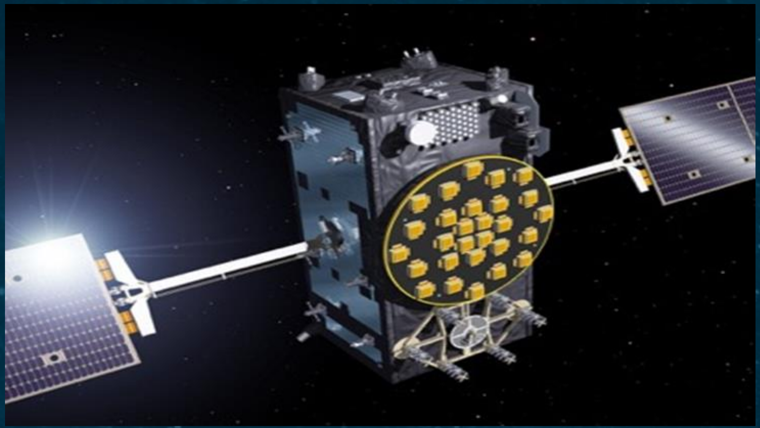
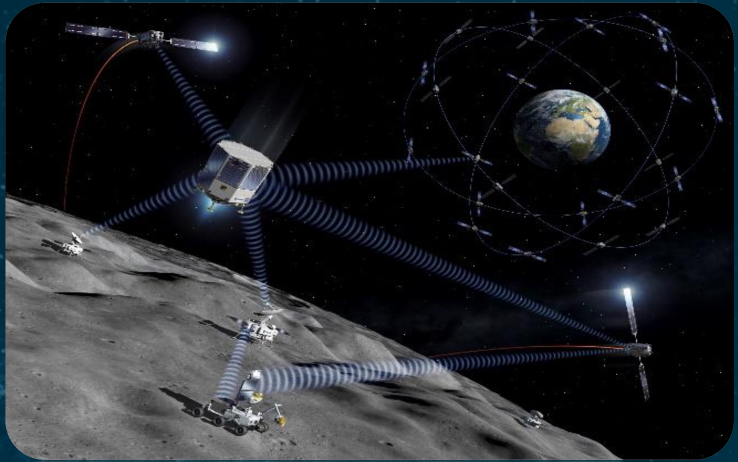
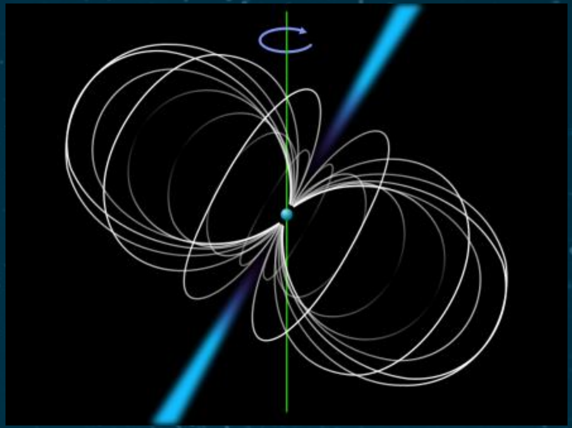






Time and Frequency Metrology in Space Missions

Javier Benedicto

ESA Director of Navigation

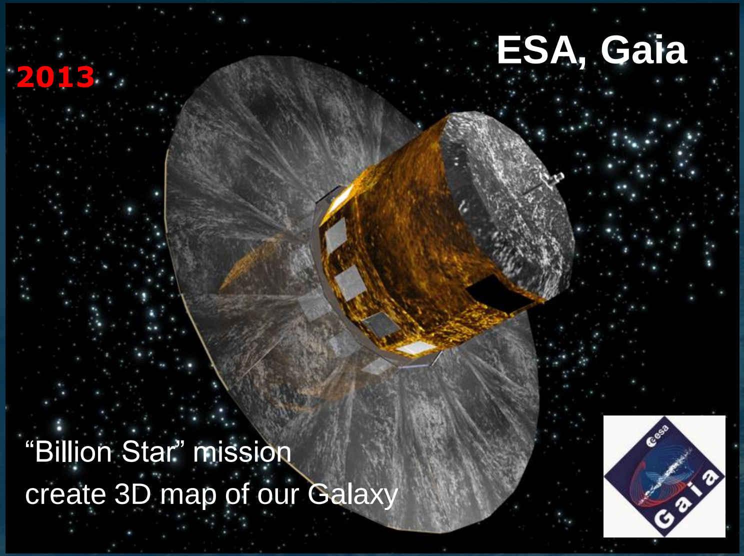
CGPM 2022

17 November 2022, Versailles

1) T/F Needs in Space Missions

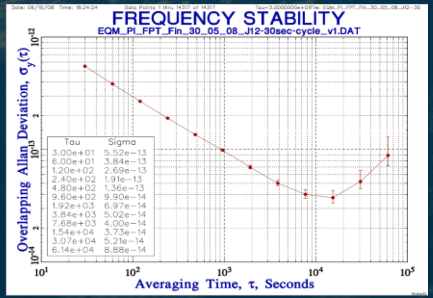
1) Frequency / Signal generation (stable, ultra-stable)
2) Time tagging (highly accurate to a reference)
3) High autonomy from Ground (i.e. Space Exploration)
4) High stability tailored to different needs
5) High level of synchronisation with a System Time or the international standard (UTC)
6) High robustness of the timing source (to particular space environment)

Space Missions (with high T/F relevance) Examples

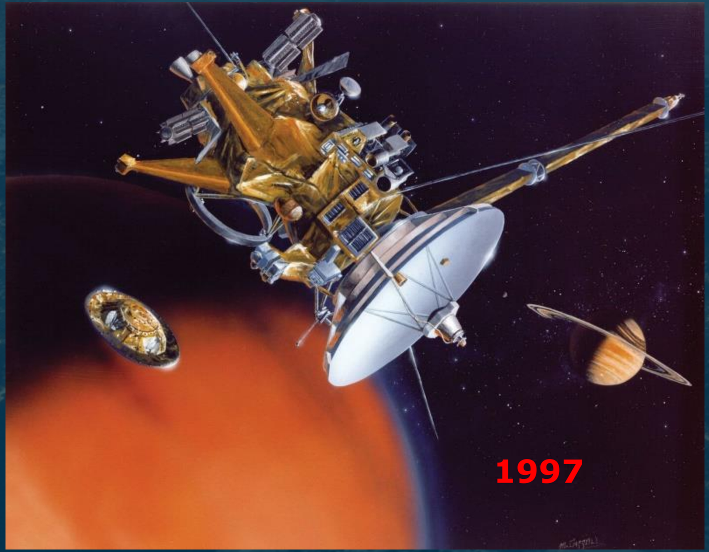


On-board time-tagging < 17ns over 6 hours (< 1e-12)

Rubidium (Rb) atomic clock



ESA, Cassini-Huygens

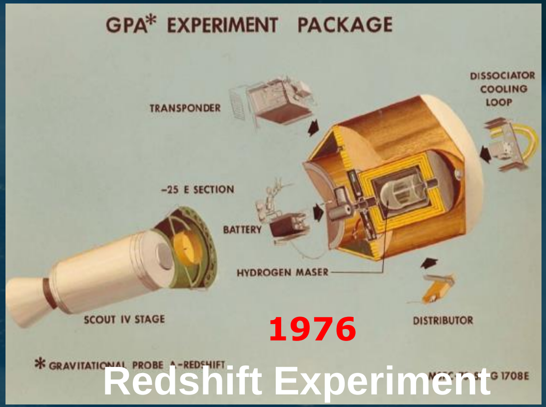


Doppler-Wind Experiment on Titan moon

Huygens probe's descent to the Titan surface on 14 January 2005

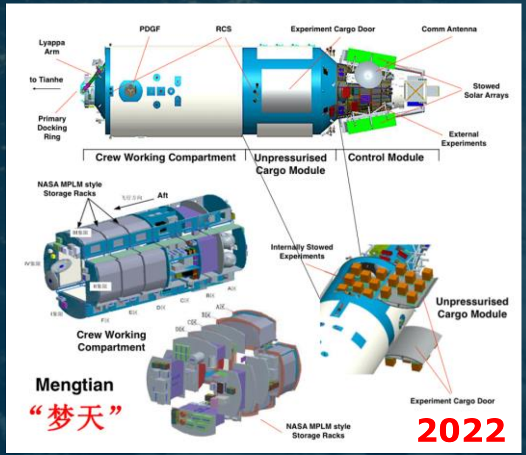
Rb-clock in Receiver
Rb-clock in Transmitter

USA, Gravity Probe-A



Hydrogen Maser

China, Mengtian

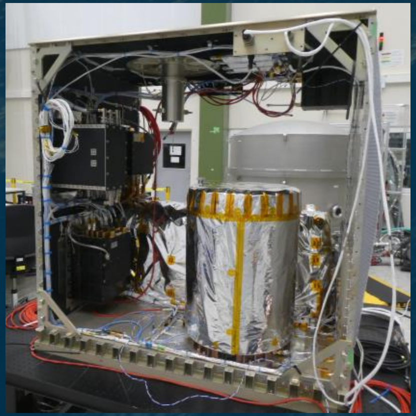


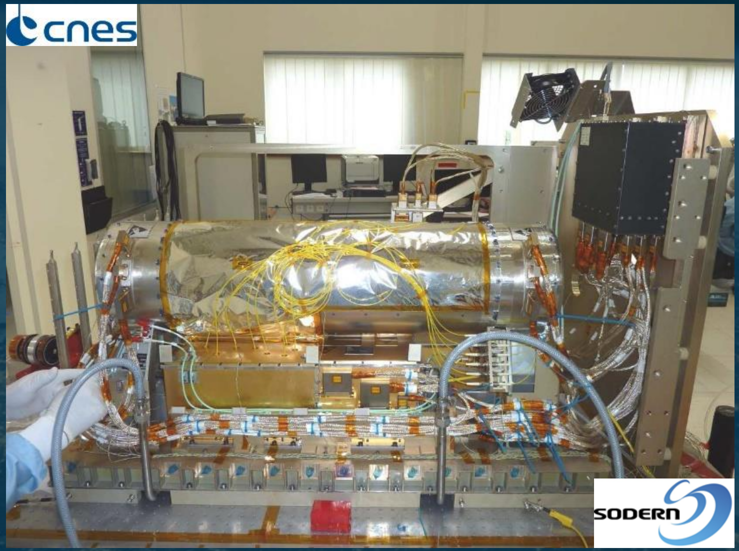
hydrogen + rubidium + optical clock

Space Missions (with high T/F relevance) Example: ACES

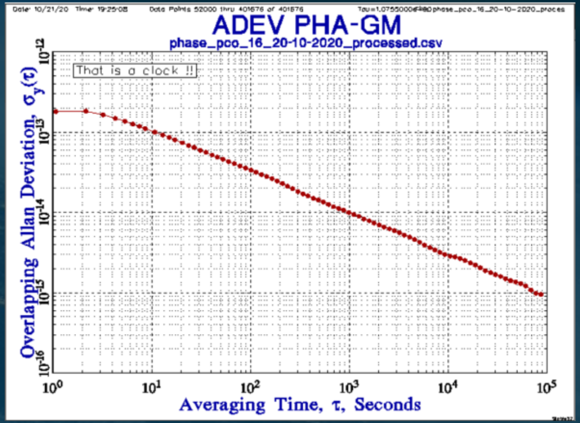
ESA - Atomic Clock Ensemble in Space (ACES)
(for Science - Relativity, Clock technology)

- **PHARAO (CNES):** Atomic clock based on laser cooled Cs atoms
- **SHM:** Active hydrogen maser
- **FCDP:** Clocks comparison and distribution
- **MWL:** T&F transfer link
- **GNSS receiver:** connected to the ACES frequency reference
- **ELT:** Optical link
- **Support subsystems**
  - XPLC: External PL computer
  - PDU: Power distribution unit,
  - Mechanical, thermal subsystems
  - CEPA: Columbus External PL Adapter





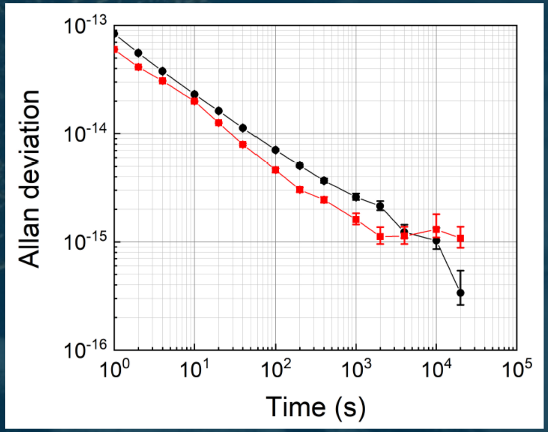
PHARAO



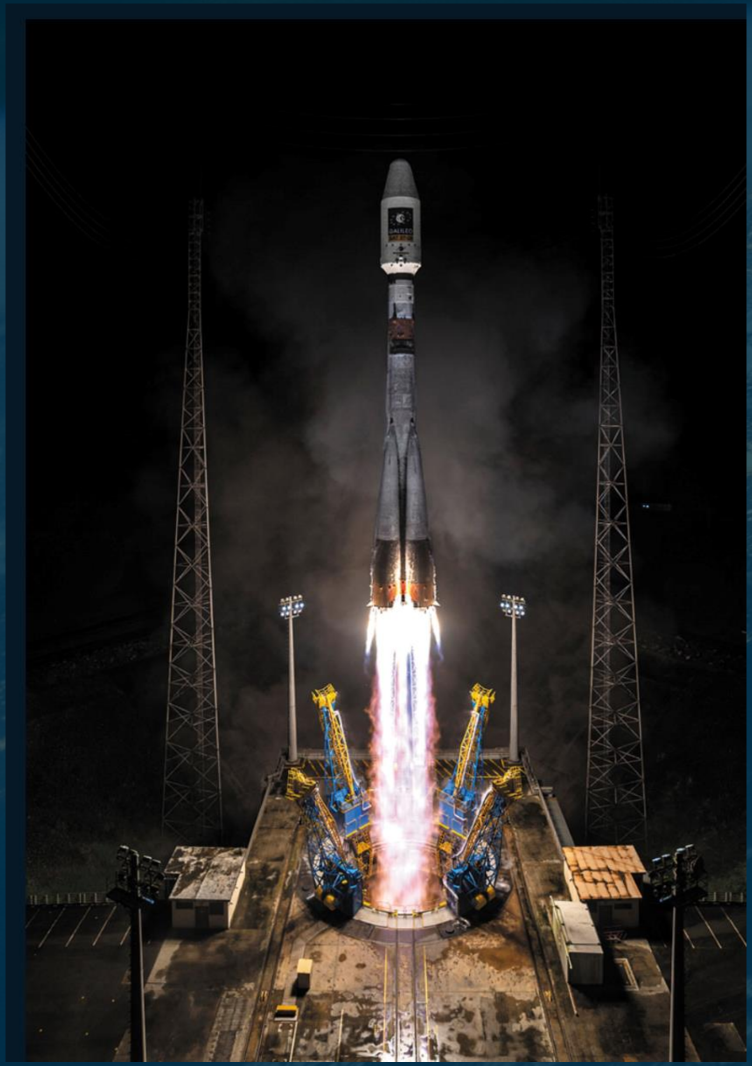
ACES Integrated System Tests

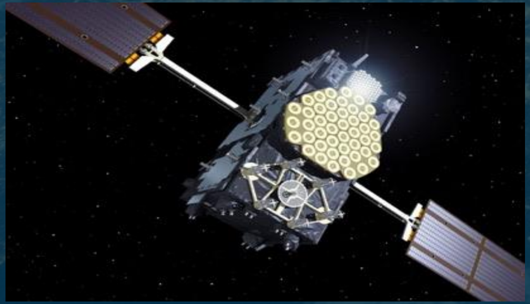
Launch planned 2025

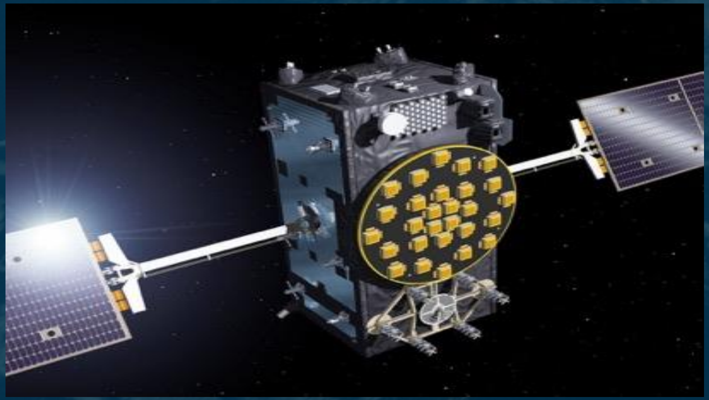
SHM

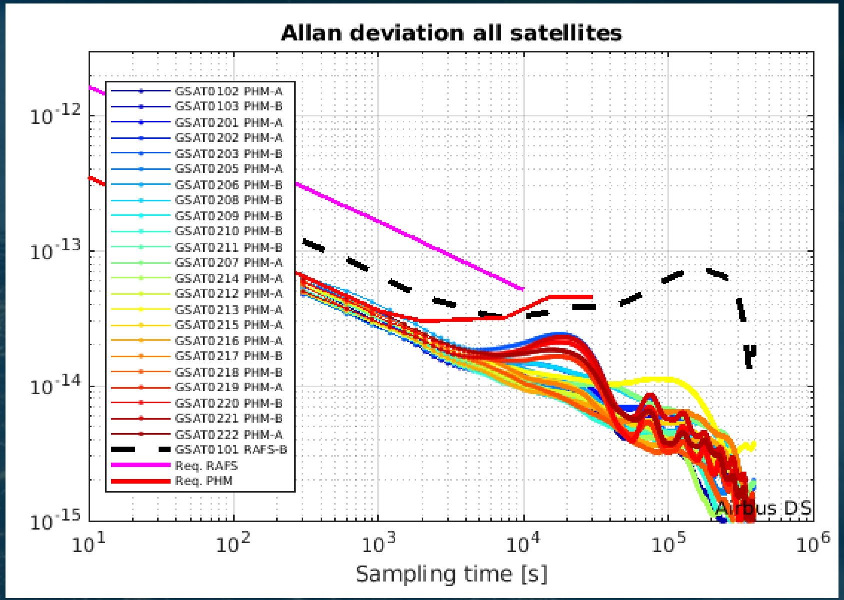


Example: GALILEO – the EU GNSS

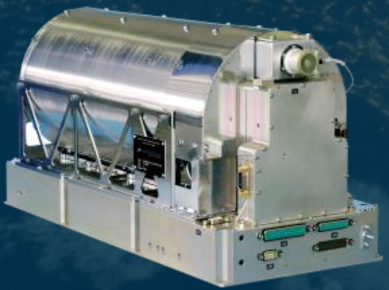


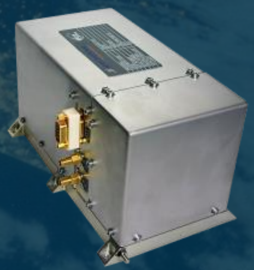




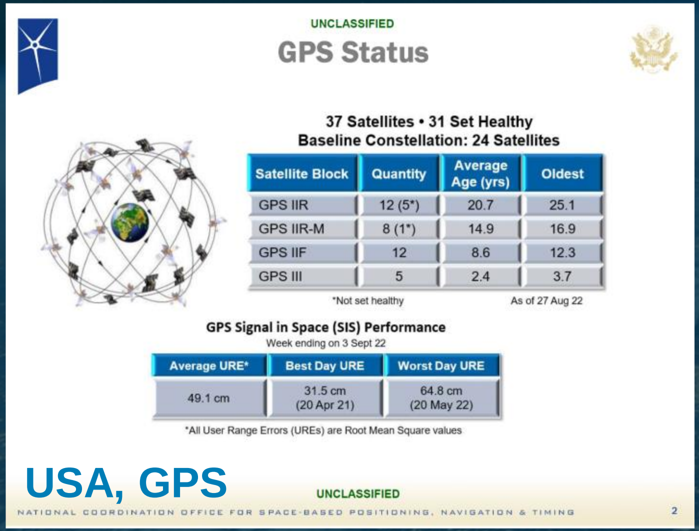


Embarked Clocks:
Rubidium Atomic Frequency Standard
Passive Hydrogen Maser



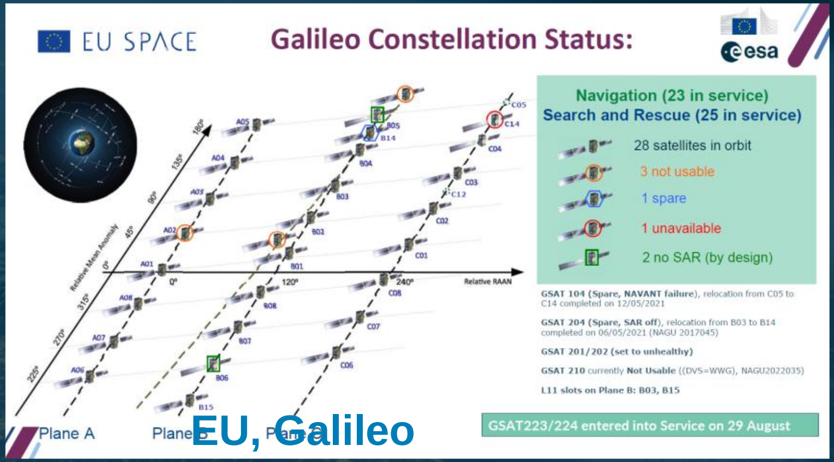


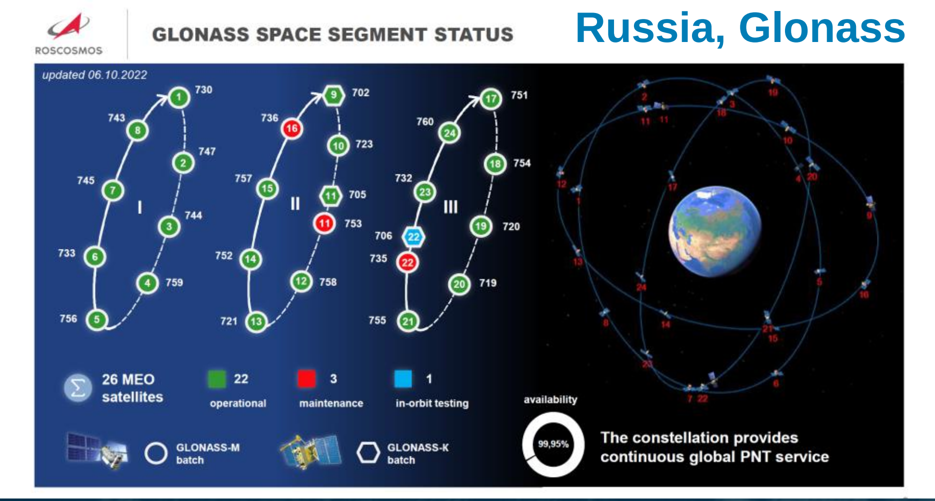
2) Global Satellite Navigation Systems (GNSS) and Time

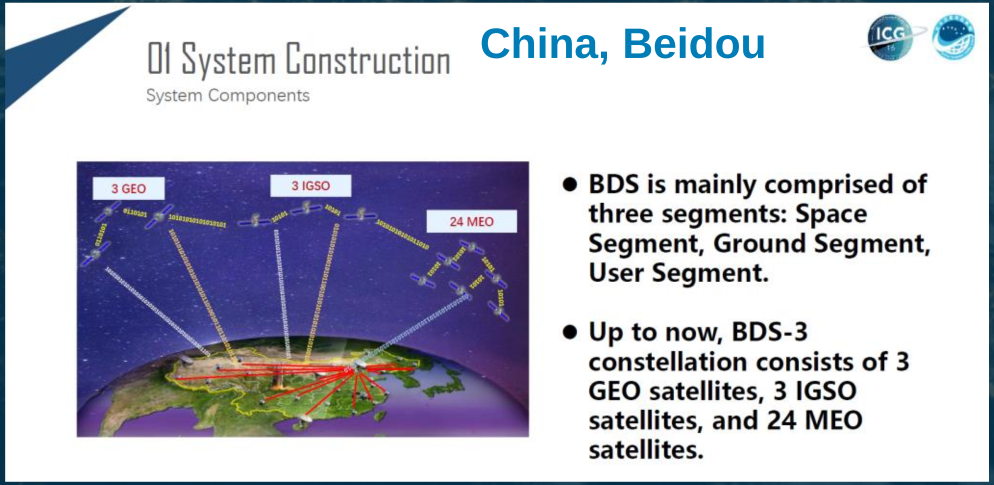


Satellite Block	Quantity	Average Age (yrs)	Oldest
GPS IIR	12 (5*)	20.7	25.1
GPS IIR-M	8 (1*)	14.9	16.9
GPS IIF	12	8.6	12.3
GPS III	5	2.4	3.7

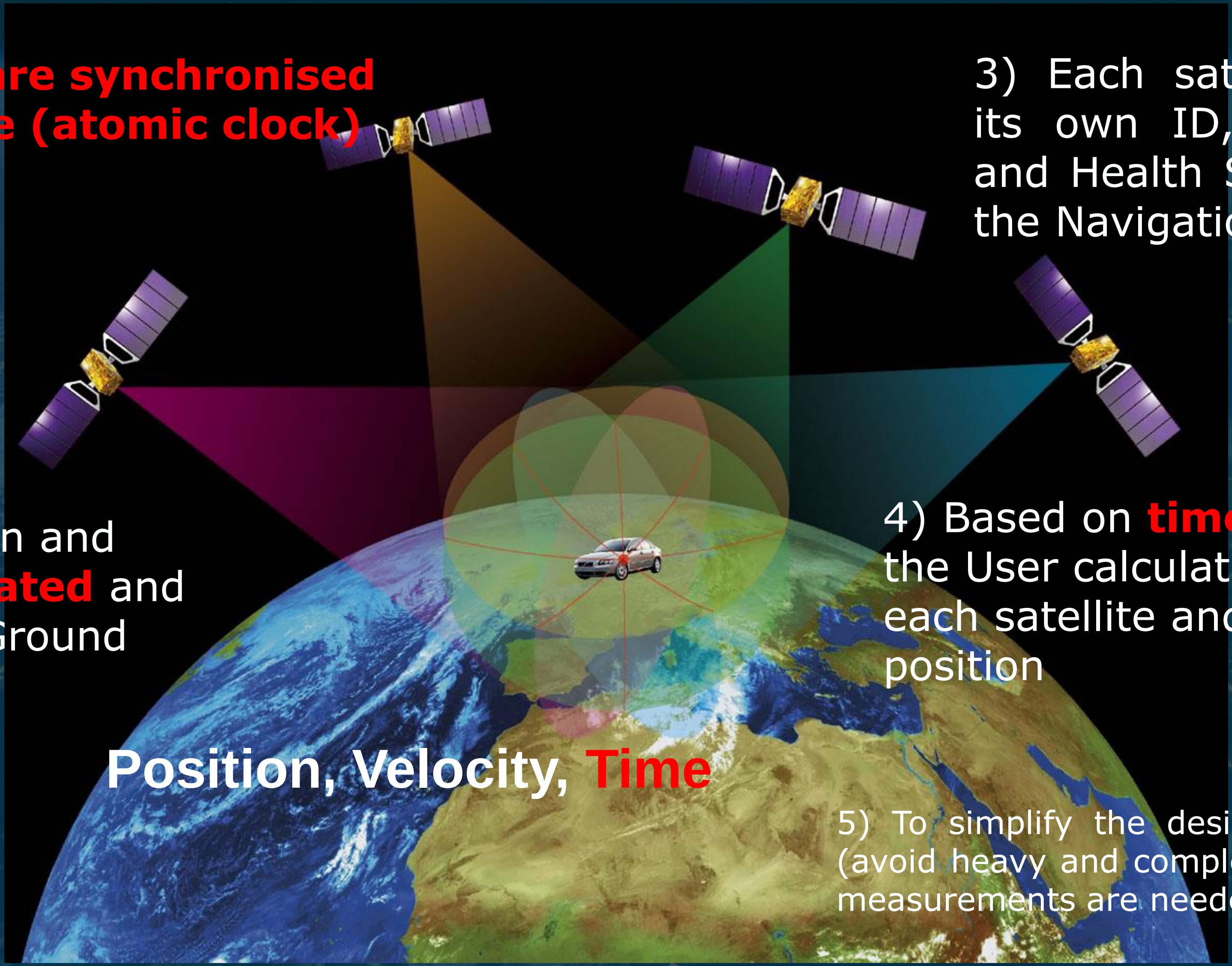
Average URE*	Best Day URE	Worst Day URE
49.1 cm	31.5 cm (20 Apr 21)	64.8 cm (20 May 22)







How does it work? It's all about Time!



1) All satellites are synchronised to a System Time (atomic clock)

2) Satellite Position and **Clock are estimated** and predicted by the Ground Mission Segment

3) Each satellite **transmits** its own ID, Position, **Time** and Health Status as part of the Navigation Message

4) Based on **time measurements** the User calculates the distance to each satellite and then its own position

Position, Velocity, Time

5) To simplify the design of the User Equipment (avoid heavy and complex atomic clocks) at least 4 measurements are needed

GNSS – Needs

1) Each GNSS - its own autonomous, real-time System time for System operations
2) Offset between different System times for user interoperability
3) Difference versus UTC for Time Service
4) Link to Earth based a Reference System with high accuracy and as such the offset UT1-UTC

Specific information is published in Signal-in-Space ICD and Service documentation

Example: Galileo Public SIS ICD

OS Issue 2.0

www.gsc-europa.eu

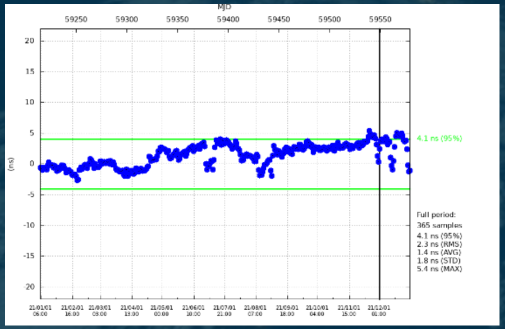
How a user can get the prediction of UTC broadcast by Galileo and how a user can use together GPS and Galileo by knowing the offset GGTO:

The Signal-in-Space ICD includes

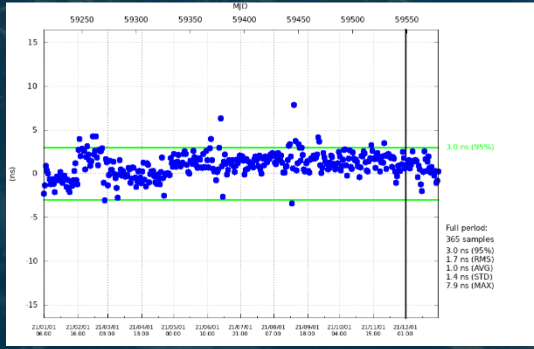
- GST-UTC Conversion Algorithm and Parameters
- GPS to Galileo System Time Conversion and Parameters

Parameter	Definition	Bits	Scale factor	Unit
A_0	Constant term of polynomial	32*	2^{-30}	s
A_1	1st order term of polynomial	24*	2^{-50}	s/s
Δt_{LS}	Leap Second count before leap second adjustment	8*	1	s
t_{0t}	UTC data reference Time of Week	8	3600	s
WN_{0t}	UTC data reference Week Number	8	1	week
WN_{LSF}	Week Number of leap second adjustment	8	1	week
DN	Day Number at the end of which a leap second adjustment becomes effective	3**	1	day
Δt_{LSF}	Leap Second count after leap second adjustment	8*	1	s
	Total GST-UTC Conversion Size	99		

Parameter	Definition	Bits	Scale factor	Unit
A_{0G}	Constant term of the polynomial describing the offset $\Delta t_{systems}$	16*	2^{-35}	s
A_{1G}	Rate of change of the offset $\Delta t_{systems}$	12*	2^{-51}	s/s
t_{0G}	Reference time for GGTO data	8	3600	s
WN_{0G}	Week Number of GGTO reference	6	1	week
	Total GST-GPS Conversion Size	42		



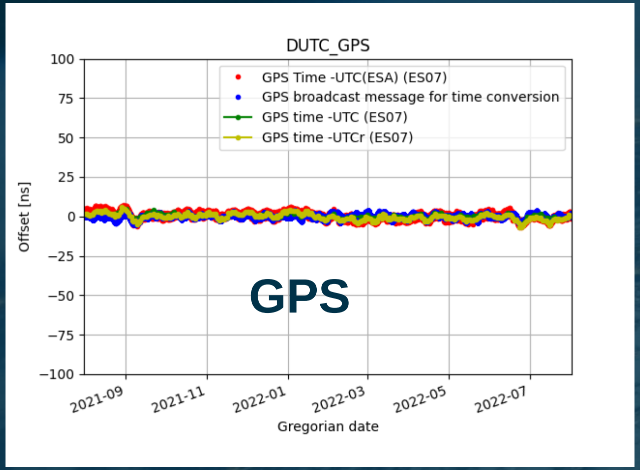
Broadcast UTC Offset

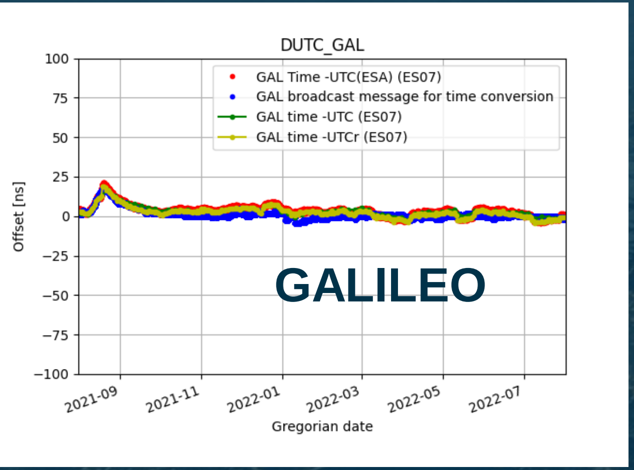


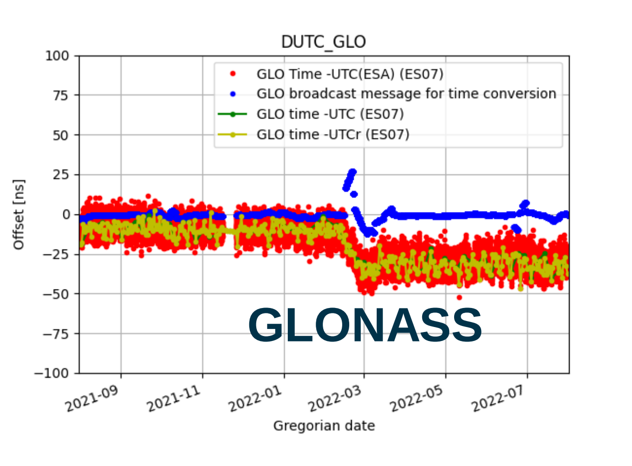
GGTO accuracy

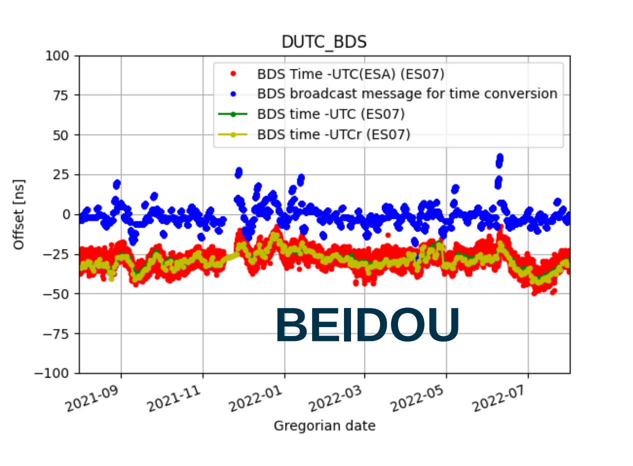
Multi-GNSS Time Monitoring (ESA-ESTEC)

GNSSTime – UTC (modulo 1sec), Aug-2021 to Aug-2022

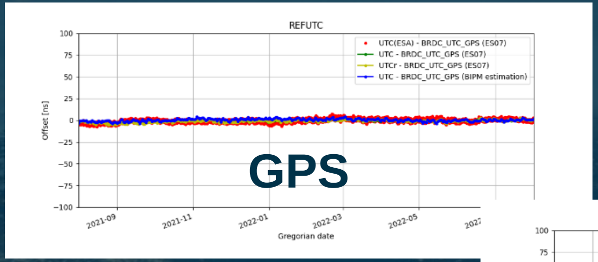


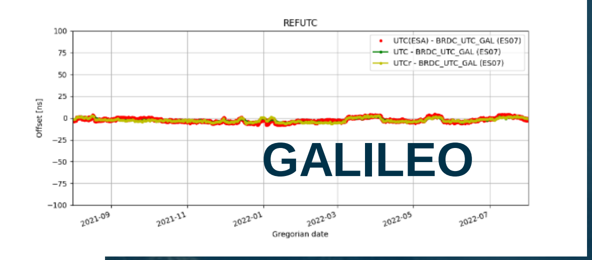


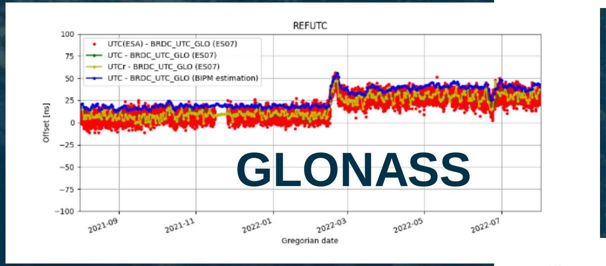


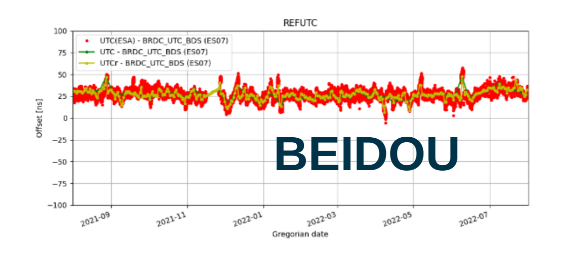


UTC – BrdcUTC, Aug-2021 to Aug-2022





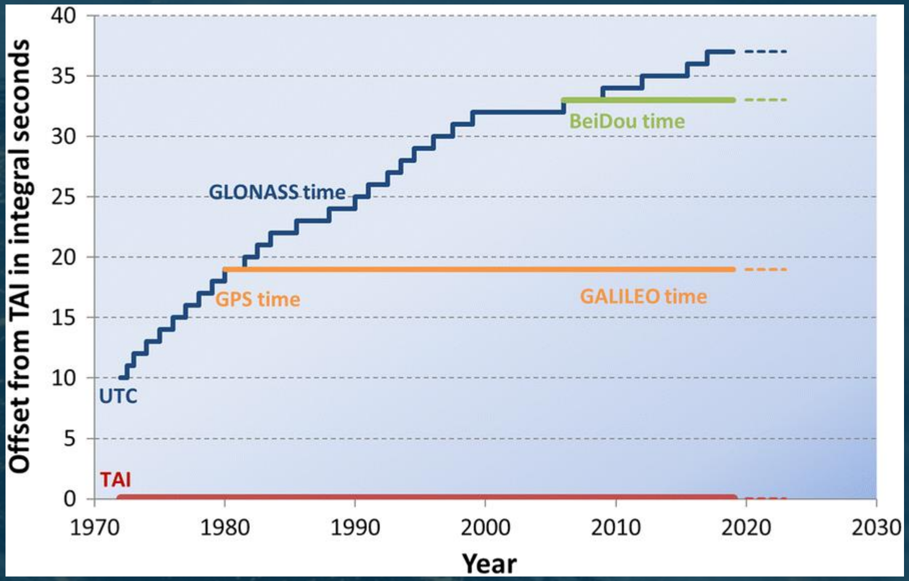




GNSS – “Time” could be so easy, but…

- ❑ **UTC is recognized** as international standard, but
  - ❑ Systems operations require a **continuous real-time time scale** to avoid any risk of failure
  - ❑ The synchronization to UTC is achieved “**modulo 1 second**” (except GLONASS)
  - ❑ The varying number of **Leap Seconds** to get UTC is **broadcast** to the users

- ❑ Nevertheless, each Leap Second introduction **can cause interruptions** in the Systems operations and user receiver, e.g.
  - ❑ GNSS core operations are based on GNSS System times, some operations are based on UTC
  - ❑ some users receivers do not correctly handle the Leap Seconds



P. Tavella, G. Petit, Precise time scales and navigation systems: mutual benefits of timekeeping and positioning, 16 Mar 2020

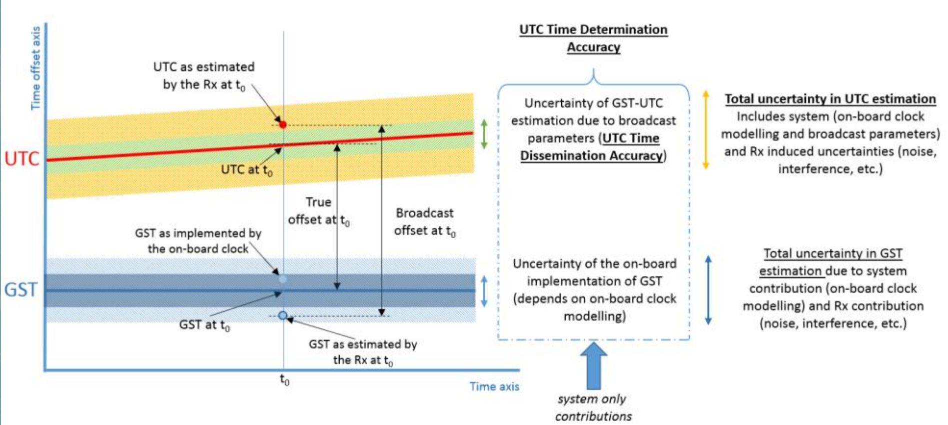
GNSS – “Time” could be so easy, but…(cont’d)

- ❑ Each GNSS system time has a different tagging of the seconds and a different offset versus UTC, changing at any Leap Second (except GLONASS). This create **risk for the interoperability and confusion** to the users

- ❑ Some **user** application
  - ❑ take **directly a System Time** (e.g. GPS) as reference for time tagging (since it is continuous vs UTC).
  - ❑ providers create their **own time reference**

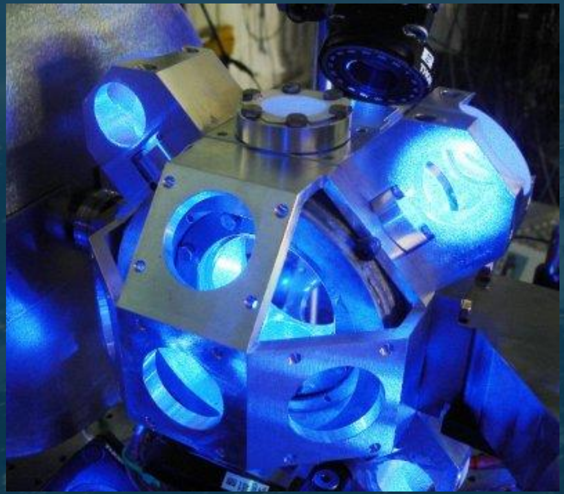
- ❑ GNSS operation, interoperability , and Time Service to the users **could be “so easy” without Leap Seconds**

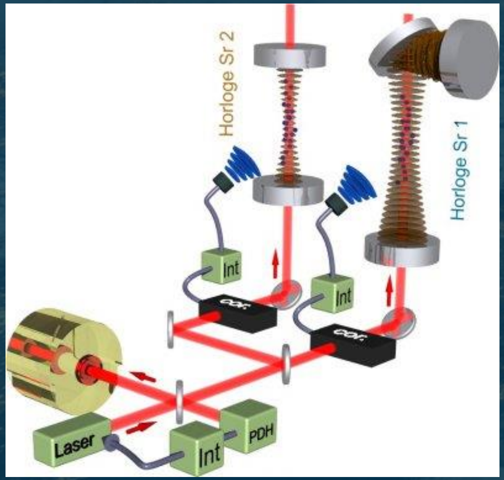
- ❑ The possibility of the first **negative Leap Second** causes concerns since it was never tested



Ref. Galileo Open Service Definition Document, Version 1.2

3) Future Clocks





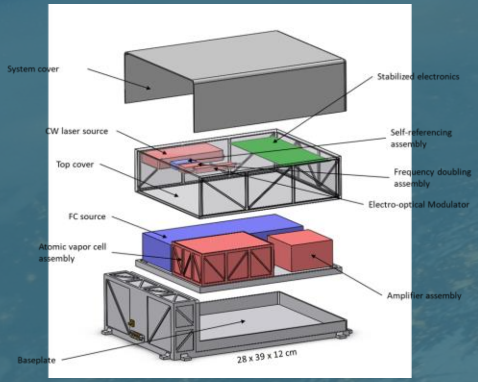
Strontium optical atomic clock
© Observatoire de Paris / SYRTE

NASA Deep Space Atomic Clock (DSAC)

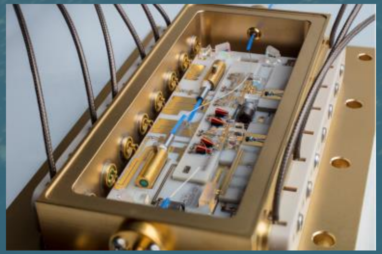
Better Clocks can contribute to better GNSS Accuracy

On-board Clocks candidates for Galileo Evolutions

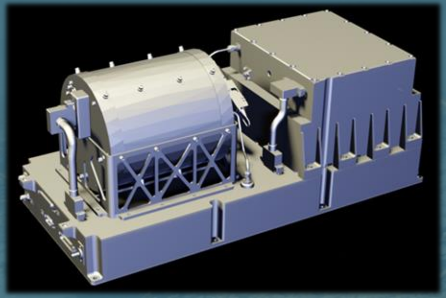
Rb Two Photons Optical Clock (CSEM)



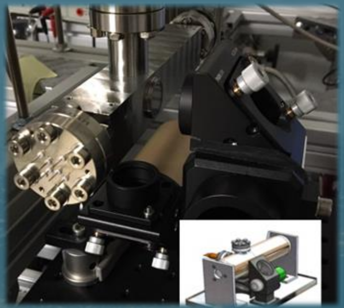
Iodine Optical Clock (SpaceTech)



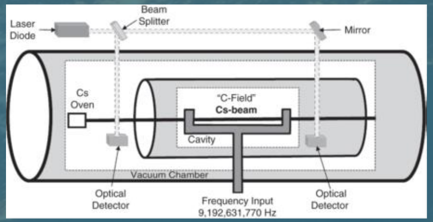
Rb Pulsed Optical Pumped Clock (Leonardo)



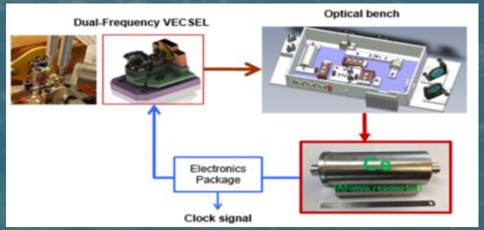
Mercury Ion Clock (Orolia)



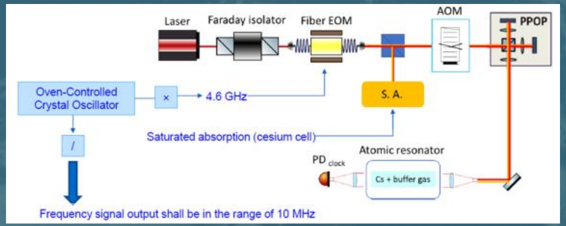
Optically Pumped Cs Clock (Tesat)

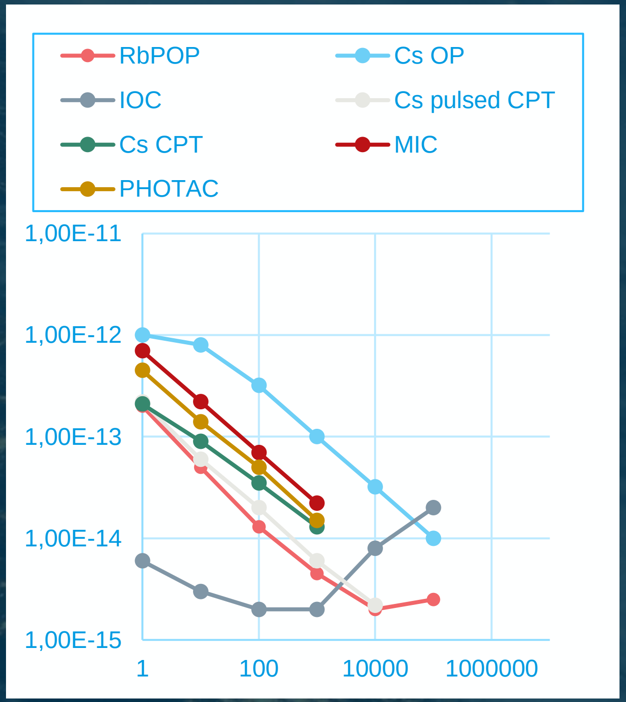


Cs Coherent Populated Trapped Clock (TAS-CH)



Cs Coherent Populated Trapped Pulsed Clock (Sodern)

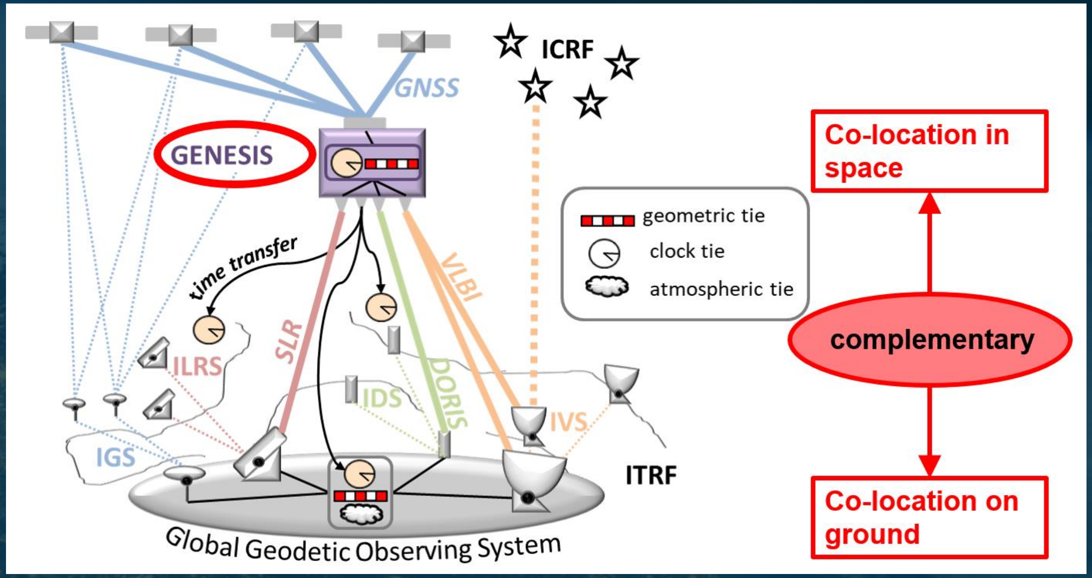




4) What's next?

GENESIS – ESA proposal

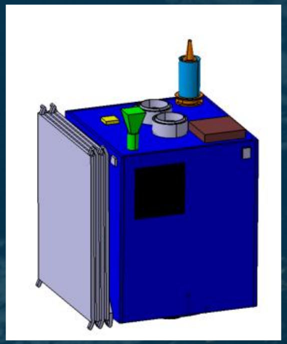
•**Program Objectives:** First ever on-board collocation of **four space GNSS/Geodetic techniques** providing a **major improvement of the Earth International Terrestrial Reference Frame** accuracy/stability **supporting GGOS goals and the UN Resolution** on sustainable development, (A/RES/69/266).



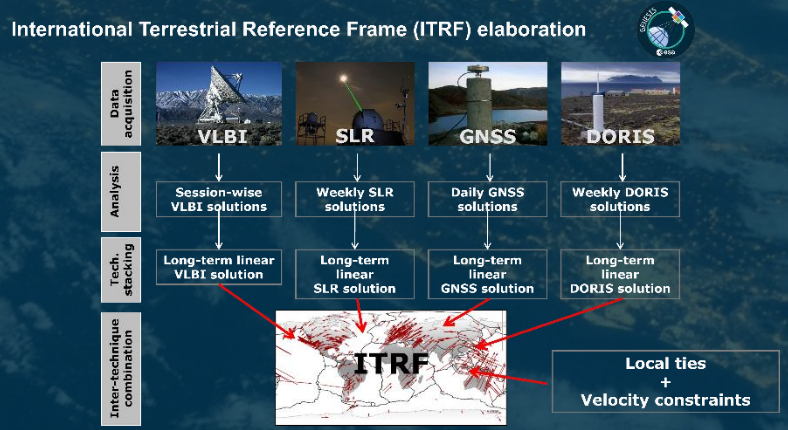
ITRF Targets

Accuracy: 1 mm

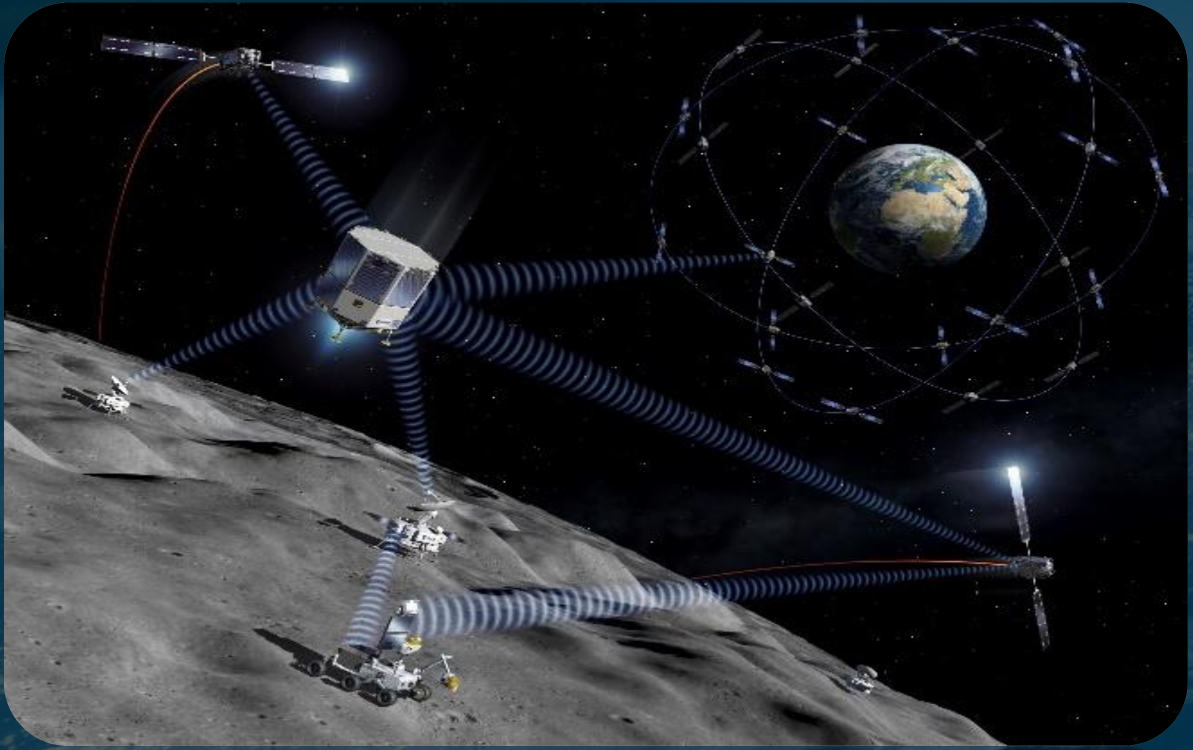
Stability: 0.1 mm per year



incl. Ultra-Stable Oscillator

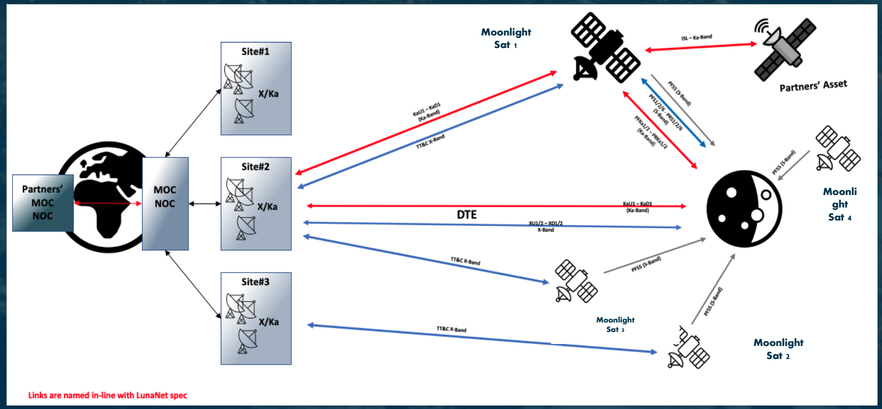


Moonlight ESA Initiative

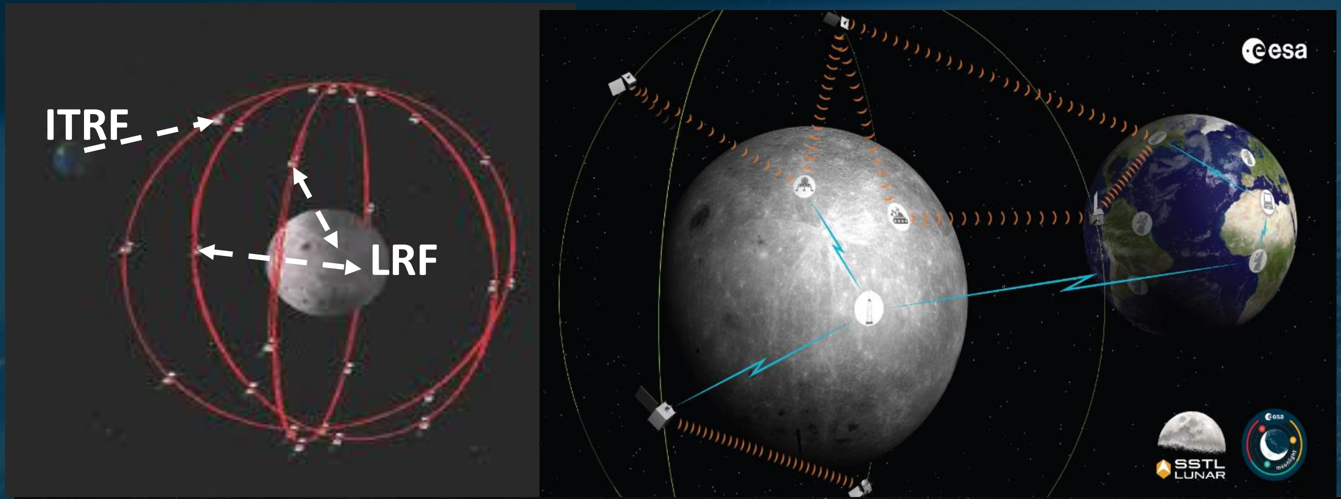


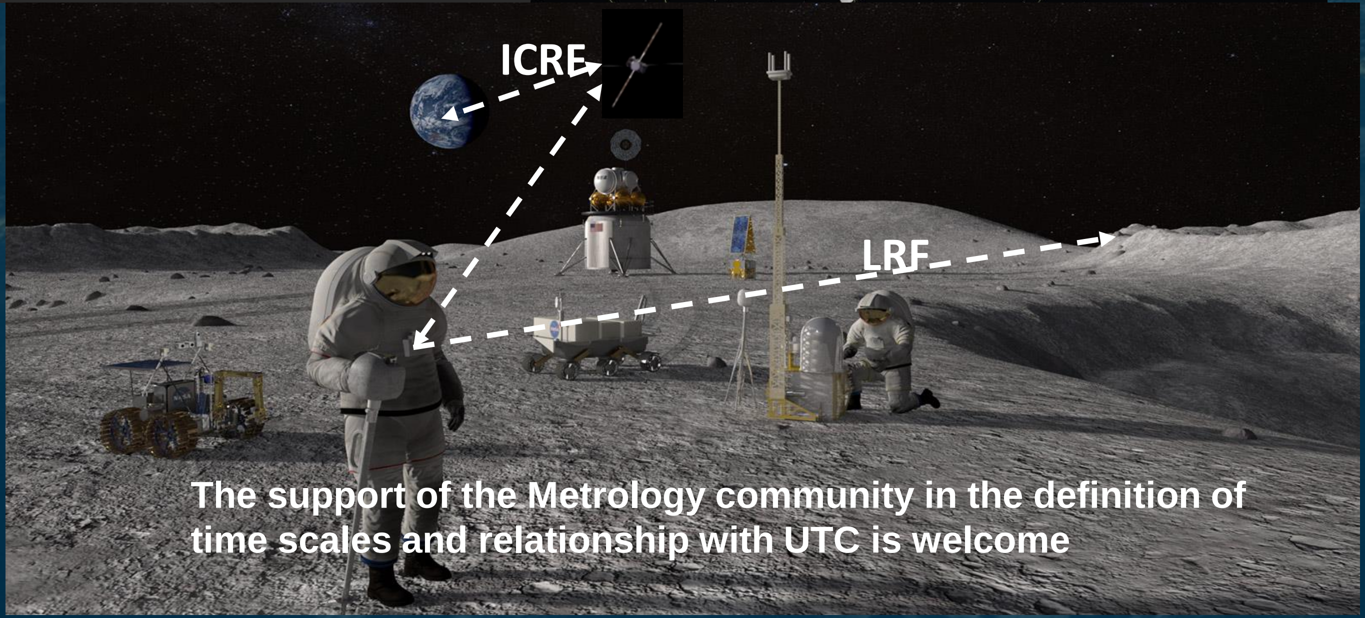
- Moonlight will provide the first dedicated infrastructure of satellites around the Moon, providing communication, navigation and time services, unlocking the potential for future Lunar missions
- A dedicated constellation of satellites around the Moon

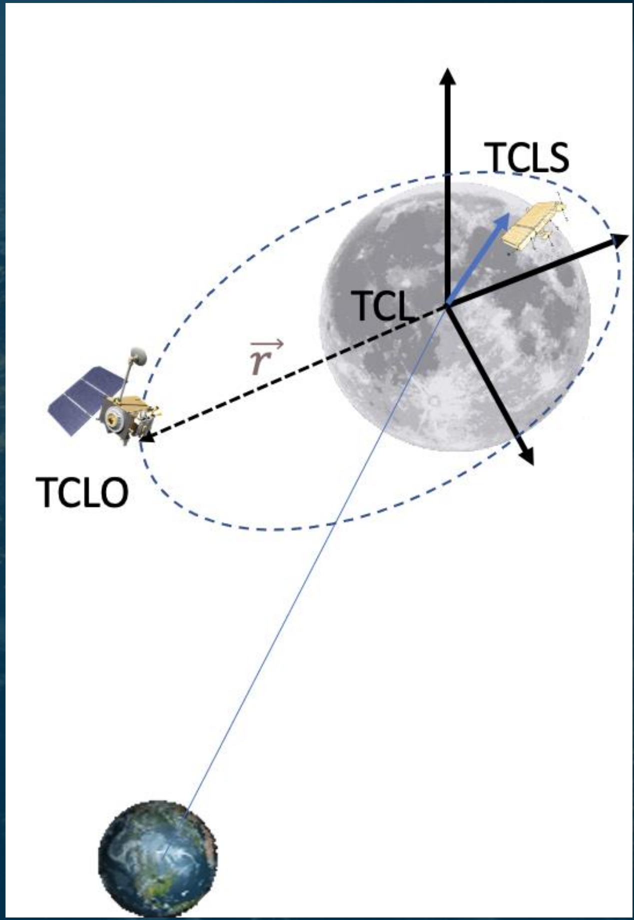
Data transport	Absolute Position
Tele-operations	Absolute Velocity
Audio/Video streaming	Universal time
Third-party payloads	Alert & Information
Over-the-top Services	Search and Rescue



International cooperation needs to be launched to define a lunar Selenodetic Reference Frame and a Lunar Time Reference applicable to lunar PNT systems







Earth-based: TCG / TAI / UTC / GPS time / Galileo Time

TCL
Time scale @ selenocenter

TCLS
Time scale @ Moon surface

TCLO
Time scale @ Moon orbiter

5) Take-aways

- A **continuous timescale** is advantageous for any Space System's operation
- Space Systems need **real-time timescales** with a high level of **continuity, availability, reliability**
- Space Systems need to be **synchronised to a recognised ground reference, i.e. UTC**

- Today GNSS do broadcast "A PREDICTION of UTC" or "a **UTC Time Service**"
- The offset **UT1-UTC** is needed with the highest accuracy (microsecond)

- **Better clocks** (stability, accuracy) can **contribute to better GNSS accuracy**.
- **Robustness** of clock technology is equally important for GNSS.

- **Space Exploration** needs to address today the **interoperability in Time Metrology** (also of Reference systems). The involvement of the Metrology community represented at the CGPM is welcome in support to this reference definition (together with IAU and the other involved organization)