ATC
Microwave-optical oscillator cold caesium atom clock for STE-QUEST

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Plan

Introduction

ATC payload (space clock)

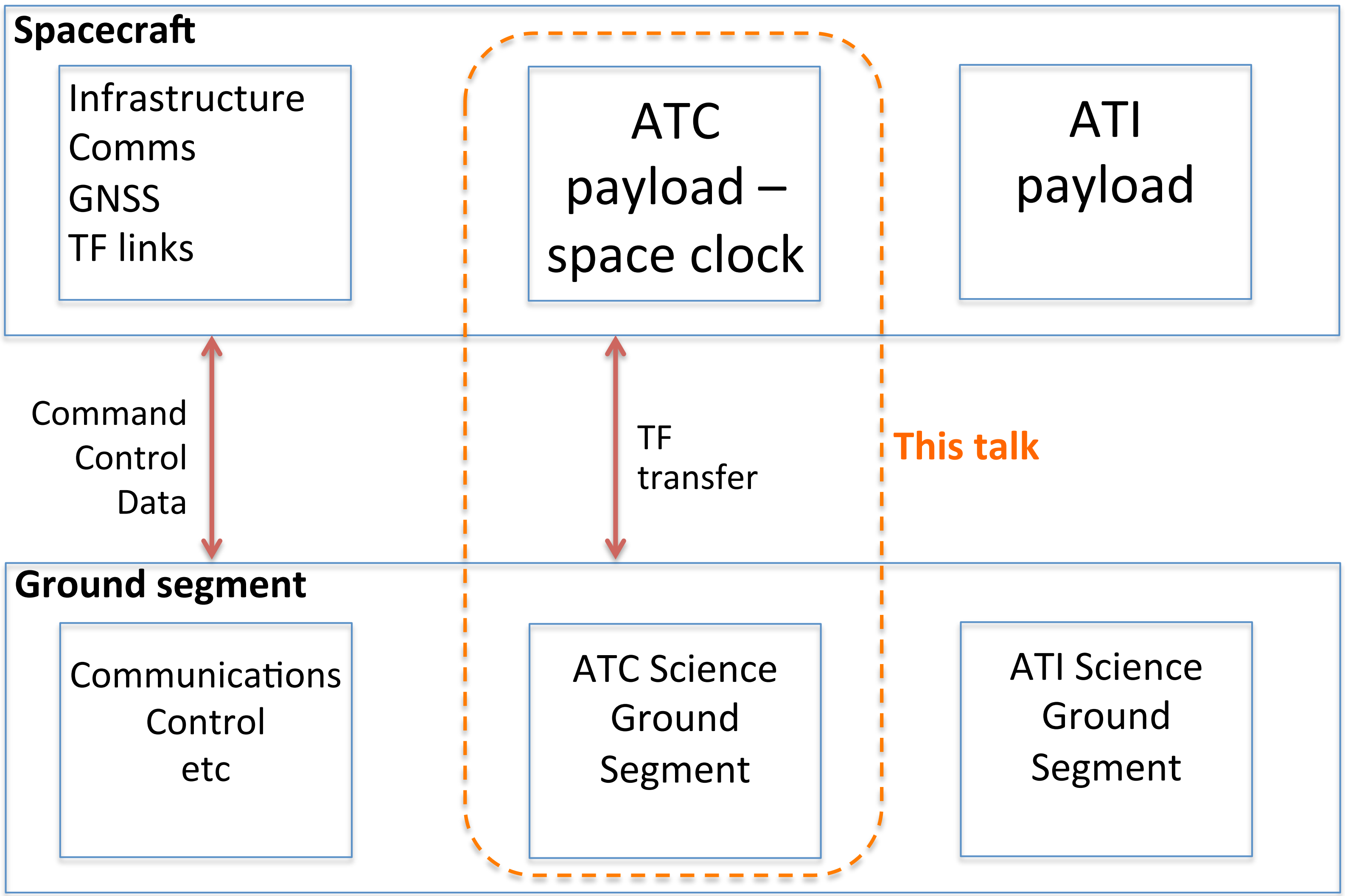
ATC science ground segment

ATC overall performance

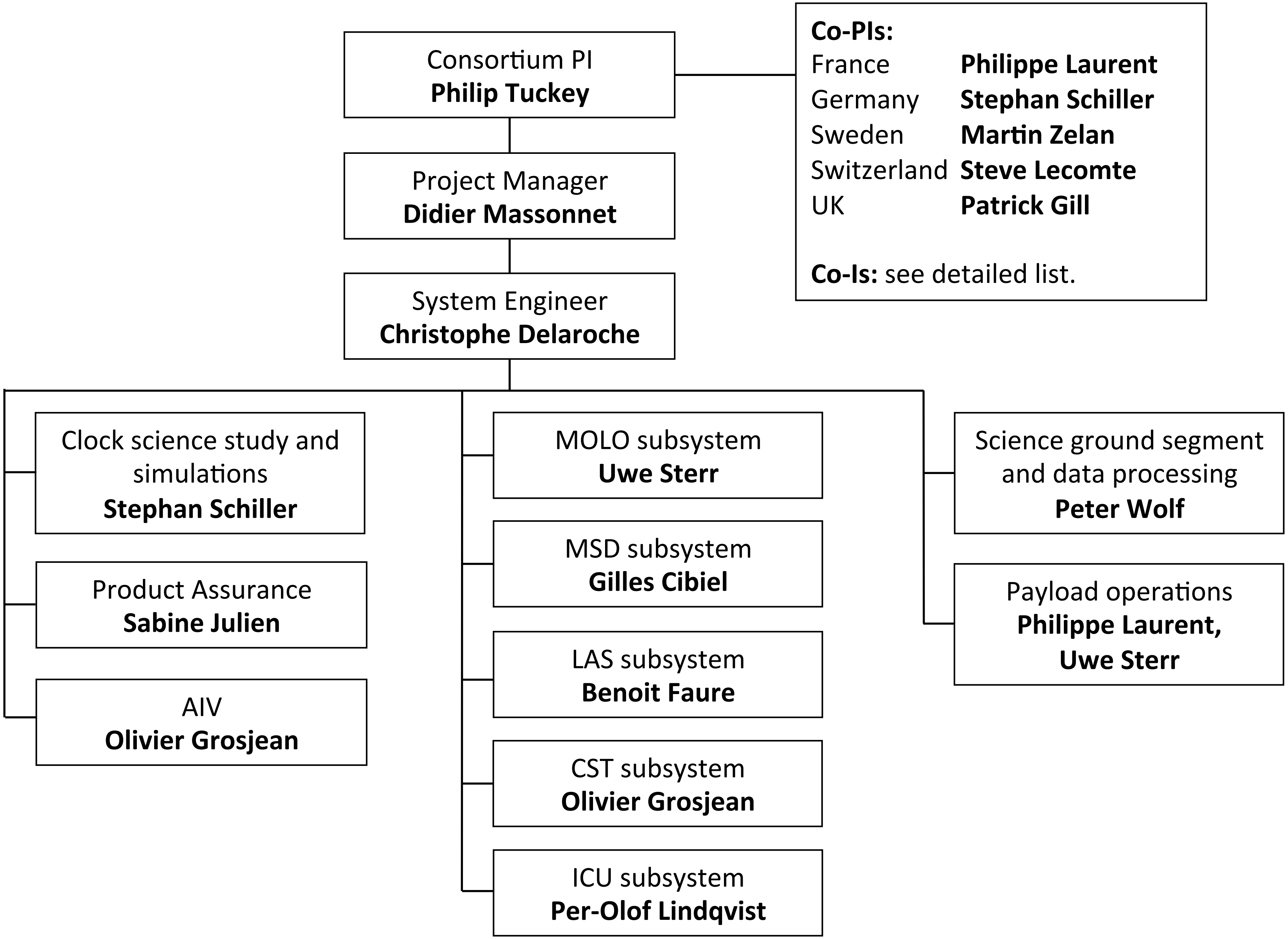
Note: See STE-QUEST Science Requirements Document for complete and precise specifications.

Introduction

Global mission structure (reminder)



ATC global organogram



ATC science objectives

N.B. ATC + TF link objectives

Primary objectives

- Earth gravitational red-shift: 2×10^{-7}
- Sun gravitational red-shift: 2×10^{-6} *with ultimate goal* 5×10^{-7}
- Moon gravitational red-shift: 4×10^{-4} *with ultimate goal* 9×10^{-5}

Secondary objectives

Clock Comparisons and International Atomic Time Scales

- Long-distance common-view ground clock comparisons at 1×10^{-18} @ few days with microwave link *or few hours with optical link*
- Space-to-ground time transfer with inaccuracy lower than 50 ps
- Synchronization of ground clocks to better than 50 ps
- Contribution to time scales at 1×10^{-16} level
- Monitoring stability of GPS, GALILEO, and GLONASS clocks (if GNSS receiver on board)

Geodesy

- Differential geopotential measurements between two points on the Earth's surface with resolution in the gravitational potential U at the level of 0.15 m^2/s^2 (equivalent 1.5 cm on the differential geoid height).

Optical and Microwave Ranging

- *Cross-comparisons of different ranging techniques: one-way optical ranging, two-way optical ranging, microwave ranging.*
- *Measurement of the differential atmospheric propagation delays in the optical and microwave.*

Space clock

Space clock requirements

Principal top-level specifications:

- **stability:** $8 \times 10^{-14} / \tau^{1/2}$, for 1 s to 7×10^{5} s (i.e. noise floor < 10^{-16})
- **accuracy:** 1×10^{-16}

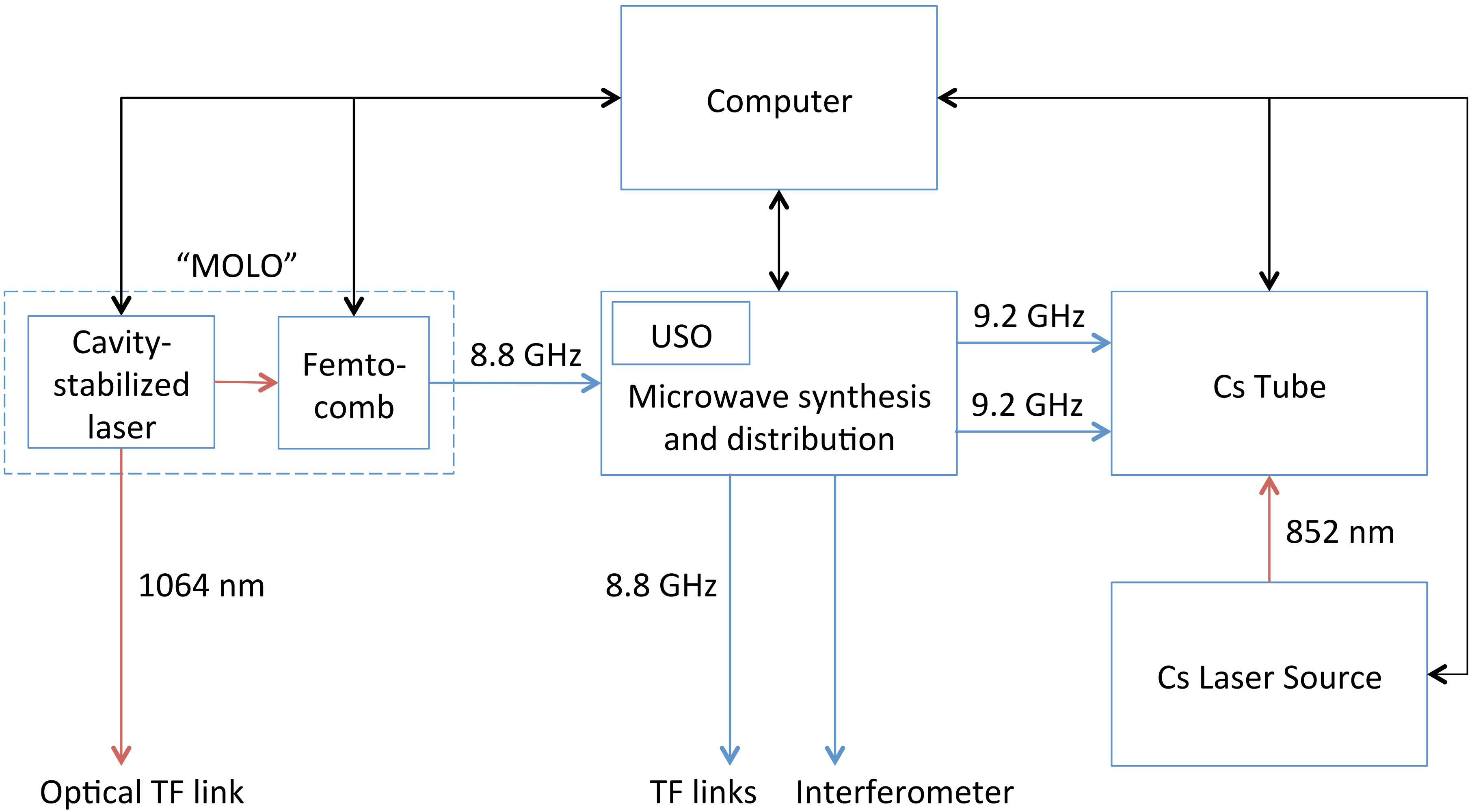
Environment:

- duration: 5 years (4 full years of measurements)
- temperature: 10 °C – 30 °C
- magnetic field fluctuations: 10 mG for 0.1 – 10 Hz
- ionizing radiation: total dose (5 years) ~ 100 krad

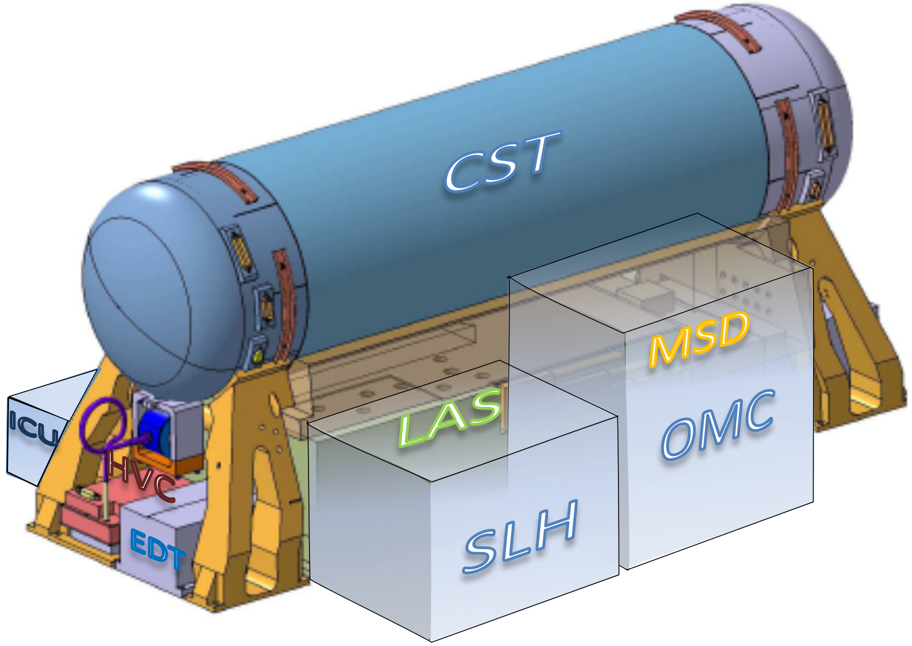
Space clock concept

- Caesium clock very similar to the **PHARAO** laser-cooled atom clock on ACES
  - flight model starts validation tests this year
  - much technology re-use
- Addition of a new ultra-(ultra-)stable local oscillator based on a cavity-stabilized laser and femto-comb, "**MOLO**"
  - stability 3.5 x 10^{-15} (after drift removal), 1 – 100 s
  - optical-microwave relative stability 3 times smaller than above, frequency offset < 3 x 10^{-17}

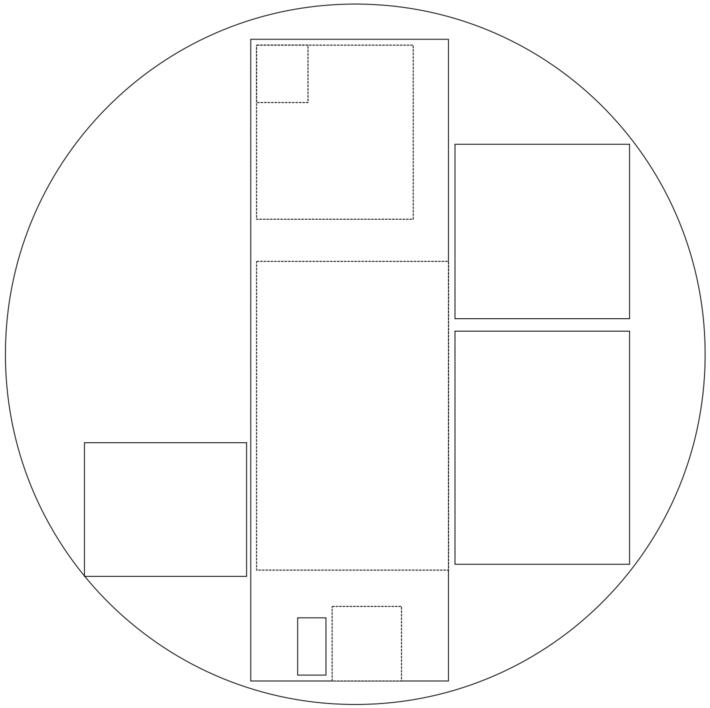
Simplified block diagram



Space clock physical layout



ATC Unit	Dimension(mm)
CST	1100x340x460
HVC	100x50x50
EDT	135x120x100
LAS	532x335x198
MSD	300x270x103
SLH	400x300x250
OMC	300x300x380
ICU	230x280x110



ATC payload groups, agencies, studies

France (CNES)		
CNES	D. Massonnet	Microwave synthesis, Cs laser source, Cs tube
LNE-SYRTE	Ph. Laurent	
Germany (DLR)		
HHUD	S. Schiller	Ultra-stable cavity and laser locking, optical-microwave conversion, femto-comb (Menlo-DLR), 1064 nm laser
PTB	U. Sterr	
Sweden (SNSB)		
SP	M. Zelan	Instrument computer
RUAG	P-O Lindqvist	
Switzerland (SSO)		
CSEM	S. Lecomte	Crystal-based femto-comb
U. Bern	A. Stefanov	Cs interrogation cavity modelling
United Kingdom (UKSA)		
NPL	P. Gill	Ultra-stable cavity and laser locking
U. Birmingham	K. Bongs	Radiation testing
USA		
Penn State	K. Gibble	Cs interrogation cavity modelling

For detailed presentations:

- talks: R. Holzwarth, S. Lecomte, U. Sterr
- posters: Q-F. Chen, I. Ernsting, P. Gill, Ph. Laurent, A. Stefanov

Space clock performance

Stability (@ 1 s)

- quantum projection: 5 x 10^{-14} with 10^6 atoms detected
- detection noise: 10^{-14}
- microwave (MOLO+synthesis): 7 x 10^{-15}
- vibration: negligible

Best possible frequency stability: 5.2 x 10^{-14} @ 1 s

With atom-number modulation to measure collision effect, average stability: 6.1 x 10^{-14} @ 1 s

Atom number, detection noise to be verified by PHARAO flight model tests

Accuracy

- cold collisions: 10^6 atoms gives shift of 5×10^{-15}. Evaluation to 5% gives uncertainty of 2.5×10^{-16}. There is some margin to reduce atom number, also expect to improve on the 5% figure (PHARAO/ACES mission).
- 1st order Doppler: effect $< 4 \times 10^{-16}$, uncertainty $< 10^{-16}$
- recoil effect: 7×10^{-17}
- Zeeman: 3 shields + servo loop (1 Hz) -> 5×10^{-17} uncertainty
- black body: measure temperature to 0.2 K -> 5×10^{-17} frequency error

PHARAO interrogation cavity simulations are on-going

Thus total frequency error currently justified is $< 2 \times 10^{-16}$, pending improvement from PHARAO/ACES results

Long term stability expected $< 10^{-16}$

Backup mode with quartz OSU:

- quartz OSU stability: 6×10^{-14}
- best clock stability: 7.8×10^{-14} @ 1 s
- systematics cannot be well measured without MOLO -> accuracy degraded ~ 10^{-15}
- long-term stability possibly also degraded

Science ground segment

ATC science ground segment concept

Space clock and TF links need (of course) a ground network to use them.

Ground segment components:

- ground stations to host link ground terminals.
- ground clocks, well-connected to ground stations
- payload operations centre and level 2 and 3 data analysis centres
- scientific data analysis centres

Many similarities to ACES ground segment.

Ground station/clock requirements

Ground stations:

- link terminal reference point uncertainty contributes noise 3x lower than link noise
- minimum of 3, around the world (+3 for optical link)

Clocks:

- **stability**: $2.5 \times 10^{-16}/\tau^{1/2}$, for 1 s to 2.5×10^{5} s
- **accuracy**: 1×10^{-18}
- at least 3 such clocks, around the world
- clock gravitational potential uncertainty: $< 3 \times 10^{-17}$ in frequency
- clock position and velocity: $< 5 \times 10^{-19}$ in frequency
- daily gravitational potential variations known to $< 5 \times 10^{-19}$ in frequency

Proposed ground stations and ground clocks network

	Baseline Primary	Alternate Primary	Secondary
Europe			
Microwave link host	INRIM	OCA	
Optical link host	OCA	INRIM	
Clock institutes	INRIM*, NPL*, PTB*, LNE-SYRTE*		HHUD, LUH
North America			
Microwave + Optical links	NIST	JPL	JPL, NRC, Stanford
Clock institutes	NIST/JILA*	JPL	JPL, NRC, Stanford
Asia			
Microwave + Optical links	NMIJ	NTSC, UWA	NTSC, UWA
Clock institutes	NMIJ*, NICT*, U. Tokyo*	NTSC, UWA	NTSC, UWA, NIM

* fibre link assumed

Ground station and ground clock funding assumptions

ESA funding:

- 3 microwave link terminals (including installation and remote operation)

Non ESA/ESA member country space agency funding:

- primary ground stations: metrological and other infrastructure, low-level maintenance
- secondary ground stations: also link terminal
- ground clock operations (including regional networks) and data provision

Payload operations and level 2 and 3 data centres

	Baseline	Alternate
IOC1 Space clock operations, L2 and L3 data generation	LNE-SYRTE	PTB, NPL
IOC2 L2 and L3 data generation	NIST	NMIJ, PTB, NPL

There may be an Instrument Operation Centre at ESA (ESOC).

Level 3 is finalized comparison data, i.e. corrected for instrumental, propagation, relativistic effects

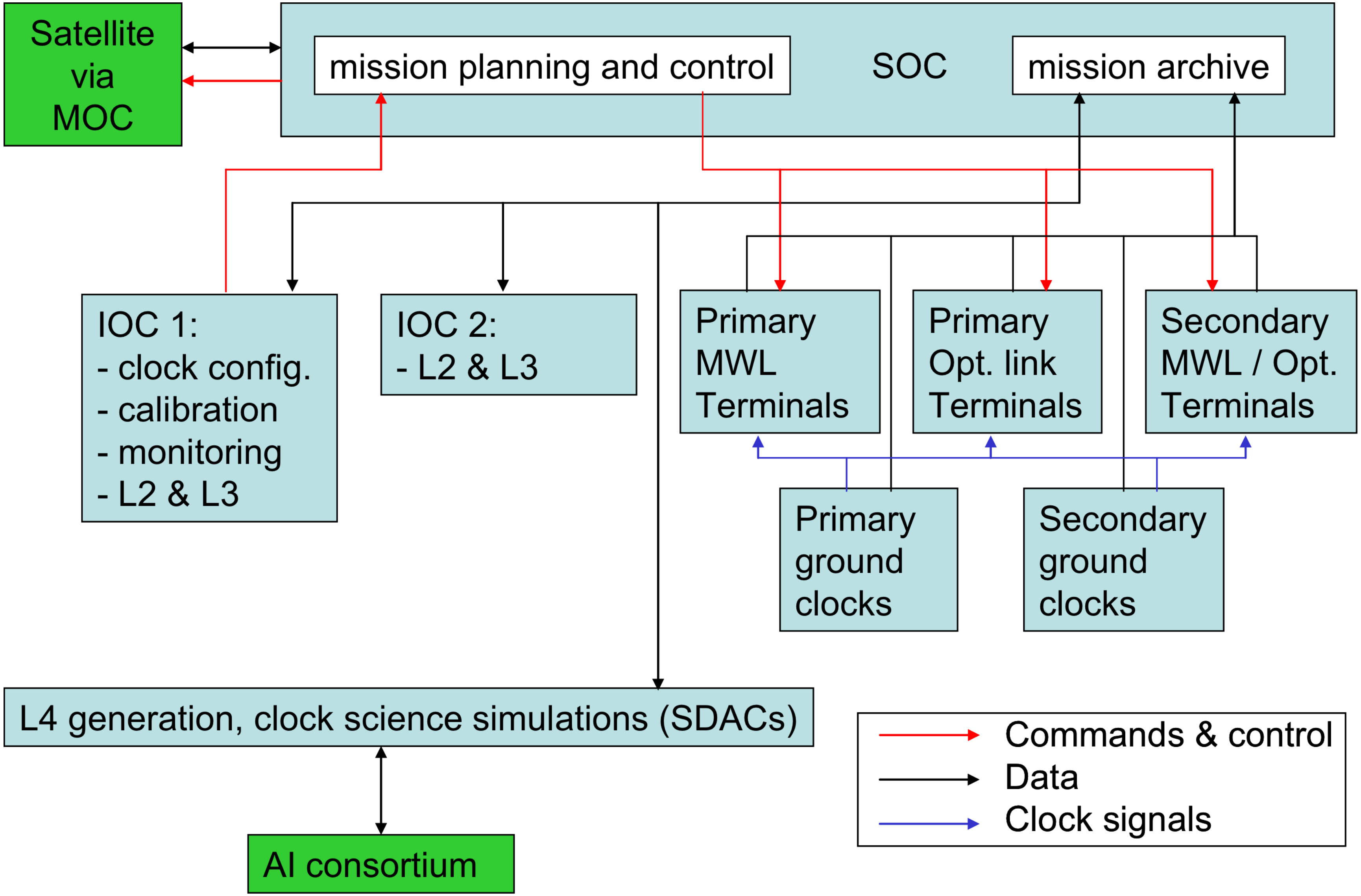
Scientific data analysis centres

Generate level 4 data: finalised scientific applications.

Groups can propose scientific applications and become scientific data analysis centres. Procedure to be defined, number not limited a priori.

Interface with ATI for some applications.

Science ground segment overview



Groups who responded to ground segment invitation

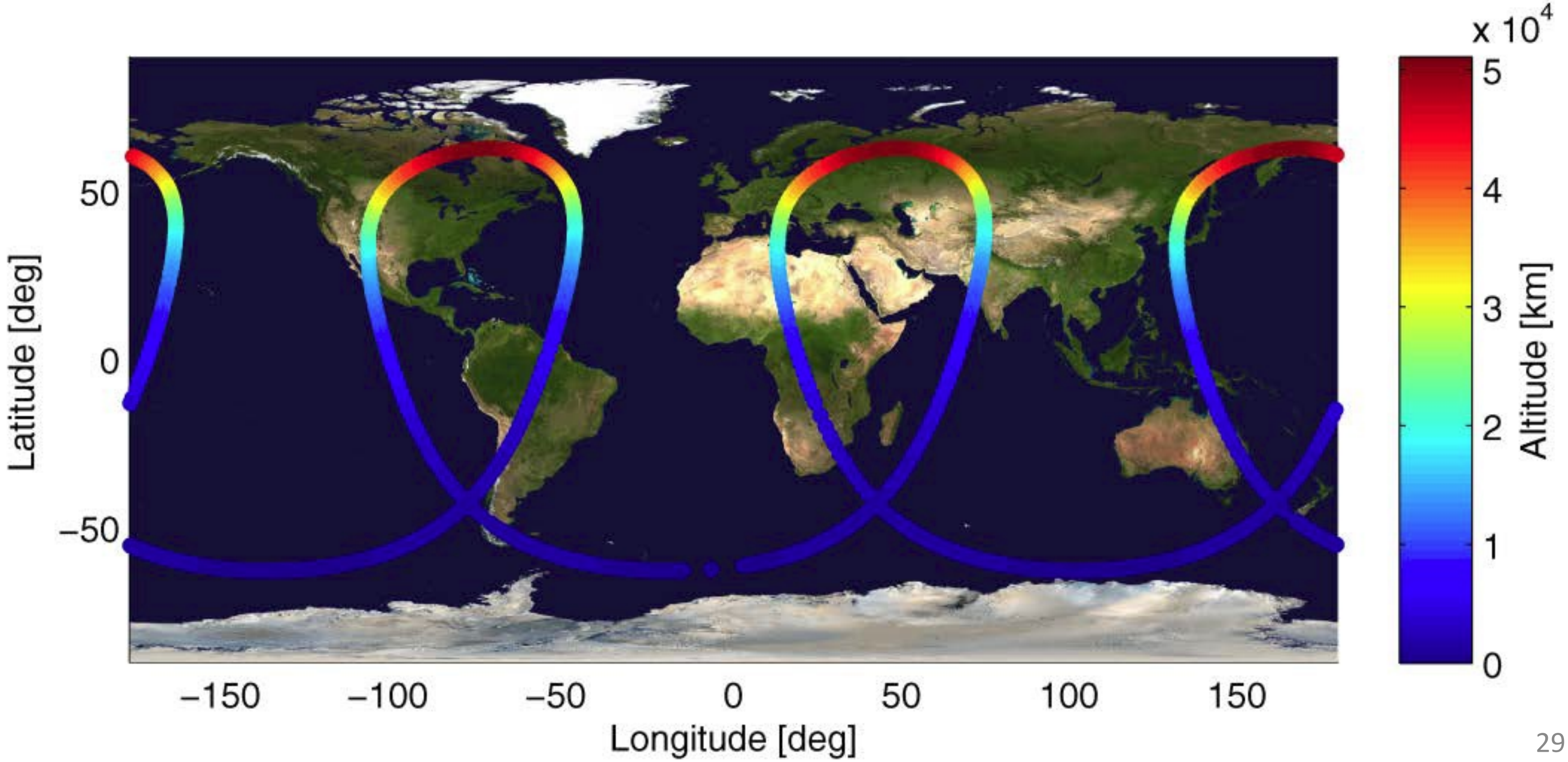
France	ENS-LKB	Christophe Salomon
	FEMTO-ST	Vincent Giordano
	GéoAzur	Etienne Samain
	UTINAM	François Vernotte
Germany	FESG	Ulrich Schreiber
	LUH	Ernst Räsel
Italy	INRIM	Filippo Levi
	Università di Bologna	Marco Prevedelli
	Università di Firenze	Guglielmo Tino
	Università di Napoli	Salvatore Capozziello
	Università La Sapienza	Luciano Iess
Netherlands	TU Delft	Eberhard Gill
Spain	ICE	Carlos Sopuerta
Switzerland	University of Zurich	Philippe Jetzer
Australia	UWA/NMIA	Mike Tobar
Canada	NRC	John Bernard
China	Peking University	Xuzong Chen
	NIM	Zhanjun Fang
	NTSC	Shougang Zhang
	SIOM	Liang Liu
Japan	NICT	Yuko Hanado
	NMIJ	Feng-Lei Hong
	Tokyo University	Hidetoshi Katori
USA	Carleton College	Jay Tasson
	Embry-Riddle University	Quentin Bailey
	JPL	Nan Yu
	NIST/JILA	Chris Oates
	Stanford University	Leo Hollberg
	University of South-Carolina	Brett Altshul

ATC+links overall performance

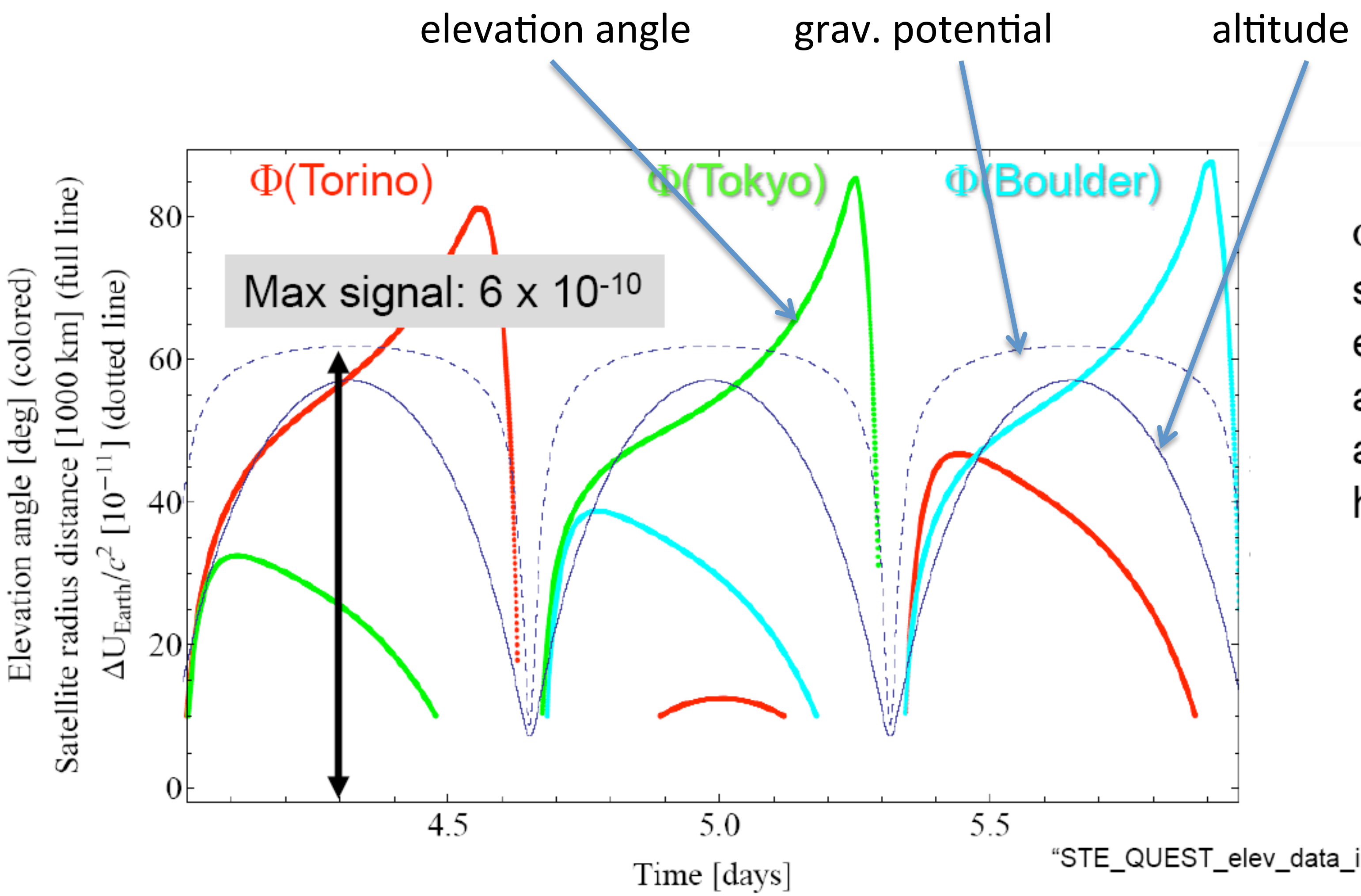
Orbit – reminder

Inclination 62.59°, perigee 700 km, apogee 51000 km, period 16 hours.

Track on Earth repeats every 3 orbits/2 days.



Orbit and visibility



Φ = satellite elevation angle above horizon

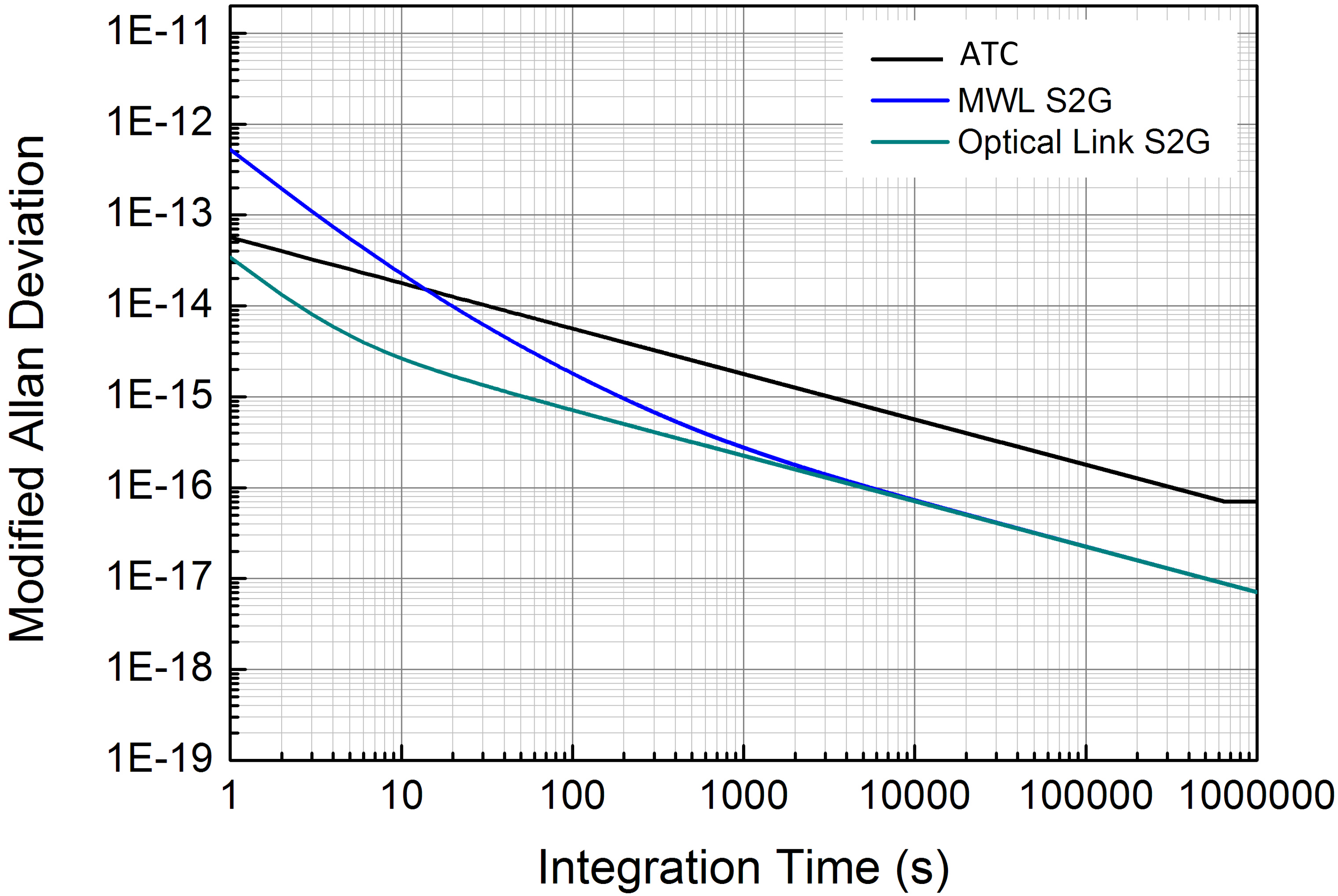
3000 – 7000 km altitude intervals are omitted

"STE_QUEST_elev_data_interval_frozen_1"

Ground-space comparisons

- can follow almost a full orbit from one ground station
- space clock stability leads to a frequency resolution of a few x 10^{-16}
- assuming independent measurements, we need ~ 10 orbits to average down to the clock accuracy ~ 10^{-16}
- should average down even faster using link phase continuity

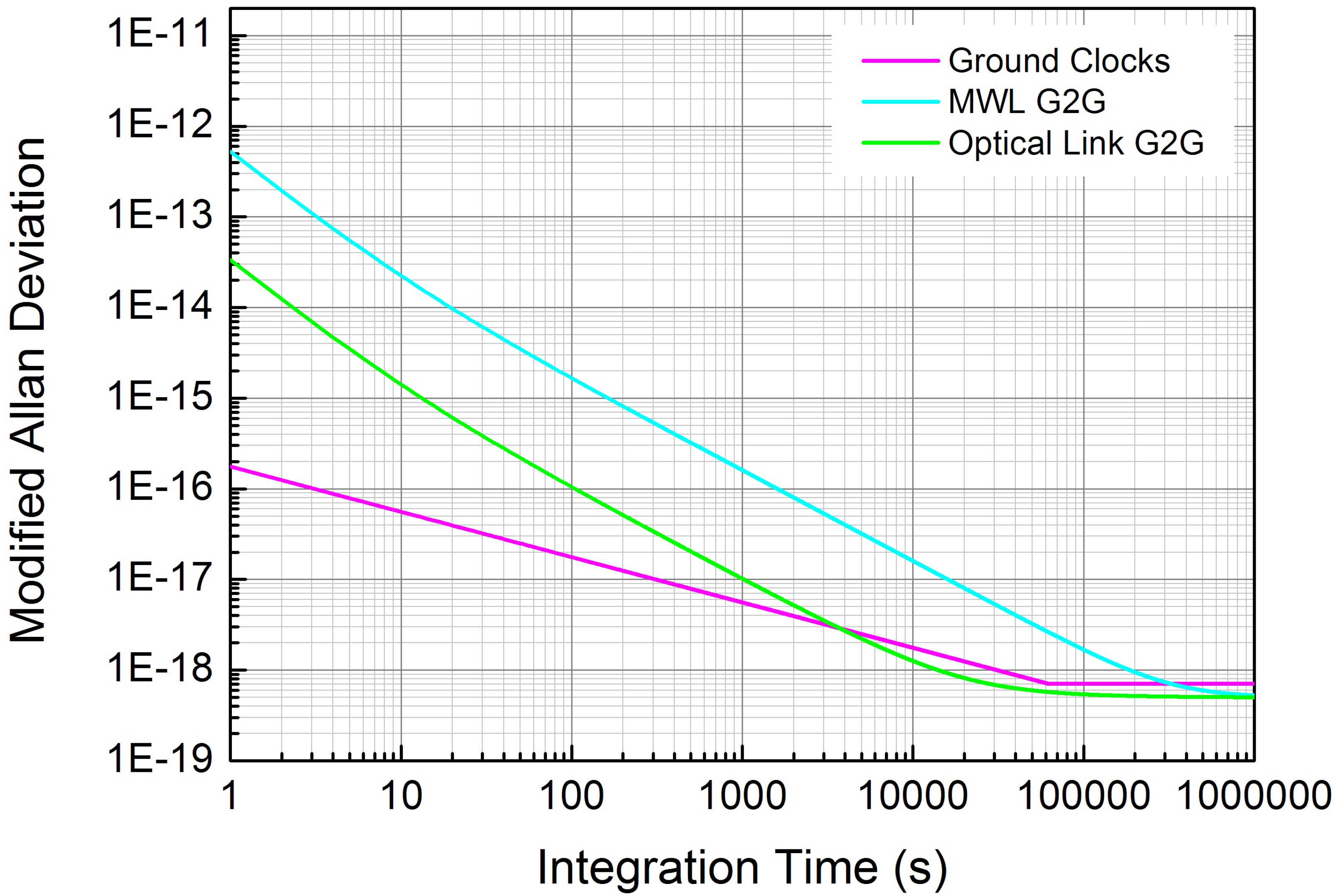
Space clock and space-ground link stabilities



Ground-ground comparisons

- over 3 orbits/2 days obtain 3 successive comparisons for the 3 pairs of ground stations Turin-Tokyo, Tokyo-Boulder, Boulder-Turin, durations 40000 s – 46000 s
- microwave link noise ~ 4 x 10^{-18} after one comparison, will average down to ground clock accuracy ~ 10^{-18} after ~ 16 orbits (faster, considering phase continuity)
- with optical link, reach ground clock limit after one comparison

Ground clock and ground-ground link stabilities



Conclusion

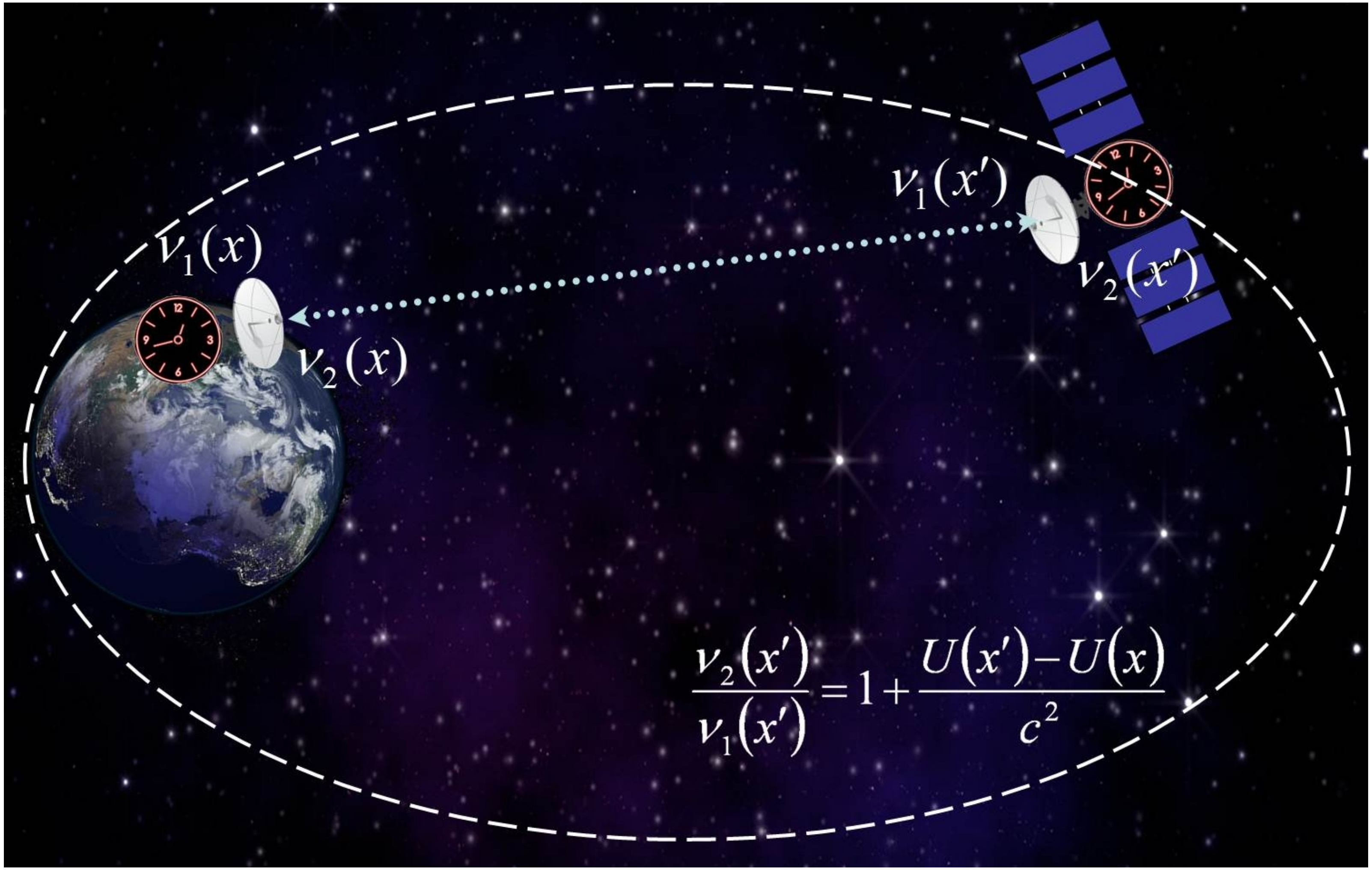
Assuming MOLO performance:

- space clock stability compliant
- space clock accuracy needs further PHARAO/ ACES results

Required TF link and ground clock performances would allow the science objectives to be attained.

Thanks for your attention

Earth redshift measurement illustration



Earth redshift measurements

Perigee redshift measurement:

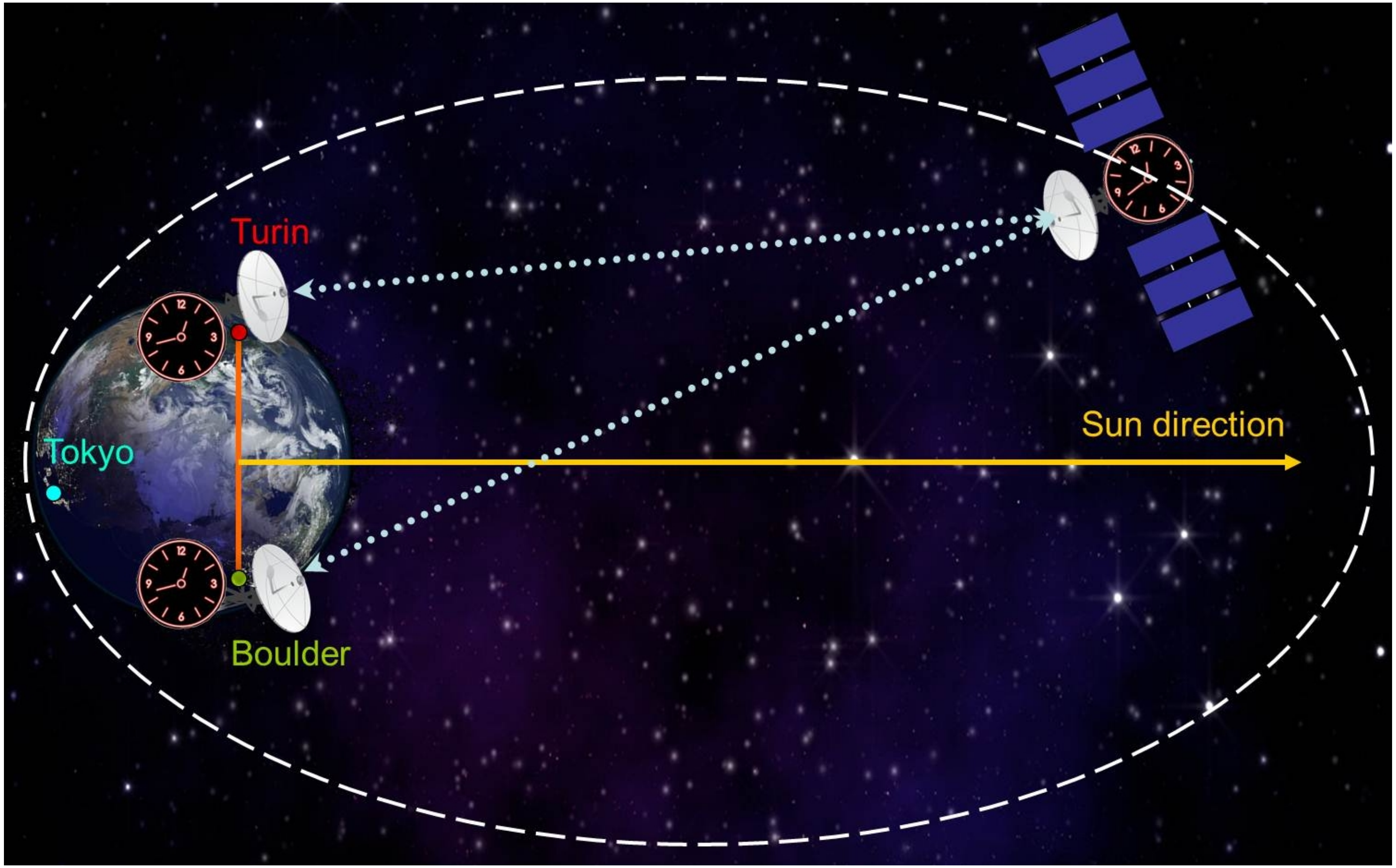
- potential difference wrt Earth's surface $\Delta U/c^2 \sim 6 \times 10^{-10} = \Delta f/f$
- thus direct measurement resolution $\sim 10^{-16}/6\times10^{-10} \sim 2 \times 10^{-7}$
- limited by space clock accuracy

Measurement of redshift modulation over orbit:

- measure frequency modulation during orbit (max/min)
- not limited by accuracy, only depends on clock stability over an orbit – independent of any unknown frequency error
- less sensitive than apogee measurement over one orbit
- simulations… averages down to 2×10^{-7} after 840 days, goes a little lower over full 4 years

No improvement with optical link cf microwave.

Sun redshift measurement illustration



Sun redshift measurement

- as Earth rotates, ground clocks approach and recede from Sun -> gravitational potential changes -> clock frequency modulation
- peak-peak amplitude ~ 10^{-12} between 2 ground clocks
- gravitational effect cancelled by 2nd order Doppler, but this term can be calculated from Earth's orbit
- search for a ground clock – ground clock frequency modulation synchronous with Earth rotation
- simulations… with microwave link, can reach a resolution of ~ 2.2×10^{-6} after 4 years of averaging
- with optical link, reach 2×10^{-6} after 72 days (assuming 25% efficiency for meteorology problems) and 5×10^{-7} over 4 years

Other objectives

Moon redshift: similar to Sun, 175 times smaller, distinguish by phase variation synchronous to Moon orbit.

TF applications: essentially covered above

Geodesy: ground-ground clock comparisons coupled with ground clock position and potential variation requirements.