GRAVITATIONAL RED-SHIFT EXPLORER (GRESE)

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GRAVITATIONAL RED-SHIFT EXPLORER (GRESE)

Theme: What are the fundamental physical laws?

Primary Goal: To test Einstein's Equivalence Principle, in particular to test the Local Position Invariance via gravitational red-shift measurements using clocks.

Spacecraft and Instruments: Single spacecraft carrying

- Space Hydrogen Maser (SHM)
- Microwave time and frequency link (MWL)
- GNSS receiver
- Laser link (optional)

Orbit: Highly elliptical orbit around Earth

Lifetime: 2-3 years

Type: S-class mission

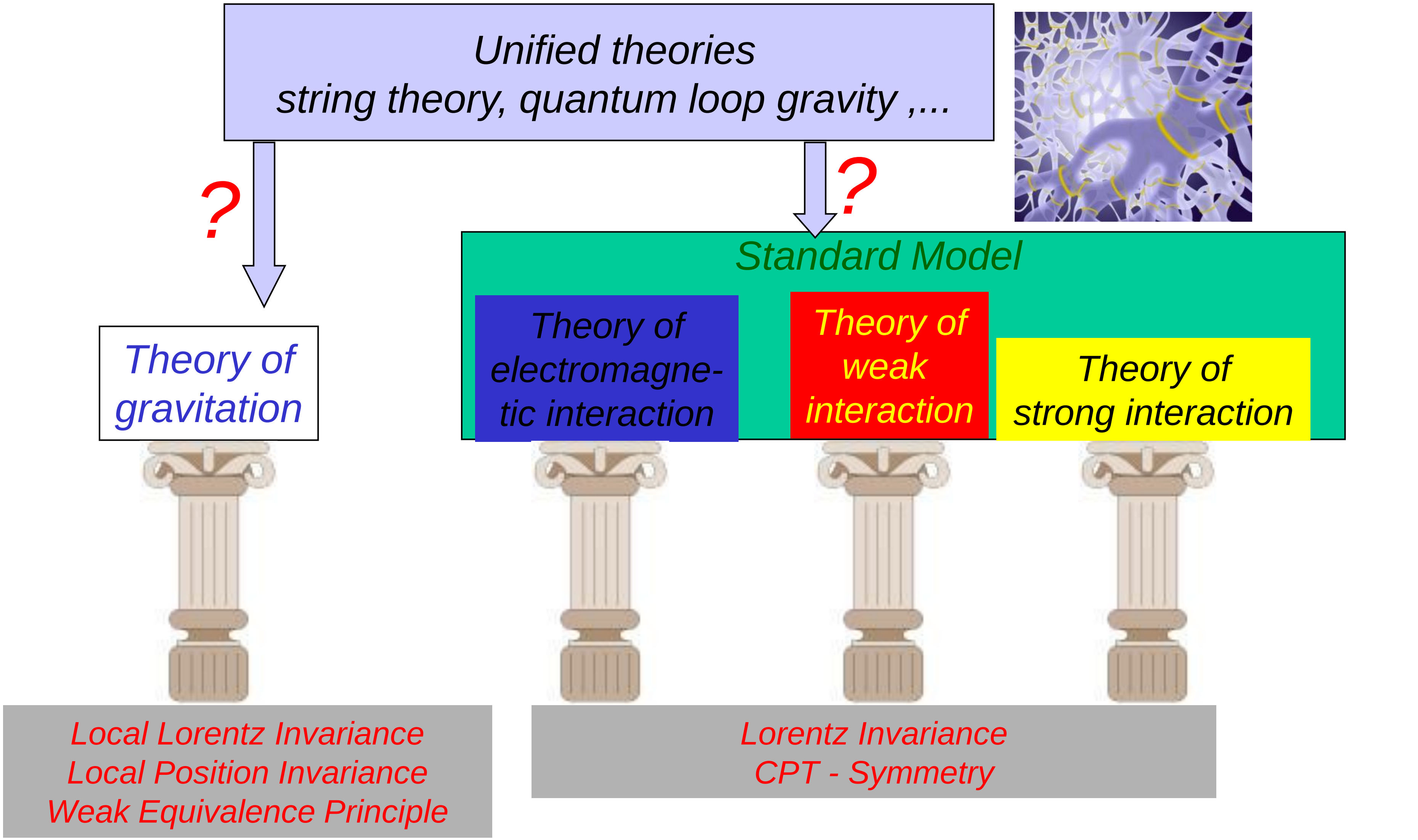
Science Rationale

- Unified description of Gravity and Quantum Field Theory not achieved
- Nature of Dark Matter (DM): unknown
- Dark Energy – Cosmological constant: what is its nature?

- Models of unification and models of Dark Energy generally involve scalar fields that
  - couple to gravity
  - couple in different ways to different ordinary matter types and DM
- Fundamental constants are expectation values of scalar fields
- Such character can lead to time- and space-varying fundamental constants
- Recent detection of first fundamental scalar field (Englert-Brout-Higgs field)

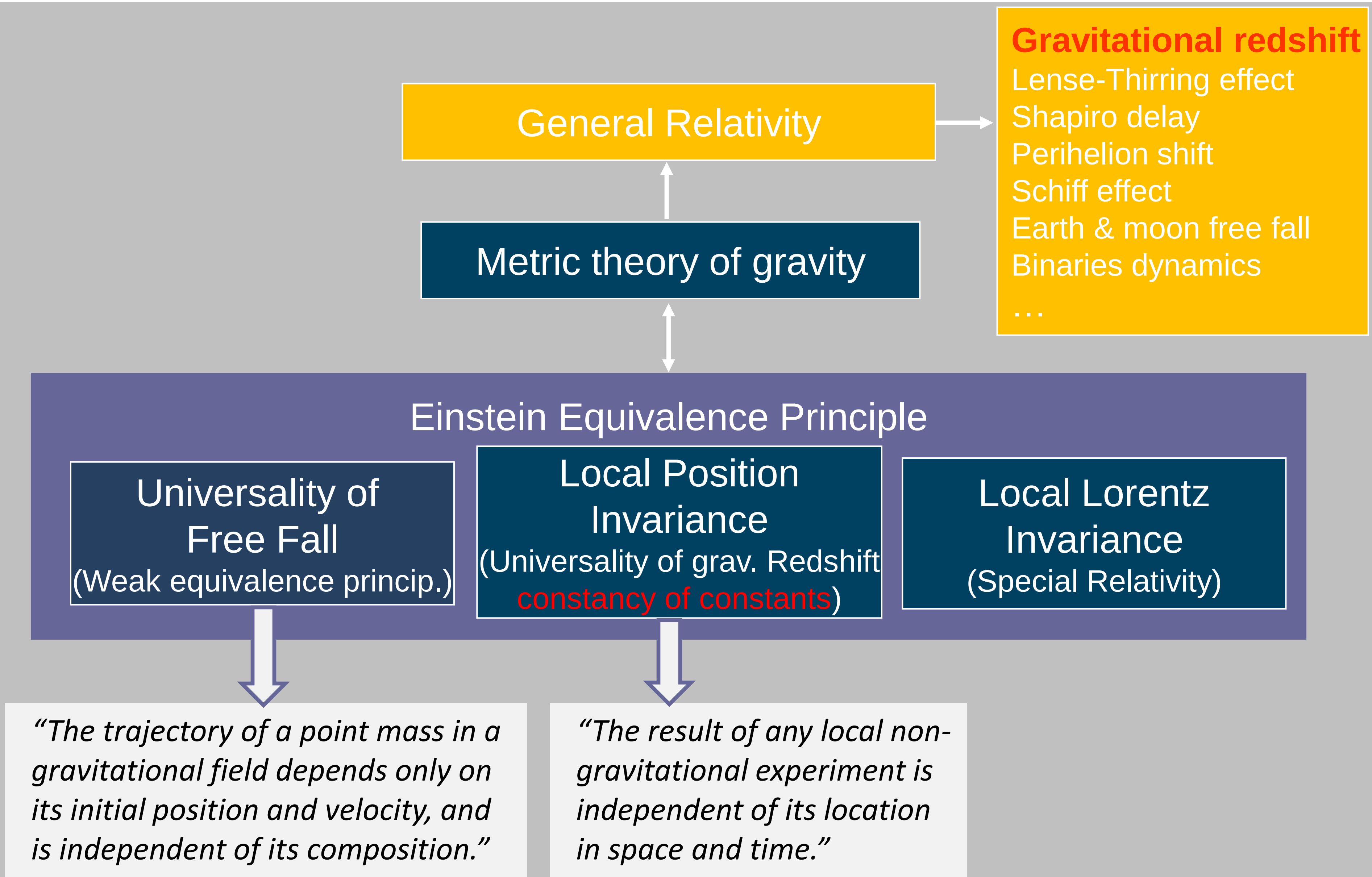
Violation of EEP is a general consequence

Motivation

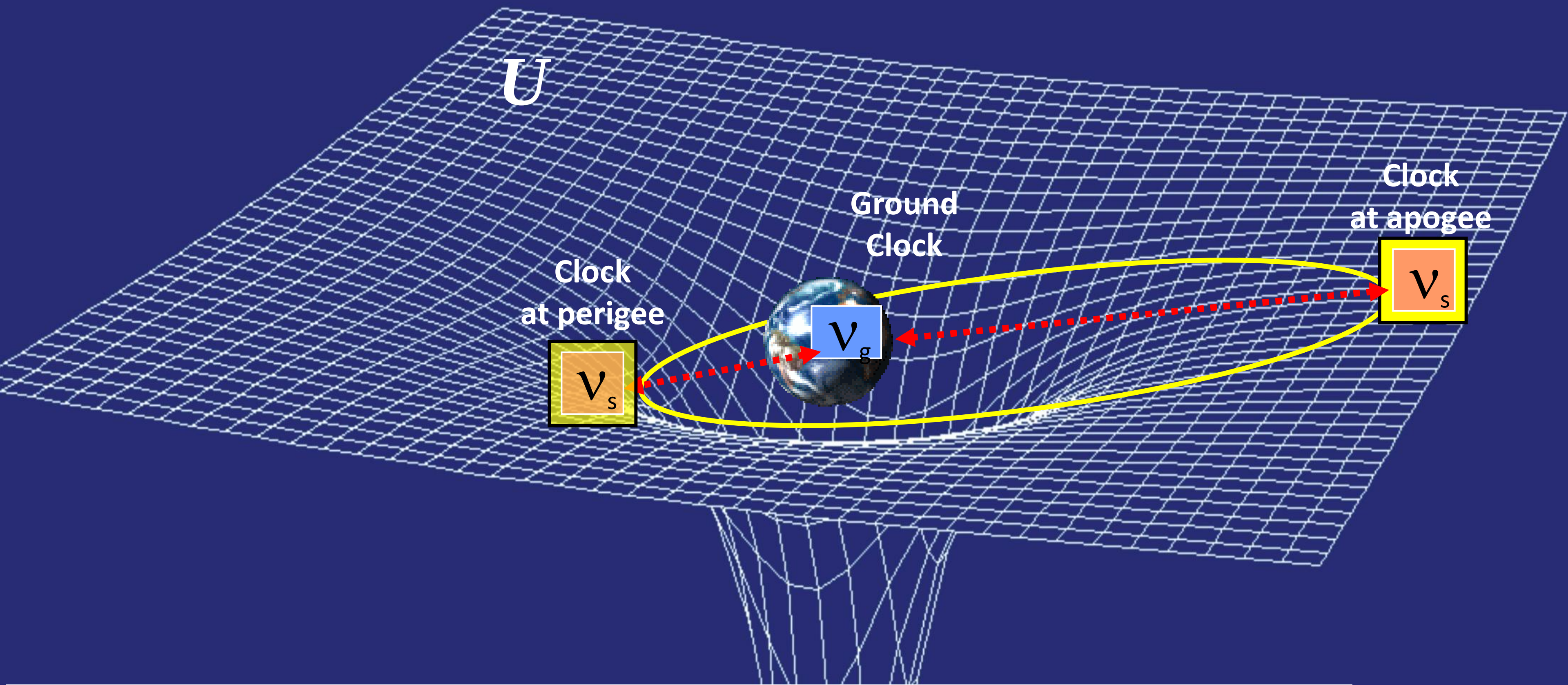


exactly valid?

The conceptual basis for tests of General Relativity



Testing Earth's gravitational time dilation

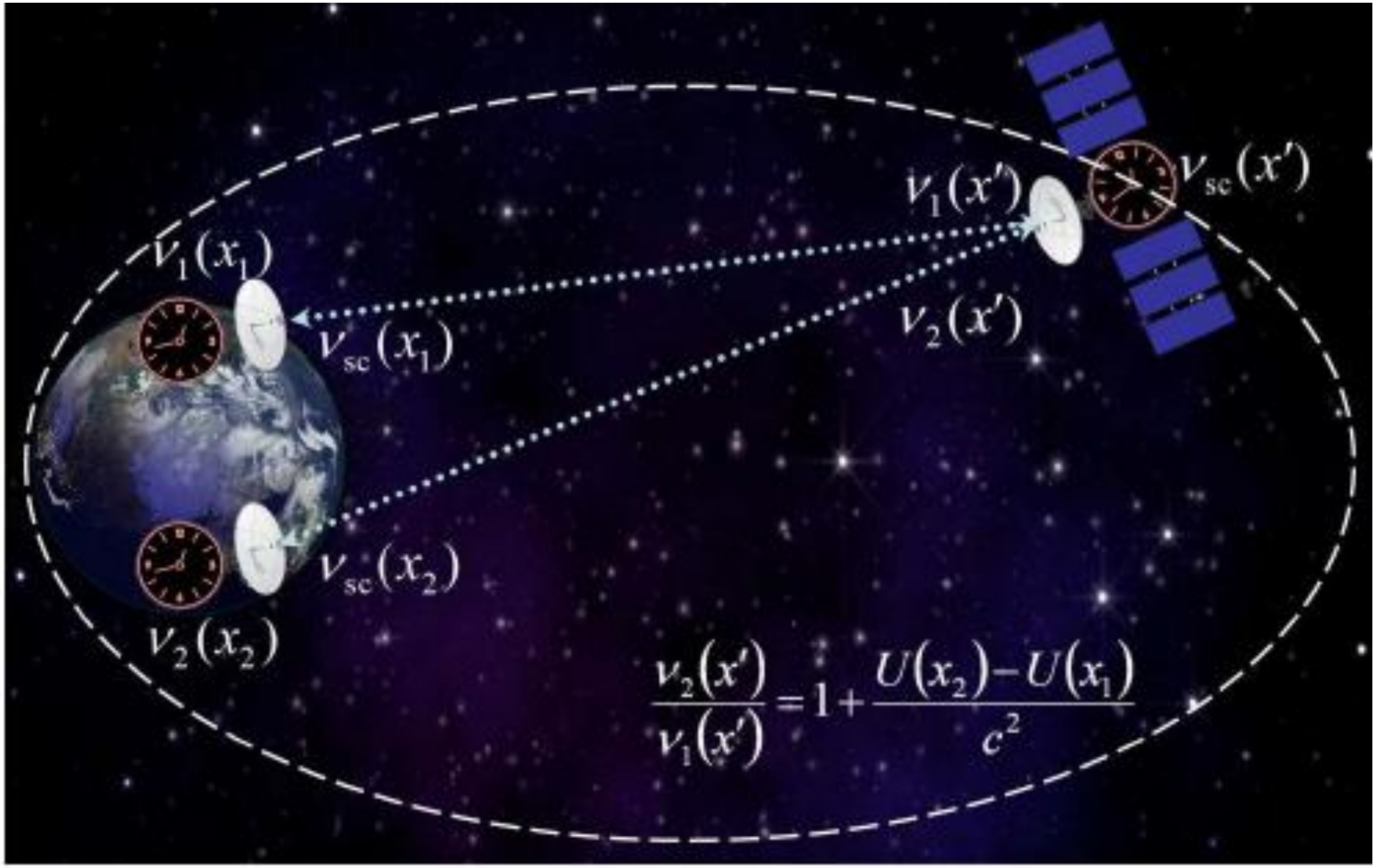


<u>Comparison between ground clock and satellite clock **at perigee and apogee**</u>

- determine: $(\nu_s(\text{apogee}) - \nu_g) - (\nu_s(\text{perigee}) - \nu_g)$
- in highly elliptic orbit, $\Delta U(\text{perigee-apogee})/c^2 \approx 6 \times 10^{-10}$

→ Measurement of time dilation in terrestrial potential with 2×10^{-6} accuracy

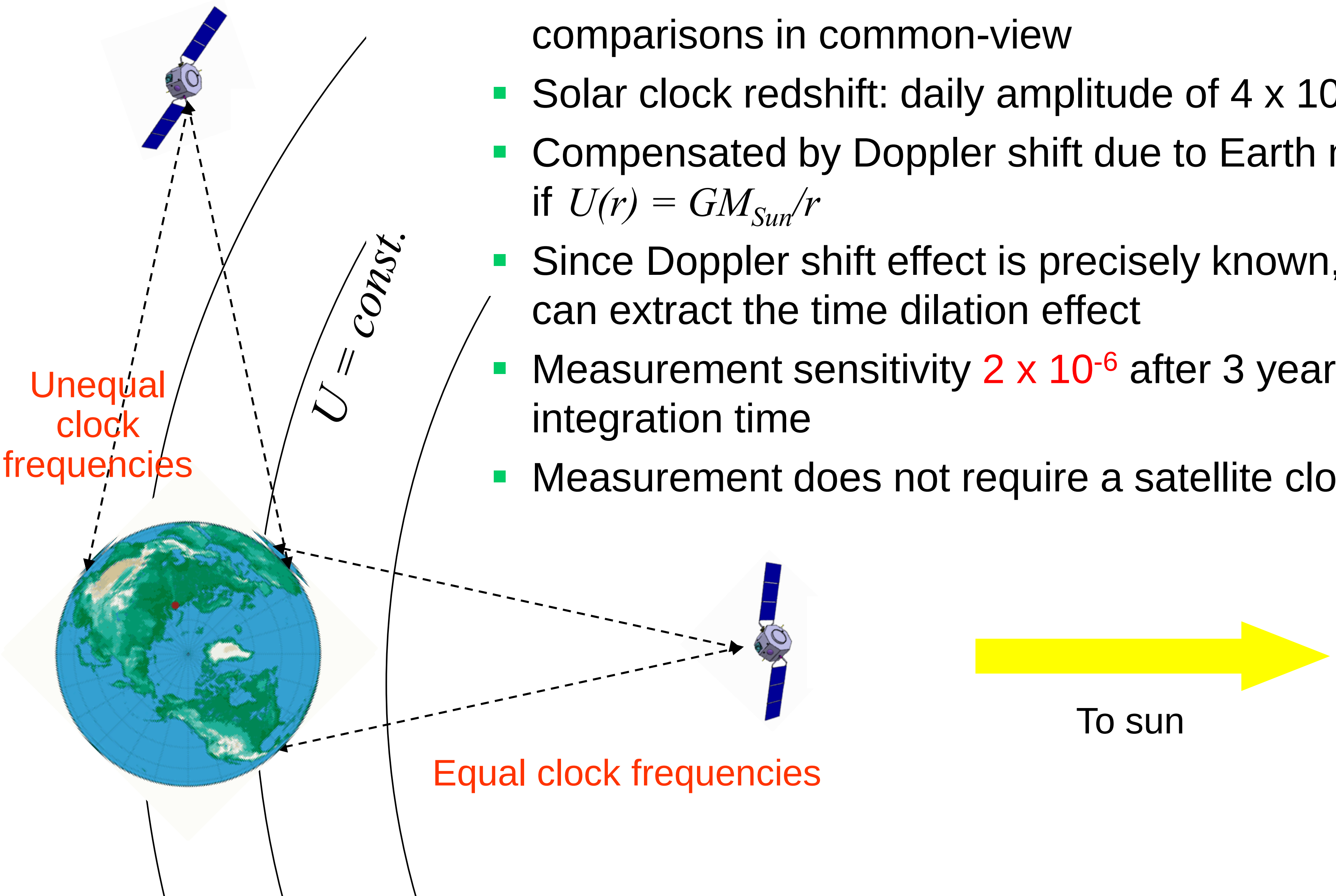
Comparing terrestrial atomic clocks via GRESE



Time dilation measurement in Sun field

- Precise test of Sun gravitational time dilation

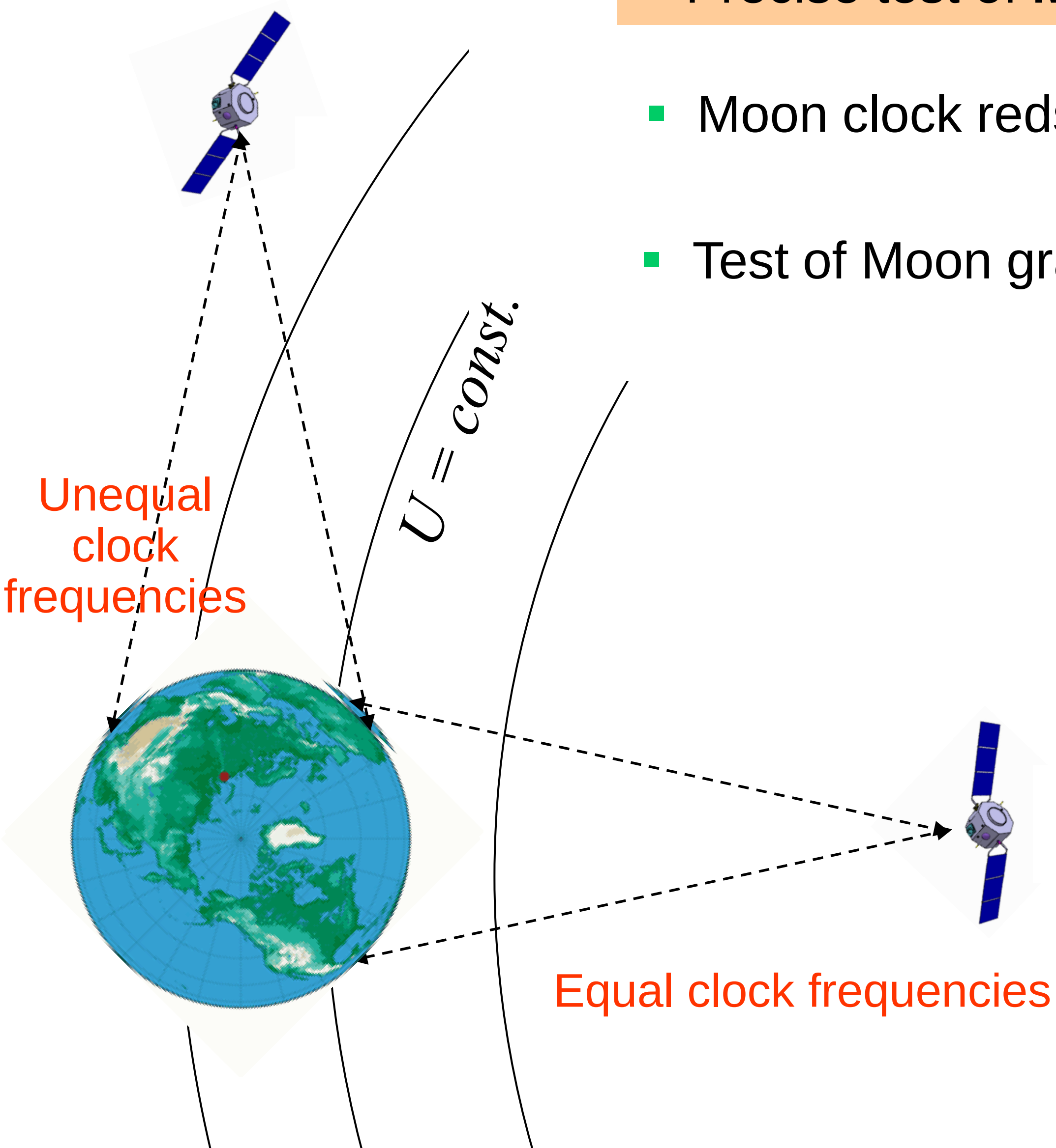
- Ground-to-satellite links allow terrestrial clock comparisons in common-view
- Solar clock redshift: daily amplitude of 4 x 10^{-13}
- Compensated by Doppler shift due to Earth motion if $U(r) = GM_{Sun}/r$
- Since Doppler shift effect is precisely known, one can extract the time dilation effect
- Measurement sensitivity 2 x 10^{-6} after 3 years integration time
- Measurement does not require a satellite clock



Moon gravitational frequency shift measurement

- Precise test of Moon gravitational time dilation

- Moon clock redshift: daily amplitude of 6×10^{-15}
- Test of Moon gravitational redshift at level **4×10^{-4}**



Moon

The gravitational frequency shift

$$\frac{\nu_{clock1}(r)}{\nu_{clock2}(r)} \cong 1 + \frac{U(r_1) - U(r_2)}{c^2}$$

$$U(r) = -\frac{GM}{r} \quad ?$$

Search for existence of additional scalar fields ϕ emanating from constituents of Earth, Sun, or Moon

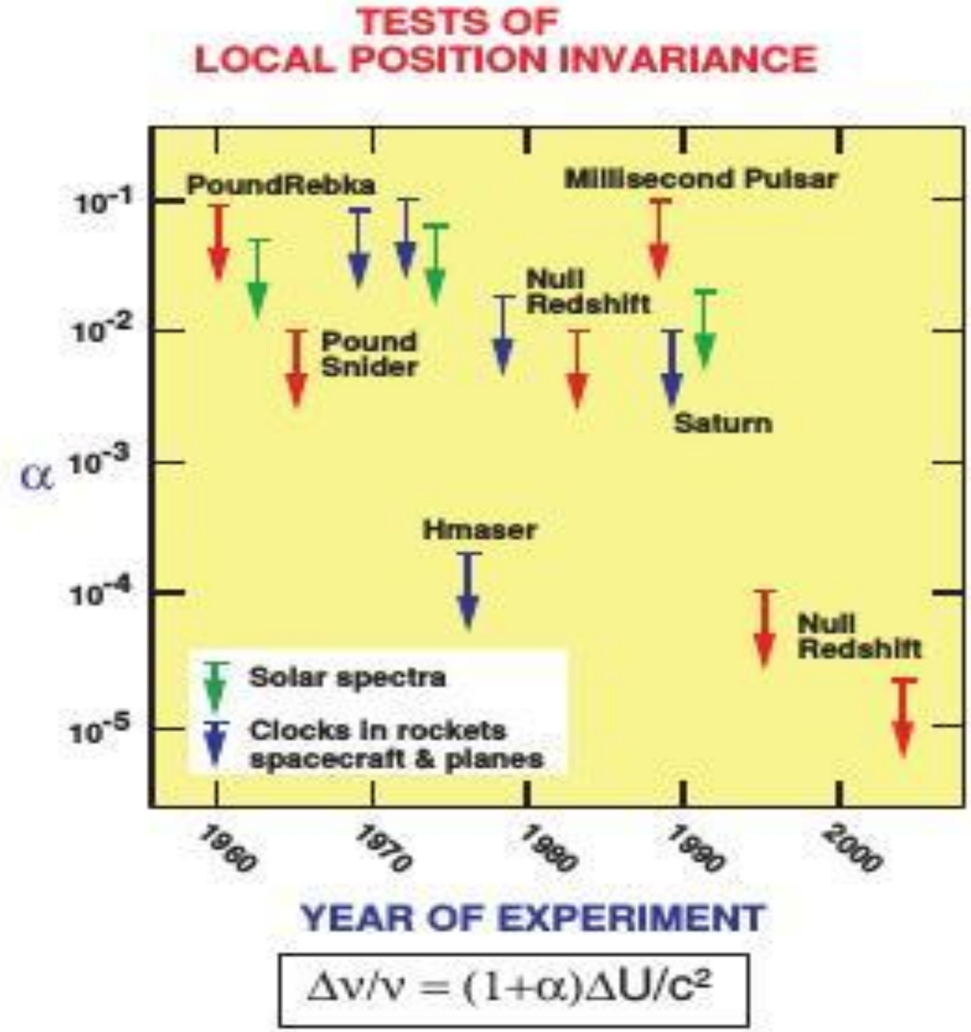
- Model $\phi_i(r) \sim S_i/r$

  where S_i may depend on the particle species contained in the massive body, and may depend on the clock type

Mass of Sun: protons
Mass of Earth: protons & neutrons

- Comparison of identical clocks at different locations r_1, r_2 will show an additional frequency shift contribution, which depends on the source type

- GRESE will set limits to S_{EARTH}, S_{SUN}, S_{MOON}



Red arrows : “null red-shift measurements” (differences α_i - α_j for two different types of clocks i and j).

Green arrow : best direct LPI tests in the Sun field.

Blue arrow : best direct LPI tests in Earth field.

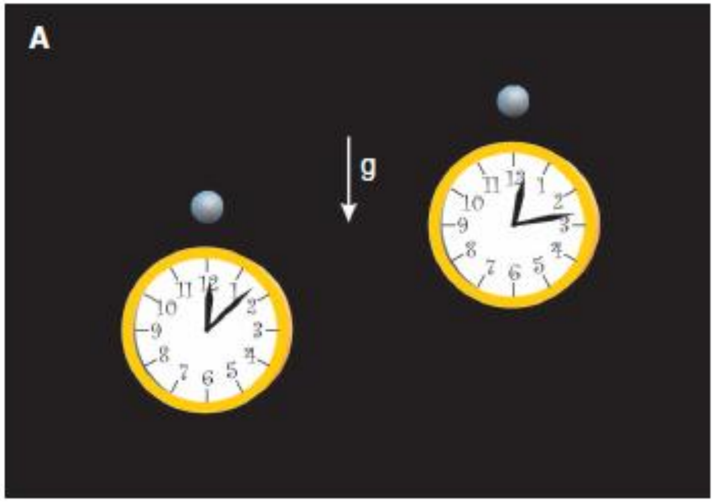
GRESE: Earth field ~ 10^{-6}, Sun field ~ 10^{-6}, Moon field ~ 10^{-4}

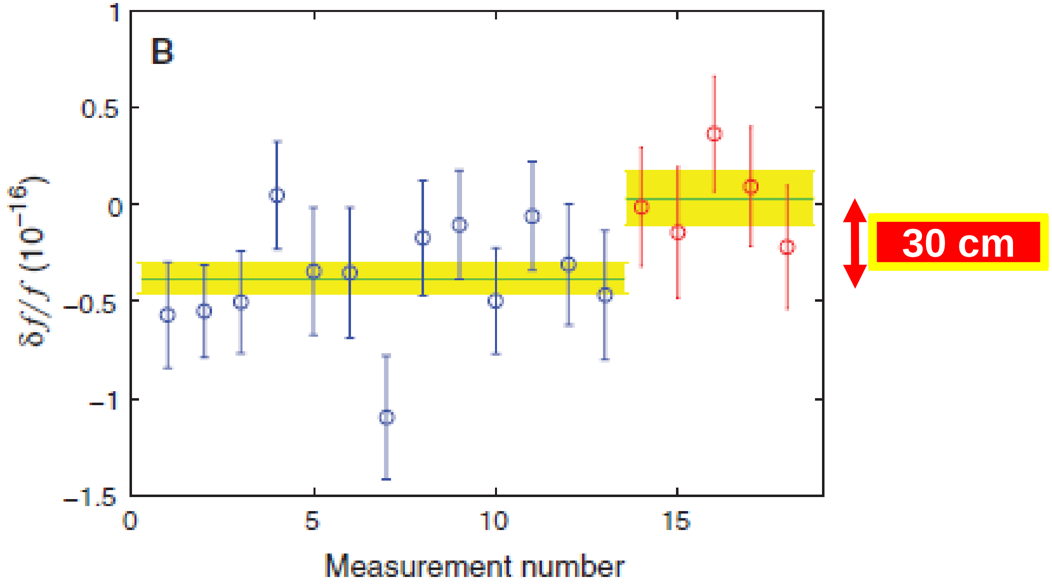
Optical clocks and Earth's gravitational potential

A new generation of atomic clocks: optical clocks

Optical Clock (NIST)
lifted up by 30 cm

Observed frequency offset
3×10^{-17}

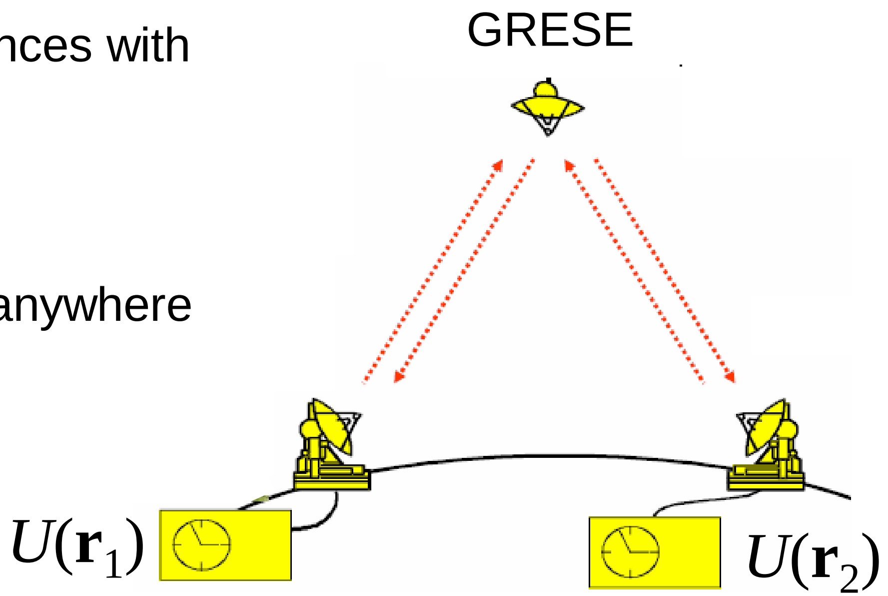




Chou CW, Hume DB, Rosenband T, Wineland DJ (2010)
***Science* 329** (5999),1630. DOI: 10.1126/science.1192720

Differential measurements of the geopotential

- With clocks of accuracy at 1×10^{-18}, it is possible to measure geopotential differences with equivalent height resolution of 1 cm
- Extremely high spatial resolution
- Good time resolution ($\approx$ 1 day)
- Transportable clocks can be positioned anywhere

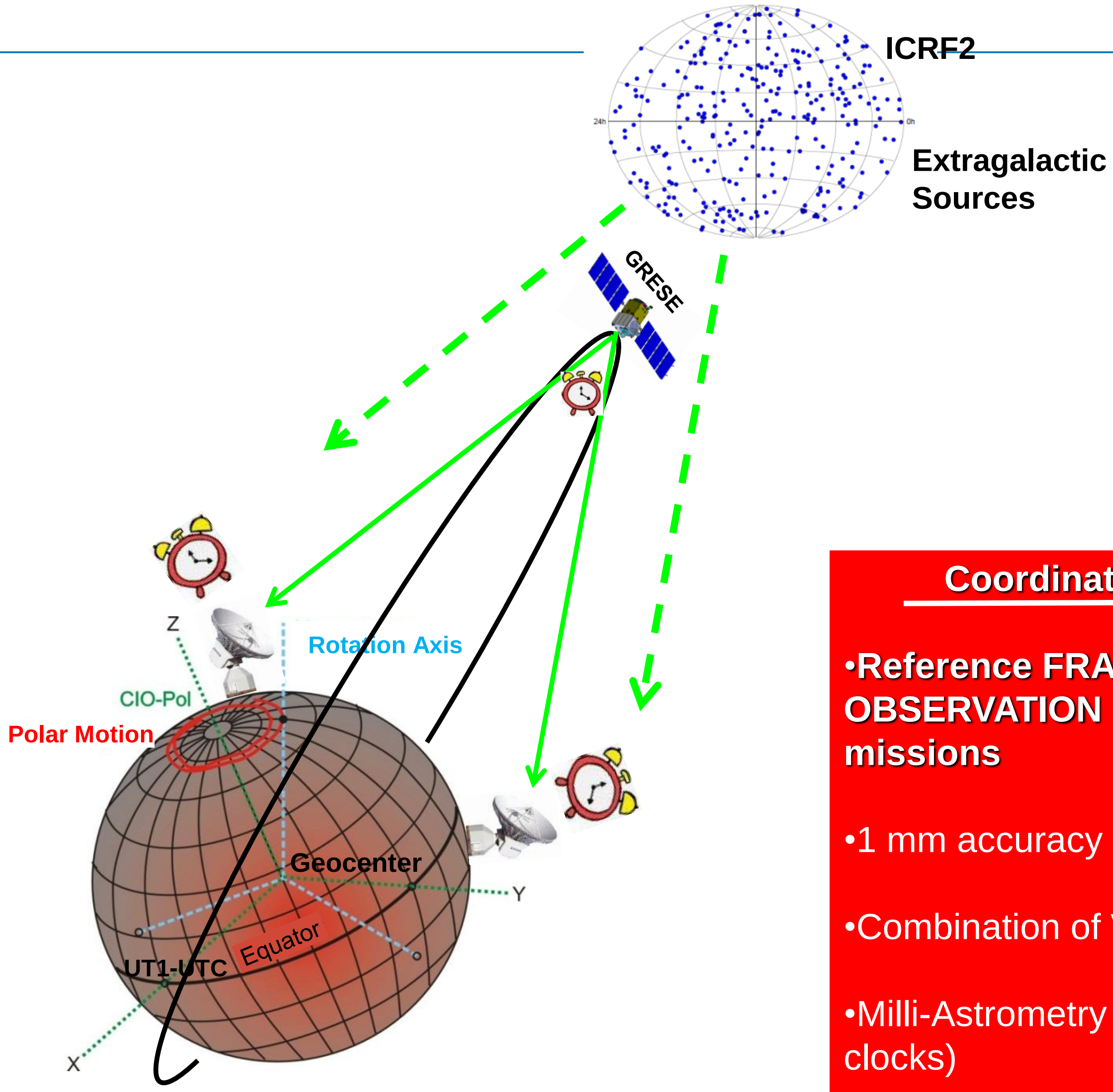


$$\frac{\nu_{clock1}(\mathbf{r})}{\nu_{clock2}(\mathbf{r})} - 1 = \frac{U(\mathbf{r}_1) - U(\mathbf{r}_2)}{c^2} \; *$$

- The onboard atomic clock is not required (only the link)

(**U* includes the velocity term)

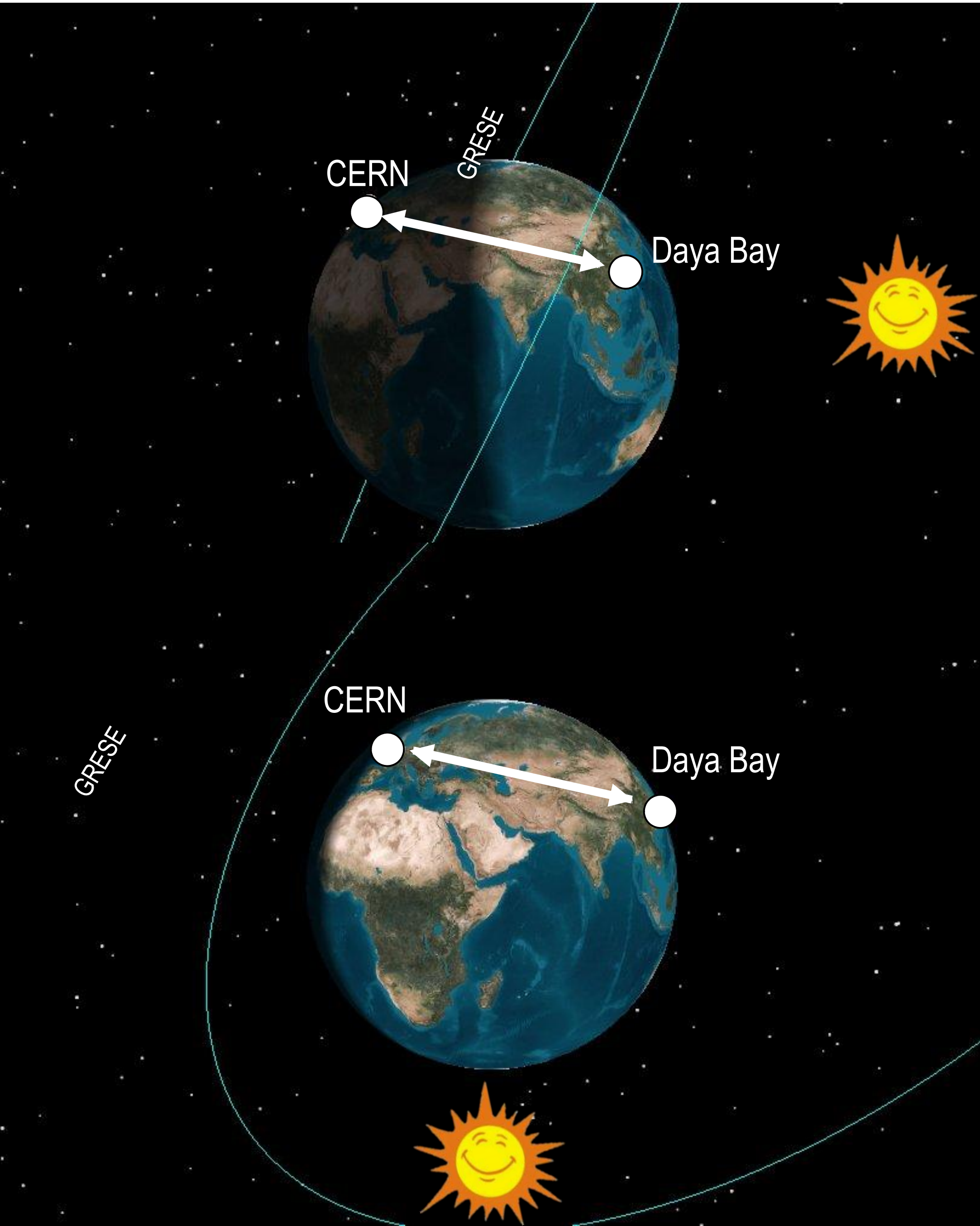
Terrestrial and Celestial Reference Frame



Coordinate System of the Earth:

- **Reference FRAME for all EARTH OBSERVATION and SPACE SCIENCE missions**
- 1 mm accuracy and 0.1 mm/yr stability
- Combination of VLBI, GNSS, SLR and DORIS
- Milli-Astrometry (using onboard/ground clocks)

GRESE Measurements of Neutrino Speed in Sun Gravitational Field

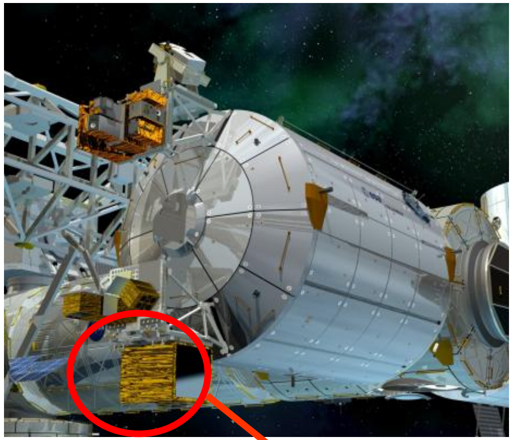


WHAT is the SPEED of Neutrinos?

Neutrinos possess mass, the speed of neutrinos should be slightly smaller than the speed of light!

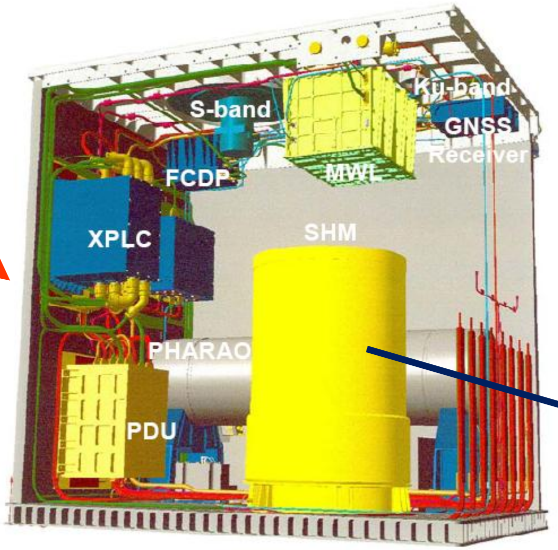
First measurements carried out between CERN and Rome (limited by GPS)

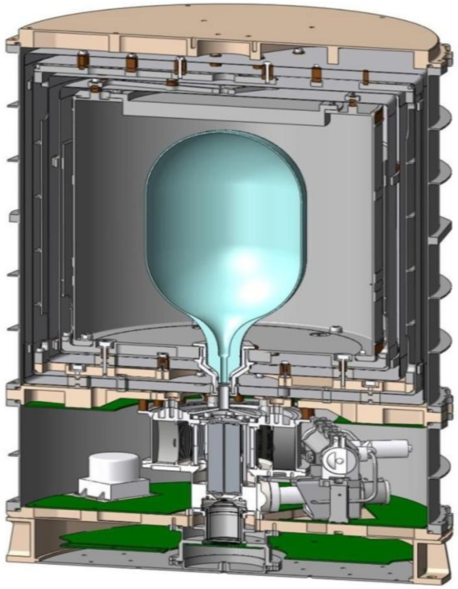
SHM under development for ACES - 1



SHM is an Active H-Maser for space applications developed by Spectratime under ESA contract with funding provided by the Swiss Space Office.

To provide excellent medium-term stability to ACES

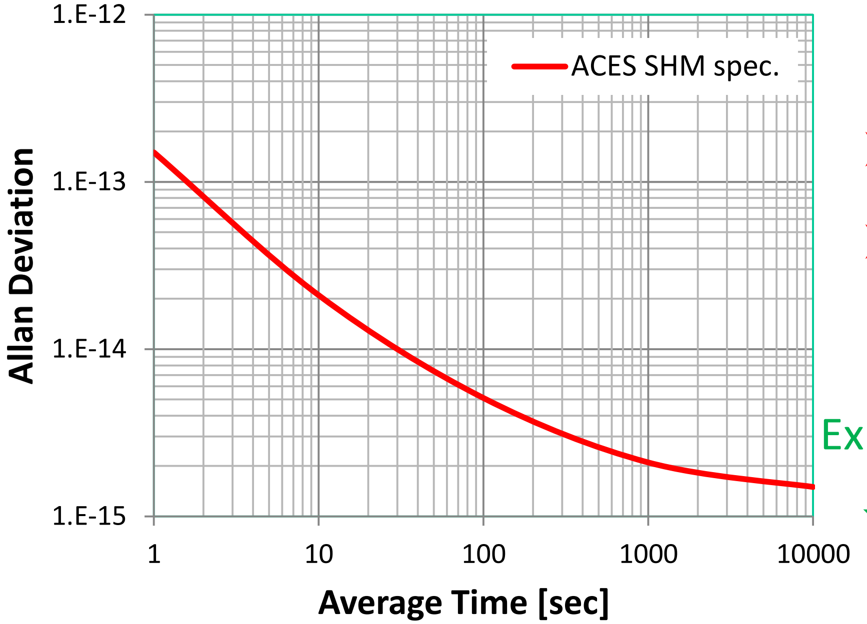




Launch: 2016
International Space Station
Mission duration: 18 months

spectratime

SHM under development for ACES - 2



- Weight: < 44 kg
- TRL 6 (09.2014)

Expected frequency stability:
< 1e-15@1day

SHM EM fully assembled

Current status and plan:

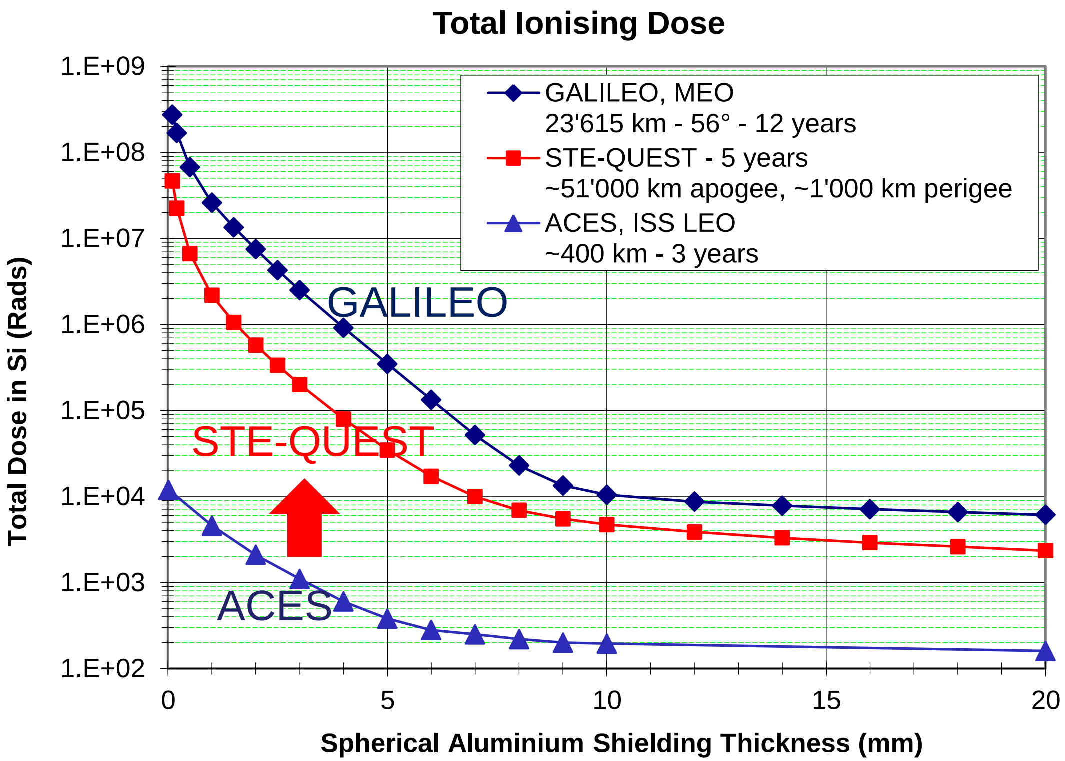
- EM2 testing phase on-going
- FM manufacturing started
- FM delivery 2015

SHM: relatively small, low-price, reliable, high-performance, high TRL space atomic clock available today for the fast, small mission in 2021

spectratime

Radiation design improvement of SHM

- More severe radiation environment in the highly elliptical orbit than ACES
- Radiation design improvements:
  - EEE components selection: Ionizing radiation tolerant, radiation hardened
  - Shielding optimization



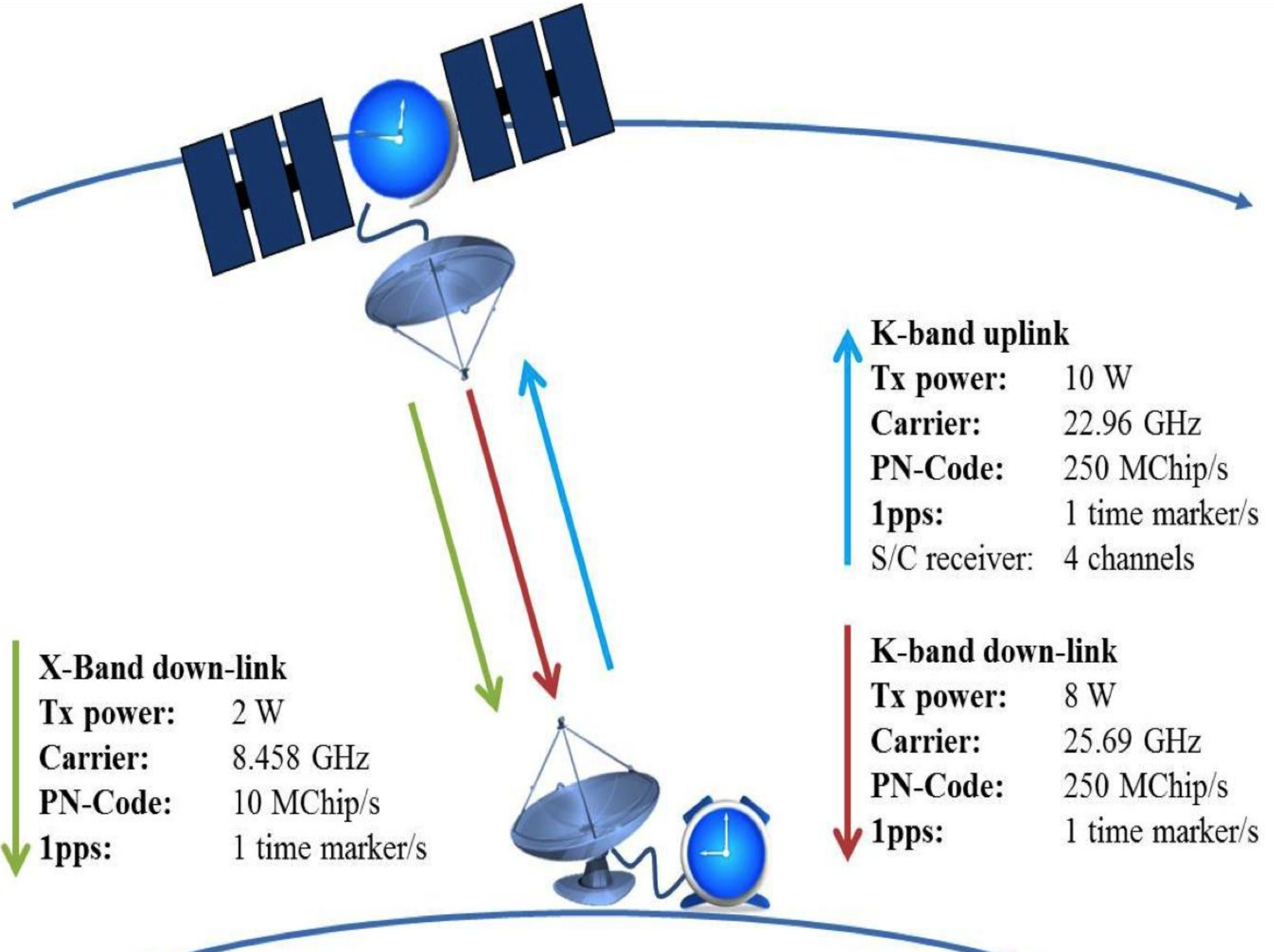
- Galileo H-maser and rubidium clocks (RAFS) have been developed and are operating in the harsh radiation environment of MEO.

SHM radiation design improvement: NOT critical for GRESE orbit

spectratime

Microwave link

Bi-directional, triple frequency link



Performance:

Link stability (ADEV):

1.6E-13/τ, 1 s ≤ τ ≤10^6 s

Ranging uncertainty:

≤ 1cm (30 ps), Code

≤ 0.1mm (0.3 ps), Carrier

Resources:

Mass: ≤ 20 kg

Power: ≤ 80 W

Operation Modes:

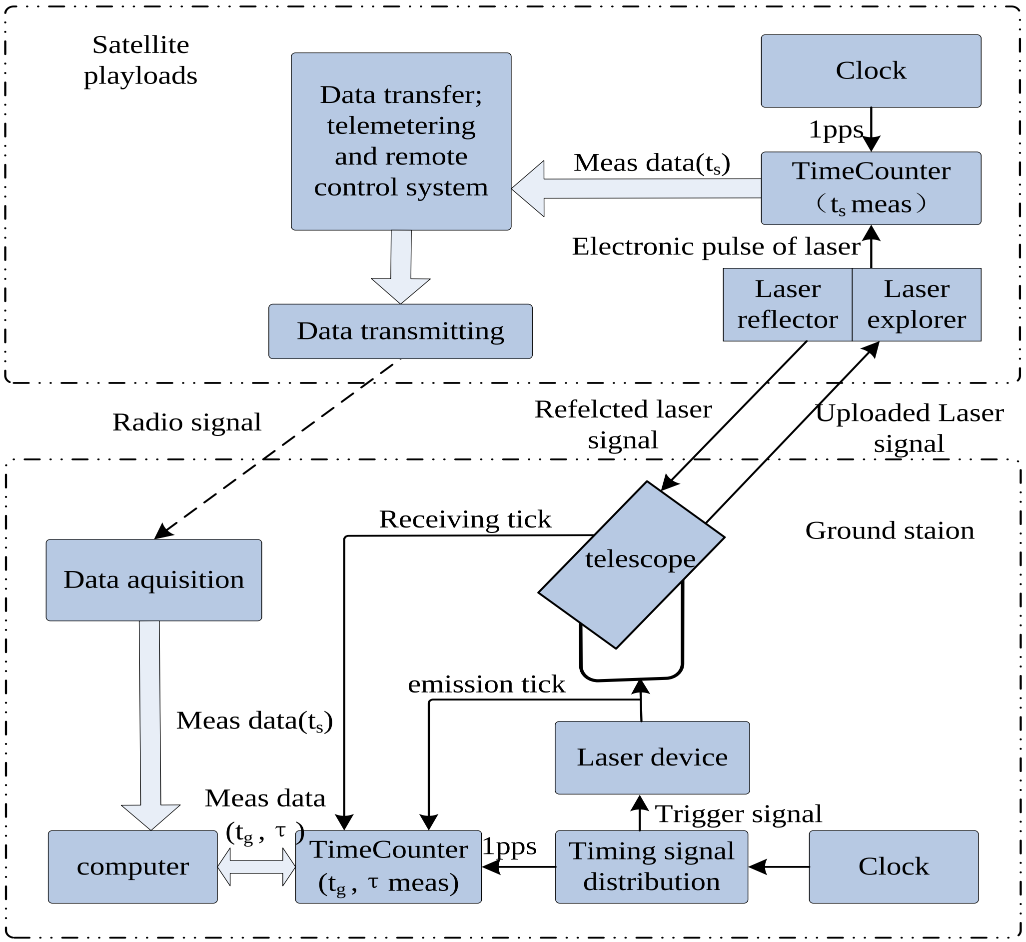
Continuous operation

TRL: need upgrade from ACES/Beidou MWL; TRL 6 by 2016 via European & Chinese developments

Heritage: MWL link for Beidou GNSS (double frequency)
MWL link for ACES (2016):
16.5 kg, 51 W, TRL 5-6 (currently)
Similar system to be developed for Tiangong space station

Laser link (optional)

Bi-directional laser link: Independent means to verify and calibrate MWL



Performance

Link stability (ADEV):

1 E-13/τ, $1\ s \le \tau \le 10^5\ s$

Ranging uncertainty: ≤ 1 cm

Resources:

Mass: ≤10 kg, Power: ≤30 W

Operational mode:

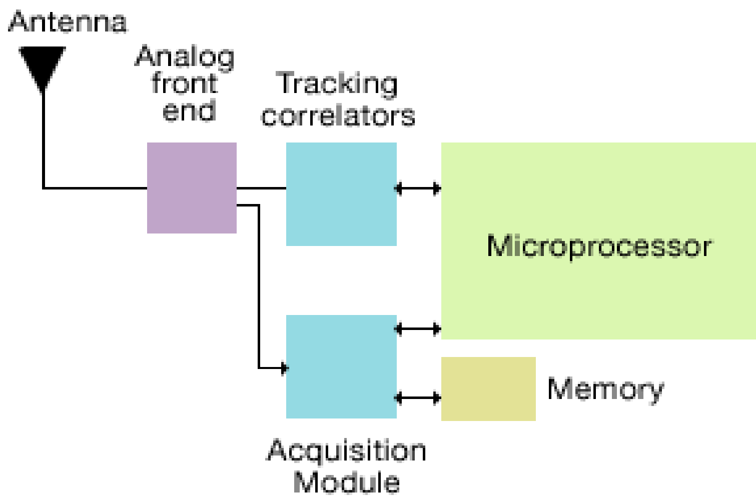
Discontinuous operation (cloud-free conditions)

TRL: 9 for 100 ps uncertainty;

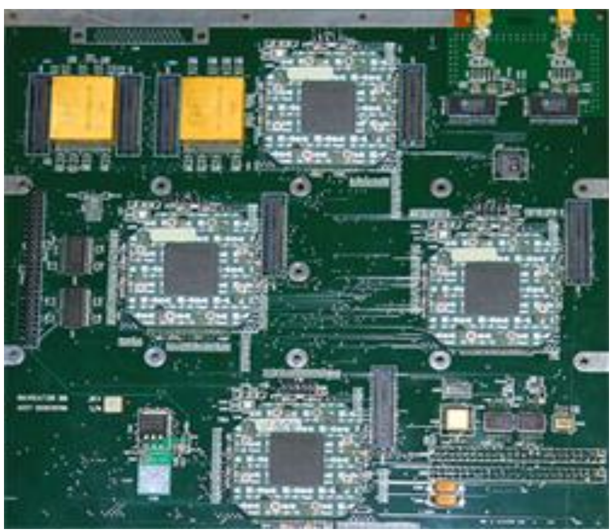
To be improved to 30 ps.

Heritage: 3 operational ground stations that perform clock synchronization on part of the Beidou GNSS satellites

On-board GNSS Receiver



Functional block diagram



Main board graph

Tracking signals:

● multi-system: GPS/GLO./BDS/GAL.(≥100sats)

● dual frequency per system: L1/L2; B1/B2; E1/E5;

Measurement accuracy:

● Code: ≤ 0.3 m;

● Carrier: ≤ 2 mm

Resources:

●Mass: ≤ 2 kg

●Power: ≤15 W

Operation Modes:

Continuous operation

TRL: ≥ 6

Orbit design and analysis

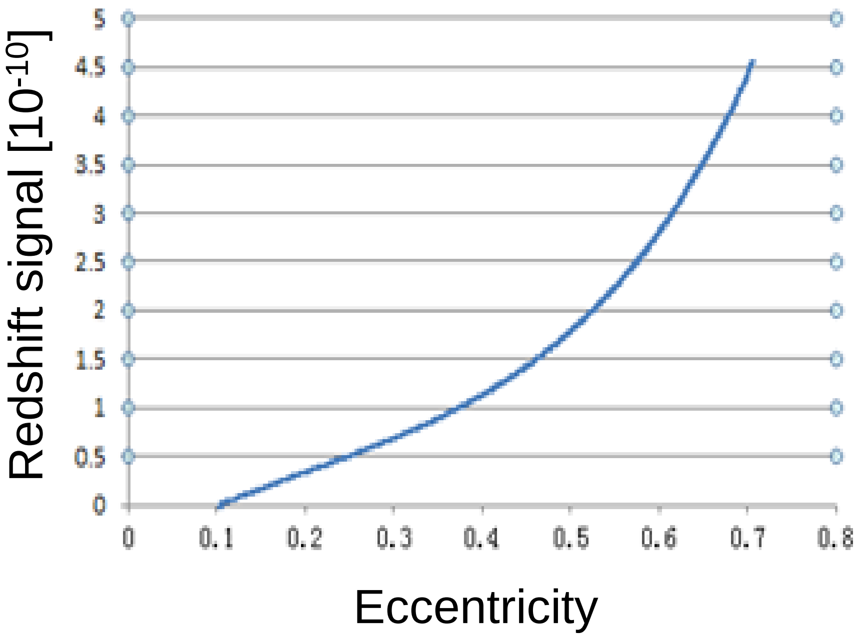
National Space Science Center, CAS

Orbit Requirements:

(1) Eccentricity: to explore red-shift, large eccentricity is necessary. The orbit should be highly elliptic.

(2) Continuous time comparison: to measure the frequency and time variations of the space clock precisely in long duration.

(3) Orbit determination condition: Besides the on-board GNSS receiver, the distribution and visibility of ground station are also very important.



The relation between orbit eccentricity and red-shift variation

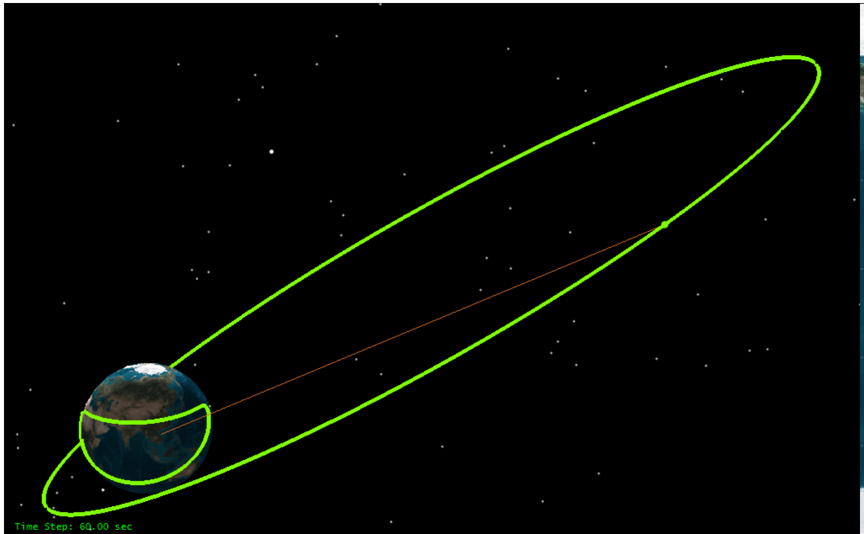
Orbit design and analysis

National Space Science Center, CAS

Scenario A

Period	86164 sec
Eccentricity	0.73
Inclination	30 deg
Argument of Perigee	278 deg
RAAN	268 deg
True Anomaly	0 deg

Apogee Altitude	66565.8 km
Perigee Altitude	5006.18 km
Inclination	30 deg
Argument of Perigee	278 deg
RAAN	268 deg
True Anomaly	0 deg

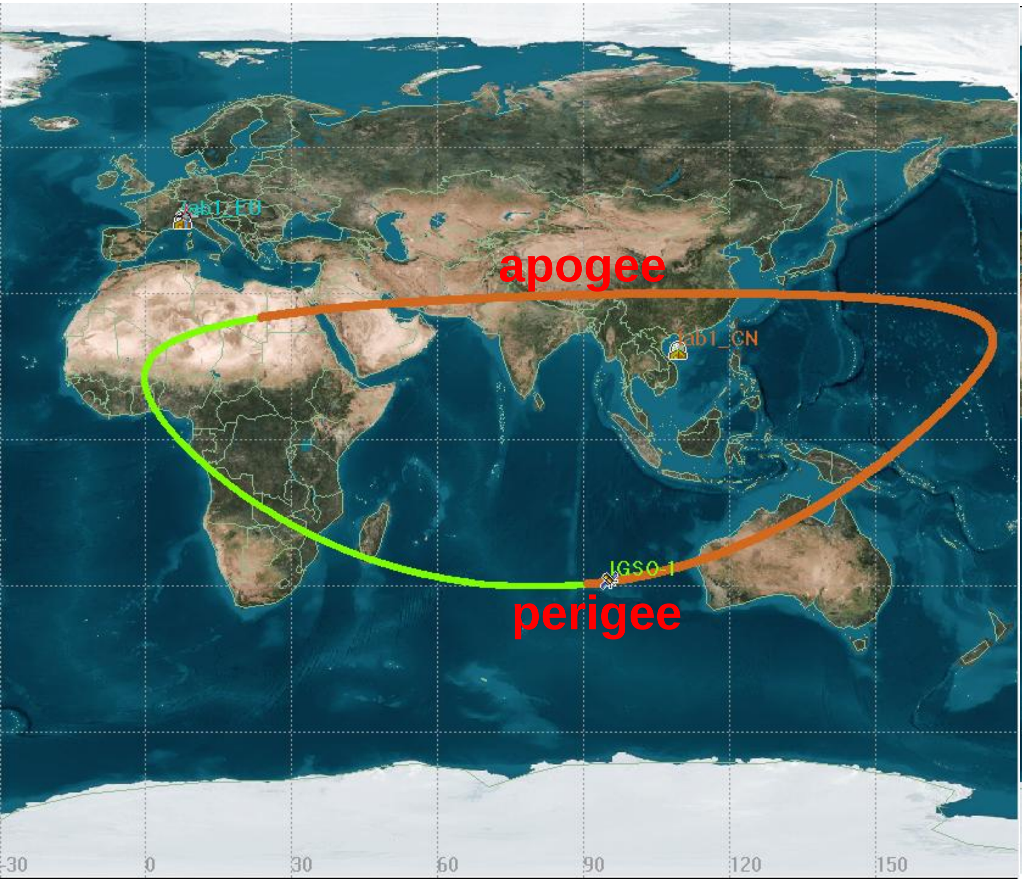


Orbit design and analysis

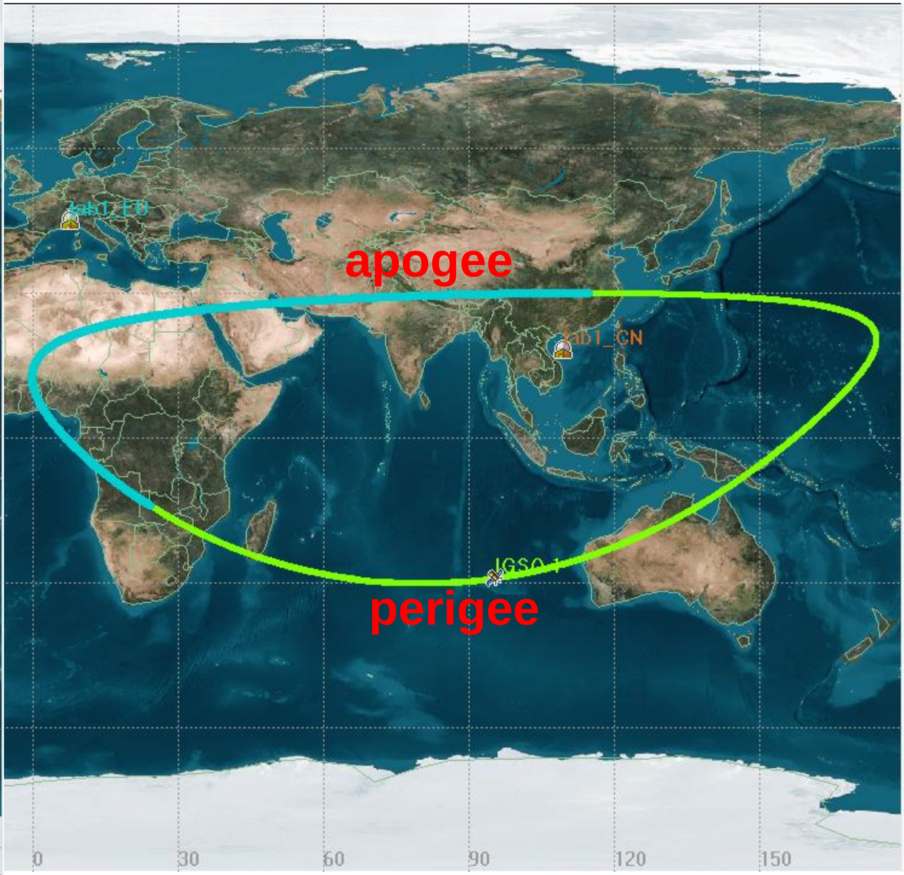
National Space Science Center, CAS

Visibility analysis for the orbit (scenario A)

Station (CN)



Station (EU)



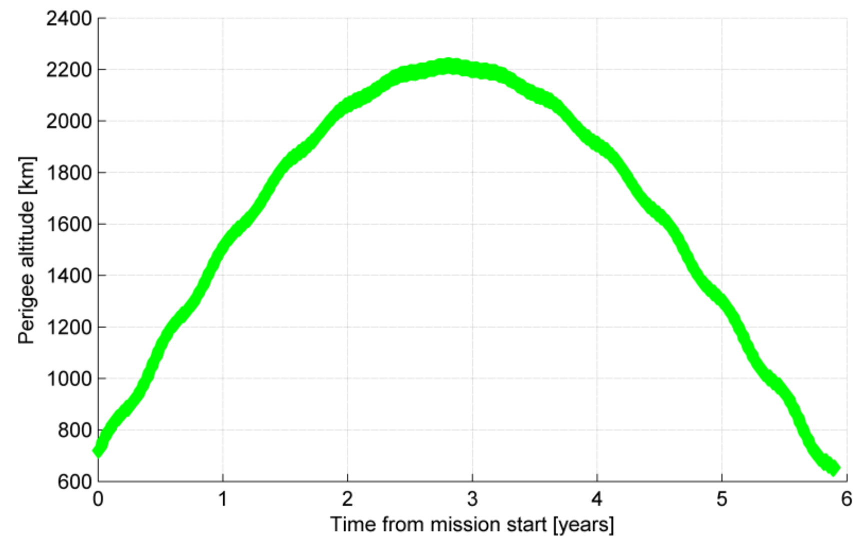
Orbit design and analysis Scenario B

Oribt Parameters (STE-QUEST)

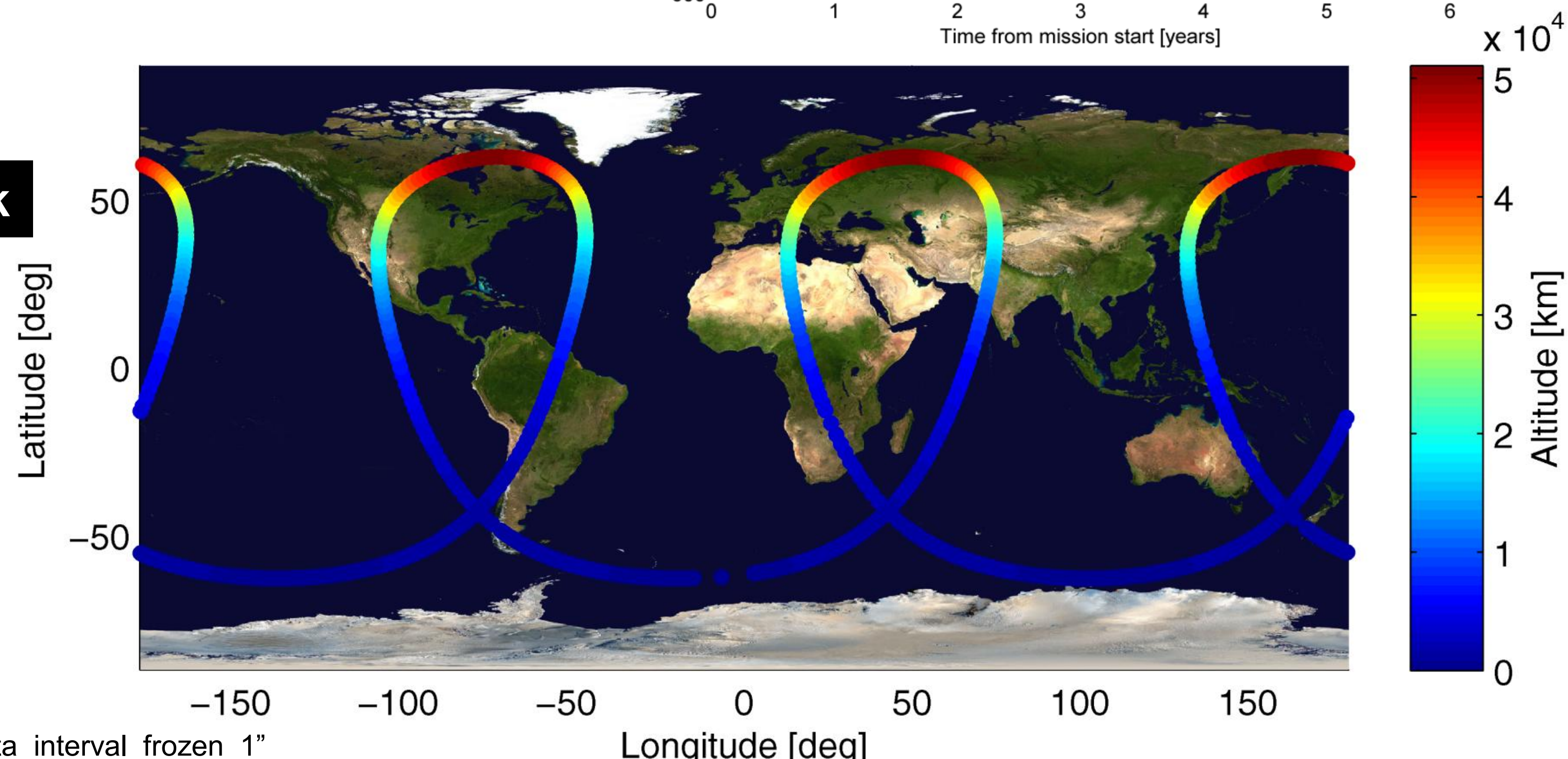
Period:	16 hours:
SMA:	32203.7 km
Eccentricity:	0.7802
Apogee Altitude:	~51000 km
Perigee Altitude:	~700 km
Inclination:	63.43 deg, argument of perigee: 342 deg
RAAN	0 deg, True Anomaly: 0 deg
Repeat pattern:	48 hours (3 orbits)
Maximum eclipse duration	3 hours

Orbit design and analysis **Scenario B**

Highly elliiptic, frozen orbit:
ground track is constant
- Period: 16 h
- Perigee altitude varies as fct. of time
- Apogee altitude: 51 000 km



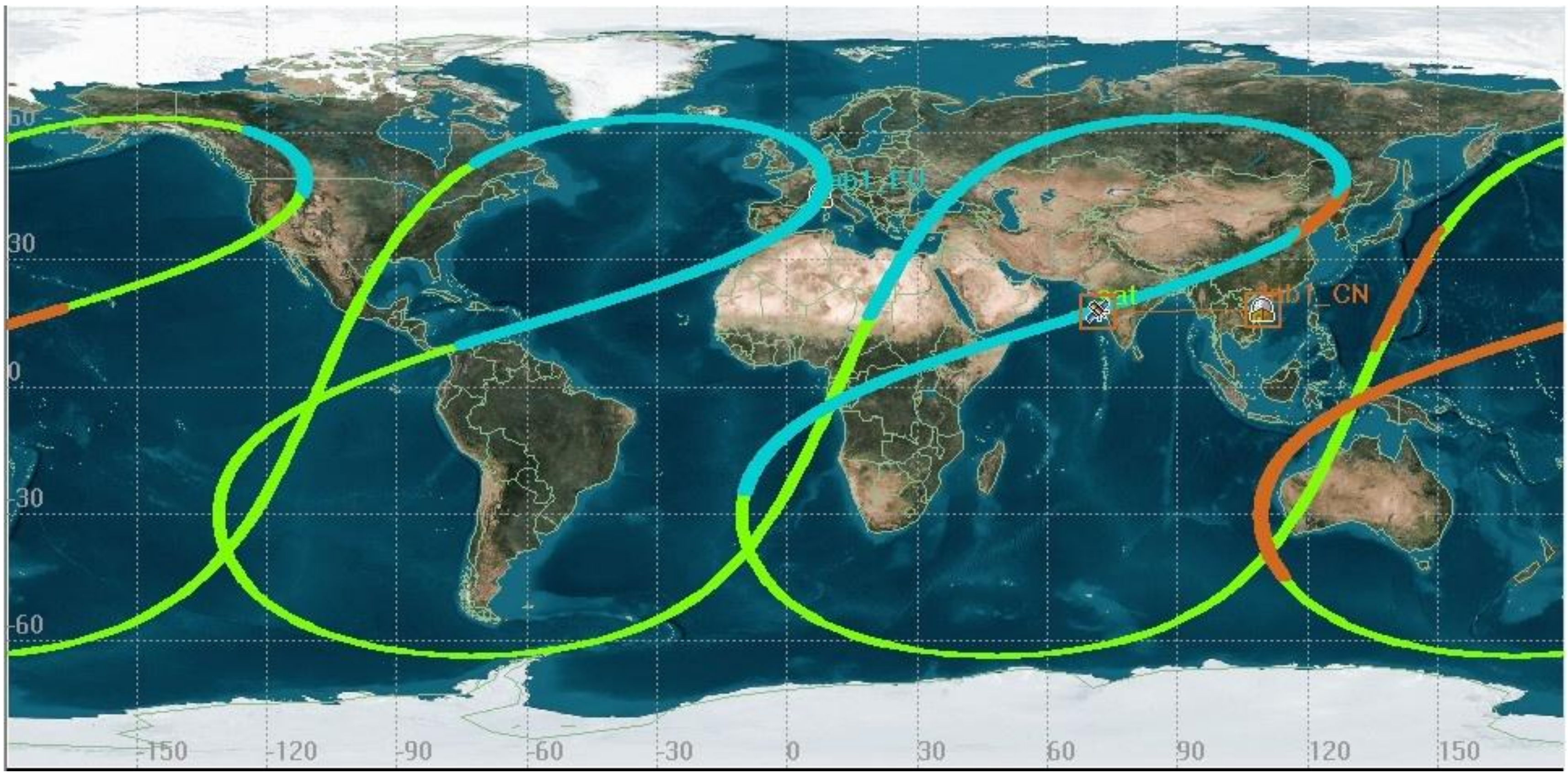
Ground track



"STE_QUEST_elev_data_interval_frozen_1"

Orbit design and analysis Scenario B

Visibility analysis for the orbit



Red: visible from China ground station
Blue: visible from EU ground station

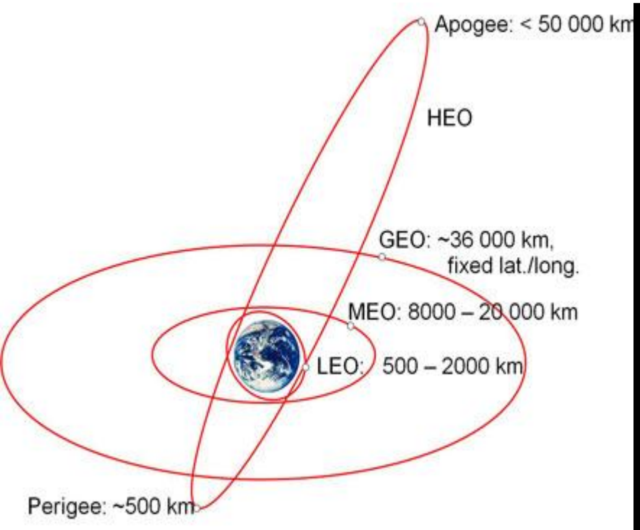
Orbit design and analysis

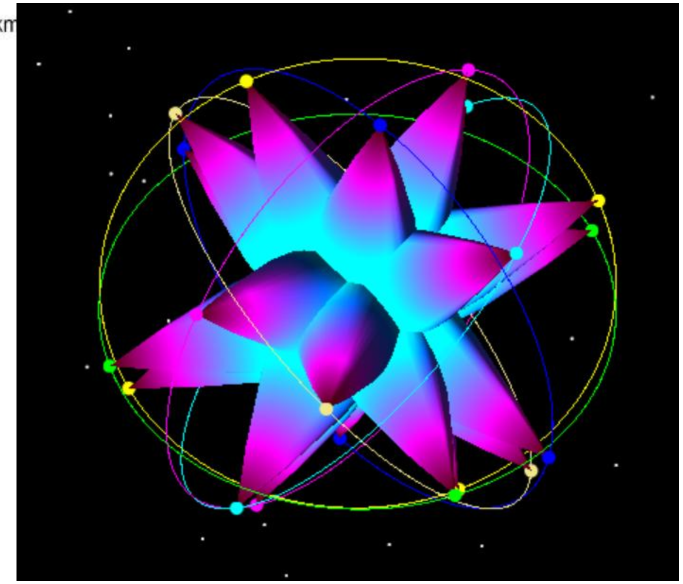
National Space Science Center, CAS

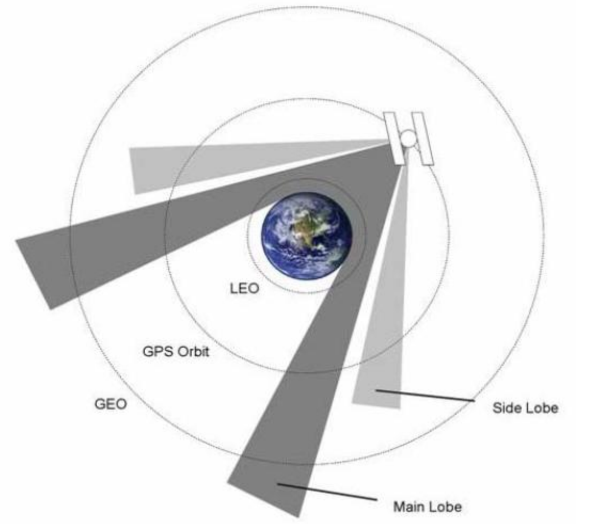
Orbit Determination Methods

Method 1: based on on-board GNSS receiver

- Orbit accuracy: ≤ 2m, 0.2 mm/s
- Orbit estimation algorithm: filter/least squares







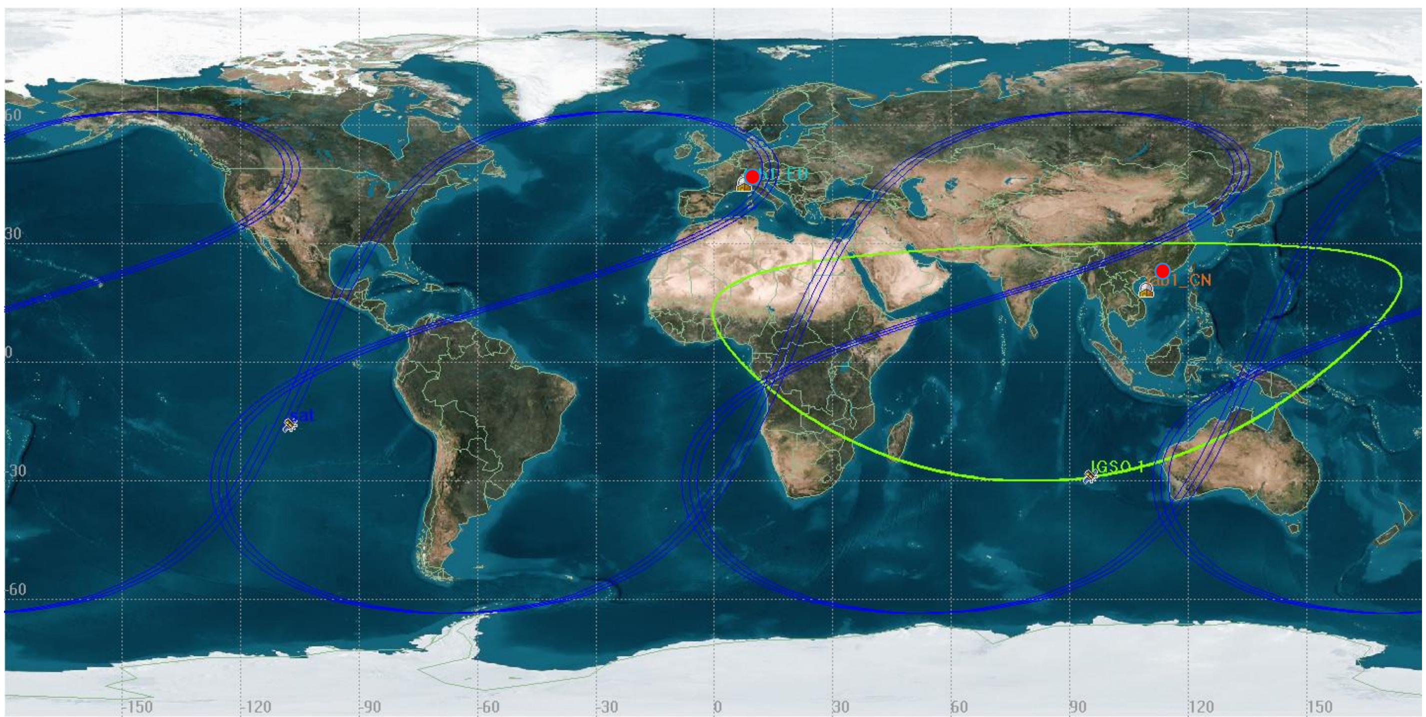
Science ground stations and clocks

National Space Science Center, CAS

4+ ground tracking stations (MWL, Ka/Ku)

- Stationary Stations (2 or more): Hainan (China), 1 (EU)
- Mobile Stations (2 or more): Vehicle mounted, 1 (China), 1+ (EU)

Support orbit determination: ≤ 0.5 cm (post-processing)
Support time comparison: ≤ 50 ps



Science ground stations and clocks: H-masers

Maser clocks in ground stations

Stationary Station (used for time comparison)

- hydrogen masers: 3
- instability(ADEV): 5E-16/day

Mobile Station

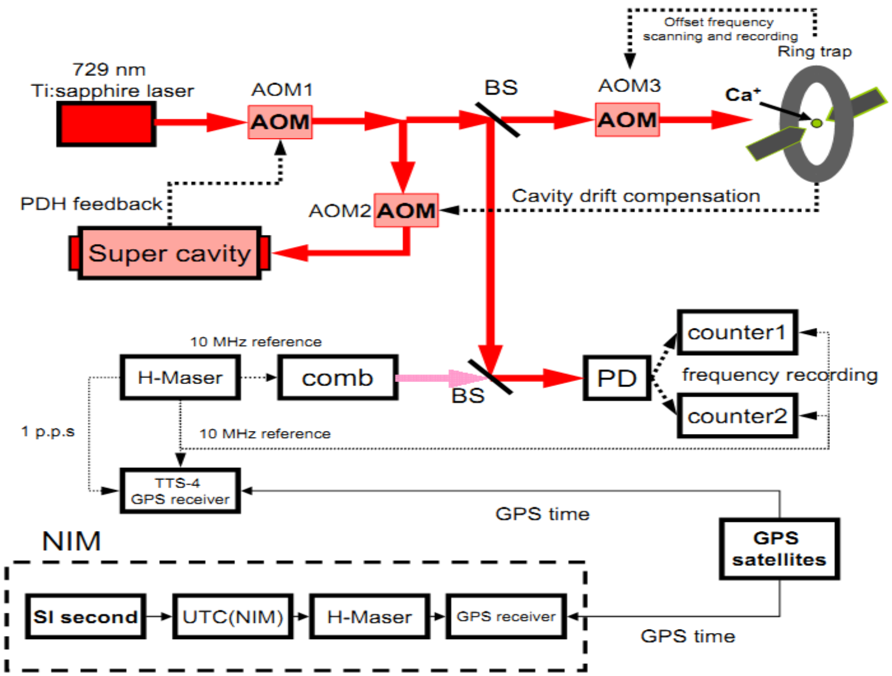
- hydrogen masers: 2
- instability(ADEV): 5E-15/day
- fiber link to the adjacent lab

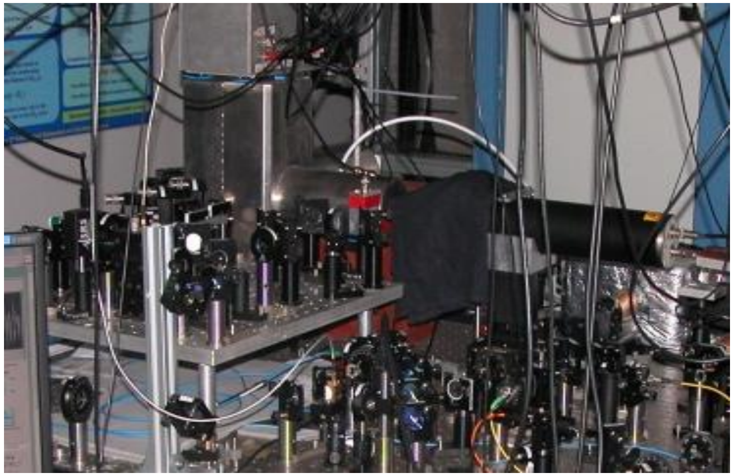
Shanghai Astronomical Observatory, CAS

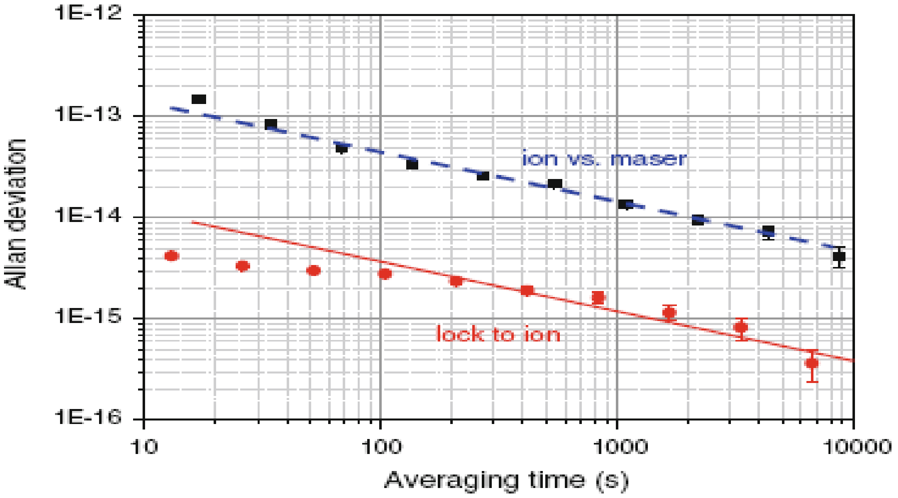
Science ground stations and clocks: optical

The optical frequency standard based on single ion $^{40}Ca^+$

Started: 2004
Current status: closed loop lock
stability 3×10^{-16} @10000s
Objective: final uncertainty: 10^{-17}~10^{-18}







Wuhan institute of Physics and Mathematics, CAS

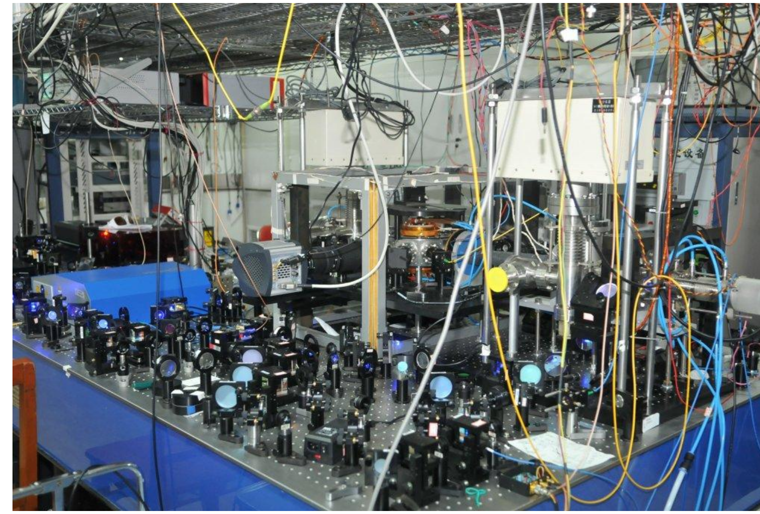
Science ground stations and clocks: optical

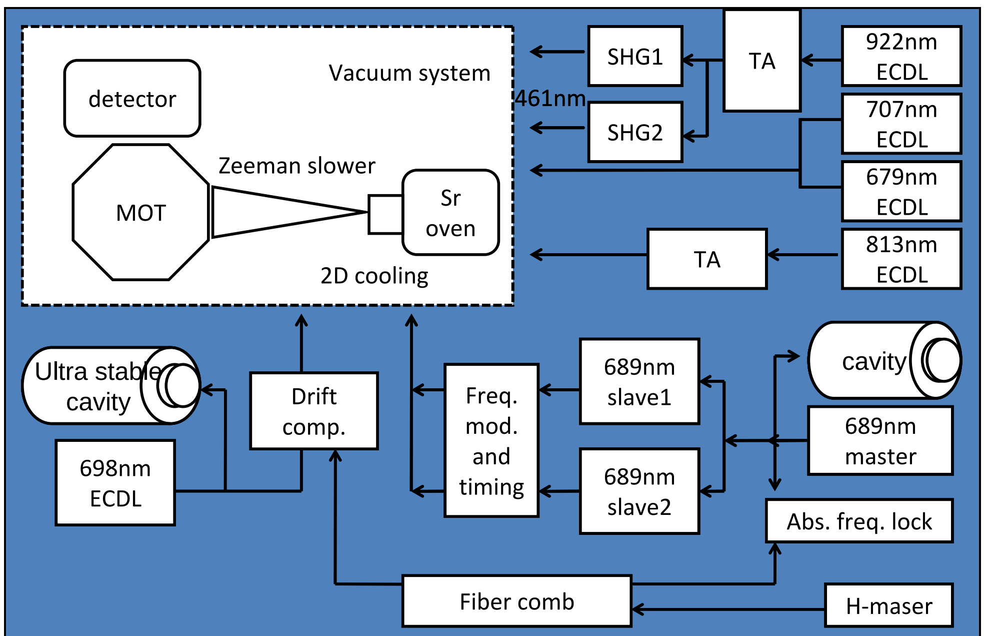
Sr optical lattice clock

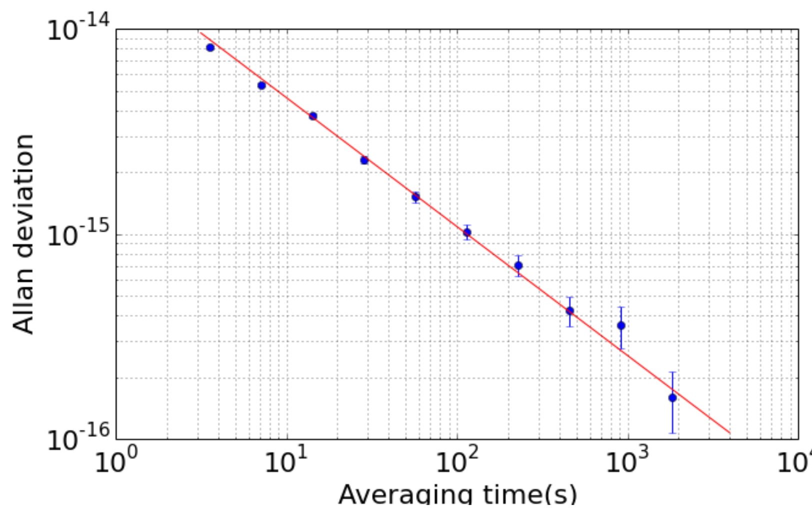
- Started: 2007
- Current status: closed loop lock

  stability 1.6×10^{-16} at 2000 s
- Objective: first evaluation in 2015

  final uncertainty: 10^{-17}- 10^{-18}







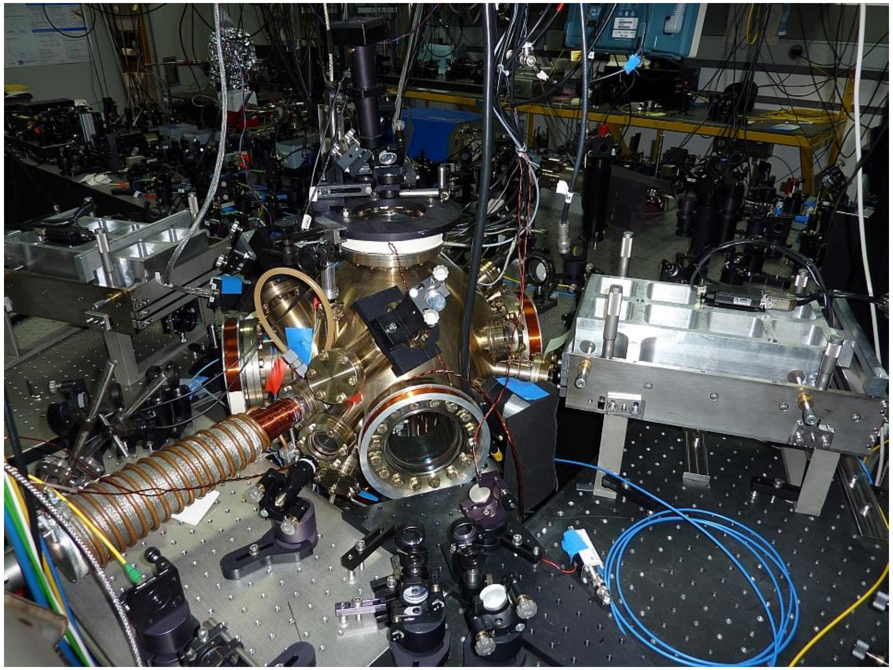
National Institute of Metrology

Science ground stations and clocks: optical

PTB Sr lattice clock

instability 4.5 x $10^{-16}/\tau^{1/2}$

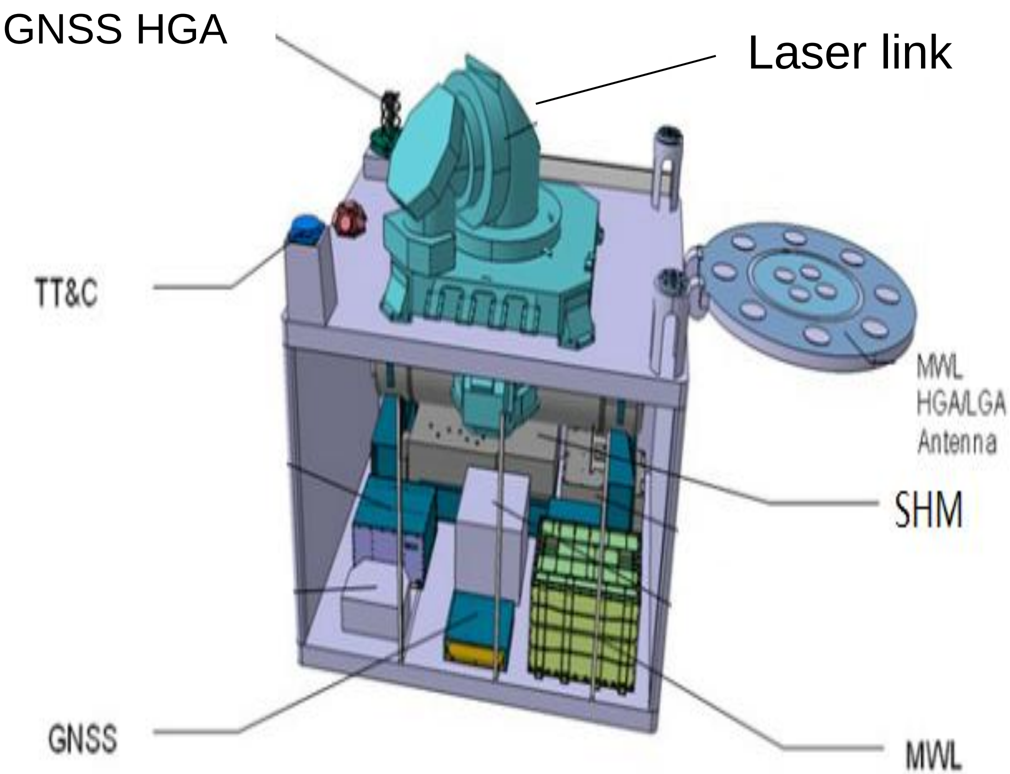
Inaccuracy currently at
1 x 10^{-17} level



- Several other optical clocks: SYRTE (F), NPL (UK), INRIM (I), ….
- More optical clocks under development in China (HUST, Wuhan)
- **Transportable** optical clocks: SOC consortium (ESA), PTB, U. Düsseldorf

Payload

Schematic of the payload module



<u>Measurement scenario:</u>

Alternating: SHM + laser link

MWL for ground clock compar.

<u>Payload mass:</u>

44 + 10 + 20 + 2 = 76 kg

<u>Payload power:</u> < 80 W;

<u>Mission duration:</u> 2-3 years

Summary

Gravitational Red-Shifts Tests:

Earth gravitational red-shift: to a fractional frequency uncertainty of 2×10^{-6} (comparable to ACES)

Sun gravitational red-shift: to a fractional uncertainty of 2×10^{-6} (today: up to few % uncertainty level)

Moon gravitational red-shift: to a fractional uncertainty of 4×10^{-4} (no measurement done so far)

World-wide comparison of atomic clocks ($\rightarrow$ redefinition of the second)
Test of time-independence of the fundamental constants

Legacy science:
Reference frame accuracy improvements,
geodesy (determination of the geopotential) etc..

Payload: hydrogen maser TRL 7 by 2015
MWL: TRL 6 by 2016

Team members and supporters

European team members:

Philippe Jetzer (Co-PI): Department of Physics, University of Zürich, Switzerland

Stephan Schiller: Institut für Experimentalphysik, Heinrich-Heine-Universität, Düsseldorf, Germany

Philip Tuckey: SYRTE, Observatoire de Paris, France

Qinghua Wang: Orolia Switzerland SA (Spectratime), Switzerland

University of Zurich UZH

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

l'Observatoire de Paris — SYRTE

spectratime

Supporters:

Michael Tobar (AU), Eberhard Gill (NL), Jay Tasson (US), Markus Rothacher (CH), Drazen Svehla (D), Carlos Sopuerta (ES), Steve Lecomte (CH), Setnam Shemar (UK) …..

The University of Western Australia

TU Delft — Delft University of Technology

Carleton College

ETH — Eidgenössische Technische Hochschule Zürich — Swiss Federal Institute of Technology Zurich

esa ESOC

CSIC

csem — centre suisse d'électronique et de microtechnique

NPL — National Physical Laboratory

Team members and supporters

Chinese team members:

Han Chunhao(Co-PI): BSNC, Beijing Satellite Navigation Center

Su Jianfeng: National Space Science Center, CAS

Wang Yiqiu: Peking University

Zhai Zaocheng: Shanghai Astronomical Observatory, CAS

Cai Zhiwu: Beijing Satellite Navigation Center

Huang Peicheng: Shanghai Astronomical Observatory, CAS

Gao Kelin: Wuhan institute of Physics and Mathematics, CAS

Fang Zhanjun: National Institute of Metrology

Shen Wenbing: Wuhan University

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Supporters:

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THANKS!

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