptic orbit)
- **Celestial Reference Frame Realization** Ground/Space VLBI. Survey of extragal. sources at higher frequencies
- To meet GGOS (Global Geodetic Observing System) requirements for terrestrial reference frame of the Earth: **1 mm accuracy and 0.1 mm/yr stability of the TRF**:
  - significantly improve **satellite altimetry and tide gauge records** of **global mean sea level rise** by using highly accurate TRF from the STE-QUEST mission
  - contribute to **mass transport in polar regions** (ice mass loss) by referencing altimetry (Cryosat, ICESat) and gravity data (GRACE, GOCE) to the common TRF
- Determination of the **long-wavelength variability in the gravity field** of Earth (central term and J2) that are either not observed or poorly observed by GRACE (e.g. J2)
- Monitoring of the Earth rotation and orientation parameters making use of the highly elliptical orbit of the STE-QUEST mission (UT1 etc.) and VLBI tracking from the ground (quasars/GNSS satellites)
- Improvements in orbit accuracy of GNSS satellites (Galileo, GPS, GLONASS…) by one order of magnitude
- Provision of a common time scale for all space geodesy techniques (VLBI, GNSS, DORIS and SLR)
- Dissemination of TRF and time anywhere on Earth or in space
- Advanced modelling of solar radiation pressure, a new way to cope with non-gravitational forces on a satellite
- High-accuracy relativistic geodesy <1 cm accuracy (using STE-QUEST metrology link)

Terrestrial Reference Frame
Geocenter Monitoring



Weekly Geocenter Estimates

Week 1	Week 2	Week 3
dx = -0.83 mm	dx = -1.78 mm	dx = -1.72 mm
dy = -0.94 mm	dy = -1.67 mm	dy = -1.22 mm
dz = -5.90 mm	**dz = -5.75 mm**	**dz = -5.60 mm**
rx = 0.021 mas	rx = 0.067 mas	rx = 0.059 mas
ry = 0.052 mas	ry = 0.055 mas	ry = -0.011 mas
rz = -0.051 mas	rz = -0.077 mas	rz = -0.051 mas
scale = 0.13 ppb	scale = 0.14 ppb	scale = 0.16 ppb

The **6-mm effect** in the Geocenter is well above the GGOS Requirement of **1 mm accuracy** and the sea level rise of **3 mm/y**

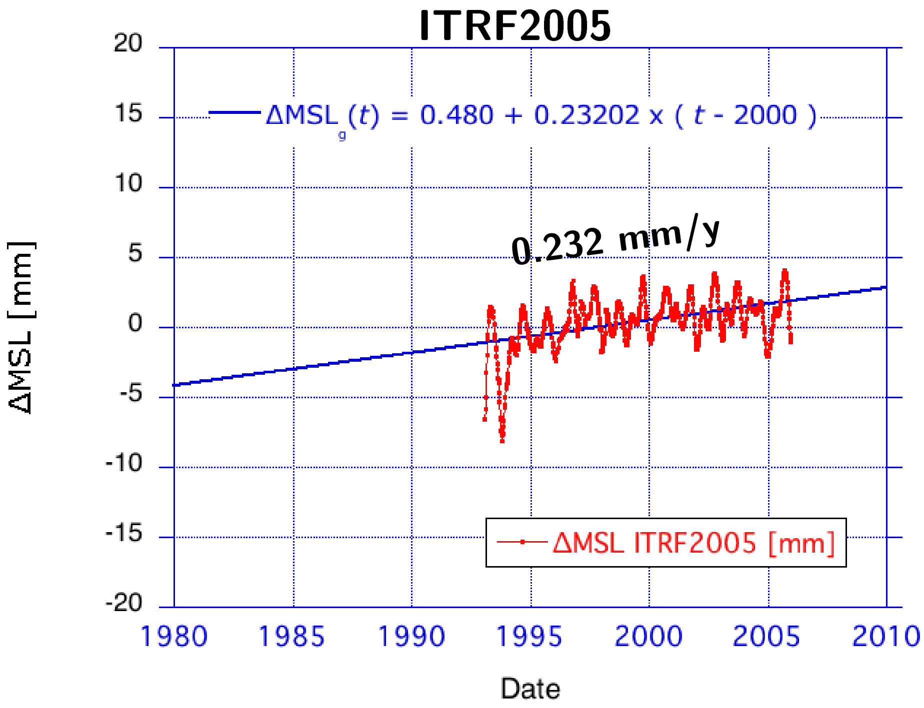
(Svehla et al., 2010)

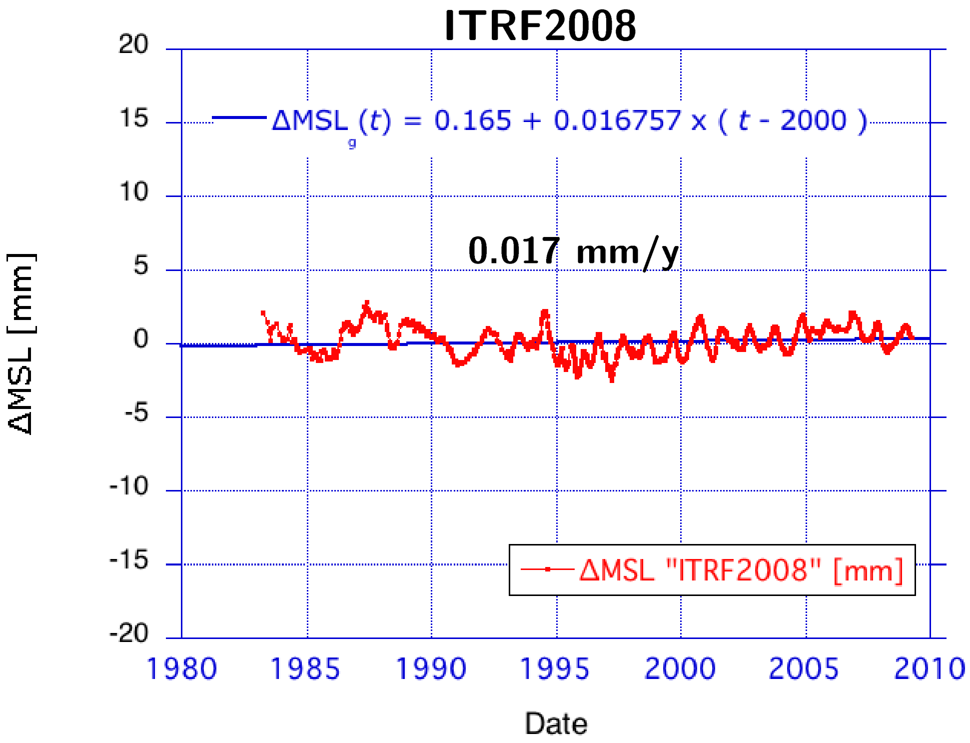
JASON-2 + GPS Constellation

(GPS+SLR+DORIS)

MSL Rate Differences Due to TRF Error

Mapping the Error in the Z-axis Rate of the ITRF onto the Mean Sea Level Rate





ITRF2005 used SLR data over 1993 - 2004

Rate bias: **0.232 mm/y**

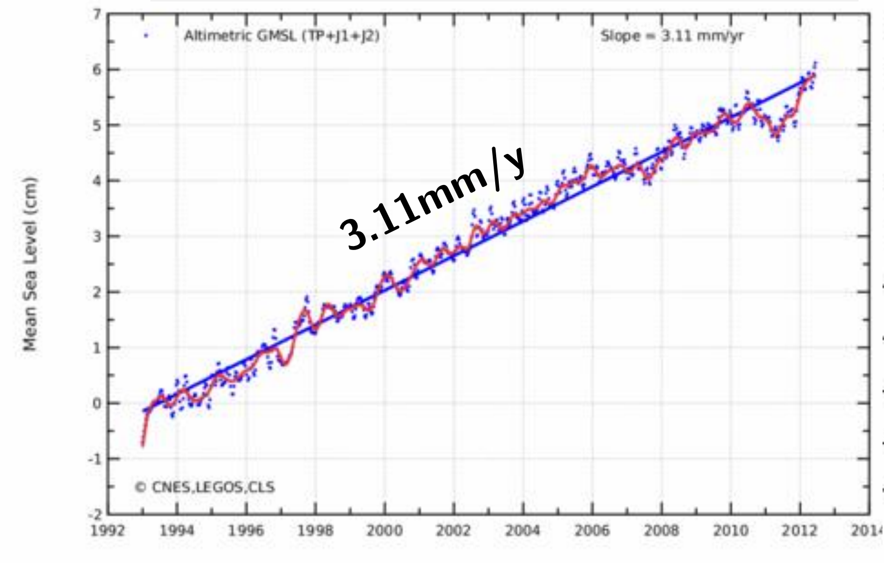
ITRF2008 used SLR data over 1983 – 2008

Rate bias: **0.017 mm/y**

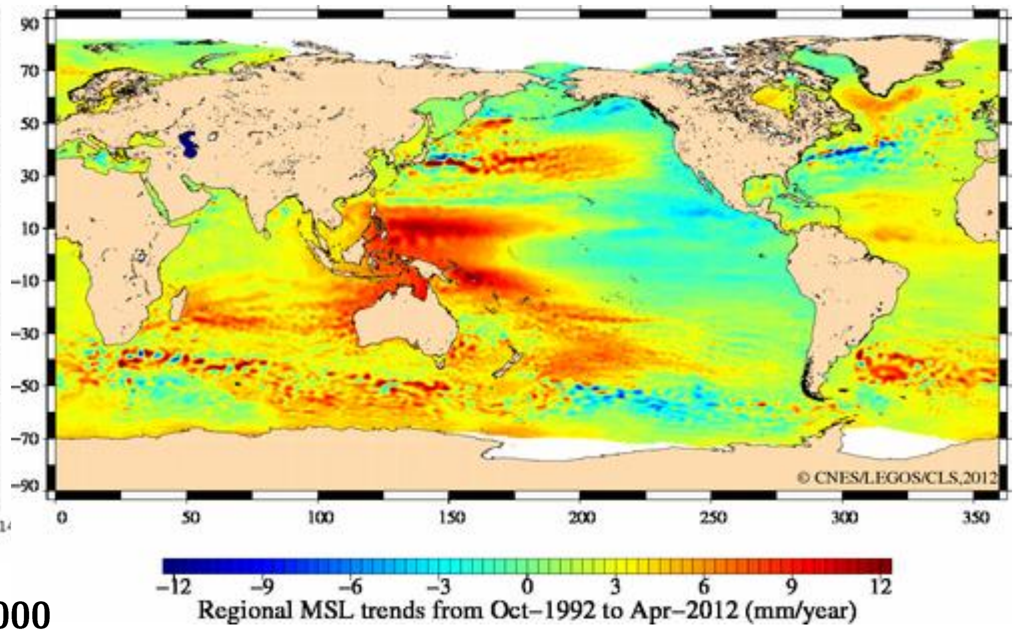
(Pavlis et al., 2012)

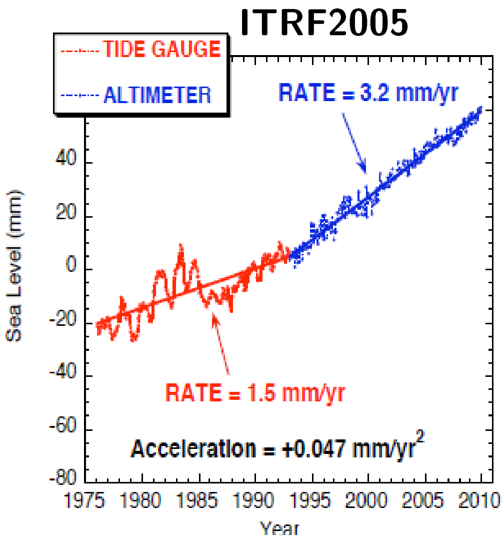
Reference Frame Requirements and Global Mean See Level

Globally averaged rate: 3.11mm/y

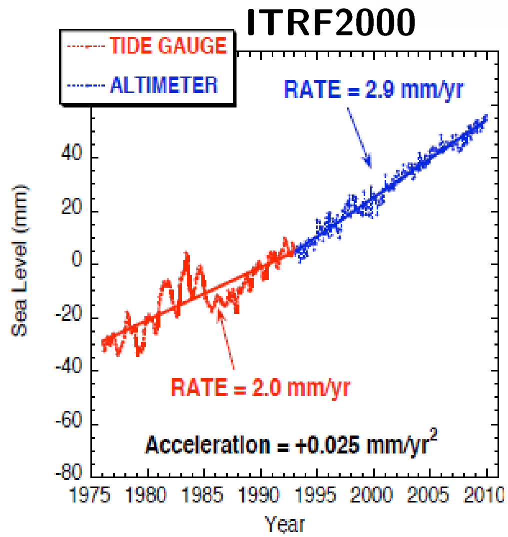


Regional rates: ±12mm/y





(Church and White, 2011)



(Bar-Sever, 2012)

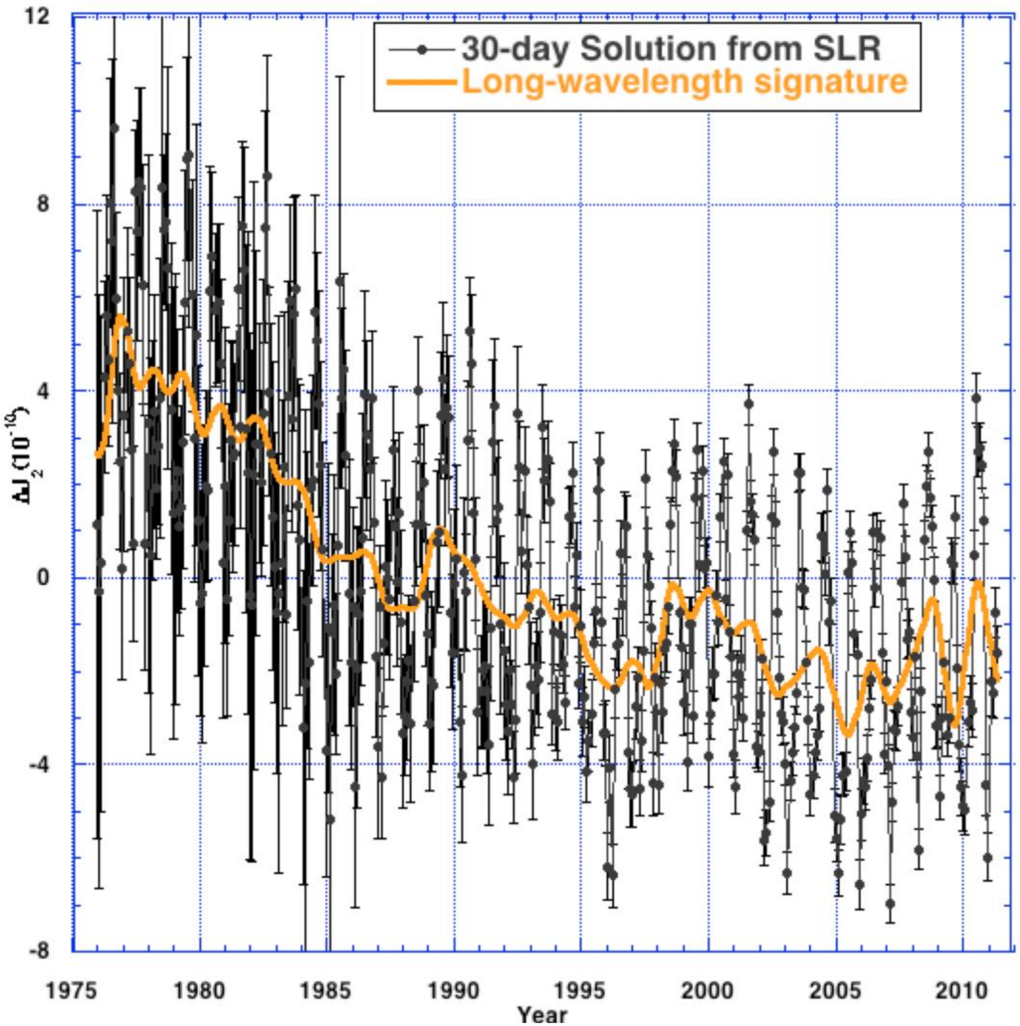
GGOS Requirements for Terrestrial Frame

$<$ **1 mm** accuracy

$<$ **0.1 mm/y** stability

We need to improve ITRF performance by a factor of 10-20!

J_2 Gravity Field Variations from SLR



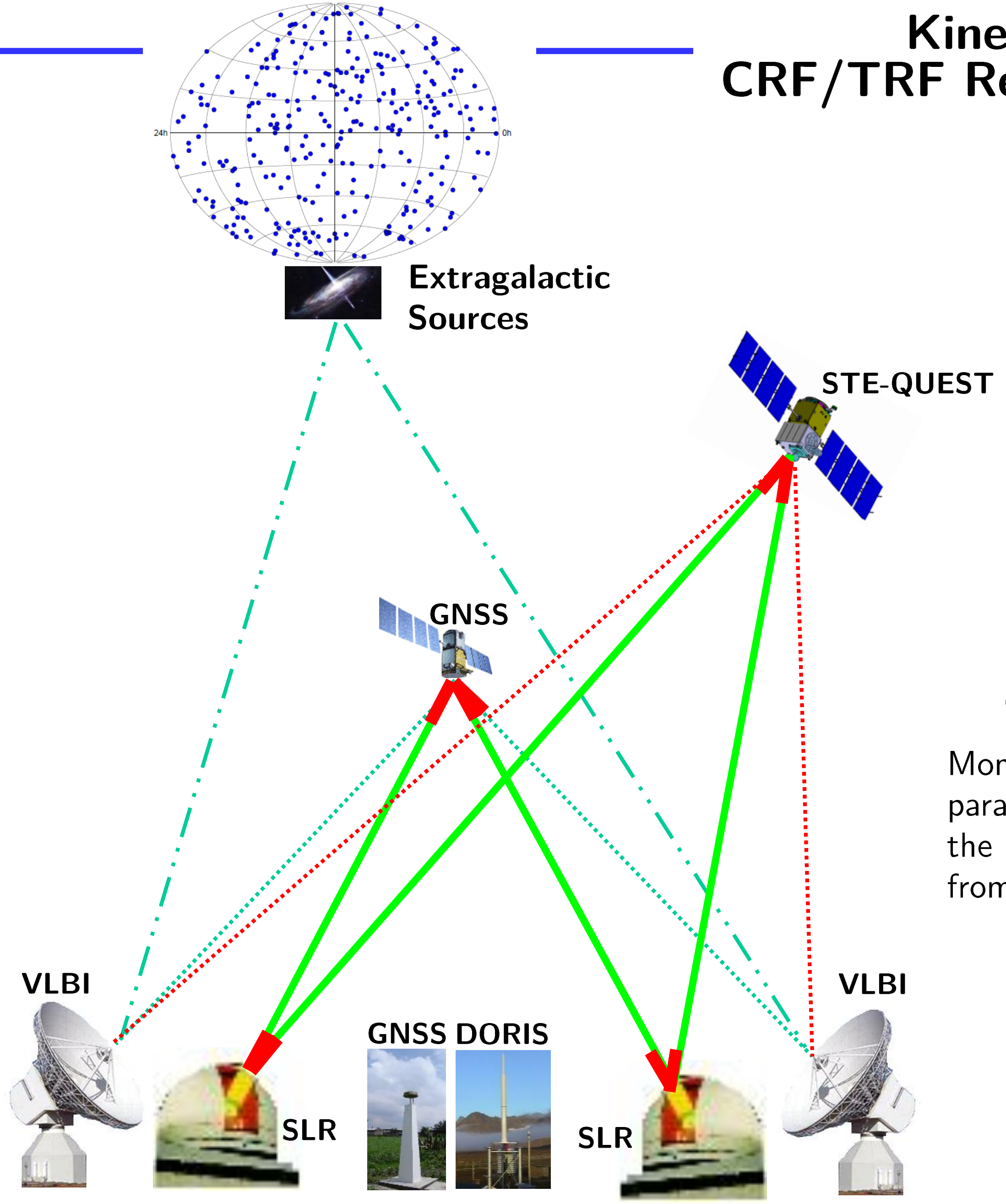
(Cheng, 2012)

Determination of the long-wavelength variability in the gravity field of Earth with STE-QUEST **(central term and J_2) that are either not observed or poorly observed by GRACE/GOCE (e.g. J_2)**

- **Highly elliptic orbit**

Long-term geoid change due to variability in J_2 is in the order of ~**0.2 mm/y**

Kinematic and Dynamic CRF/TRF Realization with STE-QUEST



Double-Difference Approach
GNSS, SLR, VLBI, DORIS

– BIAS FREE –

+

Optical/Microwave Metrology Link

+

STE-QUEST Clock

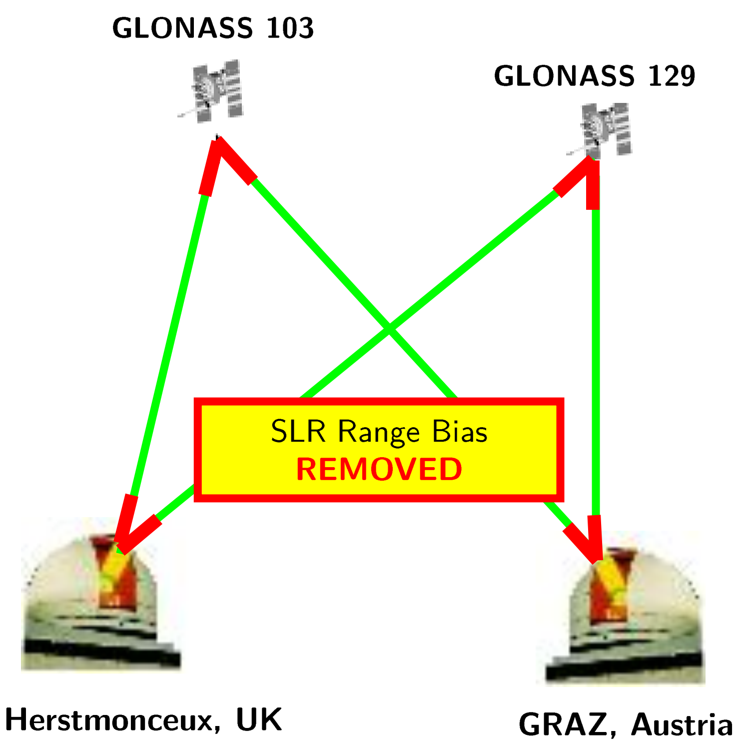
Integrated TRF+CRF+Earth Rotation

Monitoring of the Earth rotation and orientation parameters making use of the highly elliptical orbit of the STE-QUEST mission (UT1) and VLBI tracking from the ground (quasars/GNSS satellites)

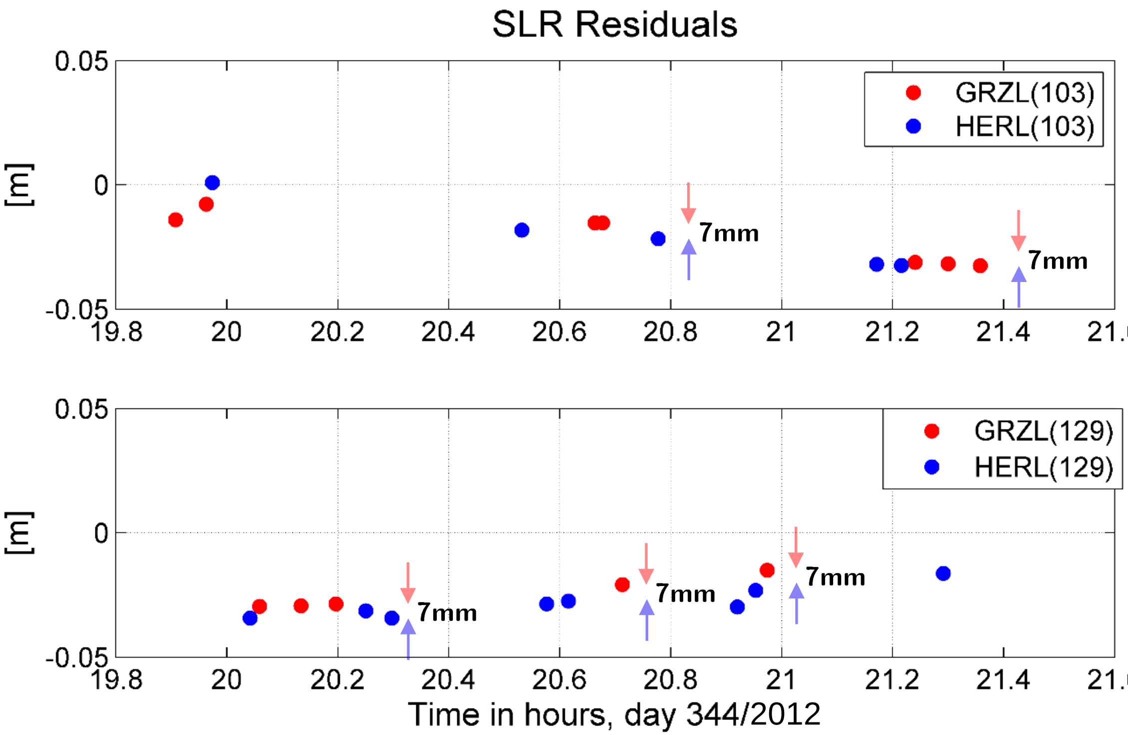
Combination of data on observation level or normal-equation level

First SLR Double-Differences: The mm-SLR!

SLR Double-Differences



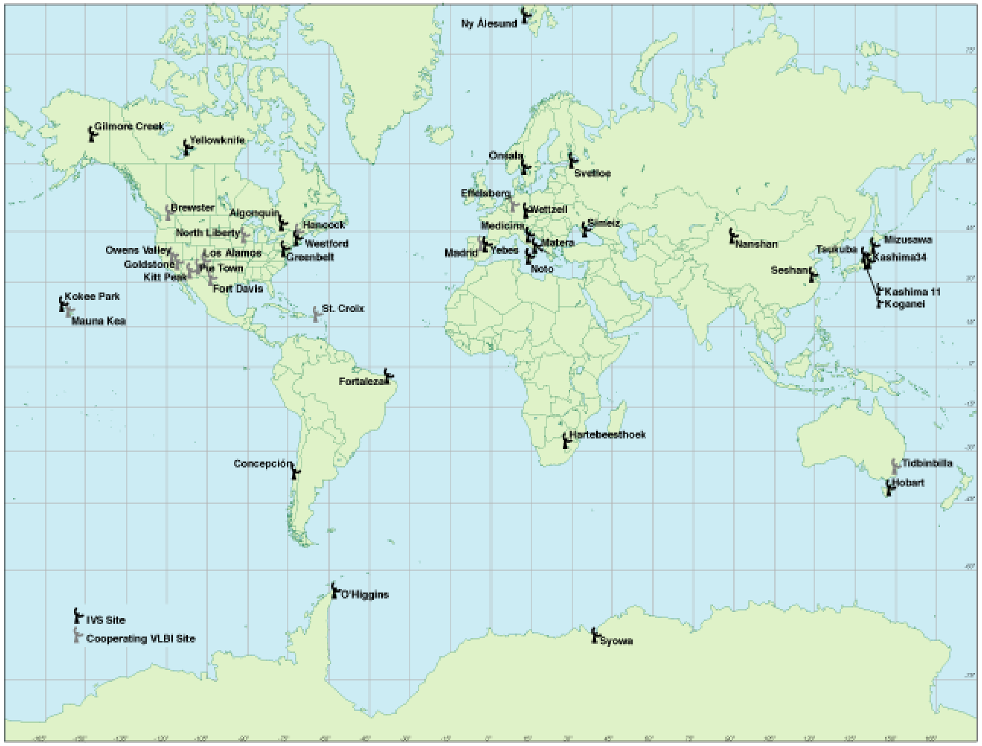
Simultaneous SLR ranging to GLONASS 103&129 at mm-level!



(Svehla et al., 2013)

Same double-difference approach could be applied to STE-QUEST with mm-accuracy!

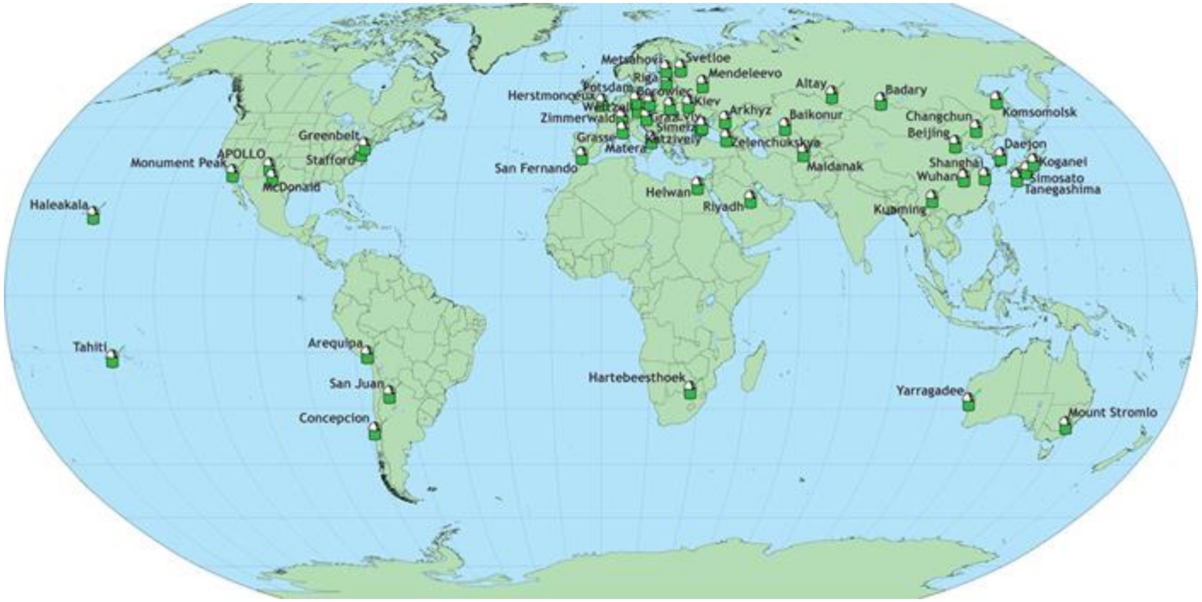
STE-QUEST and IVS - International VLBI Service of IAG



- ICRF2: S/X-Band 2.3/8.4 GHz
- VLBI2010 S/X-Band 2.3-14(18) GHz
- First Celestial frame at X/Ka-Band (8.4/32 GHz)
- VLBI is going towards higher radio-frequencies

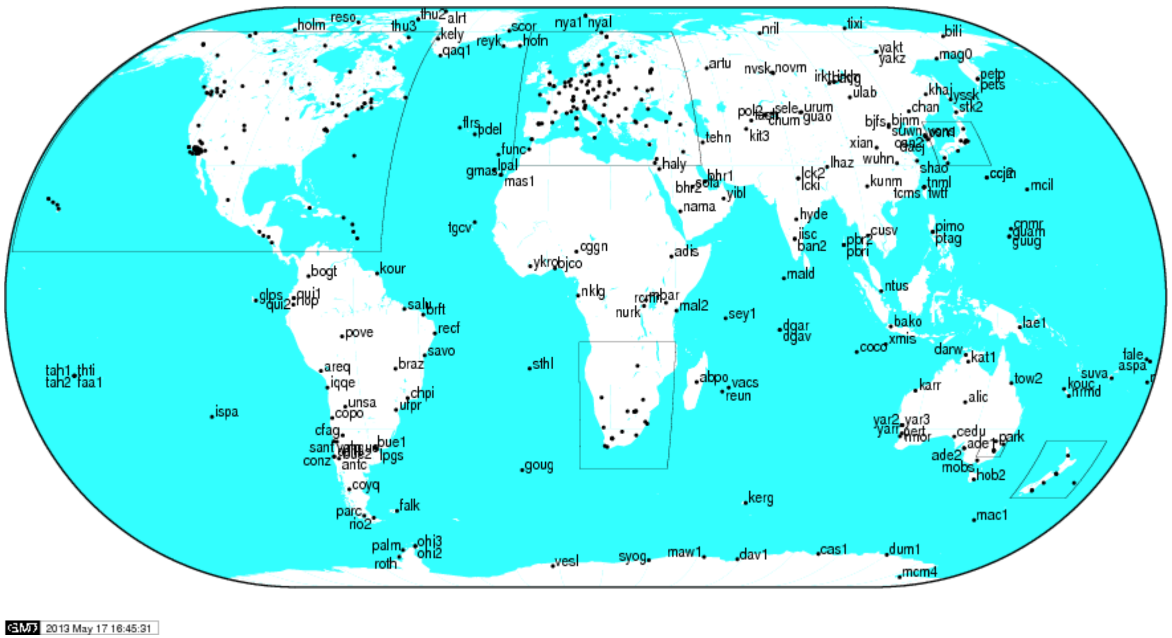
- Dedicated phased-array antenna under development for Galileo and GPS reflectometry with beam forming on receive. Heritage from the Metop, Metop-SG.

STE-QUEST and ILRS - International Laser Ranging Service of IAG



- SLR retro-reflector with zero signature
- mm-SLR ranging in double-difference mode has been demonstrated
- limit of the SLR ranging precision/(accuracy) at about 0.1-0.2 mm for the best SLR stations

STE-QUEST and IGS - International GNSS Service of IAG

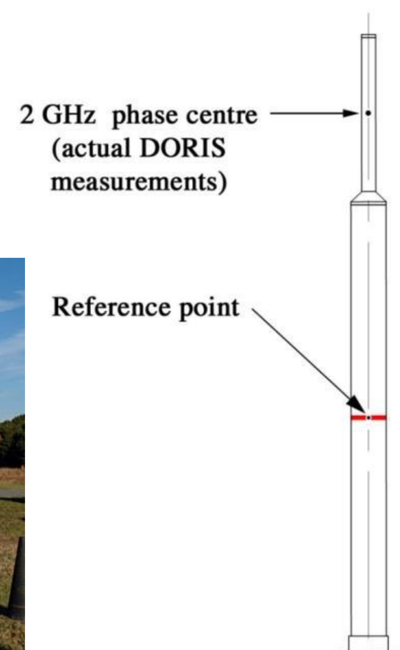


- Combined GNSS/DORIS tracking on AGGA-4 chip (ESA)
- All-GNSS-type receiver AGGA-4 (ESA) with GPS, Galileo, GLONASS, Beidou
- GOCE, Swarm, Sentinel-3, Jason-CS, etc...

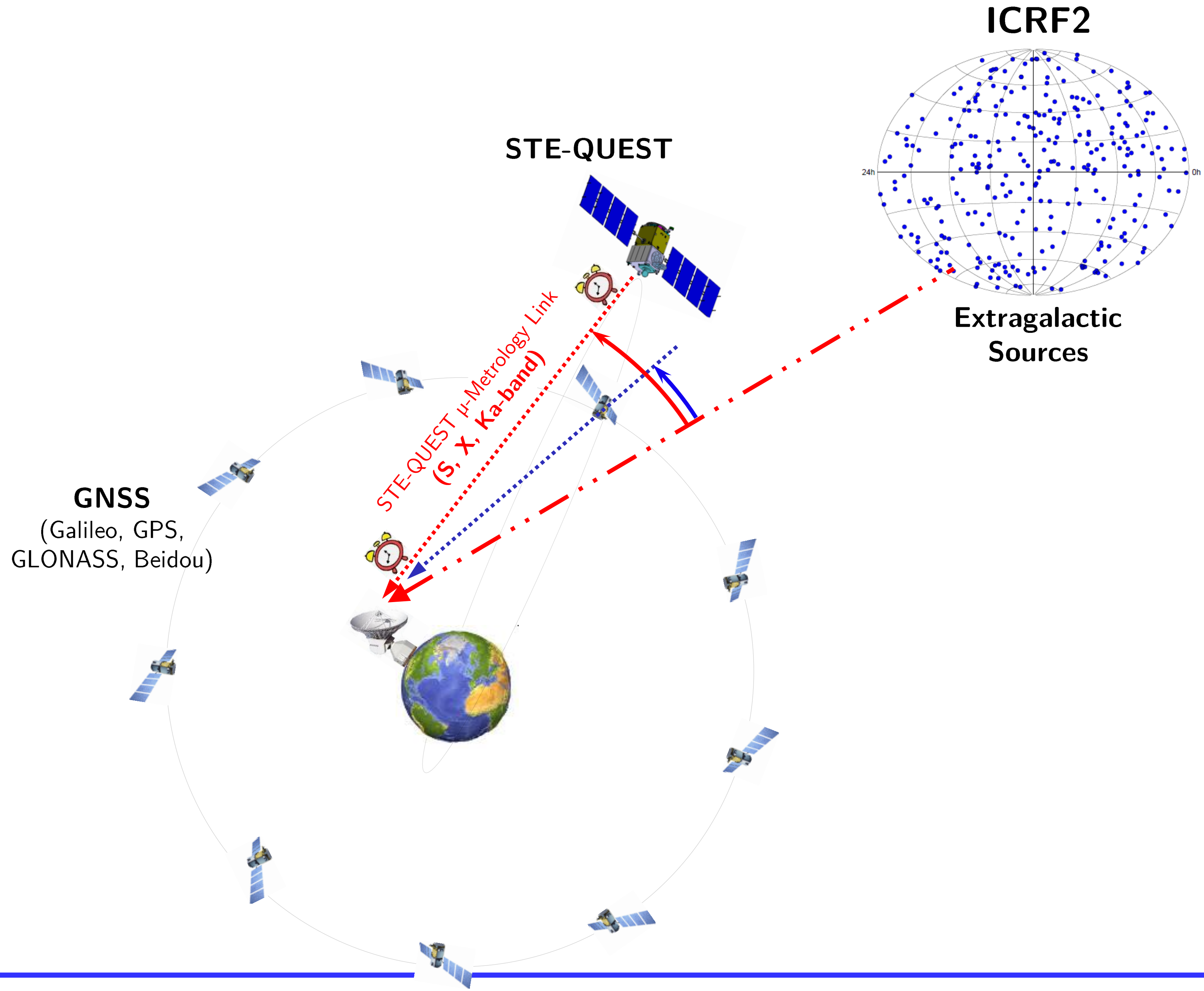
STE-QUEST and IDS - International DORIS Service of IAG

- GRASP Mission plans to use Trig GNSS receiver (second generation Blackjack GPS receiver) with DORIS tracking integrated.
- AGGA-4 chip (ESA) would need to be adapted for DORIS tracking (also for future altimetry missions).
- A dedicated flat phased-array antenna (nadir) for both GNSS and DORIS at higher altitudes.

400 MHz / 2 GHz



Ground VLBI with STE-QUEST

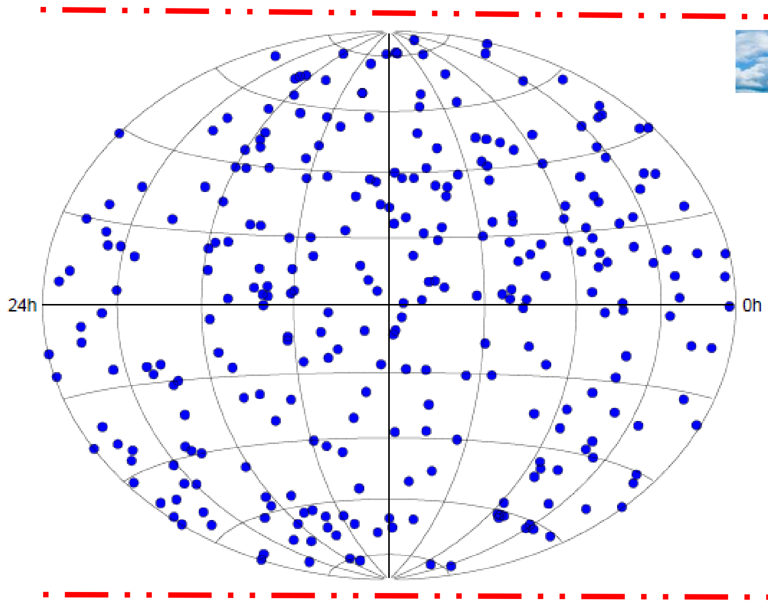


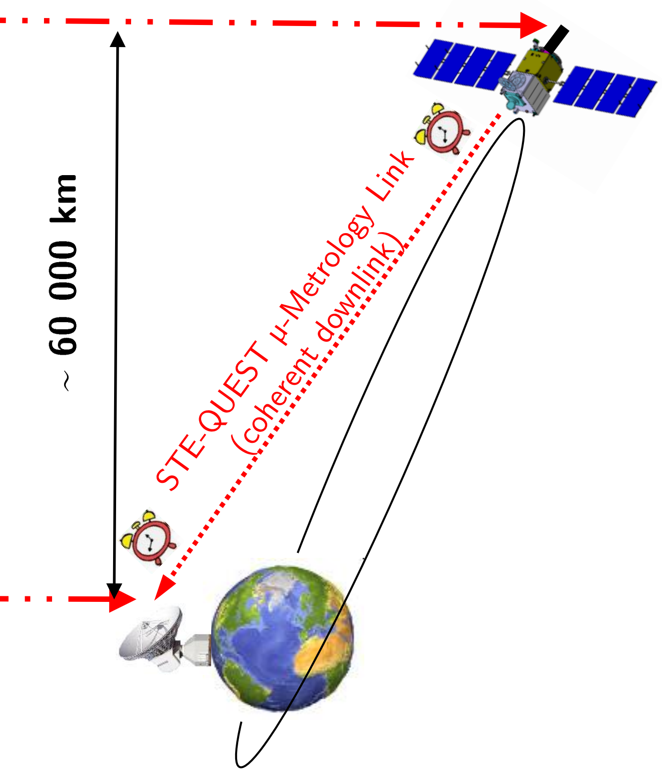
Space VLBI with STE-QUEST Clock

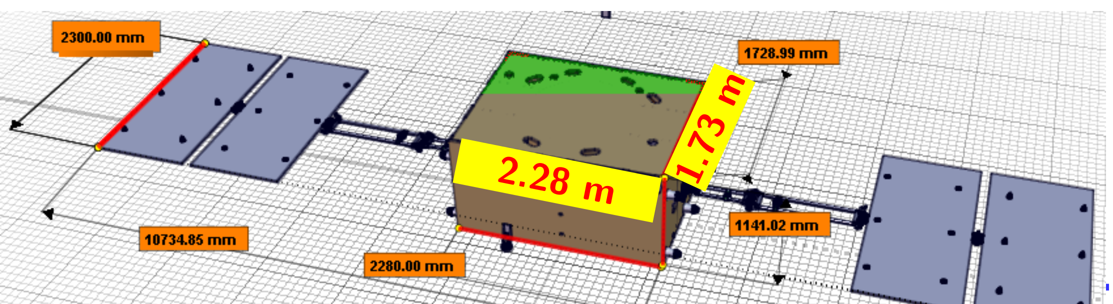
From S/X towards X/Ka/(W)-band

Advanced Phased-Array Antenna Design with beam forming on receive + STE-QUEST Clock (top side)
VLBI/(GNSS)

Extragalactic Sources





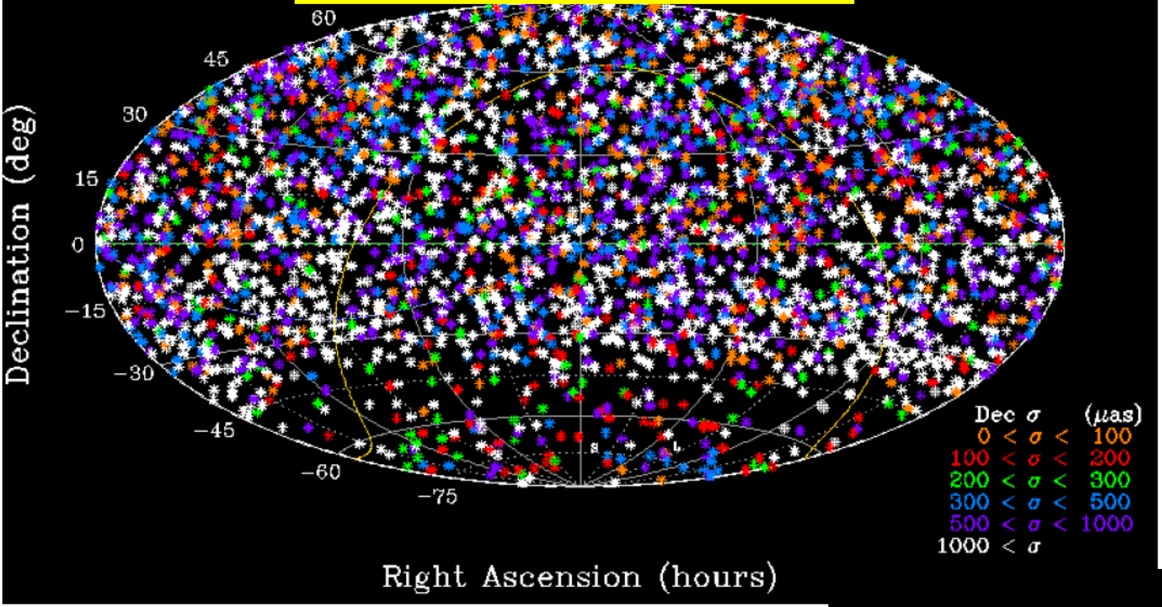


Figure/TAS

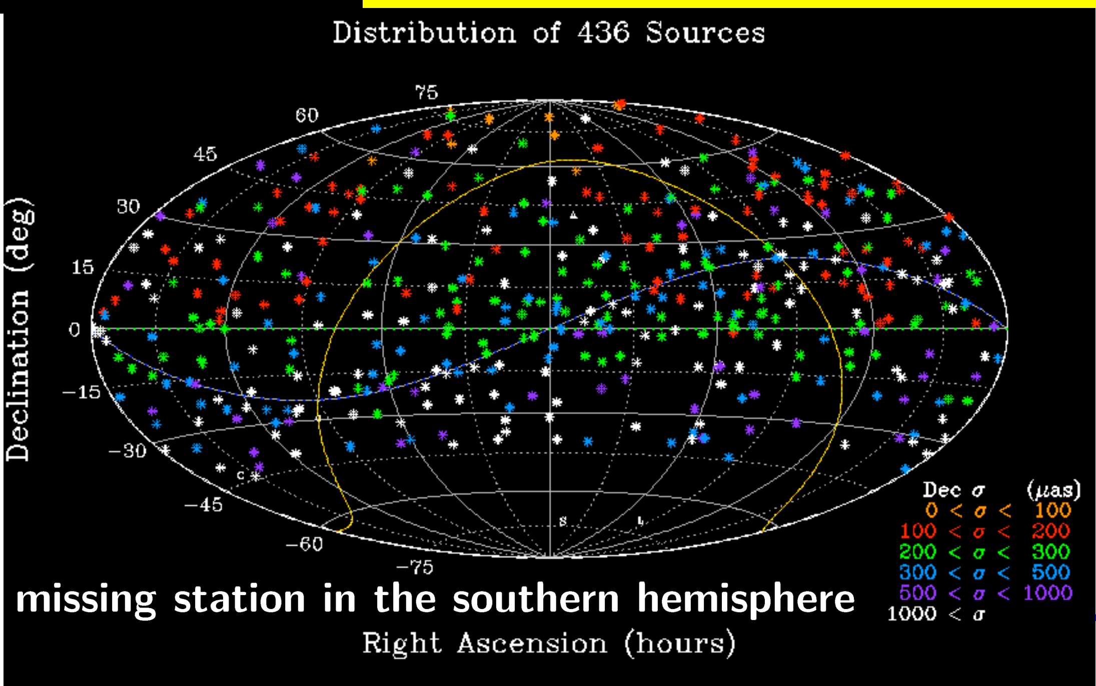
- Phased-array antenna with beam forming on receive VLBI/(GNSS)
- Making use of the high-performing STE-QUEST attitude system (GAIA AOCS)

Towards ICRF at X/Ka-Band (32 GHz)

ICRF2 S/X-Band (8.4 GHz)



ICRF at X/Ka-Band (32 GHz)
469 Sources



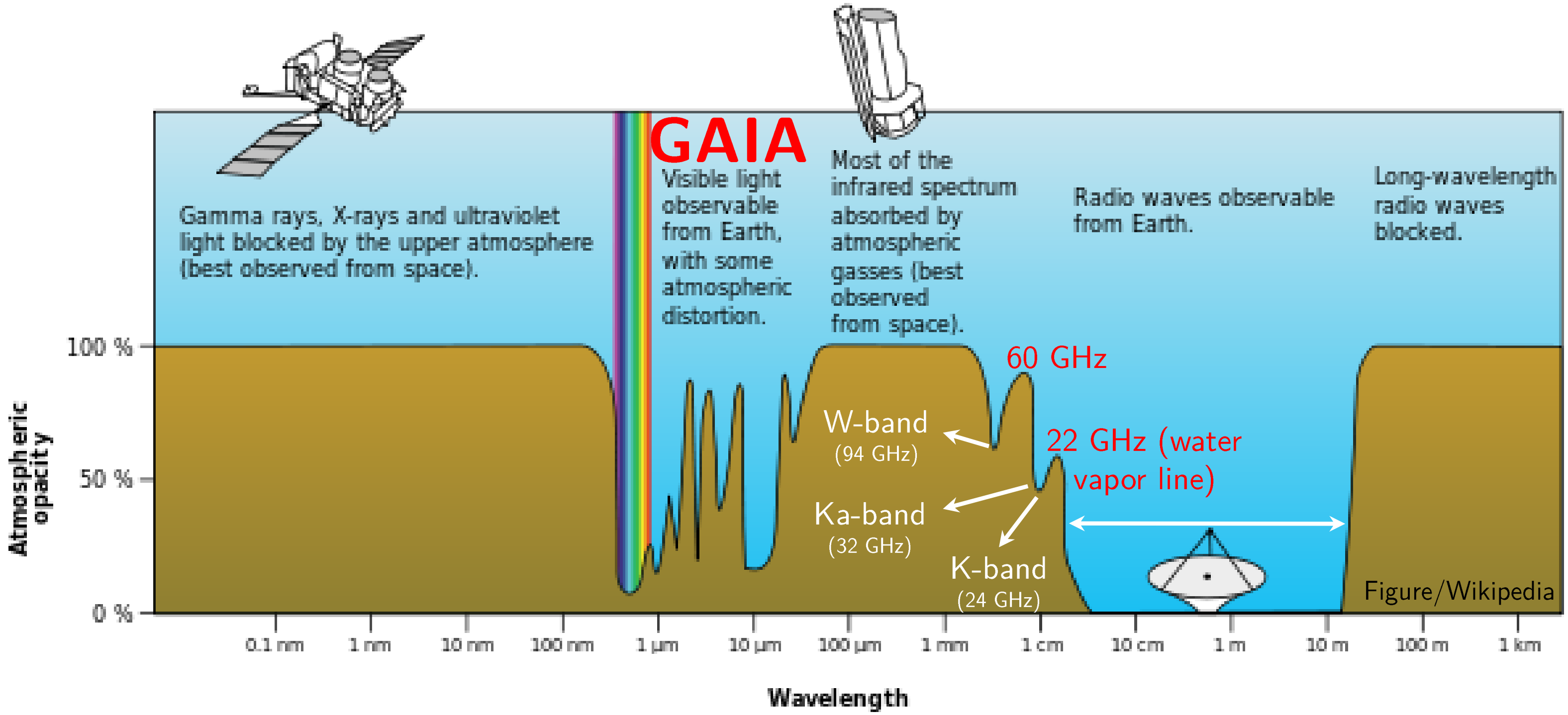
ICRF2 S/X-Band

defining sources: 295
total sources: 3414 (3119 compact sources)
Noise floor: ~ 40 μas, 5-6× better than ICRF1
Axis stability: ~ 10 μas, 2× better than ICRF1
(IERS Conventions 2010)

(used sampling rate 112 Mbps at X/Ka-Band)

(Jacobs, et al, 2010)

Survey of Extragalactic Sources at S/X/Ka/(W)-band



ICRF2: International Celestial Reference Frame at S/X-band = **2.3/8.4 GHz**

VLBI2010: 2-14 GHz, later 2-18 GHz

K-band (VLBA): **24 GHz**

X/Ka-band: 8.4/32 GHz Radio-Science Experim., Mars Reconnaissance Orbiter, BepiColombo, JUICE, Netlander

Ka/towards W-band (driven by higher telemetry rates, radio-science experiments, space missions, iono-effects, etc.)

- Higher the R/F frequency smaller is the antenna
- Possible optical data modulation – larger sampling rate (1 - <10 Gbps) – **sensitivity**

Towards ICRF at X/Ka-Band (32 GHz) and Higher (W-band)

Advantages

- main driver are new space missions (Mars Reconnaissance Orbiter, BepiColombo, JUICE, Netlander...) requiring higher telemetry rates, radio-science, improved deep-space navigation (gravity field), lower iono/soalar plasma-effects, etc.
- Higher telemetry data rates in deep space
- Onboard RF systems are smaller (antenna) and with lower weight
- Avoided RF Interference at S-band
- Ionosphere & solar plasma effects decreased by 16-100× at 32 GHz/90 GHz compared to 8 GHz
- Observation possible closer to Sun/Galactic center
- Very compact sources (spatial distribution of flux) that give more stability in positions over time!
- **Ka-positions closer to optical position (GAIA) compared to ICRF2 in S/X-band**

Disadvantages

- More weather sensitive (close to 22 GHz water vapor line)
- Antenna pointing requirements 4-10× higher at 32 GHz/90 GHz compared to 8 GHz (beam forming technique)
- In order to increase sensitivity sampling rate needs to be 4-10× higher at 32 GHz/90 GHz compared to 8 GHz

STE-QUEST Space VLBI as the link between GAIA Optical & Radio VLBI Frame

ICRF2 S/X-Band

defining sources: 295
total sources: 3414 (3119 compact sources)
Noise floor: ~ 40 μas
Axis stability: ~ 10 μas
(IERS Conventions 2010)

GAIA

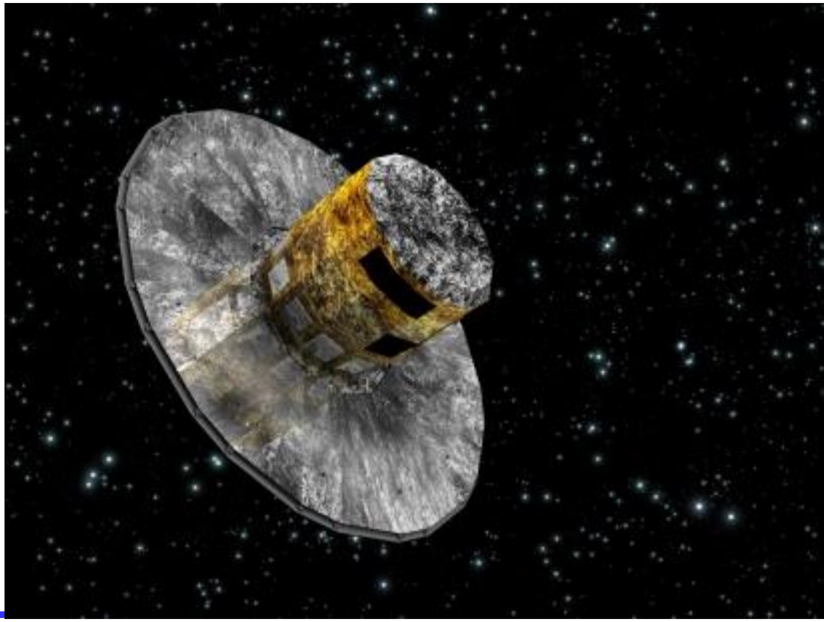
optically bright quasars (V<18 mag) ~ 2000

Motivation: Ka-positions closer to optical position (GAIA) than ICRF2 in S/X-band

- The alignment of the Hipparcos Catalogue to the ICRF was realized with a standard error of **0.6 mas** for the orientation at epoch 1991.25 and **0.25 mas/yr** for the spin (Kovalevsky et al., 1997)
- The IAU recommendations stipulate that the direction of the Conventional Reference Pole should be consistent with that of the **FK5**. (IERS Conventions 2010)

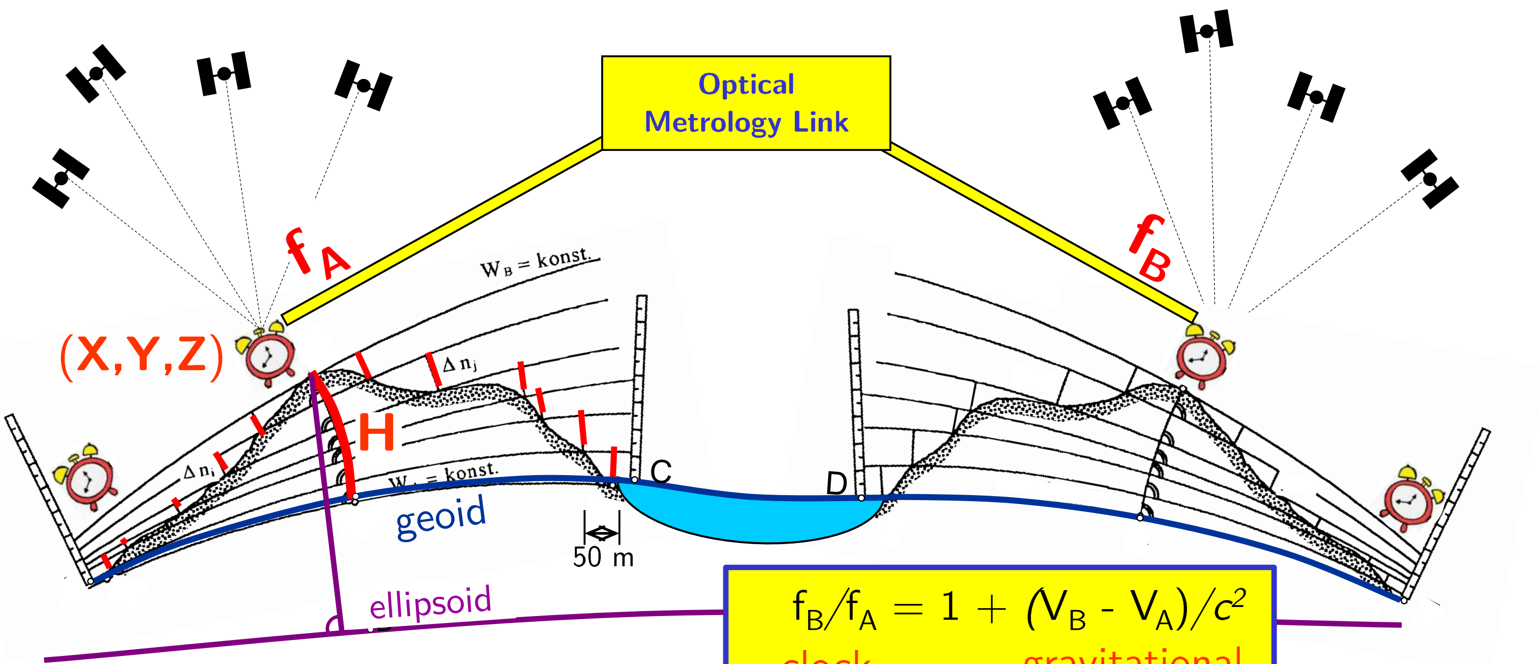
Out of 469 sources of the current Ka-band Celestial Frame:

- **132 objects are optically bright (V<18 mag)** (Garcia-Miro et al, 2012)
- for 71 there is no data
- are without data from a station in the southern hemisphere
- **5-15 μas** potential precision for 3D frame tie with GAIA (Garcia-Miro et al, 2012)



STE-QUEST: High-accuracy Relativistic Geodesy

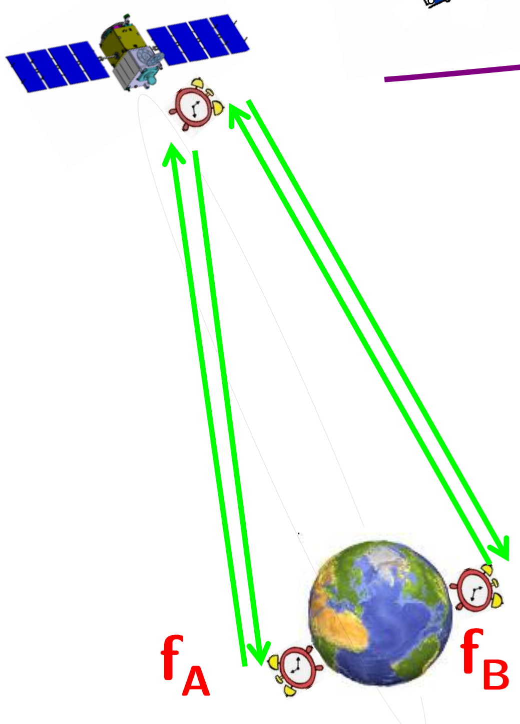
GNSS
(GPS, Galileo, ...)



$f_B/f_A = 1 + (V_B - V_A)/c^2$

clock frequency — gravitational potential

Geometry from GPS (**X,Y,Z**) + **Dynamic Heights** (**H**) from optical clocks



Metrology Link with $<10^{-18}$ accuracy is FEASIBLE!!!

- there is a solution for the metrology link after several years of looking at this problem...

Optical Metrology Link

- Atmospheric turbulences (there is a solution!)
- Long light-travel time (there is a solution!)

Microwave Metrology Link

- Higher-order ionosphere terms (there is a solution!)
- Atmospheric turbulences, multipath (there is a solution!)
- Long light-travel time (there is a solution!)

Many Thanks