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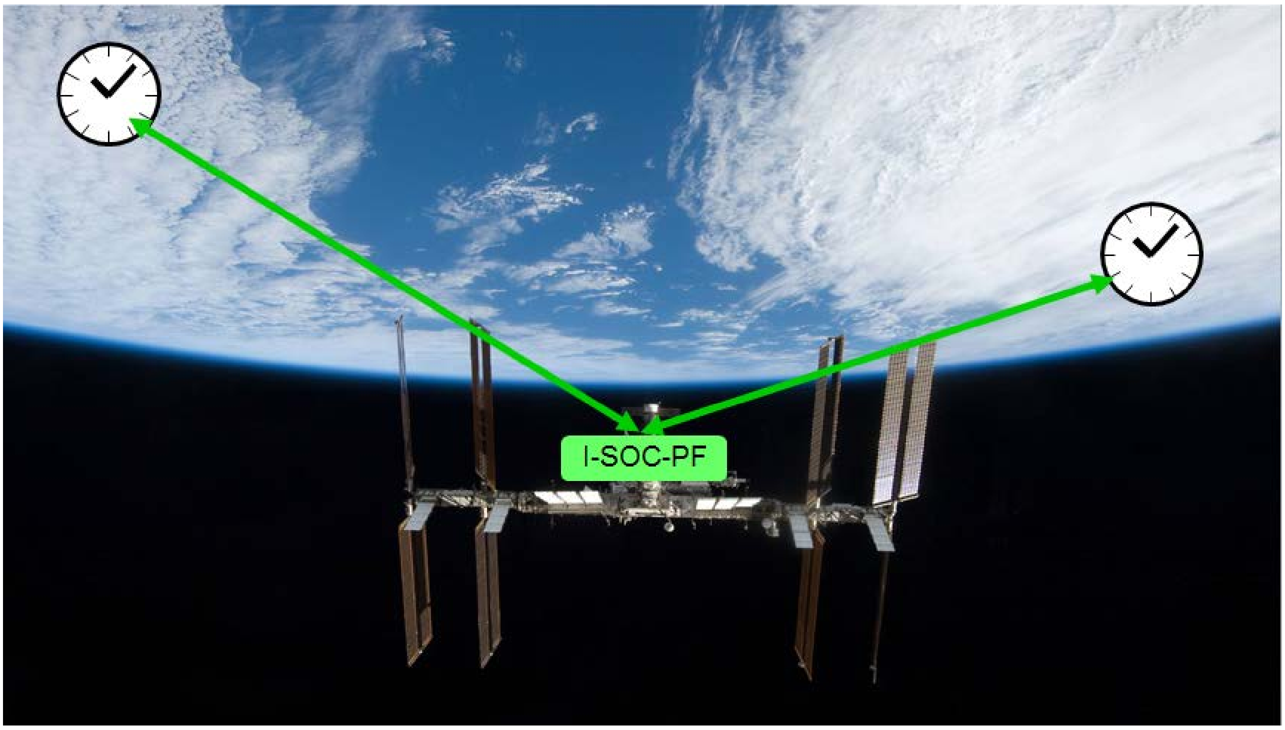
I-SOC Pathfinder Scientific Requirements



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CHANGE LOG

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References have been updated	08/05/2020	8	Sec. 1.4
Science case adapted to the I-SOC-PF mission	08/05/2020	11-15	Sec. 2.2
Mission summary updated to I-SOC-PF	08/05/2020	17-18, 20-22	Sec. 2.4
Earth redshift primary scientific objective deleted; LPI and SME tests added (now #PSO-03)	08/05/2020	23	Sec. 3.1
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Simulation results updated	08/05/2020	32-42	Sec. 3.3.2.3
I-SOC-PF clock requirements updated	08/05/2020	42	Sec. 4.2.1
Requirements, previously in Sec. 4.2.4, on On-board Frequency Generation and Distribution deleted	08/05/2020	48	old Sec. 4.2.4
Requirement on Gravitational Potential at the I-SOC-PF Clock (old #SR-PL-45) updated	08/05/2020	49	Sec. 4.3
Requirement on Gravitational Potential at the Ground Clocks (old #SR-GS-11)	08/05/2020	51	Sec. 4.5
Annex 1 to 4 updated	08/05/2020	52-77	Annex 1 to 4

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1 INTRODUCTION

1.1 Purpose

This document presents the scientific objectives of the ESA mission I-SOC Pathfinder (I-SOC-PF) and provides the top level science requirements. I-SOC-PF is both a mission in the field of fundamental physics and geophysics and a pathfinder mission for future missions with ultrastable and ultraprecise space clocks, such as the mission proposal I-SOC.

It is recalled that I-SOC is a mission in the fundamental physics domain conceived to test to high accuracy a fundamental principle of metric theories of gravitation, the dilation of time by gravity. This principle is related to the Einstein Equivalence Principle (EEP).
The scientific case for I-SOC was initially submitted as response to a call for scientific use of the ISS, in 2005. A first study (“SOC”) was performed under ESA funding in 2006-2009, followed by an EU-FP7 project “SOC2”, in 2010-2015. A EU-H2020 Initial Training Network “FACT” contributed with parts of its activity in 2013-2017. The I-SOC mission was recommended by the ESA-appointed “Fundamental Physics Roadmap Advisory Team” (FPR-AT) as a result of an extensive consultation process conducted in the fundamental physics community [RD01]. The mission I-SOC has been studied in Phase-A (scientific part) by the I-SOC science team during 2017-2019, under ESA contract 4000119716. Among others, an Experiment Scientific Requirements document for the I-SOC mission was produced [RD41].

While the scientific value of I-SOC has repeatedly been regarded as high by review committees and the national space agencies, an open issue has been the probable cost and the development duration, also in view of the operational lifetime of the ISS. In order to elucidate these issues, in April 2019 the I-SOC science team developed an estimate of the cost-at-completion (CAC), and delivered it to DLR and ESA. In addition, an Activity Plan document was produced and delivered.
In view of the high CAC for I-SOC, a simplified mission proposal was developed. This proposal is of significantly lower cost and complexity, since it is based on only a part of the originally proposed I-SOC instrument. Nevertheless, it will lead to both strong science results as well as provide in-depth technology demonstration. The latter is important for future ISS-based missions, and for future missions with optical clocks on higher Earth orbits or interplanetary missions. The proposed mission has therefore been named “I-SOC Pathfinder”.
An extended science team worked out the concept of I-SOC-PF. The mission was presented to PSWG (Physical Sciences Working Group), the ESA advisory body for Physical Sciences, on 15 October 2019. In their recommendation, PSWG confirmed the scientific interest of the mission: *The PSWG acknowledged the clear presentation by the I-SOC Pathfinder science team. The overall feeling of the PSWG is that the I-SOC Pathfinder project is excellent and will deliver high quality science.*

This I-SOC-PF Experiment Scientific Requirements document (ESR) will be the basis for the I-SOC-PF mission design during the assessment study phase, which is planned to start in 2020 and end in 2021.
During the assessment phase, it is expected that the requirements may be adjusted driven by technical feasibility within the programmatic boundaries. The I-SOC-PF Science Team

will evaluate eventual changes and submit them to ESA for approval. Any changes will be logged in this document to provide a record of the evolution.
This document also aims at showing the links between science requirements and mission performance requirements, in order to help to understand, trace, and support the analysis of the relation between mission specifications and scientific objectives.

1.2 Document Overview

The document is organized as follows. Section 2 discusses the I-SOC-PF science case, addressing the fundamental physics tests that will be conducted and providing the mission overview. The scientific objectives are detailed in Section 3 where, for each of the primary mission objectives, the measurement principle is also discussed.
The requirements breakdown is presented in Section 4, which is directly derived from the I-SOC-PF scientific objectives.
In Annex 1, the working principle of the I-SOC-PF links and its performance are explained.

1.3 Acronyms

ACES	Atomic clock ensemble in space
CDMA	Code Division Multiple Access
CTU	Czech Technical Universiy
DDS	Direct Digital Synthesizer
DLR	Deutsches Zentrum für Luft und Raumfahrt
EEP	Einstein Equivalence Principle
ELT+	European Laser Link
ESR	Experiment Scientific Requirements
FDP	Frequency Distribution Package
FPGA	Field Programmable Gate Array
FPR-AT	Fundamental Physics Roadmap Advisory Team
GOW	Geodätisches Observatorium Wettzell
GPS	Global Positioning System
GR	General Relativity
GTD	Gravitational Time Dilation
IF	Intermediate Frequency
I-SOC	Space Optical Clock on ISS
I-SOC-PF	I-SOC Pathfinder
LCT	Laser Communication Terminal
LLI	Local Lorentz Invariance
LPI	Local Position Invariance
MOC	Mission Operations Centre
MWL	Microwave Link
PN	Pseudo Noise
PPS	Pulses Per Second
PSO	Primary Science Objective
PSD	Power Spectral Density
PVT	Position, Velocity, Time
QM	Quantum Mechanics
RDS	Relativistic Doppler shift

RMS	Robertson-Mansouri-Sexl
SAW	Surface Acoustic Wave
SME	Standard Model Extension
SLR	Satellite Laser Ranging
SR	Special Relativity
SSO	Secondary Science Objective
TC	Telecommanding
TEC	Total Electron Content
TWSTFT	Two-Way Satellite Time and Frequency Transfer
USO	Ultra Stable Oscillator
USOC	User Support and Operation Center
UTC	Universal Time Coordinated
WEP	Weak Equivalence Principle

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2 TESTING THE EINSTEIN EQUIVALENCE PRINCIPLE WITH I-SOC-PF

2.1 Fundamental Physics Experiments and Space

One of the most exciting challenges that physics is facing in the present days is represented by the harmonization of gravitation and quantum theory and, more generally, by the unification of the four fundamental interactions of Nature (strong, electromagnetic, weak, and gravitational). General Relativity (GR) and Quantum Mechanics (QM) are the frameworks from which the developments of all the grand unification theories start.

GR explains the behaviour of space-time and matter on cosmologically large scales and of very dense compact astrophysical objects. GR is based on the Einstein's Equivalence Principle (EPP) which in its purest form states that:

I. *Weak Equivalence Principle (WEP)*: The trajectories of freely falling test bodies are independent of their structure and composition;

II. *Local Lorentz Invariance (LLI)*: In local freely falling frames, the outcome of any non-gravitational test experiment is independent of the velocity of the frame;

III. *Local Position Invariance (LPI)*: In local freely falling frames, the outcome of any non-gravitational test experiment is independent of where and when in the universe it is performed.

For at least half a century after its first formulation, Einstein's theory of general relativity has been considered as "a theorist's paradise, but an experimentalist's hell" [RD02]. No theory was in fact more beautiful and at the same time more difficult to test. A century later the technology and the scientific progress became mature to challenge general relativity with tests based not only on astronomical observations, but also on laboratory experiments. Recently, the spectacular first direct detection of gravitational waves from black holes has added one more jewel to the scientific crown of GR.

QM on its hand, accounts for the behaviour of matter at small scales (nanometers and below), and ultimately leads, together with special relativity, to the so-called Standard Model of strong and electroweak interactions accounting for all the observable known forms of matter.

Clocks exhibiting high stability and high accuracy can be used to perform precision tests of LLI and LPI [RD44, RD45]. WEP experiments based on matter-wave interferometry can be seen as a first and non-trivial attempt in interpreting the free fall of microscopic quantum objects and more generally Einstein's general relativity in the framework of quantum theory.

Clocks and matter-wave interferometers based on cold-atom samples have already demonstrated excellent performances for the accurate measurement of time, of tiny rotations and accelerations, and for the detection of faint forces. So far, their use has been limited to ground, the Earth's surface. These instruments have opened new fascinating perspectives for testing general relativity as well as alternative theories of gravitation, for studying quantum mechanics, and exploring the boundaries of quantum gravity.

Space can be an ideal environment for improving the performance of precision instruments and for pushing measurement accuracy to the limits. With a suitable spacecraft and orbit, Space can ensure:

- Infinitely long and unperturbed "free fall" conditions;
- Long interaction times;
- Quiet environmental conditions and absence of seismic noise;
- Huge free-propagation distances and variations in altitude;
- Large velocities and velocity variations;
- Large variations of the gravitational potential.
- Access to a large part of the surface of Earth

Therefore, a space-based laboratory is in principle able to provide unique experimental conditions, necessary to exploit the ultimate limits of quantum sensors. It can provide measurement accuracy levels not accessible on ground.

On the ISS, due to its intrinsic characteristics, only some of the above features are available in unrestricted form. For example, vibrational noise is present, and the variations in altitude and gravitational potential are very limited. Nevertheless, the ISS also provides advantages to researchers, such as the possibility to have a medium-size payload installed, which is the case for the proposed mission.

2.2 I-SOC-PF Science Case

Einstein's theory of general relativity is a cornerstone of our current description of the physical world. It is used to describe the flow of time in presence of gravity, the motion of bodies from satellites to galaxy clusters, the propagation of electromagnetic waves in the presence of massive bodies, and the dynamics of the universe as a whole. Indeed, the measurement of general relativistic effects is very challenging, due to their small size [RD03].

Although very successful so far, general relativity, as well as numerous other alternative or more general theories of gravitation, are classical theories. As such, they are fundamentally incomplete, because they do not include quantum effects. A theory solving this problem would represent a crucial step towards the unification of all fundamental forces of Nature. Several approaches have been proposed and are currently under investigation (e.g. string theory, quantum gravity, extra spatial dimensions) and all of them tend to lead to tiny violations of basic principles. Therefore, a full understanding of gravity will require experiments able to determine its connection with the quantum world. This topic is a prominent field of activity and includes the current studies of dark energy.

Precision experiments for testing the assumptions and predictions of general relativity can be performed on scales ranging from the laboratory to the solar system, in the latter case using satellites, spacecraft, or the orbiting Earth. The implementation of tests with significantly improved sensitivity obviously requires the use of state-of-the-art sensors, at least as far as it is compatible with the boundary condition of the experiment, e.g. space-compatible systems in case of satellite-based experiments.

I-SOC-PF is designed to test aspects of the Einstein Equivalence Principle related to the flow of time using quantum sensors, namely atomic clocks. Its results can be interpreted as tests of general relativity and other metric theories of gravity and as tests for the existence of new fields associated to matter.

The outcome of the I-SOC-PF mission will be either a confirmation of one of the foundations of general relativity within the accuracy provided by the instruments, or the discovery of a deviation. In the latter case, the mission would provide a first indication of the breakdown of current (classical) gravitational physics theories and could pave the way towards a unified theory of all forces.

I-SOC-PF can perform three main experiments with significantly improved accuracy.

Gravitational time dilation tests

One of the most fascinating effects predicted by general relativity and other metric theories of gravity is the Einstein's gravitational red-shift or gravitational time dilation (GTD) effect. As direct consequence of Einstein's Equivalence Principle, time runs (or clocks tick) more slowly near a massive body, the gravitational time dilation (or clock frequency red-shift). This effect can be detected when comparing identical time intervals, but measured by clocks placed at different positions in a gravitational field. The measurements consist of counting the number of the ticks of the respective clocks. The effect results in a different number of ticks measured by two clocks located at different gravitational potentials. Equivalently, one can describe the effect by stating that the frequencies of the ticks, as observed at an arbitrary location, differ.

In general, time and frequency can be transferred between locations by using electromagnetic waves directly generated from the local clock and transmitted to an arbitrary detection position x'.

Consider two identical clocks (i=1, 2), therefore having an identical oscillation frequency when operating side-by-side. When they are operated at different locations x_1 and x_2, the measurement of their frequencies at an arbitrary detection position x' yields a frequency ratio:

$$\frac{\nu_2(x')}{\nu_1(x')} = 1 + \frac{U(x_2) - U(x_1)}{c^2}. \qquad (1)$$

Here, $\nu_i(x')$ is the frequency of clock i located at x_i, as observed (measured) at the particular location x' where the comparison between the two clocks takes place (see Figure 2-1). U is the gravitational potential, which in case of a spherically symmetric body of mass M is given by $U(x) = -GM/|x|$, if GR is valid. Equation is a simplification, valid for stationary clocks and observers and for weak gravitational fields. According to Einstein's theory of general relativity, this frequency ratio is universal, i.e. it is independent of the nature of the clocks and of the type (composition) of the mass M. In addition, it is independent of x'.

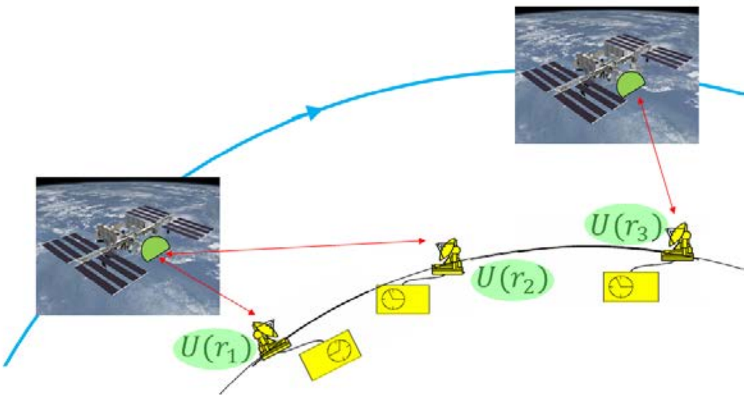

Figure 2-1: The two-way link of I-SOC-PF (red double arrows) will be used to compare the space clock to clocks on the ground located e.g. at r_1, r_2 and r_3. Specifically, it will allow to compare two clocks on the ground

in common-view (at close locations r_1 and r_2), and clocks in non-common-view (at distant locations r_1 and r_3). In this case, the ISS sequentially and individually communicates to two clocks, first at location r_1 and later at location r_3. In this latter case, the I-SOC-PF on-board clock serves as a local oscillator that transports both the value of the r_1 clock frequency and a time marker received from r_1 further on.

I-SOC-PF searches for a possible violation of the gravitational red-shift prediction (Eq. 1) specifically in the gravitational field of the Sun and the Moon. A search in the gravitational field of the Earth will be done by the ACES mission.

Such a violation may be described phenomenologically by a dependence on the gravitational potential of one or more of the fundamental constants X that determine the clock frequency: $X = X(U/c^2)$, where X is a generic dimensionless fundamental constant or a dimensionless combination of fundamental constants. Such dependence would correspond to a violation of the principle of Local Position Invariance.

In the Standard Model there are three fundamental dimensionless parameters determining the structure and energy levels of stable matter (atoms, molecules): the electromagnetic fine-structure constant α and the ratios $X_{e,q}=m_{e,q}/\Lambda_{QCD}$ of the electron mass m_e and the light quark mass m_q to the QCD (Quantum ChromoDynamics) energy scale Λ_{QCD}. The fundamental masses m_e and m_q are proportional to the vacuum Higgs field which determines the electroweak unification scale. Therefore, the constants $m_{e,q}/\Lambda_{QCD}$ can also be seen as the ratio of the weak energy scale to the strong energy scale.

Extensive studies of atomic and molecular spectra of gas clouds in the distant universe are currently undertaken to search for a difference of these constants compared to today's values (see RD04, RD05, RD06, RD07, RD08 and references therein). Also, some differences between Big Bang nucleosynthesis data and calculations can be naturally explained by a variation of fundamental constants (see RD09, RD10 and references therein).

How can a space-time variation of the fundamental constants and a dependence on the gravitational potential may occur? Light scalar fields very naturally appear in modern cosmological models, affecting the Standard Model parameters α and $m_{e,q}/\Lambda_{QCD}$. One of these scalar fields is dark energy, which causes the accelerated expansion of the Universe. Another hypothetical scalar field is the dilaton, which appears in string theories together with the graviton [RD13]. Cosmological variations of these scalar fields could occur because of drastic changes of matter composition of the Universe. During the Big Bang nucleosynthesis the Universe was dominated by radiation, then by cold dark matter, and now by dark energy. Changes of the cosmic scalar field $\varphi_0(t)$ lead to the variation of the fundamental constants $X(\varphi_0)$. Massive bodies (galaxies, stars, planets) can also affect physical constants. They have large scalar charge S proportional to the number of particles $S=s_p \cdot Z+s_e \cdot Z+s_n \cdot N$, where Z is the number of protons and of electrons and N is the number of neutrons; s_p, s_e, s_n are the scalar charges of protons, electrons, and neutrons respectively. In addition, there is also a contribution of the nuclear binding energy (scalar charge of virtual mesons mediating nuclear forces). The scalar charge produces a Coulomb-like scalar field $\varphi_s=S/R$, where R is the distance from the massive body.

The total scalar field $\varphi=\varphi_0+\varphi_s$ can therefore induce variation of the fundamental constants inversely proportional to the distance R from massive bodies,

$$X(\varphi) = X(\varphi_0 + \varphi_s) = X(\varphi_0) + \delta X(R),$$
$$\delta X(R) = dX/d\varphi \cdot S/R.$$

A nonzero δX would correspond to a violation of the Local Position Invariance principle. The gravitational potential $U(R)=-GM/R$ is proportional to the number of baryons $Z+N$ and inversely proportional to the distance. Therefore, the change of fundamental constants near massive bodies can be written as

$$dX/X = K_{X,i} \cdot \delta\left(U_i / c^2\right),$$

where the index i refers to a particular composition of the mass M. The coefficients $K_{X,i}=-(dX/d\varphi)\cdot S_i/GM_i$ are not universal. Indeed, as the Sun mostly consists of hydrogen, its scalar charge is $S_{\text{Sun}}\sim Z\cdot(s_p+s_e)$. On the contrary, the Earth contains heavier elements where the number of neutrons exceeds the number of protons ($N\sim 1.1\cdot Z$). Therefore, the scalar charge of the Earth, $S_{\text{Earth}}\sim Z\cdot(1.1\cdot s_n+s_p+s_e)$, is sensitive also to the neutron scalar charge and to the contribution of the nuclear binding.
When the frequencies of two identical clocks (of nominal frequency ν_0) at different locations are compared, Eq. becomes

$$\frac{\nu_2(x')}{\nu_1(x')} = 1 + \left[1 + \sum_X A_X K_{X,i}\right] \cdot \frac{U(x_2) - U(x_1)}{c^2},$$

where the factor $A_X = X\cdot(d\ln\nu_0/dX)$ provides the sensitivity of the clock frequency to a particular constant X and can be calculated by using atomic and nuclear theory [RD08].
In this way, the results of space-to-ground comparisons of clocks can be given as a limit for (or nonzero values of) $K_{X,\text{Earth}}$, with X being a known combination of the three fundamental constants m_e/Λ_{QCD}, m_q/Λ_{QCD}, and α. The comparison of clocks on ground (null solar GTD experiment) will give limits to $K_{X,\text{Sun}}$.
A similar argument can be made for the Moon GTD. The important observation here is, that the nuclear composition of the Moon differs from that of the Earth and of the Sun. A Moon GTD measurement is therefore complementary to that of Earth or Sun.

The Earth GTD was measured with $1.4\cdot 10^{-4}$ inaccuracy in the 1976 Gravity Probe-A experiment [RD14] by comparing a ground clock with a clock on a rocket as the height changed. The best-performing clocks available at the time, hydrogen masers, were used for this experiment. The ACES mission, planned to fly on the ISS in the 2021+ timeframe, seeks to improve this test by a factor of approximately 70, by using the a cesium cold atom clock [RD15]. Tests with precision improved compared to Gravity Probe-A have also been performed by analyzing data of Galileo satellites on erroneous (elliptic) orbits (2019).

I-SOC-PF will not be equipped (for cost reasons) with an accurate onboard atomic clock, therefore it cannot accurately measure the Earth GTD. However, it is well suited to measure the Sun and Moon gravitational time dilation, a measurement originally proposed in connection with the STE-QUEST mission proposal. This measurement will be fully complementary to the Earth gravitational time dilation determination.
Because the effect is small, extremely stable ground clocks are required. Today (2020), a few ground clocks (Europe, Japan, USA) have already reached an inaccuracy of $1\cdot 10^{-18}$. Because the activity in the field of optical clocks is increasing, by the time of the I-SOC-PF mission in 2023, it is likely that the best clocks will have further improved to the level of few times 10^{-19}.
These clocks, in combination with I-SOC-PF, will enable a test of the Sun and Moon GTD at a very attractive level, at fractional inaccuracies in the 10^{-5} and 10^{-3} range, respectively. In

comparison, the best current results for the Sun GTD are at the few % level [RD11,RD12]. To our knowledge, the tiny GTD caused by the Moon has so far not been measured. A test theory allowing interpreting these measurements has been developed [RD18].

Dark matter

Correlations between frequency fluctuations of atomic clocks can indicate the interaction of dark matter topological defects with the conventional matter that clocks are made of [RD19,RD20]. In order to detect topological defects as they cross the Earth (with putative velocity $v_g \approx 230$ km/s), it is very helpful to provide a means to intercompare ground clocks as frequently as possible.
First, I-SOC-PF will be important in supporting the development and performance tests of ground clocks, as they are being refined towards achieving best performance.

I-SOC-PF can also play a role in the direct detection of dark matter, in the following scenario. Consider a dark matter defect of size *smaller* than the Earth. After it has passed through the Earth, it will have produced a permanent phase shift (i.e. a time offset) in some clocks and no phase shift in others, depending on their overlap with the defect. This residual, permanent shift can be measured by I-SOC-PF, after the defect is gone. Thus, the I-SOC-PF mission can contribute to the search for dark matter.

One can also consider real-time detection scenarios. Suppose two clocks are in common-view with I-SOC-PF at a particular moment when a dark matter defect passes through only one of them. I-SOC-PF can in principle measure this effect. But because this situation is relatively improbable (the number of clocks on the ground being moderate) and because the duration of such intercomparisons may be short, this particular configuration may be of limited utility. Therefore, the comparison of “nearby” clocks is better performed by other means, e.g. long-distance fiber links.
I-SOC-PF in non-common-view mode is also not useful because v_g is much larger than the ISS orbital velocity (approx. 8 km/s) and so the defect is gone before the ISS performs the comparison.

Test of Local Position Invariance

One type of tests of this principle involves testing whether the fundamental constants are indeed time-independent. With every new generation of clocks these tests are repeated, taking advantage of the increased accuracy. These developments occur in widely separated laboratories, and it is usually not possible to compare the clocks in these laboratories with sufficient accuracy, except for the national metrology institutes in Western Europe (F, D, I, UK) which are linked by a fiber link.
With I-SOC-PF, clocks in all countries can be intercompared at the $1 \cdot 10^{-18}$ level. Here, the mission will make an important contribution to increase the rate of progress in this field of fundamental physics.

2.3 Additional Science with I-SOC-PF

I-SOC-PF has important applications in domains other than fundamental physics. In this section, we provide a list of topics that will be investigated by I-SOC-PF bringing a major scientific contribution in the field. With the present payload and platform capabilities, the following topics will be addressed:

Clock Comparisons and International Atomic Time Scales

Depending on application, several time scales are used which are routinely maintained by metrology institutes and international organizations. Universal Time (UT), derived from the observation of the Earth's rotation period, standardizes the biological time based on the day and night life cycle. On the other side, time scales can be built out of atomic clocks. As an example, we can mention the time scale disseminated by GPS satellites or the International Atomic Time scale (TAI). TAI is maintained by the Bureau International des Poids et Mesures (BIPM). It plays a major role as base of UTC (Universal Time Coordinated), recognized worldwide as the official international time, which differs from TAI by an integer number of leap seconds.
I-SOC-PF provides the means for connecting atomic clocks on the ground in a global network, enabling comparisons of ground clocks down to the 10^{-18} fractional frequency uncertainty level. Clock comparisons via I-SOC-PF will contribute to the realization of international atomic time scales and to improvement of their stability and accuracy. Synchronization of clocks, space-to-ground and ground-to-ground, to the 20 ps level using ELT+ will allow the distribution of such time scales to unprecedented performance levels.

Geodesy

The mission also provides a new tool for mapping the gravitational potential on the Earth's surface within continents and between continents, with high spatial resolution and at a high level of accuracy (down to 0.15 cm of differential height over the geoid). This is achieved through the measurement of the differential gravitational shift between two ground clocks with up to $3\cdot10^{-19}$ fractional frequency uncertainty. Common-view and non-common-view comparisons of ground clocks, transported to all continents and to several locations per continent, provide direct information on the geopotential differences at the locations covered by the ground clocks. I-SOC-PF will therefore contribute to establishing a global reference frame for the Earth gravitational potential and a unified height system. Such a height system is key for accurate long-term tracking of height- and gravity-related quantities like sea level rise or groundwater loss. Due to its unique high spatial and temporal resolution, this method is complementary to current and future gravity space geodetic missions such as CHAMP, GRACE and GOCE as well as to altimetry missions like JASON and Envisat in contributing to the Global Geodetic Observing System (GGOS).

Optical and Microwave Ranging

The simultaneous operation of two links in two different frequency domains (microwave and optical) allows the cross-comparison of different ranging techniques, including one-way optical ranging, two-way optical ranging, and microwave ranging. The I-SOC-PF microwave link MWL is capable of a high ranging stability, while its accuracy would need to be calibrated against optical measurements. Such studies will be important for future missions operating both around the Earth and in deep space.
At the same time, atmospheric propagation delays due to both troposphere and ionosphere, which affect ranging at both microwave and optical frequencies, can be measured.

Investigations can include the tracking of the differences of mapping functions at optical and microwave frequencies.

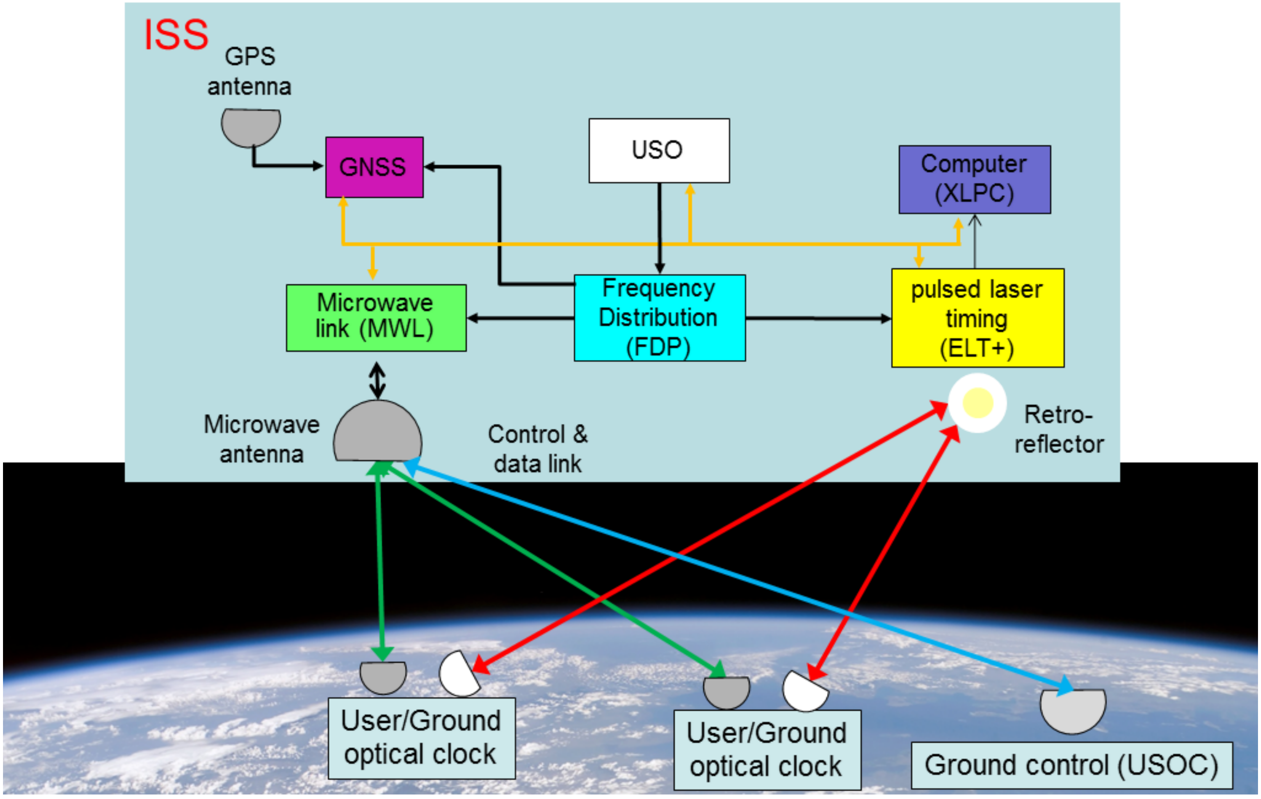

Figure 2-2: The I-SOC-PF payload and its links to ground. Some elements (e.g. Power distribution unit, PDU) are not shown).

2.4 I-SOC-Pathfinder mission overview

2.4.1 *Summary*

The I-SOC-PF instrument package consists of a clock (actually, an ultra-stable oscillator, (USO) a maser), and two different links of highest performance (red and green arrows in Figure 2-2). Key properties:

Instrument package:	External to ISS; nadir pointing
Estimated power, volume and mass:	Optical link, incl. GNSS, On-board computer (XLPC), frequency distribution (FDP): 7 kg/7 liter/30 W MWL: 33 kg/20 liter/110 W USO (H-maser): 60 kg/110 liter/60 W Temperature and magnetic field stabilization unit: 10 kg/20 liter/40 W

	Harness
Ground segment:	Laser ranging stations, stationary and mobile optical clocks with microwave terminals, reuse of ACES ground segment investments (software, ground antennae, ELT data center, commissioning experience, ground campaigns experience,...)
Host:	ISS. Payload could be attached to the Bartolomeo structure or to Columbus via the external payload adapter.
Mission duration:	3 years
Mission start:	The mission shall take place after the ACES mission, e.g. operations starting at the end of 2023;
Timeframe:	Mission completed by 2027

I-SOC-PF provides two measurement functions:

1. The USO can be synchronized with a particular ground clock, enabling the latter's time/frequency to be distributed to other locations on ground, anywhere in the ISS visibility domain, via the links. This allows comparing distant terrestrial clocks (i.e. not in common-view of the ISS).
2. When two or more clocks are in common-view of the ISS, they can be compared simultaneously with the USO. The instability due to the USO is then in common mode and is therefore rejected.

These comparisons will allow I-SOC-PF to perform a search for time variations of fundamental constants (by enabling comparisons of close and distant ground clocks), tests of the Standard Model Extension, and contribute to a search for dark matter interacting with ground clocks. Furthermore, I-SOC-PF will also develop high-performance applications in different areas of research including geodesy and Earth observation.

I-SOC-PF consists of the following elements:

- The I-SOC-PF Payload including
  - The I-SOC-PF Instrument:
    - USO (an active H-maser)
    - MicroWave Link (MWL)
    - European Laser Timing (ELT+) optical link
  - The PL support subsystems:
    - Frequency Distribution Package (FDP), including backup USO
    - GNSS receiver
    - eXternal PayLoad Computer (XPLC)

- o Power Distribution Unit (PDU)
- o Dedicated operation software, mechanical, thermal, and harness
- The Columbus External Payload Adapter (CEPA), developed by NASA/Boeing; alternatively, adapter to Bartolomeo platform.

- The Launcher/Carrier, the ISS on-orbit transportation elements.

- The ESA Columbus laboratory with the selected payload location and the corresponding Columbus Payload Integration (CPI) activities. Alternatively: Bartolomeo platform.

- The end-to-end mission operations and ground segment consisting of:
  - NASA operations and ground segment
  - Columbus ground segment, represented by the Columbus Control Centre (CCC)
  - I-SOC-PF ground segment, including
    - o The I-SOC-PF User Support and Operation Center (USOC), installed at TBR-01
    - o The distributed User Ground Stations (UGS)
    - o The I-SOC-PF data analysis center installed at TBR-02

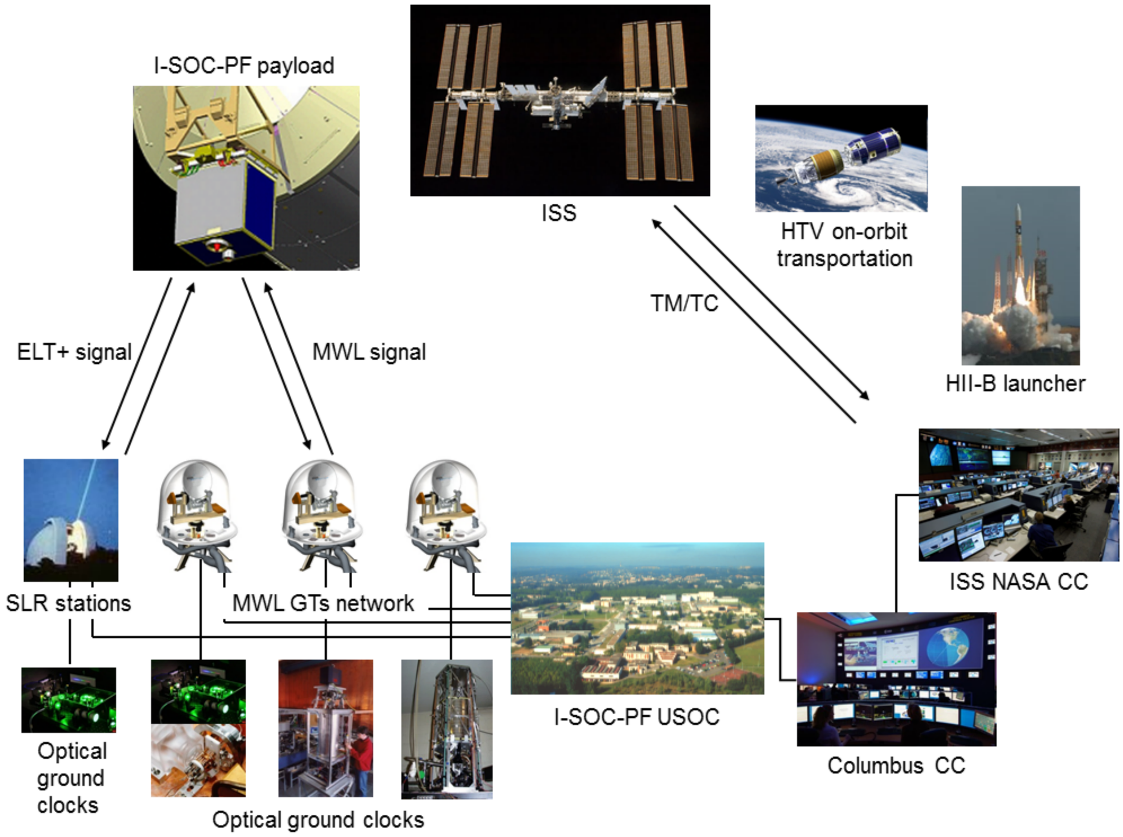

Figure 2-3: The I-SOC-PF mission elements.

2.4.2 *Key On-board Instruments*

The clock is an active hydrogen maser of high performance. The preferred instrument is the maser developed for the space mission MILLIMETRON [RD43] by the Russian company VREMYA-CH (see Annex). It can be obtained at moderate cost through agreement with the Lebedev Physical Institute (Moscow).

The maser exhibits a demonstrated fractional frequency instability of $5 \cdot 10^{-16}$ on the timescale 1 hour [RD42]. As all masers, it has a systematic frequency offset of order 10^{-13}, and a long-term drift at the low 10^{-14}/day level. However, both these properties do not impact the mission. The maser lifetime is 10 years in space.

The FDP distributes the clock signal to two time/frequency transfer systems (the links).

All data handling processes are controlled by the eXternal PayLoad Computer (XPLC): it receives data and status information from the subsystems, controls the subsystems by sending high-level commands, transmits data and information to ground, and receives commands from ground.

The mission will connect approximately 10 stationary optical atomic clocks (in national metrology laboratories and on additional reference sites) on ground and 3 – 4 transportable optical clocks (Figure 2-4) in a worldwide network and nearly continuously compare them with each other using the precise time/frequency transfer links.

At least 5 transportable optical clocks are in different stages of development today (2020) [RD24,RD26,RD27]. The transportable clock of Physikalisch-Technische Bundesanstalt (Germany) has already been transported to several locations, implementing measurement campaigns [RD25].

The links are upgrades to those already developed for the ACES mission: the microwave link MWL, and the pulsed optical link ELT+. The TRL of the former (HERO) is 4 by 2020; the latter is 6 to 9.

The comparisons can be carried out with the two clocks in common-view or in non-common-view of the ISS. In the common-view case, there is no need for a high-performance on-board clock.

In the non-common-view comparisons, on the contrary a low instability of the USO is essential; the performance of such comparisons will be limited by it.

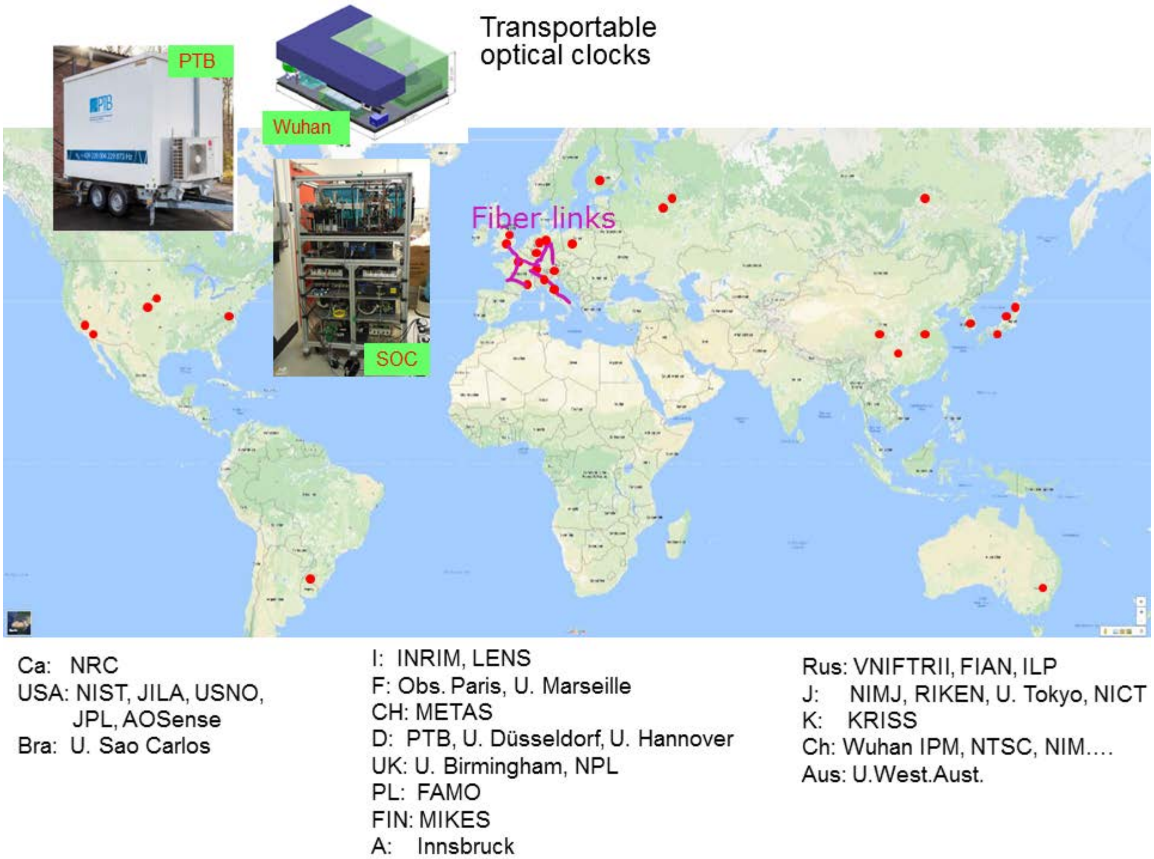

Figure 2-4
(Top) Locations with stationary high-accuracy clocks, as of 2016. The photographs show the transportable clocks [RD24,RD26,RD27].
(Bottom) The present status and future development of fiber-optical links in Europe (from[RD28]): Frequency links (green), frequency links commissioned (yellow) and time links (blue). AOS, Astrogeodynamic Observatory in Borowiec near Poznan, Poland; BEV, Bundesamt für Eich- und Vermessungswesen, Vienna, Austria; GUM, Główny Urząd Miar — Central Office of Measures, Warsaw, Poland; INRIM, Istituto Nazionale di Ricerca Metrologica, Turin, Italy; LNE-SYRTE, Laboratoire National de Métrologie et d'Essais — Système de Références Temps-Espace, Paris, France; MPQ, Max Planck Institute for Quantum Optics

Garching/Munich, Germany; NPL, National Physical Laboratory, Teddington, UK; Nikhef, National Institute for Nuclear and High-Energy Physics, Amsterdam, the Netherlands; PTB, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany; SP, Technical Research Institute of Sweden, Boras, Sweden; UFE, Institute of Photonics and Electronics of the Czech Academy of Science, Prague, Czech Republic; VSL, Dutch National Metrology Institute, Delft, the Netherlands; VTT, VTT-MIKES Metrology, Espoo, Finland. Image from Google Earth, US Dept of State Geographer, © 2016 Google, Image Landsat, Data SIO, NOAA, US Navy, NGA, GEBCO.

2.4.3 *Orbit*

I-SOC-PF will be operated on the ISS. The ISS mean altitude is approximately 400 km, with approximate 90 min period and an inclination angle of 51.6 degree. The altitude is not constant, decreasing with a rate in the range 0.5 - 2 km/month due to atmospheric drag, which is compensated with repeated orbit lift maneuvers. The altitude variation and altitude uncertainty are relevant to a certain extent and are therefore monitored by the GNSS receiver and by satellite laser ranging.

2.4.4 *Mission duration*

The planned mission duration is 36 months with the possibility of extending it. During the first 6 months (at most), the performance of the USO and of the links will be established.
In the remainder of the mission, the on-board clock will be run in an optimal configuration and perform a large number of comparisons of ground-based clocks operating both in the microwave and the optical domain.
During the whole mission duration, common view and non-common view comparisons of ground clocks will be performed. The longer the mission duration, the larger the number of such comparisons is and the larger the science output will be. For the geodesy measurements and the dark matter search the science gain is more than proportional to mission duration, since we expect more and more high-performance ground atomic clocks to become operational. For the measurement of the Sun and Moon GTD effect the gain is at most proportional to the square root of mission duration. Finally, for the goal of technology demonstration (long-term effects of space on the links), a long mission is obviously favorable.

3 I-SOC-PF SCIENTIFIC OBJECTIVES

In this section, the I-SOC-PF scientific objectives are enunciated.
For each scientific objective, the performance evaluation by simulations and numerical models is described in order to demonstrate compliance of the mission performance to the scientific objectives.
The state-of-the-art is also discussed, reporting present techniques and performance levels, the proposed measurement strategy adopted in the frame of the I-SOC-PF project, and the improvements expected with respect to available experimental results.

3.1 Primary Scientific Objectives

The top level scientific objectives of the I-SOC-PF mission are in the fundamental physics domain. As discussed in Sec. 2.2, they address precision tests of the Einstein's Equivalence Principle. They are:

#PSO-01 Measurement of the Sun gravitational time dilation (red-shift) effect to a fractional uncertainty of $2.5 \cdot 10^{-5}$.

#PSO-02 Measurement of the Moon gravitational time dilation (red-shift) effect to a fractional uncertainty of $4 \cdot 10^{-3}$.

#PSO-03 Enabling world-wide searches for time variation of fundamental constants and tests of the Standard Model Extension.

For PSO-01, PSO-02, PSO-03 the improvement compared to the ACES mission is a factor 10 (thanks to better links plus better ground clocks).

Clock Comparisons and International Atomic Time Scales

#PSO-04 Contribution to the realization of atomic time scales to fractional frequency inaccuracy lower than $1 \cdot 10^{-18}$ and synchronized to the few ps level.

Improvement compared to ACES mission: factor 100 to 1000 (better links plus factor 10 from better ground clocks and factor 10 from larger number of measurements).

Geodesy

#PSO-05 Enable mapping of the geopotential on the land masses of North America, South America, Africa, Europe, Asia, Australia, with approximately 300 km × 300 km grid size using transportable $1 \cdot 10^{-18}$ clocks, with a resolution of 0.15 m^2/s^2 (1.5 cm on the differential geoid height).

Improvement compared to ACES mission: factor 10 000 (factor 1000 from larger number of measurement points and factor 10 from higher resolution).

#PSO-06 Inter- and intracontinental differential geopotential measurements with resolution in the gravitational potential U at the level down to 0.05 m^2/s^2 (0.5 cm on the differential geoid height).

Improvement compared to ACES mission: factor 100 (factor 10 from larger number of measurement and factor 10 from higher resolution).

3.2 Additional Scientific Objectives

Clock Comparisons and International Atomic Time Scales

#SSO-01 Space-to-ground time transfer with inaccuracy lower than 50 ps via MWL and 30 ps (target: 20 ps) via ELT+.

#SSO-02 Synchronization of clocks on ground to better than 50 ps via MWL and 30 ps via ELT+ (target: 20 ps).

Optical and Microwave Ranging

#SSO-03 Cross-comparisons of different ranging techniques: one-way optical ranging, two-way optical ranging, microwave ranging.

#SSO-04 Measurement of the differential atmospheric propagation delays in the optical and microwave.

3.3 Scientific Performance

For the purpose of analysing the feasibility of the mission against its primary scientific objectives, a measurement concept based on the reference payload design has been identified. Text [in blue] refers to the scientific requirements listed in Sec. 3, derived from and relative to this reference payload.

3.3.1 *Clock Measurements*

The gravitational potential U for both ground and space clocks is a sum of three major contributions coming from Earth, Sun, and Moon:

$$U(\boldsymbol{r}) = U_{\text{Earth}}(\boldsymbol{r}) + U_{\text{Sun}}(\boldsymbol{r}) + U_{\text{Moon}}(\boldsymbol{r}). \tag{2}$$

For simplicity, here and hereafter, we omit a relativistic Doppler shift term that occurs for Earth-bound clocks (related to the spin of the Earth) and for the I-SOC-PF clock (related to ISS motion. Since the variations of the individual contributions with the position $\boldsymbol{r}$ of the satellite or of the ground stations have different signature, it is possible to independently determine them and therefore measure each of the three time dilation effects. The Moon and Sun time dilation measurements rely on ground-to-ground comparisons.

(I) The fundamental measurement event is shown in Figure 3-1. The clock on the ISS is compared with a particular clock on ground. The typical duration of an ISS pass above a ground station in Europe is about 300 s. The measurement yields the frequency ratio ν_{gc}/ν_{ISOC}. This value arises from a complex procedure involving corrections stemming from the velocities of the ground and satellite clocks (leading to second-order Doppler effects) that need to be evaluated.

(II) I-SOC-PF allows the comparisons of distant ground clocks via non-common-view comparisons (Figure 2-1). Here, the ISS and the I-SOC-PF instruments are in contact with only one ground clock at a time.
Such comparisons allow a measurement of the time dilation in the gravitational field of the Sun and the Moon (Figure 3-2). Here, the frequency ratio ν_{gc1}/ν_{gc2} of two ground clocks is measured repeatedly. The two clocks are as far apart as possible in East-West direction, i.e. on different continents. With frequent comparisons, ideally one comparison per orbit (92 min; in practice less frequently), an extended time series of frequency ratios can be obtained that will allow identifying any ~12 h modulation due to the effects of Sun and Moon (the period of the effect differs slightly for the two bodies and so the two effects can be disentangled given a sufficiently long time series).

The comparison is expected to yield zero modulation amplitude, due to the fact that the Earth is in free fall in the field of the Sun and the Moon. However, after subtracting from the data the second-order Doppler effect due to Earth motion (which can be measured independently and/or modelled), the GTD modulations due to the Sun and to the Moon field can be extracted. Sun and Moon contributions can be distinguished due to their different time signatures.
The same measurement data can also be applied to relativistic geodesy and synchronization of ground clocks.

(III) The I-SOC-PF time and frequency transfer links also allow for the common-view comparison of terrestrial clocks (Figure 2-1). In the common-view technique, two ground clocks are simultaneously compared to the space clock. The difference of simultaneous measurements then provides a direct comparison of the two clocks on the ground. This measurement does not require a high-performance frequency reference on-board the I-SOC-PF payload. Indeed, the frequency noise of the space clock, which appears as common mode in the two simultaneous link measurements, is rejected to high degree when the difference of the two space-to-ground comparisons is evaluated.
This measurement mode is also used for geodesy and synchronization of ground clocks.

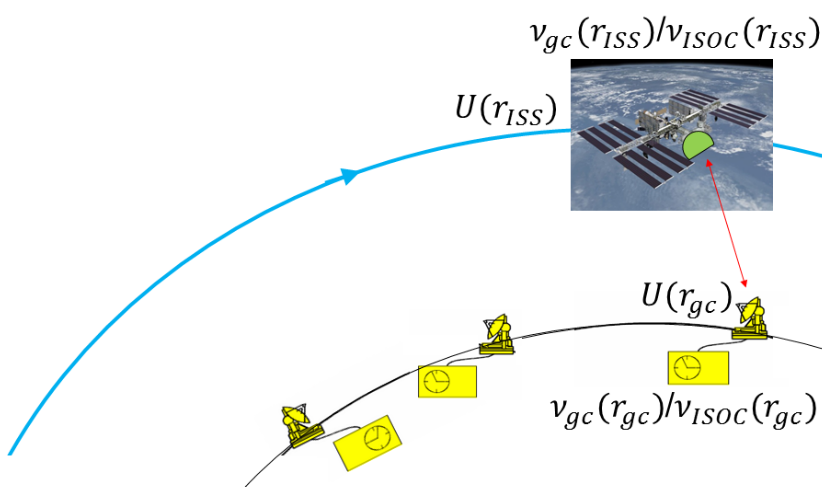

Figure 3-1: Clock comparison between ground and the ISS USO. During the relatively short fly-over of the ISS over the ground clock, the frequency ratio between the two clocks can be measured. This ratio is obtained both at the ground clock location $\boldsymbol{r}_{gc}$ and at the ISS location $\boldsymbol{r}_{ISS}$. The two ratios will be the inverse of each other, differing from unity due to the Earth GTD and the relativistic Doppler shift (ground and ISS velocities are not indicated in the figure). In a similar way, time transfer from ground to space is effected.

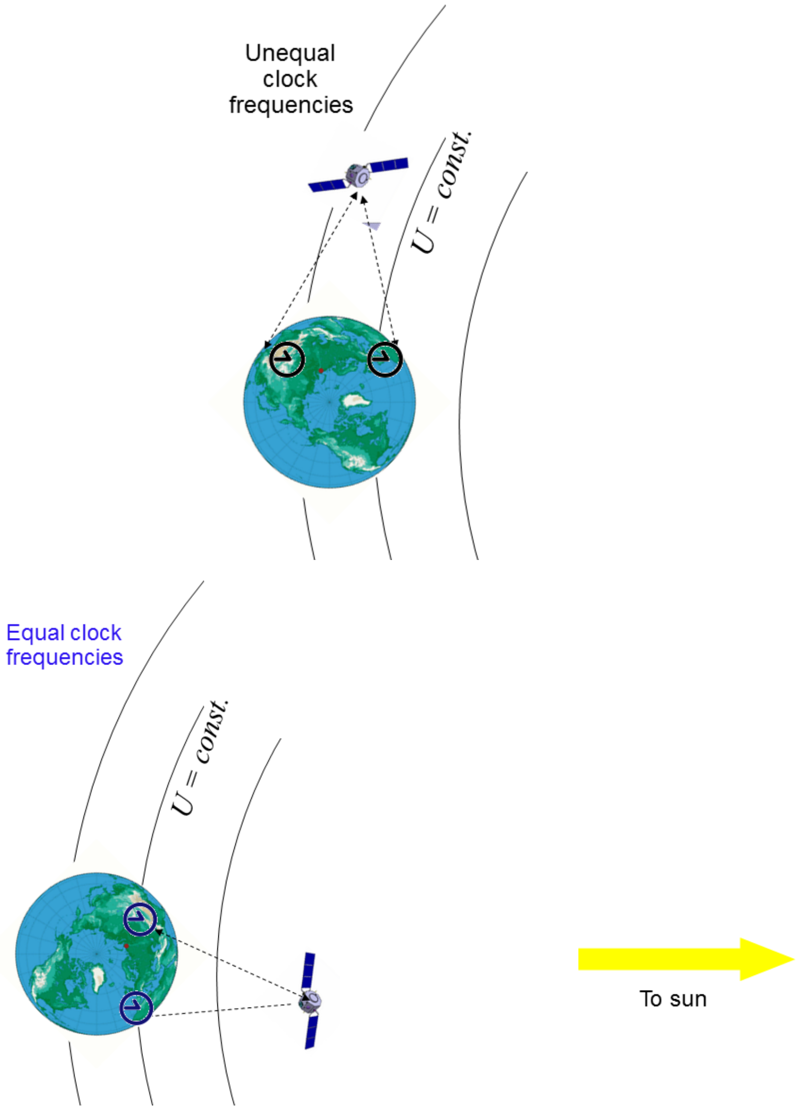

Figure 3-2: Measurement principle of the gravitational time dilation effect in the field of the Sun. Two snapshots of the orientation of a pair of clocks w.r.t. the Sun are shown. **Left**: the two clocks experience different solar gravitational potential. **Right**: the clocks experience the same gravitational potential. If the Earth center would be fixed in space, still allowing rotation around its axis, the clock frequency ratio would differ between the two orientations. Because the Earth is in free-fall in the Sun's field, the effect is nulled because of the additional effect of the relative RDS, thus satisfying the Equivalence principle. The location of the satellite is only schematic. In reality, the clocks are compared in non-common-view-mode. Due to the rotation of the Earth, the differential Sun GTD varies in time and is sampled by the non-common-view comparisons.

3.3.2 *Measurement Modeling and Assumptions*

The accuracy levels that can be achieved in gravitational time dilation tests and ground clock comparisons depend on the combination of several effects:

1. I-SOC-PF orbit and ground terminals positions:
   - ISS orbit;
   - Location of the microwave and optical link ground terminals;
   - Link visibility constraints;
2. I-SOC-PF operational constraints:
   - Mission lifetime;

- Orbital manoeuvres;
3. Clocks and links performance:
   - Instability and inaccuracy of the ground and space clocks;
   - Instability and inaccuracy of the links;
4. Relativistic effects:
   - Knowledge of ground and space clock positions and velocities;
   - Knowledge of the gravitational potential at the ground and space clock positions;

The constraints imposed by 1 to 4 are discussed in the following sections and included in the numerical simulations developed to verify the mission performance against the I-SOC-PF scientific objectives.

I-SOC-PF Ground Terminals Position

Ground stations, both fixed and mobile ones, will serve the mission.

(I) For the tests of the gravitational time dilation, the major metrology institutes having already today clocks with high accuracy are a suitable choice: Torino, Braunschweig, Paris, Teddington (all Europe), Boulder and Washington (USA), and Tokyo (Japan). In these centres, high-performance optical and microwave atomic clocks are operational today and will certainly be operational at the time of the I-SOC-PF mission.

(II) These institutes also require a regular comparison of their optical frequency standards for the purpose of generating an accurate time scale and for the search for a time variation of the fundamental constants.

(III) The ELT+ optical link requires at least one SLR station. In Europe alone, two such stations with connection to optical clocks are or will be available. The station in Borowiec (Poland) is already permanently connected to an optical clock at Copernicus University Torun (UMK) via a stabilised optical fibre link. The station in Wettzell (GOW) in Germany will be provided with a transportable optical clock. An important feature is that SLR Borowiec is in common view with SLR Wettzell. This will allow thorough testing of the time transfer and clock comparison. From these two stations, clock comparisons can be performed worldwide to other SLR stations. In particular, the SLR station near Washington is of interest, since it will be linked to the clocks of the US Naval Observatory.

(IV) The mobile microwave ground stations are chosen to perform a geodesy survey campaign with the aim of covering an area as large as possible.

The I-SOC-PF mission is open to additional groups joining as users. Indeed, there are research activities on high-performance optical clocks in progress in more countries than the above, including Korea and China.

A parameter to be taken into account is the visibility of the ground stations from the ISS. For the microwave link, 100% visibility is assumed, since microwave frequencies show only small sensitivity to weather conditions.

For the optical links, we assume 50% average probability that a given ground clock can be compared with the space clock when flies by and 25% average probability that a pair of ground clocks can perform a common-view comparison; these figures are compatible with historical weather data on clouds coverage at the baseline ground station locations.

In addition, both optical links are considered to be in full tracking mode at elevations higher than 30 degrees and lower than 85 degrees. Both the minimum and maximum elevations of optical links are limited by a number of factors: ELT+ optical receiver design, atmospheric transmission at lower elevations, available accurate atmospheric models for low elevations, backscattered background signal for zenith and very high tracking speed for elevations > 85 degrees. Therefore, the ground-ISS contact time is assumed to be 300 s at most for the microwave link and ~ 200 s for the optical link.

I-SOC-PF Operational Constraints

The duration of the I-SOC-PF routine science phase is at least 2.5 years [#SR-OP-01, #SR-OP-02]. During this phase, mission operations shall ensure the minimum measurement time needed for averaging the uncertainties in the clock GTD tests down to level stated as goals.

Clock Performances

The performance of the I-SOC-PF clock is specified in [#SR-PL-03] and [#SR-PL-04] to a fractional frequency instability not more than $5\cdot10^{-16}$ for the relevant integration time scale of 1 orbit period (for comparison with the same ground clock) and 0.5 orbit period (for comparison between maximally distant ground clocks).
Future ground clocks are here specified to have projected fractional frequency instability of $1\cdot10^{-16}/\tau^{1/2}$ [#SR-GS-01] and a fractional frequency inaccuracy of $3\cdot10^{-19}$ [#SR-GS-02].
Future mobile ground clocks are here specified to have projected fractional frequency instability of $2\cdot10^{-16}/\tau^{1/2}$ [#SR-GS-01] and a fractional frequency inaccuracy of $1\cdot10^{-18}$ [#SR-GS-02]. These values are Allan deviations. The modified Allan deviations shown in the figures (where the integration time τ is large) have values $\sqrt{2}$ times smaller.
Figure 3-3 shows the clocks' performances.

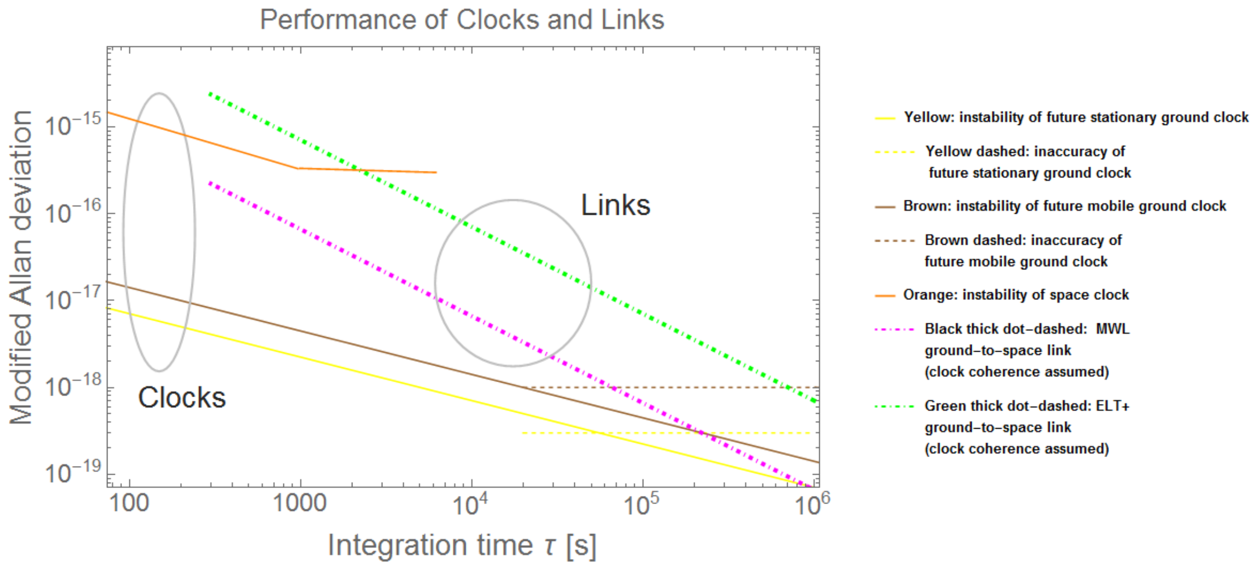

Figure 3-3: Performance of clocks and links. Here, clear weather conditions have been assumed for all ISS passes.

Link Performances

<u>Brief overview</u>

The two links of I-SOC-PF use different technology (optical vs. microwave). The inclusion of two different links is very desirable in order to allow comparing their performances and as an essential consistency check.
A very brief comparison with the links of ACES is that the expected stability performance will be a factor 8 (ELT+) and 150 (MWL) higher for I-SOC-PF. This is the result of technology improvements.
The improved MWL performances are being established in ongoing ESA industrial studies tailored on the I-SOC-PF mission proposal (see Annex). The improved ELT+ performances have already been established in tests (see Annex).

ELT+ and MWL will achieve synchronization of clock in common-view at the 10 ps and 20 ps (systematic) uncertainty level within 1 pass, respectively.

The ELT+ link will allow ground clocks frequency comparisons with fractional resolution of 1×10^{-18} reachable after approximately 10 days integration time, thanks to the long-term timing instability of 1 ps over 10^6 s.

The MWL link will allow reaching 1×10^{-18} after approximately 1 day integration time. This higher performance in terms of speed will allow performing more clock comparisons over the course of the mission than with ELT+ and therefore allow a higher science output.

Details

Requirements [#SR-PL-07] and [#SR-PL-14] define the fractional frequency instability of the I-SOC-PF microwave and optical links.

For ground-to-ground clock comparisons, the specified fractional frequency instability of the I-SOC-PF microwave link σ_{MWLgg} accounts for the following noise terms:

- White phase noise averaging down to $1.6 \cdot 10^{-14}$ after 10 s of integration time;
- Flicker phase noise with modified Allan deviation of $1.6 \cdot 10^{-13}/\tau$;
- Long-term performance $6 \cdot 10^{-17}/\tau^{1/2}$;
- Flicker floor at the $5.0 \cdot 10^{-19}$ level [#SR-PL-07];
- Inaccuracy is $5 \cdot 10^{-19}$ [#SR-PL-08].

For ELT+, TDEV is specified at 0.5 ps at 100 s, and <1 ps for longer times up to $1 \cdot 10^6$ s. At 300 s, the ISS contact time, we assume 0.5 ps.

Combining the ground and space segments, one can conclude that the precision obtainable within one pass of I-SOC-PF / ISS could be below 0.5 ps @ 100 s.
An overall timing stability ≈ 1 ps is expected for time intervals of up to 10^6 s. Thus, the best fractional accuracy possible with this method will be 1 ps/10^6 s = $1 \cdot 10^{-18}$ [#SR-PL-14], if a correspondingly stable local oscillator is on board.
The space-to-ground instability is equal to $\sigma_{link}(\tau) = \sigma_{MWLgg}(\tau)/\sqrt{2}$.
Figure 3-3 shows the I-SOC-PF links performance relevant for space-to-ground comparisons.

Orbitography

Orbitography requirements are defined in [#SR-PL-33], [#SR-PL-35], [#SR-PL-35], [#SR-GS-09, [#SR-GS-10], and further discussed below. These requirements have been derived to contribute negligible noise to the links and in modelling the gravitational frequency shift

and the second-order Doppler shift and therefore they will not be considered in the modelling of the clock comparison measurements.
The uncertainty in the evaluation of the relativistic correction due to the uncertainty of the orbit determination of space and ground clocks can be made smaller than that due to the space clock frequency uncertainty ($5 \cdot 10^{-16}$) if the orbit height uncertainty is less than 50 m. This may be deduced from the analysis of the ACES mission (clock accuracy $1 \cdot 10^{-16}$, 10 m height uncertainty), by a simple scaling argument.

Ground geopotential modelling

The uncertainty of the geopotential model has two contributions: from the static part and from the time-dependent part. In well-studied locations, such as Germany, the uncertainty of the static part is today approximately 0.1 to 0.3 m^2/s^2 (*0.1 m^2/s^2 is equivalent to 1 cm or $1 \cdot 10^{-18}$ clock inaccuracy*) [RD21]. The time-dependent contribution is dominated by the solid earth tides, approximately 5 m^2/s^2, but can be modelled at the level of 0.1 m^2/s^2 [RD23].
The uncertainty of the geopotential on the continental scale is e.g. 0.2 to 0.5 m^2/s^2 in Europe [RD22]. On the intercontinental scale the uncertainty is similar [RD23]. Thus, if the ratio of frequencies of two clocks on different continents is to be determined, the combined (factor $\sqrt{2}$) geopotential uncertainty of 0.3 to 0.7 m^2/s^2 will limit the inaccuracy to approximately $7 \cdot 10^{-18}$.
This limitation is where I-SOC-PF provides a major science opportunity. Employing ground clocks whose (natural, intrinsic) frequency ratio is known (e.g. equal to 1 if they are identical clocks), their comparison via I-SOC-PF allows a geopotential difference measurement with significantly better accuracy than today, namely to the 0.1 m^2/s^2 level.

3.3.2.1 Modeling of the link performance

The comparison of distant clocks is based on the transmission of time-tagged signals, coherently generated from the local clocks, from ground to space.
A ground clock and the space clock can be compared via a single leg of the link.
A ground clock can be compared with another ground clock using the common-view or the non-common view technique, depending on their distance.

The Common-View Technique

In this scheme, the two ground clocks, geographically close enough to be in common view with the ISS, are simultaneously compared to the same on-board time signal using two different link channels. The difference between the two space-to-ground comparisons provides the comparison of the two ground clocks.
Although a space clock is needed in the common-view comparison technique, *its frequency stability does not play a role as its noise contribution is in principle rejected in the differential measurement*. The level of rejection will however depend on the symmetry between the two channels of the link flight segment electronics.
Due to the low orbit of the ISS and the limited duration of each pass, the common-view technique will only be suitable for comparing ground clocks over relatively short distances, less than 1000 km. This has important applications for geodesy, in particular between transportable clocks. This method is not applicable for intercontinental comparisons.
The total noise in the common-view comparison has been introduced above as σ_{MWLgg} . It is equal to the quadratic sum of the noise contribution of the two space-to-ground links.
For the ground-clock-to-space-clock comparison, the noise of the link enters only once.

By repeating a common-view measurement of the frequency ratio of two clocks during N subsequent passes of the ISS, the statistical uncertainty of the mean frequency ratio can be reduced by a factor $N^{1/2}$ compared to that of a single measurement.
However, if the clocks run continuously during that time (meaning that effectively each clock has means to track the number of oscillations occurring during the whole measurement interval of N ISS passes), even a reduction by the factor N can be achieved. A necessary condition for this is that the clocks' oscillations must be *uninterrupted*.
The common-view technique requires that signals from two ground clocks can be received simultaneously on-board I-SOC-PF. In case of MWL, several channels can be implemented with modest extra cost. In case of ELT+, multiple ground systems may be operated simultaneously without any extra costs. The photon counting principle of ELT+ detection enables this mode of operation.

The Non-common-View Technique

A non-common view comparison between two ground clocks C_1 and C_2 takes place in two steps: C_1 is first compared to the I-SOC-PF time scale when in visibility with the space clock; the ISS then travels to the visibility cone of C_2 . This is represented by the dead time Δt. Then, a comparison between C_2 and the space clock follows. In a non-common view comparison, the space clock acts as a flywheel transferring the time scale from C_1 to C_2 over the dead time Δt. In this way, it is possible to compare clocks over intercontinental distances to a time resolution that will then depend on the link stability and on the time error accumulated by the space clock over the dead time.

A more sophisticated approach is described further below in the section on #PSO-01, p. 32.

An additional uncertainty is related to the relativistic correction to the time interval Δt as measured by the space clock. This correction has an uncertainty if the gravitational potential at the space clock location is not precisely known. With the on-board GNSS receiver, the orbit will be precisely monitored and the gravitational potential computed using the most precise potential models available.

The expected inaccuracy of comparisons of ground clocks in non-common view is therefore limited by the quadratic sum of the following uncertainties:

- The link noise (including signals distribution and link contribution) in the comparison between the I-SOC-PF clock and each ground clock. Over one ISS pass (~ 300 s) this term is:
    - MWL: 83 fs
    - ELT+: 0.5 ps (ground stations currently perform at 1 ps, and 500 fs is a realistic expectation for the near future)

For each link type, this noise is multiplied by $\sqrt{2}$ in case of a ground-to-ground comparison.

- The time error $\sigma_x(\tau)$ (TDEV) accumulated by the space clock over the dead time τ. It is calculated from the frequency instability $\sigma_y(\tau)$ as $\sigma_x(\tau) = (\tau/3^{1/2})$ Mod $\sigma_y(\tau)$; in the case of white frequency noise, Mod $\sigma_y(\tau) = 2^{-1/2}\,\sigma_y(\tau)$.

- The time error due to the I-SOC-PF signal distribution and link noise over the duration Δt between the two space-to-ground comparisons.

- The uncertainty in the evaluation of relativistic correction stemming from the errors in the orbit determination of space and ground clocks and in the geopotential model. This is considered negligible, because of the comparatively high instability of the USO.

The total time uncertainty can be converted into a fractional frequency uncertainty by dividing by τ. This is further elaborated on below in the section on #PSO-01.

3.3.2.2 Evaluations

An approximate computation of the expected inaccuracy of the various clock comparisons proceeds in two steps.
First, the clock and link inaccuracies are computed in the way as described above, without including the relativistic corrections. Thus, the values obtained represent the best possible case.
Second, from the values, we derive the requirements concerning the uncertainty of the relativistic corrections, i.e. of orbit determination and of geopotential values on ground and in space. We then discuss the feasibility of achieving these requirements.

3.3.2.3 Results

#PSO-01: *Measurement of the Sun gravitational time dilation effect to a fractional uncertainty of 2.5 $\cdot 10^{-5}$*

This measurement tests for a source-mass dependence of the time dilation effect, which could arise from an anomalous coupling of matter to the Standard Model quantum fields. It may also be interpreted as a search for the neutron's scalar charge.
The gravitational red-shift effect induced by the Sun is measured by comparing ground clocks in non-common-view. The Sun field contribution varies according to the orientation of the ground clock pair with respect to the Earth-Sun direction. Figure 3-2 shows the two examples of orientations of a clock pair with respect to this direction. This effect has a 24-h period and a **peak-to-peak amplitude of about $1 \cdot 10^{-12}$ between two clocks located on opposite sides of the Earth**.
As the ground clocks are in free fall with respect to the Sun, the dilation effect is actually cancelled [RD17]. Indeed, according to the Equivalence principle, "free fall" means that gravitational effects of the source mass are not discernible in the free-falling frame of reference, here the Earth. The cancellation occurs between the GTD effect and the second-order Doppler shift due to the motion of the ground clocks relative to each other [RD17]. Nevertheless, the measurement of this null effect allows achieving the primary scientific objective #PSO-01 because the second-order Doppler shift responsible for this cancellation can be calculated from the measured clock velocity (and relying on independent experimental confirmation of the validity of Lorentz transformations and thus the formula for the second-order Doppler shift) with at least the same accuracy and so the actual Sun GTD deduced from the (a priori) null result. See [RD18] for a detailed discussion of the effect.
During the time of the I-SOC-PF mission, ground clocks in the participating national metrology laboratories may have reached instabilities of $1 \cdot 10^{-19}$. Such a level would in principle enable a measurement of the Sun GTD with fractional uncertainty of $1 \cdot 10^{-7}$. In the following, we discuss whether such a level can indeed be reached.
The analysis of the Sun redshift test presented here is simplified and therefore assumes only two clocks on the ground [#SR-GS-04] with instability given by #SR-GS-01, connected to the space clock via two links with performance as specified in #SR-PL-07.

The statistical uncertainty of the frequency comparison in non-common-view mode is calculated by (following the approach used in the analysis of the ACES mission):

$$\sigma_y(\tau) \approx \frac{\sqrt{2}\sqrt{2\sigma_{x,link}(\tau_{contact})^2+2\sigma_{x,USO}(\tau_{contact})^2+\sigma_{x,USO}(T_{ISS}/2)^2}}{\tau}. \quad (3)$$

$\tau_{contact}$= 300 s is the ISS contact time. As opposed to the common-view case, here, the instability of the space clock (acting as a local oscillator), $\sigma_{x,USO}(\tau)$, does contribute substantially.

The equation is to be understood as follows (assuming the link is ELT+):
(a) the ground clock 1 is compared with USO during one pass of the ISS above the ground clock. The uncertainty has contributions: 0.5 ps from ELT+ and ($2{\cdot}10^{-15} \times 300$ s =) 0.6 ps from USO; the contribution from clock 1 itself is negligible.
(b) Then the ISS flies to the ground clock 2, employing half of an orbit period. This contributes an uncertainty of ($5{\cdot}10^{-16} \times 2700$ s =) 1.5 ps from USO;
(c) the comparison with ground clock 2 gives another 0.5 ps + 0.6 ps, as in (a).
The total uncertainty is dominated by USO and amounts to ≈ 1.8 ps.

This value is to be divided by the time interval τ (the quantity of interest) that the two clocks are supposed to measure (elapsed total time), and multiplied by $\sqrt{2}$ (one measurement at the beginning of the interval, one at the end). This is the content of eq. (3). Explicitly,

$$\sigma_y(\tau) = 2.6 \text{ ps}/\tau \quad \text{(non-common-view comparisons)} \quad (4)$$

Although the MWL link is more stable than ELT+, the overall performance for non-common-view comparisons is only slightly better, since the USO instability dominates.

For example, for the geopotential difference determination, a total time duration of $\tau = 10^6$ seconds can be chosen (≈ 11 days). Thus, a comparison at the level $2.6{\cdot}10^{-18}$ is achievable. After 1 month, the level $1{\cdot}10^{-18}$ is reached. After 1 year, a level below $1{\cdot}10^{-19}$ is reached. This is an extraordinarily low level.

We assumed phase coherence to be able to be kept over the whole integration time. This is a reasonable assumption, since (1) in the space segment of I-SOC-PF there will only be robust RF electronics and (2) for the ground clocks, we expect that phase coherence will be achieved by the time of the mission.

We now proceed to the analysis of the measurement procedure for the GTD test. The concept is shown in Figure 3-4.

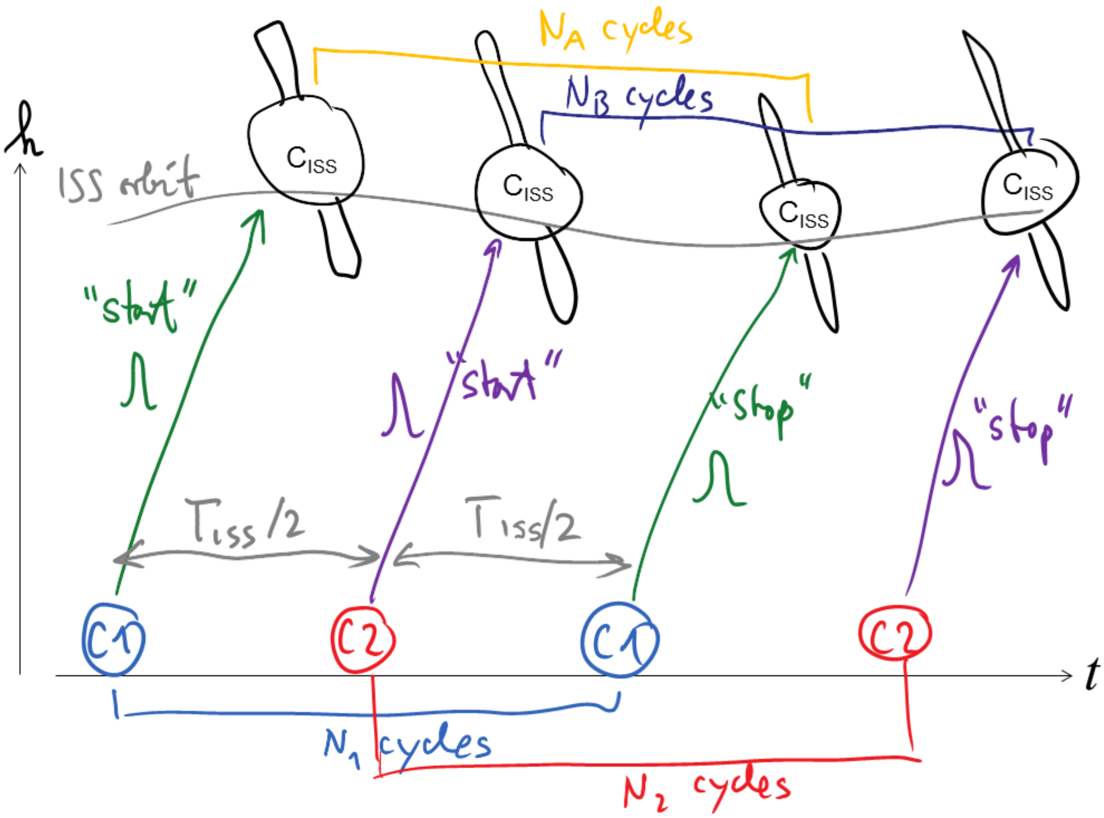

Figure 3-4: Principle of the measurement of the Sun's (null) gravitational time dilation effect. One measurement block is shown, which consists of two interleaved measurements by the I-SOC-PF clock C_{ISS} of two time intervals defined by two (identical) ground clocks C1, C2. The slant of the arrows indicating the start/stop pulses is for clarity only.

We consider two clocks, C1, C2 which are located approximately on opposite sides of the Earth. The goal of a single measurement "block" is to determine the ratio of local time intervals $T_1(N_1)/T_2(N_2)$ elapsed during N_1 oscillations of C1 and N_2 oscillations of C2. T_1 and T_2 are chosen to be approximately equal to one ISS period T_{ISS}. Thus the measurement block has duration of approximately 1.5 T_{ISS}, about 140 min.
The measurement is performed by sending "start" and "stop" pulses to the ISS clock from each clock C1, C2. The ISS clock C_{ISS} records the number of own oscillations N_A that occurred between start-stop signals received from clock C1, and the equivalent number N_B during the interval defined by start-stop signals received from clock C2. In terms of the ISS clock's time scale, the corresponding time intervals are T_A and T_B.
From the measured values N_A and N_B, the ratio of ground clock frequencies can be determined.
This measurement block is first performed around a time at which the two clocks are "parallel" to the Earth-Sun line, then, approximately 12 h later, when they are "anti-parallel", see Figure 3-2. Over the course of the mission, a time series of frequency ratios is built up. Of course, the measurement blocks cannot always be done when the clocks are optimally oriented, but only when the ISS orbit passes overhead.
Neglecting again Doppler shifts, and applying Eq. (1), we can set up the relationships:

$$\frac{T_1}{T_A} = \frac{N_1/\nu_{C1}}{N_A/\nu_{USO}} = 1 - c^{-2}\left(\frac{1}{T_A}\int_{T_A} U\big(\boldsymbol{r}_{USO}(t')\big)dt' - \frac{1}{T_1}\int_{T_1} U\big(\boldsymbol{r}_{C1}(t')\big)dt'\right), \qquad (5)$$

$$\frac{T_2}{T_B} = \frac{N_2/\nu_{C2}}{N_B/\nu_{USO}} = 1 - c^{-2}\left(\frac{1}{T_B}\int_{T_B} U\big(\boldsymbol{r}_{USO}(t')\big)dt' - \frac{1}{T_2}\int_{T_2} U\big(\boldsymbol{r}_{C2}(t')\big)dt'\right). \qquad (6)$$

We divide these two equations by each other and obtain:

$$\frac{\nu_{C2}}{\nu_{C1}} = \left(\frac{N_2/N_1}{N_B/N_A}\right)\left(\frac{1-c^{-2}\left(\frac{1}{T_A}\int_{T_A} U\left(\boldsymbol{r}_{USO}(t')\right)dt' - \frac{1}{T_1}\int_{T_1} U\left(\boldsymbol{r}_{C1}(t')\right)dt'\right)}{1-c^{-2}\left(\frac{1}{T_B}\int_{T_B} U\left(\boldsymbol{r}_{USO}(t')\right)dt' - \frac{1}{T_2}\int_{T_2} U\left(\boldsymbol{r}_{C2}(t')\right)dt'\right)}\right). \qquad (7)$$

This expression states that it is possible to determine the ratio ν_{C2}/ν_{C1} of the two ground clock frequencies after transmitting to ground (by data link) the values of N_A, N_B measured on the ISS and combining them with the values N_1, N_2 measured locally on the ground. The second factor is a correction factor and is further discussed below.

The expression (7) does not depend on the intrinsic space clock frequency ν_{USO} any more. Thus, the inaccuracy of the space clock, i.e. the deviation of its frequency from the "ideal" value, does not matter (as long as it is constant). Only the stability of its frequency matters (perfect stability is implicitly assumed in the above derivation, so the instability does not appear explicitly). The fractional instability of USO + links will directly impact on the statistical error of the derived ratio and is discussed further below.

In order to compute the ratio ν_{C2}/ν_{C1}, the second factor in the expression must be known. It can be Taylor-expanded, since the integrals containing U/c^2 are small. We then see that the factor depends on the gravitational potential difference at the C1, C2 ground clock locations and on the difference in mean gravitational potential at the ISS location during the orbital segments of duration T_A and T_B,

$$\Delta U_{AB} = \frac{1}{T_A}\int_{T_A} U\left(\boldsymbol{r}_{USO}(t')\right)dt' - \frac{1}{T_B}\int_{T_B} U\left(\boldsymbol{r}_{USO}(t')\right)dt'$$

It describes the variation of ISS potential between two orbit tracks shifted in time by half an orbital period, i.e. partially overlapping (see Figure 3-4). These two orbit segments are similar, and so the difference is expected to be small.

We now consider the uncertainties affecting the second factor in eq.(7): (I) for the ground clocks and (II) for ISS orbit [#SR-PL-33, #SR-GS-09], stemming from the fact that we need to take the difference between the measurements in two blocks 12 h apart.

(I) While the terrestrial contributions $U\left(r_{C1}(t')\right)$ and $U\left(r_{C2}(t')\right)$ are nearly constant in time, nevertheless, any variation with a 24-h period and constant phase over the duration of the whole measurement campaign will give rise to a systematic error. The ocean tides have a 12-h period and do not contribute directly. As described above, today's modelling of the time-dependent gravitational potential is accurate at the level of 0.1 m^2/s^2 (1 cm, $1\cdot 10^{-18}$). An improvement by a factor of 2 may be expected by the time of the mission, to a level $5\cdot 10^{-19}$. This gravitational-potential-modelling limitation leads to an inaccuracy of $5\cdot 10^{-7}$ for the Sun's gravitational time dilation. However, we need to establish whether this can actually be reached given the performance of I-SOC-PF link and space clock.

(II) Since the measurement is performed via non-common-mode clock comparisons, using the ISS clock as a relay device, we also have to take into account the variation of the gravitational potential of the ISS clock between the times at which the two comparisons with each ground clock are performed. We must consider the uncertainty of the variation of the expression ΔU_{AB} over the time scale of 12 h,

$$\varepsilon_{12h} = \sqrt{\langle(\Delta U_{AB}(t) - \Delta U_{AB}(t + 12\ h))^2\rangle}\ .$$

For the Earth GTD, we have argued that a 40 cm uncertainty in the ISS altitude is required (taking into account the cancellation with Doppler effect). That uncertainty refers to a time average of $U\big(\boldsymbol{r}_{USO}(t')\big)$ itself. This uncertainty may actually be reduced for ΔU_{AB} , it being a difference.
Consider a (hypothetical) goal accuracy of Sun GTD of $5 \cdot 10^{-7}$. This equivalent to $1 \cdot 10^{-12} \cdot 5 \cdot 10^{-7} = 5 \cdot 10^{-19}$ clock uncertainty or 0.5 cm altitude uncertainty in ε_{12h} if the 2nd-order Doppler effect is neglected. This translates into approximately 5 cm ISS altitude variation uncertainty if the cancellation with the second-order Doppler effect is taken into account. This is a requirement on the systematic plus statistical error over the whole duration of the measurement campaign. A large number of measurements during the campaign is expected to bring the nominal 40 cm uncertainty for U down to the specific uncertainty ε_{12h} = 5 cm.

We now consider the uncertainty reachable in the measurement of the first factor in Eq. (8). It amounts to $\sqrt{2}\sigma_y(T_{ISS})$ (the factor $\sqrt{2}$ stems from having two non-common-view comparisons per block). Using a variation of the estimate leading to eq.(4), this yields $\sqrt{2} \times \sqrt{2} \times 3.2$ ps/5400 s $\approx 1.1 \cdot 10^{-15}$, USO-dominated. The instability of the ground clocks can be neglected in comparison.
We assume that one can perform 2 measurements per day, for 1000 days, as also shown in the figure. This results in a measurement uncertainty reduced by $\sqrt{2000}$:

$$2.5 \cdot 10^{-17}.$$

The gravitational potential modelling uncertainty (equivalent to $5 \cdot 10^{-19}$) is therefore negligible, and so is the ground clocks instability.

Thus, we find that a total fractional inaccuracy for the Sun GTD test at the level of

$$\mathbf{2.5 \cdot 10^{-5}}\ ,$$

limited by statistical uncertainty of the USO.

The assumed long coherence time of the clocks cannot, unfortunately, be made use of when searching for a periodic modulation of the ground clock frequencies.

The best current results for the solar gravitational frequency shift are at the few % level [RD11,RD12]. Thus, I-SOC-PF provides a large improvement in accuracy.
If the clock comparisons are extended to additional ground clocks, the statistical uncertainty as well as geopotential uncertainty will be reduced.

It is likely that the ACES mission will attempt a determination of the Sun's time dilation effect. The improvement of I-SOC-PF compared to the ACES mission is expected to be a factor of 10, due to the better stability/accuracy of ground clocks, better stability of the I-SOC-PF links, and better modelling of the gravitational potential corrections.

#PSO-02: *Measurement of the Moon gravitational time dilation to a fractional uncertainty of $4 \cdot 10^{-3}$*

The I-SOC-PF mission also provides the possibility to measure the gravitational time dilation induced by the Moon. To our knowledge, no such measurement has been performed before.

The measurement protocol is the same as for the Sun time dilation measurement: a frequent comparison of two ground clocks at large distance in East-West direction. A hypothetical violation signal phase is correlated with the Moon's position. The period of the signal sought differs slightly from 24 hours, because the Moon orbits the Earth. In order to differentiate a Moon signal from a Sun signal the measurements must therefore extend at least over several weeks. This requirement is satisfied since measurements will be performed over a substantial fraction of the mission duration in order to maximize statistical accuracy.
The Moon-related effect is reduced compared to the effect of the Sun, by a factor

$$\left(M_{\text{Sun}}/d_{\text{Sun}}{}^{2}\right)/\left(M_{\text{Moon}}/d_{\text{Moon}}{}^{2}\right) \approx 175.$$

The square dependence on the distance *d* between Earth and Moon or Earth and Sun stems from the fact that in a modulation-type measurement, where the distance change of each ground clock to the Moon and the Sun is much smaller than *d*, a Taylor expansion can be used to estimate the result.
The peak-to-peak Moon effect on the comparison of ground clocks is thus approximately at the $6{\cdot}10^{-15}$ level for a Europe-Tokyo and a Boulder-Tokyo comparison.
The statistical and systematic errors are similar to the Sun case, because the signal period is similar.
Thus, we can simply scale the estimate performed for the Sun field time dilation by the above ratio of effect amplitudes and find that the Moon field dilation test can be performed with uncertainty of

$$\mathbf{4{\cdot}10^{-3}}.$$

There are no previous determinations of the Moon time dilation. However, it is likely that such comparisons will be made during the ACES mission. The improvement of I-SOC-PF compared to the ACES mission is expected to be a modest factor, due to the better stability/accuracy of ground clocks, better stability of the I-SOC-PF links, and better modelling of the gravitational potential corrections.

#PSO-04: *Enabling world-wide searches for time variation of fundamental constants and tests of the Standard Model Extension.*

I-SOC-PF can compare clocks in common-view and non-common-view to the $5{\cdot}10^{-19}$ level within 2 months. This implies that I-SOC-PF can give rapid support to clock development on the ground, and will enable a test of Local Position Invariance improved by approximately a factor of 10 compared to the time of ACES.
In principle, if the integration time is chosen to be the full mission duration, the level of $1{\cdot}10^{-18}$/(mission duration/1 month) $\approx 3{\cdot}10^{-20}$ is possible with both ELT+ and MWL assuming their stability is maintained over such long time. This is an outstanding perspective. It can be realized, if by the time of the mission the most advanced clocks (or clock ensembles) are capable able to operate coherently (uninterruptedly). Rapid progress in this direction is expected over the coming years.

#PSO-04: *Contribution to the realization of atomic time scales to fractional frequency inaccuracy lower than $1{\cdot}10^{-18}$ and synchronized to the ps level.*

Thanks to the precise timing capability, I-SOC-PF will allow the worldwide synchronization of the local timescales on the picosecond level compared to the ns uncertainty that is available at present.
I-SOC-PF will offer the possibility to compare primary standards to a frequency uncertainty better than 10^{-18} (see the discussion on #PSO-01 above). Clock-to-clock comparisons will be

used to evaluate the accuracy of global time scales. As an example, TAI might exhibit a long-term drift due to some unidentified source common to all commercial cesium standards that dominate TAI. In this case, comparisons of clocks based on different atomic transitions would allow highlighting that drift. Such comparisons, reaching a frequency uncertainty below the 10^{-18} level with I-SOC-PF, will be used to characterize the long-term behavior of atomic time scales and to set bounds on time variations of the fundamental physical constants. This will also accelerate the process leading to a redefinition of the SI second based on clocks operating in the optical domain.

We foresee that the development of ground clocks in the coming years will provide clocks with $3{\cdot}10^{-19}$ *intrinsic* inaccuracy (i.e. without considering the gravitational potential-related inaccuracy). This level is expected to be reachable without requiring a space-based comparison of distant clocks. Instead, comparisons of co-located same-type clocks and intercomparison of distant clocks via transportable clocks will be employed.

The use of I-SOC-PF is then to distribute time/frequency signals of these clocks world-wide. As shown in Figure 3-3, the ELT provides a time/frequency transfer uncertainty below $1{\cdot}10^{-18}$ for integration times longer than 10 days. The accuracy of this distribution will be limited not by I-SOC-PF but by gravitational potential modeling for the ground clocks locations and the ISS orbit (in case of non-common view distribution).

One application of this distribution is to monitor the primary optical clocks' drifts with respect to each other. This monitoring can be done and is useful independently of an accurate knowledge of the gravitational potential at the clock's position, provided that the time-dependent potential variations can be modeled. As discussed in #PSO-01, we may expect this to be possible at the $5{\cdot}10^{-19}$ level.

With the establishment of the I-SOC-PF time/frequency distribution capability to a number of primary receiver stations, each of them can be used as a node of a combined space-ground distribution system. The atomic time scale would be distributed from the primary receiver to a large number of surrounding users within a radius of several 100 km by means of a fiber-optic network.

I-SOC-PF will thus provide means for establishing, testing, and applying an integrated space-to-ground network concept for time and frequency distribution.

Within Europe, a network based on optical fibers is already under full development in Europe and will be completed by the time of the I-SOC-PF mission.

#PSO-05: ***Enable mapping of the geopotential on the land masses of continents with approximately 30 km grid size, with a resolution of 0.15 m²/s² (1.5 cm on the differential geoid height).***

The ISS orbit covers more than 50% of the Earth surface. Thus, comparisons of ground clocks located over a large fraction of land mass can be performed via I-SOC-PF. This unique feature can be taken advantage of so as to implement, in principle, a simultaneous mapping campaign on all continents.

The proposed concept for mapping a given region (part of a continent) with fairly high spatial resolution is based on using a pair of transportable clocks 1 and 2 that both have $1{\cdot}10^{-18}$ inaccuracy. This is a realistic value at the time of the I-SOC-PF mission, given the strong development activity of such devices. Currently (2020) the lowest inaccuracy reached is $7{\cdot}10^{-17}$ [RD24].

These two clocks will be placed in sequence at neighbouring points $\boldsymbol{r}_i$, $\boldsymbol{r}_{i+1}$, of a large-scale raster (at distance $|\boldsymbol{r}_i - \boldsymbol{r}_{i+1}| \approx 30$ km). In each configuration, the two clocks will be compared in common-view mode via I-SOC-PF. The clock frequency difference of the two clocks yields the gravitational potential difference $U(\boldsymbol{r}_{i+1}) - U(\boldsymbol{r}_i)$. The high spatial and temporal

resolution of the geopotential measurements will complement conventional satellite gravimetry surveys which have a much more coarse spatial resolution (few 100 km).
If we consider coherent oscillation of both ground clocks over the duration τ, then

$$\sigma_y(\tau) = 2\sigma_{x,link}(\tau_{contact})/\tau$$

The factor 2 arises because there are two ground-space link connections at the beginning of the time interval and two at the end, and the four uncertainties add quadratically. The uncertainty $\sigma_{x,link}(\tau_{contact})$ has the approximate values:

MWL: 50 fs
ELT+: 1 ps

The $1{\cdot}10^{-18}$ noise level for common-view comparisons is reached after approximately:

MWL: 1.5 days
ELT+: 12 days

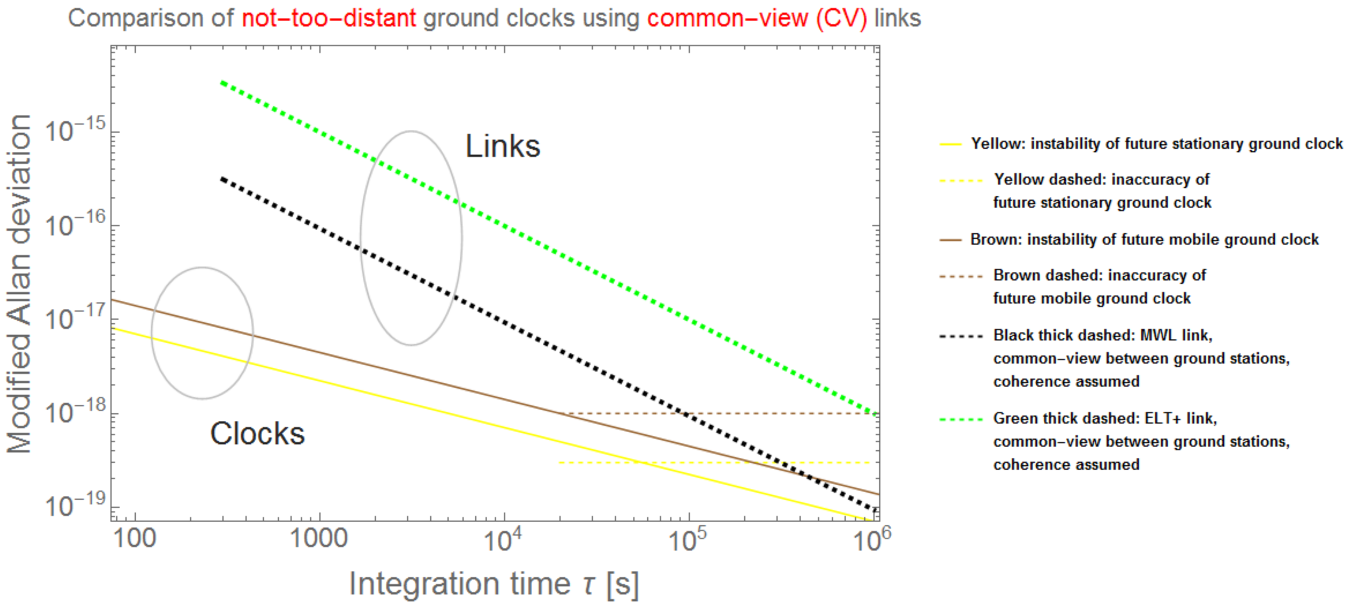

Figure 3-5: Performance of common-view clock comparisons, for clocks at distances of up to several 100 km. The dotted lines show that the links provide $1{\cdot}10^{-18}$ uncertainty of the clock comparison after approximately 1.5 and 12 days, respectively. Further reduction occurs with longer integration time. This plot addresses the science goals: tests of local position invariance, world-wide time scale and relativistic geodesy. Clock coherence is assumed over the integration time τ.

The short measurement duration enabled by the I-SOC-PF links leads to the following scenario:
The pair of mobile clocks (operated in trailers) assigned to a given region will be staffed by a small team of 3-4 persons. The team performs one clock comparison at one new site pair of the grid every 5 days. The 5 days include 1 day for transportation (only 1 clock needs to be transported per 4-day session, over a distance of twice the grid size), 1 day for setting up the measurement, 1 day for verifying systematic effects, 2 days for measurement.
Over the ISS mission duration (600 days of link availability), this makes approximately 120 grid points. For a grid size of 30 km, this is an area of 330 km × 330 km.
We point out that if this raster approach is used, the error of the potential difference between distant grid points will be significantly higher than for neighboring grid points, by a factor equal to the square root of the number of in-between grid points.

In an advanced scenario, a large number of teams and clocks could allow mapping of a sizeable part of a continent.
Note that three transportable optical clocks already exist today, and more are under development.

#PSO-06: *Inter- and intracontinental differential geopotential measurements with resolution in the gravitational potential U at the level down to 0.05 m^2/s^2 (0.5 cm on the differential geoid height)*

While the daily modulation of the frequency difference between two ground clocks on different continents is of relevance for determining the Sun or Moon time dilation effect, the time-independent contribution (or mean) provides the difference in the Earth gravitational potential at the clock locations. This quantity is of interest for geophysics applications.
We are here considering next-generation clocks, having inaccuracy at the $3{\cdot}10^{-19}$ level. A small number of them will exist by the time of the mission, probably only in national metrology laboratories. Such clocks can be compared to a frequency uncertainty of $5{\cdot}10^{-19}$, limited by the combined clock and link inaccuracy [#SR-GS-02,#SR-PL-08]. This corresponds to the determination of the difference of local geopotential values to 0.05 m^2/s^2, equivalent to 0.5 cm resolution on the geoid height. The I-SOC-PF mission will be able to reach this accuracy during the duration of the mission (≈ 100 days).
Extending on this, a second measurement campaign will consist in placing 2-3 high-performance ($1{\cdot}10^{-18}$ inaccuracy) transportable optical clocks at suitably chosen points on the Earth and operate them there for the duration of the mission.
Together, the above clocks have the scope to (i) to determine the time-variation of the geopotential (with time resolution equal to 1 month), (ii) to provide “anchor” data for improving the models generated by satellite gravimetry [RD22].

For intercontinental distances, the link resolution has been discussed in connection with eq. (4) (non-common-view). The national metrology laboratory clocks can be compared in non-common-view at the $1{\cdot}10^{-18}$ level (1 cm differential geopotential height) within ≈ 1 month. The given integration times assume that phase continuity is maintained.

For moderate distances, the common-view link resolution has been discussed above. The national metrology laboratory clocks can be compared in common-view at the $3{\cdot}10^{-19}$ level within 4 days using MWL. This will allow determining the time evolution of the geopotential with a time resolution impossible with satellite gravimetry. This opens up a new dimension in geodesy and can be of significant interest for geophysics models.
National metrology laboratory clocks at moderate distances are also linked by high-performance fiber-optic links. Thus, comparisons of their clocks can be performed with completely independent techniques. *This represents an important performance test of the I-SOC-PF links and will be part of the I-SOC-PF characterization at the beginning of the mission.*

#SSO-01: *Space-to-ground time transfer with inaccuracy lower than 20 ps using ELT+*

The MWL and ELT+ link will also allow the synchronization of ground and space time scales with an absolute accuracy of 50 ps and 20 ps, respectively. This is about a factor 100 better than present state-of-the-art GNSS and similar systems. Space-to-ground synchronization experiments require careful calibration of the differential delays uplink - downlink before launch and their continuous monitoring during flight.

#SSO-02: *Synchronization of clocks on ground to better than 20 ps*

Ground clocks synchronization will also be performed during common-view contacts. Time uncertainty (bias) levels below 50 ps and 20 ps are expected to be achieved with the MWL and the ELT+ technology. Although the errors of the two links cumulate, direct calibration of the link delays by means of reference ground terminals will be possible. In addition, as only the double difference of the uplink – downlink delays at the two ground clocks will play a role, it will also be possible to cancel instrumental effects at the space hardware. As an example delay variations induced by temperature fluctuations at the I-SOC-PF instrument will be highly correlated bringing to a cancellation of this environmental effect in the double difference.

#SSO-03: ***Cross-comparisons of different ranging techniques: one-way optical ranging, two-way optical ranging, microwave ranging***

The on-board corner cube reflector will in addition allow ranging of the ISS at the centimeter level providing useful data for the validation and the improvement of the orbit determination of the on-board clock.

The simultaneous operation of the ELT+ optical link and MWL will allow the calibration of MWL for ranging measurements. In addition, space-to-ground clock synchronization experiment performed both using the microwave and the optical link will test one-way ranging performances and cross-compare different ranging techniques (1-way vs 2-way, optical vs microwave).

#SSO-04: ***Measurement of the differential atmospheric propagation delays in the optical and microwave***

The relative variation of clock de-synchronization measurements (space-to-ground) performed by ELT+ and MWL along the ISS orbit will give access to the difference in the propagation delays both in the optical and microwave domain. This information can be used to improve the modelling of ionosphere and troposphere propagation delays as well as for space weather applications.

3.3.3 *Systematic tests*

Systematic tests shall be done during the mission. They will be provide a strong check of overall system performance.

1. "Three-corner-hat" method for 3 clocks that can be compared in common-view (not necessarily all three simultaneously): from the clock comparisons 1-2, 2-3, 3-1 the respective potential differences U_{12}, U_{23}, and U_{31} are obtained. The sum must be equal to zero because of the properties of the potential:

$$U_{12} + U_{23} + U_{31} = 0$$

2. Three clocks in relative vicinity, e.g. in Europe, are required (available as of today) and also three terminals, for the duration of this test. Two of the terminals would later be sent to Japan/US, as foreseen.

3. "Three-corner-hat" method for 3 clocks that are on different continents, Europe/US/Japan, and that are compared in non-common-view: again, the sum of the potential differences must satisfy: $U_{12}+U_{23}+U_{31} = 0$.

4 I-SOC-PF MISSION SCIENTIFIC REQUIREMENTS

The set of scientific requirements listed in this section allows fulfilling the I-SOC-PF mission objectives described in Section 3. Issues that still need to be resolved will be identified with a TBR (To Be Resolved) and collected in the TBR list in Annex 4.
When needed, explanatory text is provided before the requirement. The applicable requirement is then preceded by the text **Requirement**. After each requirement, we indicate the responsible Party for its implementation and verification, the Party being ESA or the I-SOC-PF Science Team (Resp.: ESA or Science Team).
Requirements applicable to the flight hardware or to operations will be under the direct responsibility of ESA. Those applicable to the ground hardware will be implemented and verified by the I-SOC-PF Science Team, data analysis activities included.

4.1 Mission requirements

#SR-PL-01 ***Accommodation of the I-SOC-PF Payload***
Requirement: The I-SOC-PF payload shall be accommodated external to the ISS, with the microwave antenna and the optical receiver pointing nadir.
Resp.: ESA

#SR-PL-02 ***Performance in the On-flight Environment***
Requirement: All performance requirements of the instruments and subsystems shall be met in the on-flight environment of the ISS.
Resp.: ESA

4.2 Main Instrument requirements

4.2.1 *Space Clock*

#SR-PL-03 ***USO Instability***
Requirement: The fractional frequency instability of the USO, expressed in Allan deviation, shall be smaller than $8{\cdot}10^{-15}$ for integration time $\tau = 100$ s, and smaller than or equal to $5{\cdot}10^{-16}$ between 2000 s and 6000 s.
Resp.: ESA

#SR-PL-04 ***USO Inaccuracy***
Requirement: The USO fractional frequency inaccuracy shall be smaller than $1{\cdot}10^{-12}$.
Resp.: ESA

#SR-PL-05 ***Magnetic Field Variations with Time***
Requirement: The magnetic field near the USO shall be continuously monitored.
Resp.: ESA

#SR-PL-06 ***Mechanical Vibrations and Spurious Accelerations***
Requirement: The accelerations (three components) shall be continuously monitored at the USO location.
Resp.: ESA

4.2.2 *Time and Frequency Transfer Link: MWL*

#SR-PL-07 ***Microwave Link Instability***
This requirement specifies the performance of the I-SOC-PF microwave link for (a) ground-to-ground clock comparisons and (b) space-to-ground clock comparisons.
For ground-to-ground clock comparisons the specified fractional frequency instability of the I-SOC-PF microwave link σ_{MWLgg} accounts for the following noise terms:

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white phase noise averaging down to $1.6 \cdot 10^{-14}$ after 10 s of integration time,
flicker phase noise with modified Allan deviation of $1.6 \cdot 10^{-13}/\tau$,
long-term performance $5.9 \cdot 10^{-17}/\tau^{1/2}$, and
flicker floor at the $5.0 \cdot 10^{-19}$ level.

The space-to-ground instability is equal to $\sigma_{MWLgg}/\sqrt{2}$.

Requirement (a): The modified Allan deviation of the noise introduced by the I-SOC-PF microwave link in the comparison of two clocks on the ground shall be smaller than

$$\sqrt{(5.0 \cdot 10^{-13}/\tau^{3/2})^2 + (1.6 \cdot 10^{-13}/\tau)^2 + (5.9 \cdot 10^{-17}/\tau^{1/2})^2 + (5.0 \cdot 10^{-19})^2}$$

for integration times τ, expressed in seconds, between 10 s and $2 \cdot 10^6$ s.

Resp.: ESA

Requirement (b) The modified Allan deviation of the noise introduced by the microwave link in the comparison of the on-board clock with clocks on the ground shall be $\sqrt{2}$ smaller than the one given under (a).

Resp.: ESA

#SR-PL-08 ***Time and Frequency Transfer Inaccuracy***

This requirement defines the measurement accuracy and takes into account the end-to-end link including electronics and media contributions.

Requirement: The I-SOC-PF time and frequency transfer MWL link shall be able to compare the space clock and clocks on ground to a fractional frequency inaccuracy smaller than $1 \cdot 10^{-16}$ as well as to compare ground clocks to a fractional frequency inaccuracy smaller than $5 \cdot 10^{-19}$.

Resp.: ESA

#SR-PL-09 ***Phase Comparison Measurements per Second***

Phase measurement (code, carrier or code and carrier) have to be performed inside the transceivers in space and on the ground. Measurements taken at the on-board transceiver shall be transmitted to ground.

Requirement: The I-SOC-PF time and frequency transfer links shall be able to provide at least one phase comparison measurement per second between the space clock and the ground clock with 1 Hz measurement bandwidth.

Resp.: ESA

#SR-PL-10 ***Phase Continuity over the Link Dead-time***

This requirement is important for the I-SOC-PF links to reduce the measurement duration of space-to-ground and ground-to-ground comparisons of clocks in the presence of long dead time intervals.

Requirement: The space and ground terminals of the I-SOC-PF time and frequency transfer links shall be able to carry out space-to-ground and ground-to-ground time transfer with the link-induced differential time error between any two observations separated by a dead-time T_d being less than TDEV(T_d), where TDEV represents the time deviation[1] resulting from #SR-PL-07 for the microwave link. This requirement shall be maintained over a minimum measurement interval of 20 days.

[1] The time deviation (TDEV) related to the modified Allan deviation (ModADEV) by the following relationship: $\mathrm{TDEV}(\tau) = \mathrm{ModADEV}(\tau) \cdot \tau/\sqrt{3}$, where τ is the integration time.

Resp.: ESA

#SR-PL-11 ***Minimum Number of Independent Channels of the Microwave Link***

This requirement ensures the possibility of performing common-view comparisons with the I-SOC-PF microwave link with a larger number of users, so as to produce more data and enable consistency tests.

Requirement: The microwave link MWL shall be able to simultaneously compare the space clock with at least four clocks on ground[2].

Resp.: ESA

#SR-PL-12 ***Characterization of Absolute Delays for Space-to-ground Time Transfer Experiments***

Space-to-ground time transfer experiments with I-SOC-PF (#SSO-01) require the calibration of the differential delays between uplink and downlink in MWL. This includes calibration of the differential delays between uplink (transmission from ground to reception in space) and downlink (transmission from space to reception on ground) and of the differential propagation delays in the atmosphere due to the non-reciprocal paths of uplink versus downlink.

Requirement: The differential delays (uplink - downlink) of the I-SOC-PFMWL used for the dissemination of the I-SOC-PF time scale (space-to-ground) shall be determined to a time uncertainty smaller than 50 ps.

Resp.: ESA

#SR-PL-13 ***Characterization of Differential Delays for Ground Clocks Synchronization[3]***

Clock synchronization experiments (#SSO-02) require the differential calibration of the I-SOC-PF MWL terminals installed at the two ground clocks locations. This includes the calibration of the differential delays (uplink-downlink) for each space-to-ground link.

Requirement: The differential delays (uplink - downlink) of the I-SOC-PF MWL used for the synchronization of two clocks on ground shall be determined to a time uncertainty better than 50 ps.

Resp.: ESA

4.2.3 *Time and Frequency Transfer Link: ELT+*

4.2.3.1 ELT+ End-to-end Requirements

ELT+ operation requires the involvement of ground-based Satellite Laser Ranging (SLR) stations. Participation of these stations to the I-SOC-PF mission requires dedicated agreements between ESA and the scientific institutes responsible for the ground stations operation. Such agreements will also define the responsibilities for the verification of the requirements applicable to the laser ranging stations.

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[2] 4 additional independent channels would be desirable to develop applications in areas other than fundamental physics.

[3] Calibration activities might require the availability of transportable ground terminals to characterize the differential delays in the I-SOC-PF links through a common-clock measurement.

In this section, we define the ELT+ end-to-end performance requirements. These requirements will be later broken down into requirements applicable to the space and to the ground segment hardware. ESA will only be responsible for the requirements applicable to the space segment. Fulfillment of ELT+ ground segment requirements will be under the direct responsibility of the I-SOC-PF Science Team and of the participating SLR stations.

#SR-PL-14 ***Space-to-Ground Clock Comparisons via ELT+***

Requirement: The ELT+ optical link shall be able to compare the space and ground clock with an induced equivalent noise in time deviation lower than

$$\sigma_X(10\text{ s} \le \tau < 300\text{ s})_{ELT+} = 5\cdot 10^{-12}\cdot \tau^{-1/2}\text{ s}$$

$$\sigma_X(300\text{ s} \le \tau \le 10^6\text{ s})_{ELT+} = 1\cdot 10^{-12}\text{ s}$$

where τ is the integration time expressed in s.

Resp.: ESA and Science Team

#SR-PL-15 ***Space-to-Ground Clock Comparisons via ELT+***

The ELT+ fractional frequency inaccuracy when comparing the space clock with clocks on the ground shall be below $1\cdot 10^{-18}$.

Resp.: ESA and Science Team

#SR-PL-16 ***Calibration of ELT+ Delays for Space-to-ground Time Transfer***

Requirement: The delay in the ELT+ link for the dissemination of the I-SOC-PF time scale shall be calibrated to an uncertainty below 20 ps (15 ps as target). This includes the processes of: laser pulse emission/reception and time stamping in the ground clock time scale, laser pulse reception on-board I-SOC-PF and time stamping in the I-SOC-PF time scale, two-way propagation of the laser pulse in the atmosphere from the reference emission point on ground to the reference reception point in space and back to the reference reception point on ground.

Resp.: ESA and Science Team

#SR-PL-17 ***Calibration of ELT+ Differential Delays for Ground-to-ground Time Transfer***

Requirement: The differential delays of ELT+ links for the synchronization of two ground clocks shall be calibrated to an uncertainty below $\sqrt{2}\cdot 20$ ps ($\sqrt{2}\cdot 15$ ps as target).

Resp.: ESA and Science Team

4.2.3.2 ELT+ End-to-end Space Segment (SS) Requirements

ELT+ space segment requirements are under ESA responsibility.

#SR-PL-18 ***Space-to-ground Clock Comparisons via ELT+: Space Segment Performance Budget Allocation***

Requirement: The following performance budget is allocated to the ELT+ space segment (SS) for the time deviation of the space-to-ground clock comparisons via ELT+:

$$\sigma_X(10\text{ s} \le \tau < 300\text{ s})_{ELT+(SS)} \le 3\cdot 10^{-12}\cdot \tau^{-1/2}\text{ s}$$

$$\sigma_X(300\text{ s} \le \tau \le 10^6\text{ s})_{ELT+(SS)} \le 0.5\cdot 10^{-12}\text{ s}$$

These figures include, among other noise terms related to ELT+ space segment, on-board detection and time stamping in the local clock time scale, geometric effects related to the offset between reflection at the corner cube and detection equivalent points, atmosphere propagation effects, relativistic effects.

Resp.: ESA

#SR-PL-19 ***Calibration of ELT+ Delays for Space-to-ground Time Transfer: Space Segment Performance Budget Allocation***

Requirement: 3 ps of time error are allocated to the space segment for the calibration of ELT+ differential delays in the space-to-ground time transfer via ELT+. This figure includes, among other terms related to the space segment, laser pulse reception on-board I-SOC-PFand time stamping in the local clock time scale, propagation in the retro-reflector, retro-reflector to ELT+ optics and geometry contribution.
Resp.: ESA

#SR-PL-20 ***On-board Time Tagging***
Requirement: ELT+ laser pulses shall be time stamped when received at the on-board detector in the on-board clock time scale.
Resp.: ESA

#SR-PL-21 ***ELT+ Multi-user Capabilities***
This requirement ensures the possibility of performing common-view comparisons with the I-SOC-PF optical link.
Requirement: ELT+ will be able to perform two simultaneous space-to-ground clock comparisons without significant degradation of the link performance (less than 10% in time deviation).
Resp.: ESA

4.2.3.3 ELT+ End-to-end Ground Segment (GS) Requirements

ELT+ ground segment requirements are under the responsibility of the I-SOC-PF science team and of the participating ground-based SLR stations.

#SR-PL-22 ***Space-to-Ground Clock Comparisons via ELT+: Ground Segment Performance Budget Allocation***
Requirement: The following performance budget is allocated to the ground segment (GS) for the time deviation of the space-to-ground clock comparisons via ELT+:

$$\sigma_X(10\text{ s} \le \tau < 300\text{ s})_{ELT+(GS)} \le 4\cdot 10^{-12}\cdot \tau^{-1/2}\text{ s}$$

$$\sigma_X(300\text{ s} \le \tau \le 10^6\text{ s})_{ELT+(GS)} \le 1\cdot 10^{-12}\text{ s}$$

These figures include, among other noise terms related to the SLR station, on-ground detection and time stamping at the SLR station in the local clock time scale and geometric effects related to local ties.
Resp.: Science Team

#SR-PL-23 ***Calibration of ELT+ Delays for Space-to-Ground Time Transfer: Ground Segment Performance Budget Allocation***
Requirement: 20 ps (15 ps as target performance) of time error are allocated to the ground segment for the calibration of ELT+ differential delays in the space-to-ground time transfer via ELT+. This figure includes, among other terms related to the SLR station, laser pulse emission/reception and time stamping in the local clock time scale, propagation effects due to local ties.
Resp.: Science Team

#SR-PL-24 ***On-ground Time Tagging***
Requirement: ELT+ laser pulses shall be time stamped when emitted and received at the ground laser ranging station in the local clock time scale.
Resp.: Science Team

#SR-PL-25 ***Transportable ELT+ Calibration Device***
Requirement: A transportable ELT+ Calibration Device shall be available for on-site calibration of related signal delays.
Resp.: Science Team

#SR-PL-26 ***Common-View Clock Comparisons with ELT+***
Requirement: The distribution of ELT+ laser ranging stations on ground shall ensure that at least two of them are in common view with respect to the ISS orbit for longer than 100 s.
Resp.: Science Team

#SR-PL-27 ***SLR Station Ranging Performances***
Requirement: ELT+ reflector shall allow ranging to 20 ps one-way time uncertainty per shot (15 ps target) and it shall provide precision in a sense of TDEV not worse than 0.4 ps @ 100 s.
Resp.: ESA and Science Team

4.2.4 *On-board GNSS System Requirements*

#SR-PL-28 ***Orbit determination capabilities***
Requirement: The GNSS system shall allow orbit determination of the I-SOC-PF clock and links to the performance level required for fulfilling the I-SOC-PF science objectives (see #SR-PL-33 to #SR-PL-38).
Resp.: ESA

#SR-PL-29 ***GNSS receiver tracking capabilities***
Requirement: The GNSS system shall be able to receive and track GPS, GALILEO/GIOVE, and GLONASS signals in the L1, L2, and L5/E5a bands.
Resp.: ESA

#SR-PL-30 ***Comparison of clocks via the GNSS network***
Requirement: It shall be possible to lock the internal timing of the GNSS system on the I-SOC-PFclock.
Resp.: ESA

#SR-PL-31 ***Data rate of GNSS science measurements***
Requirement: I-SOC-PF shall support buffering and transmission via telemetry of the generated GNSS scientific data up to a volume of 80 MB/day.
Resp.: ESA

#SR-PL-32 ***GNSS Receiver Driven by the I-SOC-PF Clock Signal***
The GNSS receiver can also be used to monitor GPS, GALILEO, and GLONASS timescales once connected to the I-SOC-PF clock signals.
Requirement: It shall be possible to lock the internal timing of the on-board GNSS system on the space clock signal.
Resp.: ESA

4.3 Orbit and Gravitational Potential Determination in Space

#SR-PL-33 ***Orbit Determination of the Link Reference Points in Space***
Requirement: The uncertainty in the orbit determination (position, velocity, time) of the I-SOC-PF link reference points (e.g. antenna phase center) in space shall introduce a noise in the comparison between the USO and ground clocks that, expressed in Allan deviation, shall be 3 times smaller than the links noise (see #SR-PL-07).
Resp.: ESA

#SR-PL-34 ***Orbit Determination of the USO***
Requirement: The uncertainty in the orbit determination (position, velocity, time) of the clock reference point (i.e. atom interrogation region) over the integration time of 1 orbital period shall introduce a noise in the evaluation of the clock relativistic frequency shifts that, expressed in Allan deviation, shall be 3 times smaller than the clock noise (see #SR-PL-03).

Resp.: ESA

#SR-PL-35 ***Gravitational Potential at the I-SOC-PF Clock***

In the Sun/Moon GTD measurement modality, the gravitational potential variation over the time scale of 12 h at the space clock location shall be known to an inaccuracy lower than equivalent to the ground clock inaccuracy.

Requirement: The error in the determination of the gravitational potential variation at the space clock location shall lead to a fractional frequency uncertainty due to Sun and Moon GTDs smaller than $5\cdot10^{-19}$ over the appropriate averaging time for the ground-to-ground comparison.

Resp.: ESA

#SR-PL-36 ***Relative Positioning of MWL Antenna and ELT+ Reference Point***

Requirement: The relative positions of the MWL antenna phase center and the ELT+ reference point both on ground and in space shall be known with 1 mm inaccuracy.

Resp.: ESA

#SR-PL-37 ***ISS Attitude Data for Relative Positioning of MWL Antenna and ELT+ Reference Point On-board I-SOC-PF***

Requirement: Access to ISS attitude data with adequate accuracy is required to define the vector between MWL antenna position and ELT+ reference point on board I-SOC-PF.

Resp.: ESA

#SR-PL-38 ***Orbit Prediction for ELT+ Laser Stations Pointing***

Requirement: Orbit prediction to an uncertainty of 300 m along the link direction is required to point ELT+ laser ranging stations and to ensure night-time operation. A target performance of 15 m is desirable to also allow day-time operation.

Resp.: ESA

4.4 Ground Segment

4.4.1 *Ground Clocks Requirements*

The development, the operation and the maintenance of ground clocks (laboratory instruments or transportable optical clocks) is under the responsibility of the I-SOC-PF science team. This includes provision of all the necessary resources, logistics, and manpower for fulfilling the requirements listed below.

#SR-GS-01 ***Ground Clocks Instability***

Requirement: The fractional frequency instability of the mobile ground clocks participating to the I-SOC-PF mission expressed in Allan deviation shall be smaller than $2\cdot10^{-16}/\tau^{1/2}$, for integration times τ, expressed in seconds, between 1 s and 250 000 s. For the stationary clocks, it shall be $1\cdot10^{-16}/\tau^{1/2}$.

Resp.: Science Team

#SR-GS-02 ***Ground Clock Inaccuracy***

Requirement: The fractional frequency inaccuracy of the mobile ground clocks participating to the mission shall be smaller than $1\cdot10^{-18}$, that of the stationary clocks in metrology laboratories, smaller than $3\cdot10^{-19}$.

Resp.: Science Team

#SR-GS-03 ***Calibration of local UTC by Ground Clocks for Contributing to Atomic Time Scales with I-SOC-PF***

The possibility of participating with I-SOC-PF to the generation of atomic time scales requires that at least two ground clocks be linked to an international atomic time scales (e.g. UTC) with instability better than $1 \cdot 10^{-16}$ after a few days of integration time.
Requirement: A minimum number of two ground clocks with performance as specified in #SR-GS-01 and #SR-GS-02 shall allow calibrating local UTC to an uncertainty better than 20 ps after 5 day of integration time.
Resp.: Science Team

#SR-GS-04 ***Minimum Number of Ground Clocks***
The minimum number of ground clocks required for I-SOC-PF is driven by the need of performing the Sun and Moon GTD measurement with a consistency check. This sets the minimum number to 3 ground clocks, each located on a different continent.
Requirement: A minimum number of 3 ground clocks with performance as specified in #SR-GS-01 and #SR-GS-02 and connected to the I-SOC-PF time and frequency transfer microwave link is required.
Resp.: Science Team

#SR-GS-05 ***Minimum Number of Clocks in Common-view for Geodesic Mapping***
Requirement: At least two mobile clocks shall be available with supporting vehicles and personnel.
Resp.: Science Team

#SR-GS-06 ***ELT+ Ground Clocks***
Requirement: A minimum number of two ELT+ laser ranging stations shall be operated having time/frequency links to high-performance clocks of instability and inaccuracy lower than $1 \cdot 10^{-17}$.
Resp.: Science Team

4.4.2 *Additional Ground Segment Requirements*

#SR-GS-07 ***Co-location of Microwave and Optical Link Ground Terminals***
This requirement ensures the possibility to cross-compare different ranging techniques (#SSO-03) and conduct studies on atmospheric propagation delays both in the microwave and optical domain (#SSO-04).
Requirement: One I-SOC-PF ground station, as a minimum, shall be equipped with both a microwave and optical ground terminal of the ELT+ link, both referred to the same time scale generated from the local or fiber-linked clock.
Resp.: ESA and Science Team

#SR-GS-08 ***Data Processing and Archiving***
Requirement: The I-SOC-PF science data center shall process the telemetry received from the I-SOC-PF payload and from the participating ground stations (science, housekeeping, and ancillary data) to allow generating the I-SOC-PF science products. The complete set of I-SOC-PF raw data and higher data products shall be archived at the I-SOC-PF science data center.
Resp.: Science Team

4.5 Position and Gravitational Potential Determination at the Ground Stations

#SR-GS-09 ***Position of the Link Reference Points on Ground***

Requirement: The uncertainty in the determination of position, velocity, and time of the links reference points (e.g. antenna phase center) on ground shall introduce a noise in the comparison between the ground clocks that, expressed in Allan deviation, shall be 3 times smaller than the links noise (see #SR-PL-07).
Resp.: ESA and Science Team

#SR-GS-10 ***Ground Clock Position***
In order to perform differential geopotential measurements to 1.5 cm (#PSO-05) or to 0.15 cm (#PSO-06), a the determination of each clock altitude to an uncertainty lower than 1 cm or 0.1 cm is needed ($< 1\cdot10^{-18}$ or $< 1\cdot10^{-19}$ level).
Requirement: The error in the determination of each ground clock position (mainly elevation) and velocity shall introduce a relative frequency uncertainty in the evaluation of the gravitational red-shift and of the second-order Doppler effect smaller than or equal to $5\cdot10^{-19}$ for the mobile clocks and smaller than or equal to $5\cdot10^{-20}$ for the ultra-precise metrology laboratory clocks.
Resp.: Science Team

#SR-GS-11 ***Daily Variations of the Earth Gravitational Potential at the Ground Clocks***
Daily variations of the Earth gravitational potential need to be quantified at the specified level to perform GTD tests in the Sun and Moon fields. The most stringent requirement stems from the Sun GTD test, since the effect of the Sun is stronger than that of the moon.
Requirement: Variations of the Earth gravitational potential at the ground clock location with 1-day period shall be modeled to a fractional frequency uncertainty smaller than $5\cdot10^{-19}$, with the ultimate goal of $2\cdot10^{-19}$.
Resp.: Science Team

4.6 Operations

Operations requirements are under ESA responsibility.

#SR-OP-01 ***Mission Duration***
The science goals define the mission duration. This requirement takes into account both the measurement time, as derived in the previous section of this document, and the duration of the initial instruments calibration phase. The characterization of the instruments will be performed after on-orbit commissioning and it will be continuously verified and possibly improved during the mission lifetime.
Requirement: The I-SOC-PF mission shall be operated at nominal levels for a minimum duration of 3 years.
Resp.: ESA

#SR-OP-02 ***Instruments Calibration***
Requirement: A duration of 6 months is allocated for the calibration and on-orbit performance characterization of the I-SOC-PF subsystems.
Resp.: ESA

#SR-OP-03 ***Payload Telemetry***
The tuning and the monitoring of the I-SOC-PF instruments and subsystems, in particular during the I-SOC-PFon-orbit calibration and performance characterization, require near-real time availability of the payload science telemetry. This requirement defines the typical time availability of payload telemetry.
Requirement: The parameters defining the performance of I-SOC-PF instruments and subsystems shall be included in the I-SOC-PF telemetry to be downloaded and made

available at the I-SOC-PF ground segment in near-real time, e.g. with a delay only depending on link availability and low-level data processing needed to generate the product.
Resp.: ESA

#SR-OP-04 ***Telecommanding (TC) Capabilities***
The tuning and the monitoring of I-SOC-PF instruments and subsystems, in particular during the I-SOC-PF on-orbit calibration and performance characterization, require near-real time telecommanding capabilities. This requirement defines the typical time interval between telecommand generation at the I-SOC-PF ground segment and its execution on board the spacecraft.
Requirement: The parameters defining the performance of I-SOC-PF instruments and subsystems shall be adjustable by telecommand from ground in near real time, e.g. with a delay only depending on link availability and low-level data processing needed to execute the telecommand.
Resp.: ESA

#SR-OP-05 ***Availability of Space-to-ground Comparison Data***
Requirement: The results of the space-to-ground clock comparisons, both via MWL and ELT+, shall be made available at the ground segment in near real time, e.g. with a delay only depending on link availability and low-level data processing needed to generate the results.
Resp.: ESA

#SR-OP-06 ***Availability of Orbit Information Data***
Requirement: Quick-look orbitography data with sufficient accuracy to evaluate space-to-ground comparisons of clocks at the 10^{-15} level shall be made available in near-real time, e.g. with a delay only depending on link availability and low-level data processing needed to generate the product. The final orbitography for clock comparisons at full performance level shall be available with latency not exceeding 15 days.
Resp.: ESA

#SR-OP-07 ***Mission Operations, Monitoring and Control***
Requirement: The I-SOC-PF USOC shall be responsible for mission operations, monitoring and control, as well as for the archiving of all the data and data products.
Resp.: ESA

Annex 1 I-SOC-PF CLOCK AND LINKS

A1.1 The clock of I-SOC-PF

The proposed clock is an active hydrogen maser produced by the company Vremya CH (Russia). The mission I-SOC-PF is in the fortunate position to capitalize on the development of a next-generation maser for the space-VLBI observatory mission MILLIMETRON, due to be launched in this decade. This maser is a follow-on development of the maser VCH 1010 developed for and successfully operated in the mission “Radioastron” (2011-2019) for 8 years [RD42].

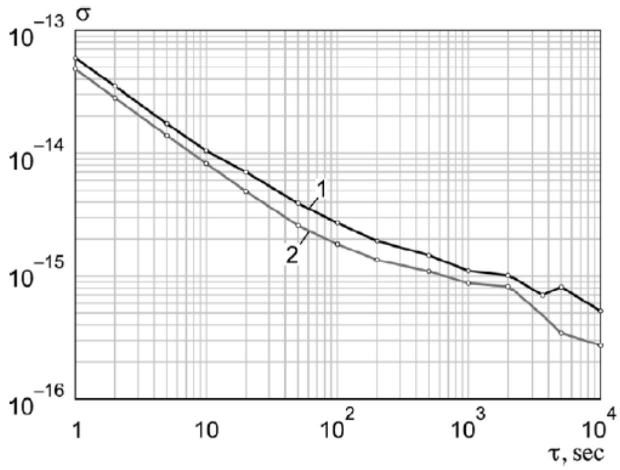
The specifications for the frequency stability of the MILLIMETRON maser for that mission are (Allan Deviation):

$\sigma \leq 2 \cdot 10^{-15}$, for $\tau = 100$ s,

$\sigma \leq 5 \cdot 10^{-16}$, for $\tau = 1000 - 3600$ s.

The company has developed, manufactured and tested the technological units of the device intended for ground experimental testing, and in the near future will begin to manufacture and test the flight units.

The figure shows a technological unit and the current performance [RD43].



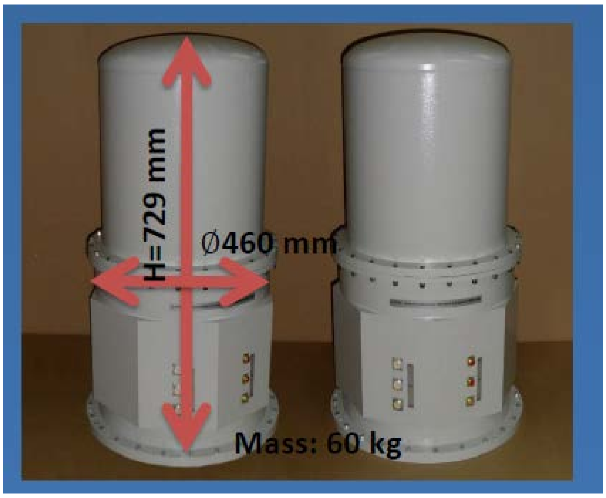


Figure A- 1 Left: Measured frequency instability σ of a prototype unit of the MILLIMETRON hydrogen frequency standard with the system of adiabatic rapid passage turned off (*1*) and turned on (*2*). From [RD43]. Right: Photo of device.

A1.2 The links of I-SOC-PF

A1.2.1 MICROWAVE LINK (MWL)

A1.2.1.1 *Design*

The MWL design is an evolution of the science link presently under development for the ACES mission. The end-to-end system is composed of a flight segment unit and a distributed network of ground terminals, respectively connected to the clocks on-board the STE-QUEST spacecraft and on the ground. The input clock signal is up-converted and used to coherently generate the microwave signals that are transmitted through the atmosphere and received by the remote terminal at the other end of the link. The space segment provides 4 independent receiving channels capable of performing up to 4 simultaneous comparisons of the space clock with clocks on ground.

The comparison of two ground clocks in common-view can be obtained by evaluating the difference of the two simultaneous space-to-ground comparisons. As the noise of the space clock is in common-mode, common-view comparison can be carried out without the need for a high performance on-board clock. A commercial ultra-stable quartz oscillator is indeed sufficient for this purpose.

The comparison of a ground clock with the space clock by means of MWL consists in measuring the desynchronization between the space clock and clocks on the ground, or equivalently the difference between the space clock proper time τ^s and the ground clock proper time τ^g at a given coordinate time t.

While propagating from space to ground and vice-versa, the phase of the signal is perturbed by several effects that need to be evaluated and corrected for. They are:

- The range between the ground station and the spacecraft, responsible for propagation delays on the order of 400 km/c $\approx$ 1 ms.
- The propagation delays induced by the troposphere, typically ranging between 10 ns and 100 ns, depending on the local atmospheric conditions and satellite elevation.
- Ionosphere propagation delays, varying between 0.1 ns and a few ns and depending on the frequency.
- Multipath effects: The detection of the direct signal can be disturbed by reflections (multipath signal) generated at surfaces in the immediate vicinities of both the space segment and ground terminal antennae. The multipath signal combines with the direct signal introducing a delay depending on relative phase and amplitude.
- Internal delays due to the ground terminal and flight segment electronics: Such delays need to be carefully calibrated before launch and continuously monitored during the mission.

MWL is an asynchronous three-frequency link based on a two-way geometry, which operates continuously with an up-link in the Ka-band and two down-links in the Ka and X-band (Figure A- 2).

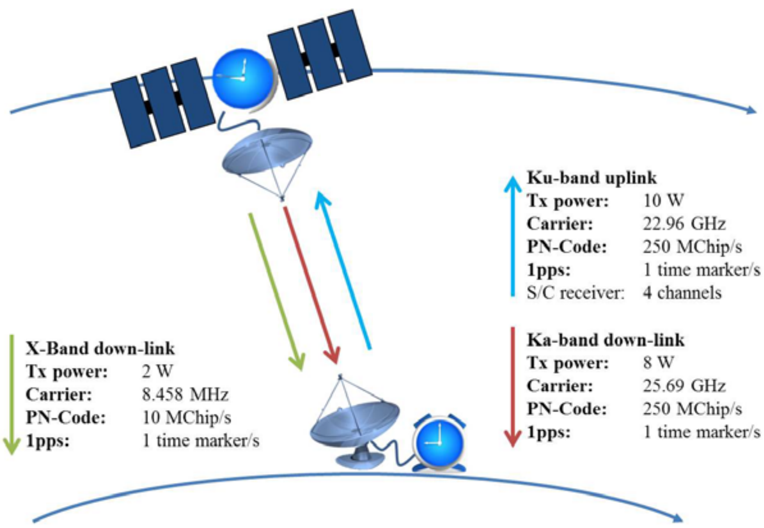


Figure A- 2 MWL architecture

The two-way configuration is important to correct for the range-induced delays, which cancel to first order when the desynchronization between the space and the ground clock is calculated. Residual corrections due to link asymmetries depend on the knowledge of antennae phase centre positions as well as on the two-way geometry of the link. The two-way configuration is also important for removing the non-dispersive delays introduced by the propagation through the troposphere. Frequency dependent tropospheric delays, if not corrected, can still degrade the performance of the MWL link. A semi-empirical correction model, similar to the one developed in [RD29] for the ACES mission can be used to estimate this effect and remove it to the required level. Ionospheric delays are frequency-dependent and they influence with opposite sign both group and phase velocity of the microwave signal. To this purpose, the link measures the differential delay on the Ku-band and X-band downlink signals to calculate the total electron content (TEC) of the ionosphere and correct for the ionospheric time delay [RD30].

The two ends of the link transmit a carrier that is phase-modulated by a pseudo-noise code (PN-code) at a rate of 250 MChip/s. Carrier and code are both coherently generated from the local clocks. The code and the carrier phase of the received signal are compared to their local replicas at the space and ground terminals. While the noise on code phase measurements defines the long-term stability of the link, the ultimate performance can only be reached with carrier phase measurements. To this purpose, the code signal is also used to remove phase cycle ambiguities, allowing for continuous phase comparison measurements on the carrier signal. The PN-sequence is also modulated with a PPS (Pulse Per Second) that defines the on-board time scale.

As shown Figure A- 3, acquisition and tracking is achieved by correlating the incoming signal, down-converted to the intermediate frequency IF, with an early and late replica of the locally generated PN-code sequence [RD31]. The use of narrow early-late correlators is important to control multipath effects [RD32]. The 1st IF is mixed with a replica of the carrier frequency shifted according to the experienced Doppler effect. After the early-late correlator, the signal is cleaned in a surface acoustic wave (SAW) filter and digitised in a fast A/D converter. A/D conversion as well as signal correlation can be digitally implemented in a field programmable gate array (FPGA). Using fast electronics, internal delays can be precisely controlled with respect to standard analogue beat techniques. Local code and carrier frequencies are generated by direct digital synthesizers (DDS), which are phase-locked to the local clock and controlled by the tracking loops.

Following the ACES heritage, the space antenna is designed for circular polarisation in order to optimally reject multipath and suppress Faraday rotations in the Earth magnetic field. The beam angle shall allow coverage of the Earth in the main lobe at all orbit conditions. Choke rings are used to improve directivity and reduce the effects of signal reflections.

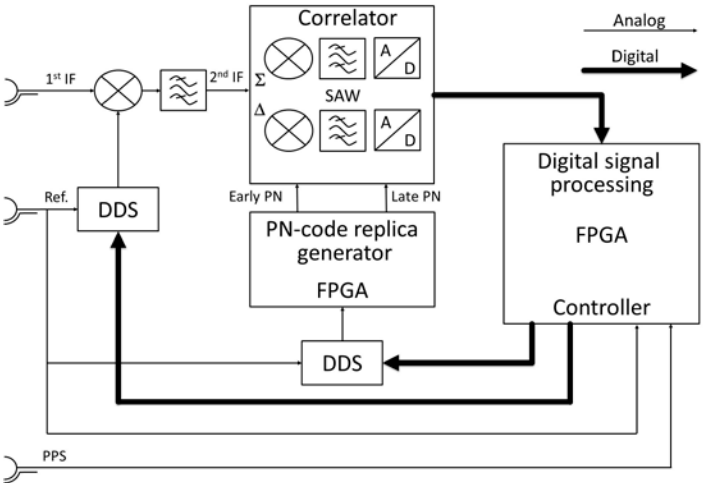


Figure A- 3 Schematic of code signal tracking in MWL.

The MWL ground terminal design follows the ACES technology after re-adaptation of the systems to the Ka-band and X-band frequencies. It is a microwave station interfacing the local clock on ground to the ISS payload (Figure A- 4). To reduce phase instabilities due to the tracking motion, the electronics unit is rigidly attached to the antenna unit. The antenna is a 60 cm offset reflector with a dual-band feed system automatically pointed in azimuth and elevation by a steering mechanism. A computer controls the steering unit based on the STE-QUEST orbit prediction files, collects telemetry and science data both from the local clock and the MWL GT electronics, and interfaces directly with the Mission Operations Center (MOC). The system is housed below a protective radome cover, which also allows stabilizing the temperature by an air conditioning system.

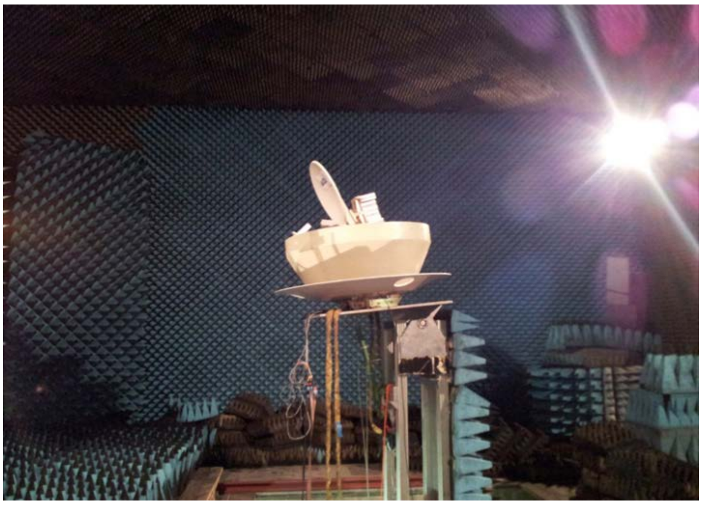


Figure A- 4 ACES MWL ground terminal under test in compensated compact range facility. The I-SOC-PF ground terminals will be based on the ACES technology.

Due to the early-late correlator properties, only multipath signals which result to be time-shifted by less than 1 chip for the carrier and 1.5 chip for the code introduce errors on the phase comparison measurements [RD33]. Therefore, reflections from surfaces at more than 2 m are strongly attenuated by the PN-code autocorrelation properties. The effect of reflections from shorter distances will have to be minimized through a careful antenna design and its positioning on-board the spacecraft.
The link stability requirement reported in#SR-PL-07 translates into a time error with a flicker phase noise as low as 92 fs [RD34]. Reaching the ultimate link performance requires a control on the delays affecting code and carrier phase measurements at a few tens of femtoseconds. This translates into an optimized thermal design of the end-to-end link. To that purpose, a two-stage temperature control system is foreseen both for the flight segment and ground terminal electronics. In addition, early digitization of the science signal, use of short cables and signal paths, symmetric designs for amplifiers and other critical components become important to meet the scientific requirements. Finally, the calibration of the terminal delays against temperature variation will be performed both in space and on the ground and continuously updated during the mission lifetime thanks to built-in test loop transponders.
The key link parameters have been identified, the link budget at apogee has been calculated for different elevation angles and atmospheric conditions (clear sky or rain), together with the S/N and the expected jitter (white phase noise) of the code and phase comparison measurements. From the design, a link availability better than 99% can be predicted.

A1.2.1.2 *Interfaces and resource requirements*

The interfaces at the MWL ground terminal and at the flight segment unit with the signals generated by the local clock (USO or atomic clock) include:

- 100 MHz reference input signal coherently generated by the USO or atomic clock;
- 1 PPS input for synchronization, calibration and test purposes;
- 1 PPS output for synchronization, calibration and test purposes.

On the ground, the connection between the local clock and the MWL input connector shall not degrade the performance of the clock signal itself. This connection is under the responsibility of the institutes operating the ground clocks. Distances of several hundreds of kilometres can today be covered by fibre links introducing negligible noise on the distributed clock signal. The PPS output port is also the reference point for performing time transfer experiments. This connector provides a timing signal synchronously generated from the local atomic clock.
MWL phase comparison measurements are time tagged both in space and on the ground in the local clock timescales. In addition, absolute internal delays at reception and transmission need to be calibrated to 1 ns. This includes the calibration of the MWL flight segment and ground terminal channel delays from reception at the antenna reference point to time stamping in the local time scale and from time stamping in the local time scale to emission at the antenna reference point. Control of internal delays at reception and emission is important to correctly apply the two-way formula and achieve optimal rejection of phase variations due to the Doppler effect. Finally, phase comparison measurements shall be linked to UTC with an uncertainty better than 1 μs to correctly retrieve velocity and position of the clocks and the antennae reference points from the orbitography files (see Sec. 3.3.2).
MWL is also used to perform time transfer experiments. To this purpose, the MWL ground terminals need to be calibrated against a transportable unit that will be kept as a reference.

Calibration campaigns will take place as a minimum at the beginning and at the end of the mission.
Standard data links are used by the terminals to transfer telemetry, housekeeping, and science data as well as to receive telecommands, orbitography files, etc. Communication between the ground terminals and the MOC takes place through the internet.
The MWL flight segment unit has a mass of 33 kg and a power consumption of 110 W. Both figures include 20% of margin at unit level.

A1.2.1.3 *Operation requirements*

MWL space-to-ground contacts are scheduled on the basis of the visibility windows available at each ground station. As discussed before, weather conditions do not pose any restriction to MWL operation.
MWL uses Code Division Multiple Access (CDMA) to simultaneously connect up to 4 ground terminals to the 4 receiving channels of the flight segment unit. At signal acquisition, frequency and delay of the code oscillator need to be steered on the basis of the predicted range and Doppler shift. Range and Doppler steering files are prepared by MOC and uploaded before the start of each pass to support signal acquisition routines. The MWL ground terminal is automatically pointed in azimuth and elevation by a steering mechanism controlled by a computer on the basis of the orbit prediction files generated by MOC. Signal acquisition is expected to start slightly above the horizon, with the system entering the full tracking mode before reaching 5 deg of elevation.
Both the flight segment unit and the ground terminals are remotely controlled by MOC.

A1.2.1.4 *Heritage*

The development of the I-SOC-PF MWL will take advantage of the ACES heritage and of the STE-QUEST mission study. Many of the techniques and procedures discussed before have already been established and tested in the frame of the ACES mission. The ACES MWL engineering model has been completed and tested. The flicker floor of the carrier phase measurements has been measured to 70 fs, compatible with the I-SOC-PF needs. The instrument is now undergoing signal simulator tests to characterize the performance under realistic signal dynamics.

An upgrade of the ACES MWL to a space mission with a high Earth orbit (STE-QUEST) has been considered.

The issues identified to upgrade MWL were the following:

- Frequency plan to be re-adapted to Ka-band and X-band;
- Antennae design and power amplification stages to be dimensioned to the link budget;
- High speed electronics, now available, to be implemented to increase the chip rate to 250 MChip/s (compared to the 100 MChip/s of the ACES MWL) and to perform an early digitization of the regenerated code and carrier signals.

An ESA study has addressed the above issues relative to that orbit and showed compatibility with the STE-QUEST scientific requirements. A second study named HERO (participants: Wiser, Thales Alenia Spazio, Universita di Roma, and others) is underway since 2018 to verify experimentally the performance through a breadboarding activity of the critical system elements.

This new system HERO has specifications that fit the need of I-SOC-PF.

HERO OVERVIEW

The HERO Transceiver has been conceived in view of fulfilling the scientific goals of the STE-QUEST mission and it performs two fundamental tasks:

1. compare the phase of the incoming code with respect to the phase of a locally generated replica and derive the relative delay with an accuracy of 20 ps or better, on a maximum measurement time-window (integration time) of 120 s.
2. compare the phase of the incoming carrier to that of the local reference and measure the relative phase shift with an accuracy < 4 ps (30 degrees rms or approximately $\lambda/10=0.15$ cm) over an integration time < 1 s.
   For longer integration time the uncertainty will average down, to a level of 0.03 ps for $\tau > 1000$ s.

Similar to the ACES MWL, this link uses continuous-wave carrier radiation, but a special modulation technique allows precise and fast phase measurements. Furthermore,

Two different frequencies are used for up-link and down-link

An additional down-link in X band (~ 10 GHz) is employed for ionospheric delay calibration.

The HERO system is characterized by:

Earth-to-Space link: 26.5 GHz
Space-to-Earth link: 30.5 GHz
Chip rate = 200 Mcps
Code length = 20 000 chips
Code Period = 0.1 ms
Code chip rate and carrier are coherently synthesized
Data Period = 0.1 ms (coherent with code epoch): this is the time duration for a single phase measurement
Built-in Test Loop Translator (TLT) for on-board group delay calibration purpose.

These specifications will ensure a low phase measurement instability, and also a goal ground-to-space delay uncertainty < 8.5 ps.

The top-level architecture of the HERO transceiver is shown in the block diagram. As can be seen, the main subsections are the following:

- Analog Receiver Module (RXM)
- Analog Transmitter Module (TXM)
- Digital Module (DM)
- Test Loop Translator Module (TLTM)

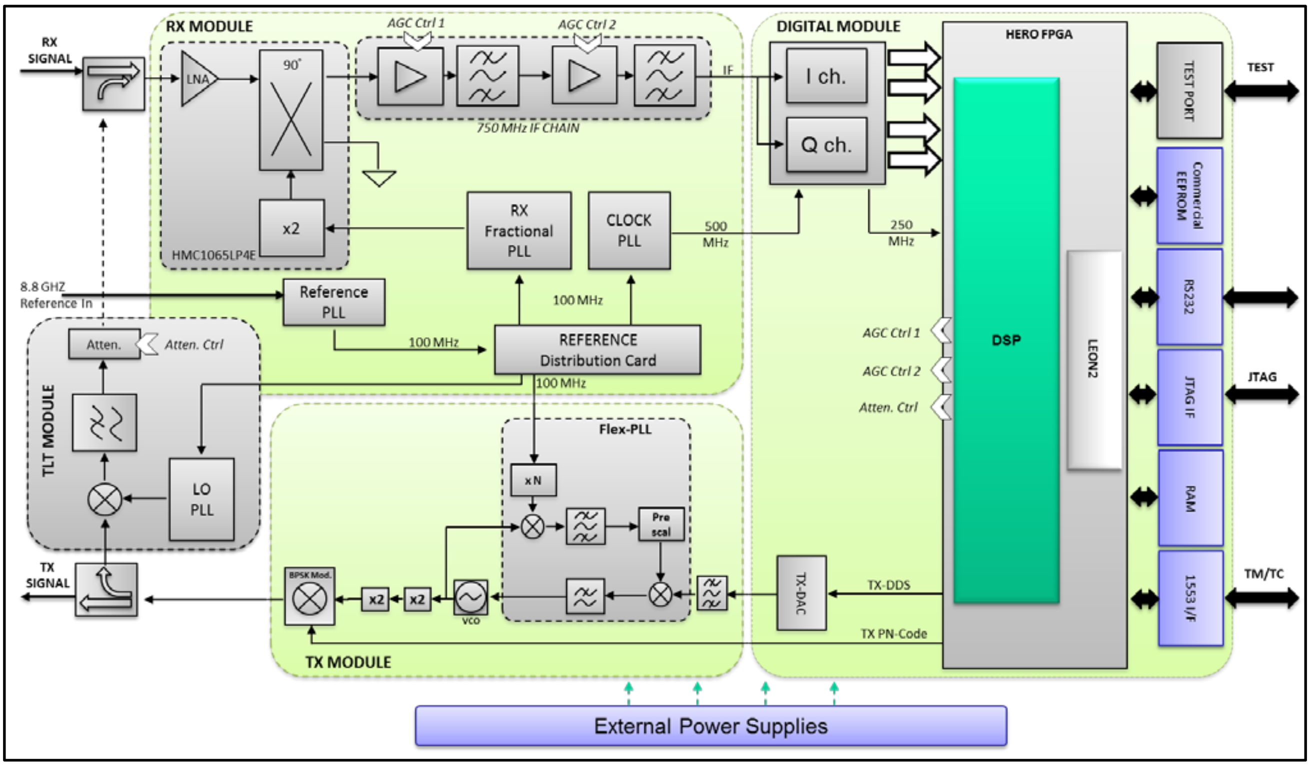


Figure A- 5 HERO Transceiver architectural block diagram

The **RXM** module is in charge of low-noise amplification of the incoming signal in Ka-band and of the frequency down-conversion at IF frequency (750 MHz). The Local Oscillator (LO) generator circuit inside the RXM is based, for the on-board transceiver, on a Fractional-N PLL synthesizing a Ku-Band carrier that is frequency multiplied × 2 to get the desired LO frequency in the Ka-band (the × 2 frequency multiplier is directly implemented in the Ka-band front-end hybrid). For the on-ground RXM configuration, the LO signal is generated by means a Fractional-N PLL synthesizing a X-Band carrier that is frequency multiplied × 2 and, finally, to get the desired LO frequency, is × 2 multiplied inside the Ka-Band front-end hybrid.

The **TXM** inputs are the baseband modulating code (TX PN-Code) generated by the HERO FPGA and a low-frequency Reference Tone (TX-DDS) able to steer the transmitted frequency. It is mainly based on the usage of an X-Band Flex PLL that exploits the experience made in the frame of BepiColombo program.

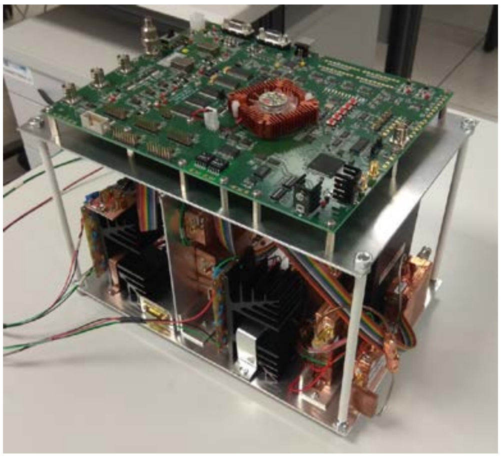
The **DM** represents the core of the Transceiver and is based on a System-on-chip approach: a dedicated FPGA (so-called HERO FPGA) includes the entire signal processing functions required by HERO/STE-QUEST application, as well as a general purpose Microprocessor which is in charge of low-rate processing and overall equipment management, including TM/TC. This architectural approach provides a great flexibility thanks to the combination of custom logic, mainly devoted to specific high-rate signal processing tasks, and high-level software.

Thus, as an evolution compared to MWL on ACES, on HERO the code correlation is fully performed in the digital domain. Therefore the transceiver architecture is different from the one reported in Figure A- 3.

The **TLTM** is in charge of translating the TX signal to the RX frequency for on-line calibration. Its output signal level will be adjustable so as to provide amplitude a few dB below that of the useful signal.

The HERO Transceiver has been developed at Breadboard-level and it is currently under test; validation of the relevant performance is expected by 2020.

Design and development of HERO breadboard has been carried out in view of flight solution. In particular, the HERO flight model will be based on TAS-I Ka-Band Transponder (KaT) product platform which achieved TRL 9 in the frame of JUNO and BepiColombo missions. Actually, HERO flight model will re-use several RF building blocks from heritage while its digital core will be duly tailored according to the specific functions and performance under validation in the frame of relevant ESA study.



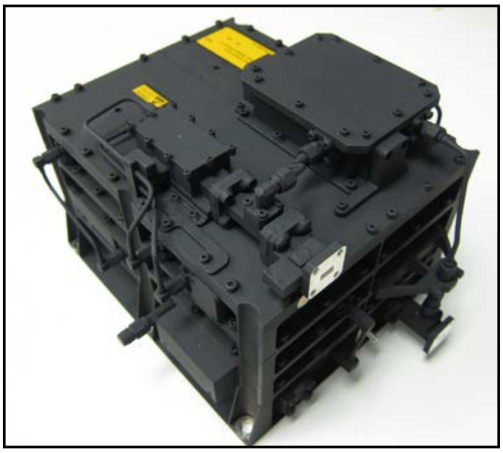


Figure A- 6 HERO transceiver breadboard and KaT flight model (BepiColombo - MORE)

A1.2.2 ELT+ LASER TIME TRANSFER

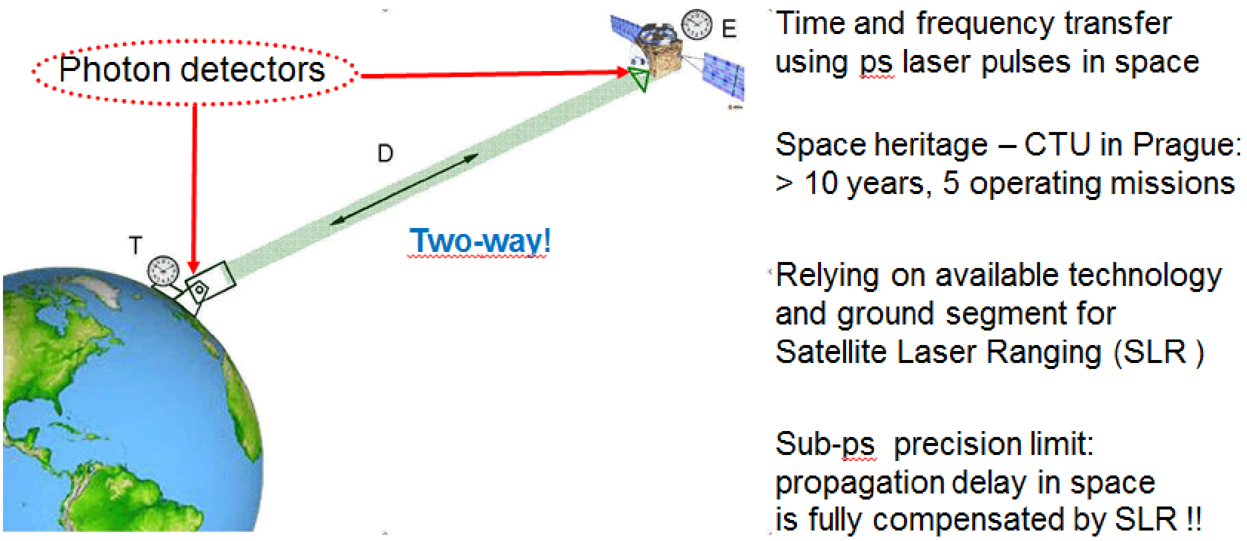


Figure A- 7 Principle and characteristics of the ELT+ link.

A1.2.2.1 *Design*

ELT+ is a pulsed laser time transfer technique. See Figure A- 7 for the principle. It is based on an existing and mature technique of satellite laser ranging (SLR). The ultra-short laser pulses fired at 1 kHz repetition rate towards the satellite by a ground laser ranging station are time tagged with respect to the ground time scale**.** They are detected in space and also time-tagged in the local time scale. At the same time the optical retroreflector is re-directing a part of the laser pulse back towards the ground station. Detecting the reflected optical pulse on a ground is providing accurate two-way propagation time and hence it is providing the information about the ground-to-space signal propagation delay.

A1.2.2.2 *Application to I-SOC-PF science goals*

Pulses received by the ISS at the beginning and end of a time interval T (as defined by a ground clock) can be correlated with timing pulses generated by the space clock. Thus, the time interval T can be measured in terms of the time scale defined by the space clock. If T is for example defined as the interval corresponding to M cycles of the ground clock oscillation, I-SOC-PF will be able to determine the number of cycles M' of the space clock hat correspond to M. The ratio M'/M corresponds to the frequency ratio ν'/ν and contains information about the GTD.

By receiving on the ISS pulses arriving from different ground stations with respective clocks, it will be possible to compare the frequencies/time intervals of ground clocks.

The detection, on ground, of the retroreflected pulses serves to determine the ground-to-space propagation delay and to correct for it in the clock comparison measurements.

Note that this measurement procedure requires the cycle counting to be gapless, both on ground and in space. Loss of single or few cycles give rise to additional measurement errors.

In absence of such additional uncertainty, the fractional accuracy of measuring a time interval (or determining a frequency ratio) is given by $\Delta t(T)/T$, where $\Delta t(T)$ is the timing error (TDEV) arising in the pulse reception over the time interval T. This holds for common-view comparisons. For non-common-view comparisons, one has to add the time error arising from the on-board clock as it accrues during flight of the ISS from one ground station to the other (for a general discussion of extrapolation errors, see [RD38]).

The application of this concept to the Sun/Moon GTD, where a putative signal would give a frequency ratio varying periodically (period close to 24 h), has been discussed in connection with #PSO-01 and 23#PSO-02 above.

A first estimate of the expected timing performance of the ELT+ laser time transfer for the I-SOC-PF mission is presented here. The data are based on the best results obtained in experiments of individual parts of the ELT laser time transfer chain within the last years. Considering the physical nature of all the individual contributors, no significant improvement is expected to appear in laser time transfer technique of ELT type in the future.

A1.2.2.3 *Space segment*

The key parts of the ELT+ space segment are a photon counting detector, an epoch timing system and a passive optical retroreflector. Recently, a number of improvements of technology components of the laser time transfer signal chain occurred. The timing performance of photon counting detectors and epoch timing systems has improved several times [RD35,RD36].

The performance of the detector, the timing system, test laser pulses ~ 40 ps long, and an electro-optical switch was tested in indoor experiments at CTU in Prague. The precision in a sense of TDEV is 0.4 ps @ 100 s. Improvement of this value down to 100 fs @ 100 s is expected. A long-term stability better than 0.4 ps from 100 s to 100 000 s was verified experimentally and repeatedly. Timing stability better than 0.5 ps over $1{\cdot}10^6$ s is expected as a qualified estimate. These values are valid for a laser repetition rate of 1 kHz. Realistic margin exists, thanks to laser pulse lengths expected to be < 10 ps in future SLR operation.

A1.2.2.4 *Ground segment*

The ground SLR systems participating in I-SOC-PF are expected to operate at 1-2 kHz rate, using laser pulse lengths of ~ 10 ps. The precision of determining one-way ground-to-space delay will be better than 0.4 ps for averaging time 100 s. This value is expected to be obtained when ranging to a spherical laser retroreflector – a Luneburg sphere ([RD37], Figure A- 9 right). The long-term stability of a good SLR system will be below 1 ps (0.5 ps as a goal) over hours up to one month. This estimate is based on a performance of the world’s most stable SLR system (Graz, Austria). No significant improvement is expected in the future.

Another important element of the ground segment is the link between the ground clock and the SLR system. Usually the clock is not located where the timer and the respective detectors are. In addition to that, one also has to consider that one is dealing with time signals and hence with signals having very high bandwidth. The full electronic generation and transfer of these signals is not a trivial matter and usually accumulates an significant amount of transfer delay. Figure A- 8 left, illustrates this with a long-term time comparison of pps pulses between the SLR station at the Geodätisches Observatorium Wettzell (GOW, Germany) and its time laboratory. Over the period of almost one month, the electrical time transfer experiences a temperature-induced diurnal delay variation of about 100 ps. Perturbations in the laboratory due to people interaction or air-conditioning failure exacerbate this to excursions of 600 ps peak to peak.

In preparation of the ACES time transfer experiments with the precursor laser link ELT, at the GOW an all-optical two-way time and frequency distribution system has been installed, based on a mode-locked pulse laser. This reduces the local time transfer uncertainty between the clock laboratory and the SLR system to about 1 ps (Figure A- 8, right). A closed-loop two-way balanced optical cross correlator technique ensures the long-term stability of the system. With a high-performance optical clock stationed at GOW, it is expected that one can obtain a ground-to-space time-transfer performance long-term stable at the level of a few ps.
This distribution system, and an optical clock, will be available during the I-SOC-PF mission.

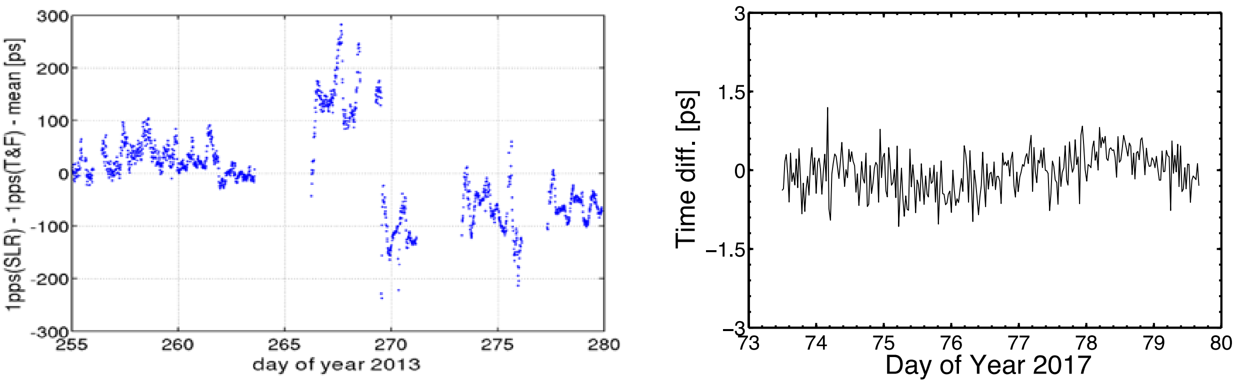


Figure A- 8 Time comparison between the SLR system and the time laboratory at GOW. The purely electrical comparison (left panel) shows variations at the level of 600 ps, while the optical two-way mode-locked laser time transfer is stable to within 1 ps, thus reducing the biases considerably (right panel).

A1.2.2.5 *Overall laser time transfer performance*

Combining the ground and space segments, one can conclude that the precision obtainable within one pass of I-SOC-PF / ISS could be below 0.5 ps @ 100 s. The value of overall timing stability ≈ 1 ps is expected for time intervals of up to 10^6 s. Thus, the maximum fractional accuracy possible with this method, after 10^6 s integration time, will be 1 ps/10^6 s = $1 \cdot 10^{-18}$. This value is relevant for common-view ground clock comparisons. Considering the nature of all the individual contributors to noise and systematic errors, no significant improvement of these values is expected.
For non-common-view ground clock comparisons, we must take additionally into account the on-board clock instability. Over the timescale of 1/2 ISS pass (clocks on opposite sides of the Earth), the timing instability is 1 ps/2700 s ≈ 4×10^{-16}. This value is comparable to the clock instability over that interval (5×10^{-16}) and therefore ELT+ performance is adequate.

A1.2.2.6 *Interfaces and resource requirements*

Data flow
Uplink: – very limited data volumes – control commands only. Total data volume expected is well below 100 bits / orbit.
Downlink: The operational ELT+ will generate measurement data at a rate ~ 200 kbits / s. This data flux must be accepted by the control computer. To reduce the total data volume stored on-board and downlinked to ground, the data blocks corresponding to (possible) laser time transfer activity can be stored and downlinked only. This approach might reduce the data volume for on-board storage and downlink more than 30-fold. To enable efficient operation of ELT+ link, the data must be downlinked to the ground data center at least once per ISS orbit.

Resources
Power: – the total power requirements of the ELT+ hardware is ~ 13 W. The power supplies voltages in a range of +/-5V are needed only. The highest voltage operated in a detector is below 30 V.
Timing signals: – the clock signal of 100 MHz is needed for the epoch timing device. In addition the "1PPS" epoch reference. These clock frequency and epoch reference will define the local time scale. In addition the UTC timing signal (1 PPS or similar) will be needed for gate generation for the ELT+ detector.

A1.2.2.7 *Operation requirements of space segment*

The laser retroreflector will operate in free space, nadir looking, without additional requirements.
The optical detector will operate with the input aperture opened into free space, nadir looking. The operational temperature of the detector itself can be within a range of -40 up to +30 deg. C. The temperature change over one orbit should be within 6 K (analogy to ACES/ELT).
The epoch timing device will operate inside the instrument. The operational temperature of the timing device itself can be within a range of -40 up to +30 deg. C. The temperature change over one orbit should be within 2 K.
To provide maximum system stability, all the electronics is expected to be powered all the time.

A1.2.2.8 *Heritage*

ELT+ has heritage from ACES (where it is named ELT) and several previous missions of laser time transfer. Within the last two decades 5 operational space missions were performing time transfer using laser light. The experiment prepared by CNES is operational on board of Jason-2 mission (launched by NASA, June 2008). The device called T2L2 is operating at an altitude ~ 1500 km above the Earth surface. It provides the precision in a sense of time deviation ~ 10 ps at 200 s integration time. The overall timing performance is limited by the quality of on-board clock – a quartz oscillator. The main limitation of systematic errors is the multiphoton concept of laser time transfer. The systematic errors of the system are on a level of 100 ps.
The photon counting concept was used for the first time on board of Compass satellites both on GNSS orbits (2 satellites) and on inclined geostationary orbits (2 satellites). The laser

time transfer system was operational during the years 2007 to 2012. The precision was typically 30 ps @ 500 s integration time. It was limited by data volume available for downlink communication and hence by the experiment repetition rate of 1 to 10 Hz only. For the ACES mission, the laser time transfer link ELT was prepared. It is based on a photon counting approach to minimize the systematic errors. The nominal repetition rate is 100 Hz. The extensive ground tests verified the performance better than 3 ps at 100 s integration time and the stability of ~ 1 ps over long time intervals exceeding $1 \cdot 10^6$ s.
For all the listed space missions the optical receivers for both space and ground segments were developed at CTU in Prague. In all listed missions the planned laser time transfer performance was achieved.
The laser time transfer ELT+ will be based on a heritage of the ELT optical detector and on the newly developed New Pico Event Timer (NPET) developed at CTU in Prague. This event timing system is currently used as an epoch timing device for calibration purposes of a ground segment participating in ELT mission.
A laser retroreflector of a special concept (Luneburg sphere, Figure A- 9) has to be used to reach sub-ps precision. The retroreflectors of this type and origin have a space heritage (Meteor 3, Blits,...).

A1.2.2.9 *Budget of the space segment*

Photon counting detector (Qualified estimate based on ELT/ACES mission experience)

mass	0.5 kg
power	< 0.6 W
dimensions	110 x 110 x 170 mm

Epoch timing device (estimate based on laboratory sample of device)

mass	1 kg
power	12 W
dimensions	160 x 250 x 42 mm

Signal cabling (Qualified estimate based on ELT/ACES mission experience)

mass	< 0.5 kg
dimensions	-

Laser retroreflector + holder (space heritage)

mass	1 kg
power	0 W
dimensions	100 x 100 x 100 mm^3

Comments

The detector and laser retroreflector have to be installed on the external part of Columbus module (or Bartolomeo),
The shape of the detector and epoch timer may be modified, once necessary
Their total mass and power consumption cannot be reduced significantly,
The space-qualified laser retroreflector is commercially available (Russian origin); it has TRL 9.

The detector is already well developed (TRL 7). The event timing unit for ground use exists [RD39] and has been extensively tested. It has TRL 6. In field experiments, CTU researchers together with the Graz laser ranging station achieved an overall performance of laser time transfer having instability < 0.4 ps TDEV @ 100 s [RD40]. The long-term instability of the ELT+ measurement chain was shown to be < 1 ps TDEV for integration times of several days.

Figure A- 9 shows prototypes of the relevant elements.

Figure A- 9 Left: Single-photon detector prototype. Center: Epoch (event) timing unit prototype. Right: Luneburg sphere (laser retroreflector).

Annex 2 COMPOSITION OF THE I-SOC-PF SCIENCE TEAM

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C. Lisdat, Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, DE
M. Zawada, N. Copernicus University (UMK), Torun, PL
C. Salomon, Laboratoire Kastler Brossel (ENS), Paris, FR
U. Hugentobler, Technische Universität München (TUM), München, DE
U. Schreiber, Technische Universität München (TUM), München, DE
C. Sopuerta, Institute of Space Sciences (ICE, CSIC and IEEC), Cerdanyola del Valles, ES
J. Lodewyck, Observatoire de Paris (OBSPARIS), FR
J. Nastula, Space Research Center (CBK), Warsaw, PL

Annex 3 SCIENCE TEAM SIGNATURE PAGES

Email support statements; signatures will be provided later.

Ulrich Schreiber

Von:	Schreiber, Ulrich <ulrich.schreiber@tum.de>
Gesendet:	Montag, 4. Mai 2020 20:36
An:	Prof. Schiller Stephan
Betreff:	Re: I-SOC PF: Status and Required Document
Kennzeichnungsstatus:	Gekennzeichnet

Dear Stephan,

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Kind regards, Ulrich

Luciano Iess

Von:	Luciano Iess <luciano.iess@uniroma1.it>
Gesendet:	Dienstag, 5. Mai 2020 10:26
An:	Stephan Schiller
Betreff:	Support for I-SOC Pathfinder

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Luciano Iess

Dipartimento di ingegneria meccanica e aerospaziale
Università La Sapienza
via Eudossiana 18,   00184 Roma, Italy
Tel +39 06 44585336

Kai Bongs

Von: Kai Bongs <K.Bongs@bham.ac.uk>
Gesendet: Montag, 4. Mai 2020 15:57
An: step.schiller@hhu.de
Cc: Yeshpal Singh
Betreff: RE: I-SOC PF: Status and Required Document

Dear Stephan,

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Thank you very much and best wishes,

Kai.

Prof. Kai Bongs

Director of Innovation – College for Engineering and Physical Sciences
PI of the UK National Quantum Technology Hub in Sensors and Timing
www.quantumsensors.org
Midlands Ultracold Atom Research Centre
School of Physics and Astronomy
University of Birmingham
Birmingham, B15 2TT
phone: +44 121 414 8289
fax: +44 121 414 8277
e-mail: k.bongs@bham.ac.uk

Ivan Prochazka

Von: Ivan Procházka <ivan.prochazka@fjfi.cvut.cz>
Gesendet: Montag, 4. Mai 2020 14:40
An: Stephan Schiller
Betreff: RE: I-SOC PF: Status and Required Document

Dear Stephan,

1. My statement:

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Ivan Prochazka
Czech Technical University in Prague
Czech Republic

Christian Lisdat

Von: Christian.Lisdat@ptb.de
Gesendet: Montag, 4. Mai 2020 13:48
An: Stephan Schiller
Betreff: I-SOC PathFinder

Dear Stephan,

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.
Best regards,

Christian Lisdat

PD Dr. Christian Lisdat
Physikalisch-Technische Bundesanstalt
AG 4.32 Optische Gitteruhren
Bundesallee 100, 38116 Braunschweig
Fon: +49 (0)531 / 592 43 20 Fax: +49 (0)531 / 592 43 05

Michal Zawada

Von: Michał Zawada <zawada@fizyka.umk.pl>
Gesendet: Montag, 4. Mai 2020 14:05
An: Stephan Schiller
Betreff: Re: AW: I-SOC PF: Status and Required Document

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Bogdan Mihalcea

Von:	Bogdan Mihalcea <bogdan.mihalcea@inflpr.ro>
Gesendet:	Montag, 4. Mai 2020 13:07
An:	Stephan Schiller
Betreff:	Re: AW: I-SOC PF: Status and Required Document

Dear Stephan,

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Best regards,
Bogdan Mihalcea

--
Snr. Research Scientist 2
National Inst. for Laser, Plasma, and Radiation Physics (INFLPR) Low Temperature Plasma Lab.
Atomistilor Str. Nr. 409
077125 Magurele, Ilfov County
Romania
Phone: +4021-4574437
Fax: +4021-4574243
Mobile: +40-770-230640
http://pcp.inflpr.ro

Markus Rothacher

Von:	Markus Rothacher <markus.rothacher@ethz.ch>
Gesendet:	Montag, 4. Mai 2020 12:54
An:	Stephan Schiller
Betreff:	Re: I-SOC PF: Status and Required Document

Dear Stephan,

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

With best regards,
Markus

Philippe Jetzer

Von: Philippe Jetzer <jetzer@physik.uzh.ch>
Gesendet: Montag, 4. Mai 2020 12:46
An: Stephan Schiller
Betreff: Re: AW: I-SOC PF: Status and Required Document

Dear Stephan

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Best regards

Philippe

Uwe Sterr

Von: Uwe.Sterr@ptb.de
Gesendet: Montag, 4. Mai 2020 18:52
An: Stephan Schiller
Betreff: Re: AW: I-SOC PF: Status and Required Document

Dear Stephan,
I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Best regards
Uwe

Christophe Salomon

Von:	Christophe Salomon <salomon@lkb.ens.fr>
Gesendet:	Montag, 4. Mai 2020 18:31
An:	Stephan Schiller
Cc:	Ivan Procházka; Kai Bongs; Yeshpal Singh; Luciano Iess; Rodolphe Le Targat; Jerome Lodewyck; U. Sterr; Christian Lisdat; Urs Hugentobler; Schreiber, Ulrich; zawada@fizyka.umk.pl; Christophe Salomon; Philippe Jetzer; Markus Rothacher; Laurentiu Caramete; sopuerta@ice.csic.es; Bogdan Mihalcea; Mauro Di Benedetto
Betreff:	Re: I-SOC PF: Status and Required Document

Dear Stephan,

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Best regards
Christophe

Urs Hugentobler

Von:	Urs Hugentobler <urs.hugentobler@tum.de>
Gesendet:	Montag, 4. Mai 2020 22:05
An:	Stephan Schiller
Cc:	Schreiber, Ulrich
Betreff:	Re: I-SOC PF: Status and Required Document

Dear Stephan Schiller,

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Urs Hugentobler
Research Facility Satellite Geodesy
Technical University of Munich

Carlos Sopuerta

Von:	Carlos F. Sopuerta <sopuerta@ice.csic.es>
Gesendet:	Dienstag, 5. Mai 2020 09:40
An:	Stephan Schiller
Betreff:	Re: AW: I-SOC PF: Status and Required Document

Dear Stephan,

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Best regards,

Carlos F. Sopuerta

--

Carlos F. Sopuerta
Institute of Space Sciences (ICE, CSIC and IEEC) Campus UAB, Carrer de Can Magrans s/n
08193 Cerdanyola del Valles (Barcelona, Spain)
PHONE: + 34 93 737 9788 (ext. 933021)

Jerôme Lodewyck

Von:	Jérôme Lodewyck <jerome.lodewyck@obspm.fr>
Gesendet:	Dienstag, 5. Mai 2020 13:56
An:	Stephan Schiller
Cc:	Rodolphe Letargat
Betreff:	Re: I-SOC PF: Status and Required Document
Anlagen:	jerome_lodewyck.vcf

Dear Stephan

in reply to your message,

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

However, in order to more efficiently balance our workload, I will from now on be the sole contact point for this project for the optical clocks team at SYRTE.

Best regards,

Jérôme

Jolanta Nastula

Von:	Jolanta Nastula <nastula@cbk.waw.pl>
Gesendet:	Dienstag, 5. Mai 2020 14:44
An:	step.schiller@hhu.de
Cc:	zawada@fizyka.umk.pl; Jerzy Nawrocki; plejba@cbk.poznan.pl; Anna Długosz
Betreff:	from Jolanta Nastula

Dear Profesor Schiller

I agree in supporting the I-SOC Pathfinder project as a member of the science team and approve the current version of the I-SOC Pathfinder Experiment Scientific Requirements.

Yours sincerely

prof. dr hab. Jolanta Nastula

Annex 4 TBR LIST

List of issues related to the I-SOC-PF Scientific Requirements to be resolved.

	Description	Input needed	Date
TBR-01 : USOC Location	Location of the I-SOC-PF User Support and Operation Center (USOC) to be identified.		
TBR-02: DAC location and functions	Location and specific functions of the I-SOC-PF data analysis center to be detailed.		