Campaign White Paper:

Global Time and Frequency Transfer for Clock-Based Fundamental Physics Tests

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I. Introduction

We present a staged mission concept to expand the global coverage of time and thereby enable new tests in fundamental physics, specifically of the Einstein Equivalence Principle, as well as new capabilities in geophysics and timekeeping. The first stage of the proposed campaign is the I-SOC-pathfinder (I-SOC-PF) ISS mission, which has been developed by a science team under auspices of the European Space Agency and could be implemented as early as 2026. The second stage of the proposed campaign would extend current terrestrial comb-based high-precision optical time transfer (OTT) to a geosynchronous mission, enabling common-view time transfer between the world's most stable optical clocks and could follow a few years behind I-SOC-PF. Together, these staged missions would provide high-accuracy fundamental physics experiments for: (i) improved tests of the gravitational red shift through comparison of ground clocks in different gravitational fields of the Sun and Moon[1], as well as (2) searches for dark matter[2–4] and (3) tests of local position invariance[5,6] by creating a globally connected network of clocks. In addition, they would revolutionize international time keeping and provide entirely new capabilities in clock-based geodesy. This progression of missions follows the current technology readiness levels of the subsystems and avoids dedicated launches, as the I-SOC-pathfinder would be external to the ISS while the Geo-OTT could piggyback on another Geo mission (in particular an optical communication mission which would have many of the same free-space optical telescope requirements.) or a dedicated mission (at higher total cost). These two missions could take place in parallel with the development of a high accuracy optical lattice clock for a future mission, e.g. the proposed FOCOS mission[7]. Finally, these staged missions provide an excellent opportunity for cross collaboration between ESA and NASA in the area of fundamental physics with immediate near-term impact.

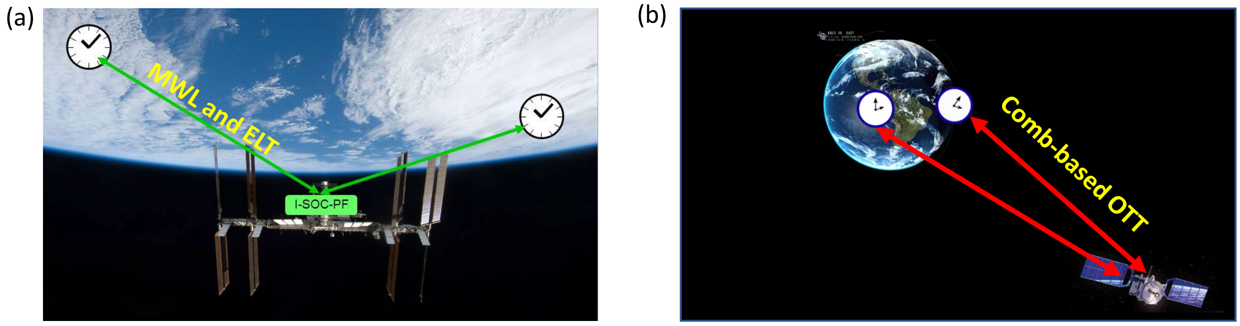

Figure 1: We propose two staged missions that will enable near term global time transfer for fundamental physics tests of general relativity, searches for dark matter, and local position invariance tests, as well as allowing for an improved definition of global time and clock-based geodesy. (a) The ESA I-SOC pathfinder mission proposed for the ISS and (b) a proposed Geo-OTT mission that flies a comb-based Optical Time Transfer (OTT) mission at geosynchronous orbit for global common-view time-frequency comparisons between future state-of-the-art ground-based optical clocks. The discussion of the I-SOC-pathfinder mission and the scientific objectives in this white paper follows directly from the scientific requirements document, ESA reference SCI-ESA-HRE-ESR-ISOC[8], currently under review. The science goals achievable by the I-SOC-pathfinder are already significant, while the follow-on Geo-OTT mission would provide orders of magnitude improvement through higher precision clock comparisons.

II. Scientific Objectives

One of the most well-known consequences of Einstein's theory of general relativity is the gravitational red-shift or gravitational time dilation effect. It is a direct consequence of the Einstein Equivalence Principle that time runs more slowly near a massive body. This effect can be measured by comparison of the elapsed time between two clocks in different gravitational fields. This effect does not only appear between, say, a clock on the surface of the earth and one in orbit. It also appears between two clocks on earth because of the differential gravitational field of the Sun or Moon. (See Figure 1.) For two clocks located on opposite sides of the earth, this effect has a 24-hour period and a peak-to-peak amplitude of 1×10^{-12}. While this effect is smaller than the redshift between a ground-based and orbiting clock, its measurement *does not require* flying a high-accuracy optical lattice clock. Instead, it can exploit existing and continuously improving ground-based optical clocks.

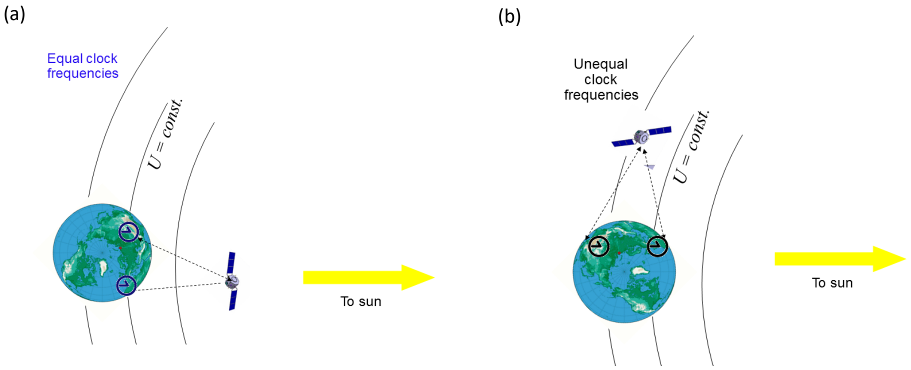

Figure 2: Measurement of the gravitational redshift due to the field of the Sun. (a) At one point in the Earth's rotation, the two ground clocks experience the same gravitational potential and therefore redshift, but (b) at another point in the rotation, the two ground clocks experience a differential gravitational field, and therefore redshift. Because the Earth is in free-fall in the Sun's field, this differential redshift is exactly cancelled by the second-order Doppler shift, thus satisfying the Equivalence Principle. A measurement of this null effect tests the Equivalence Principle. For the first mission, I-SOC-PF, the clocks would not be in common-view as shown but measured sequentially as the ISS passed overhead. For the second mission, Geo-OTT, the measurement would be made in common view, and thus would be more precise. This figure is taken from Ref. ([8]).

We note that since the ground clocks are in free fall with respect to the sun, the time dilation effect is cancelled since the redshift is exactly cancelled by the second-order Doppler shift due to motion of the ground clocks with respect to each other[1]. However, the measurement of this null effect still achieves the fundamental measurement of the gravitational redshift[1,9] because the second-order Doppler shift can be separately calculated from the measured clock velocity, relying on independent experimental confirmation of the validity of Lorentz transformations, with at least the same accuracy. The actual Sun gravitational time dilation is then deduced from the null result.

Beyond this cancellation, there remain tidal effects that are predicted to lead to daily variations larger than 1×10^{-17} between distant clocks[10]. Such signals are impossible to detect with currently available time-and-frequency transfer techniques, but could be precisely measured, for the first time, with the proposed missions.

For the I-SOC-PF mission, the clocks on nearly the opposite side of the earth cannot be viewed in "common-mode" configuration but instead the on-board Hydrogen maser serves to holdover time between comparisons. This limits the time transfer, regardless of whether the microwave link or laser link is used, to an instability of about 2.6ps/τ between overpasses, where τ is the time interval[8]. If one assumes phase-coherent clock operation over 11 days, the two ground clocks can be compared to 2.6×10^{-18}. Assuming the ground clocks can support this level of accuracy, the fractional uncertainty in the red shift measurement is then $2.6\times10^{-18}/1\times10^{-12} = 2.6\times10^{-5}$. Longer observation times could lead to even higher accuracy measurements.

For the common-view Geo-OTT mission, the limitation of the holdover from the onboard clock is drastically reduced since the two measurements are nearly instantaneous. As discussed below and in References ([11–17]), comb-based optical time transfer has demonstrated residual instabilities of $10^{-16}/\tau^{3/2}$, with noise floors below 10^{-18}, through up to 30 km of turbulent air [12,14] and at closing velocities of ~20 m/s[16], similar to those expected for a geosynchronous orbit. The latency associated with the 0.25-second time-of-flight from ground to geo will degrade the performance somewhat as it leads to an effective 0.25 s "holdover time" at the satellite. But even so, a compact onboard quartz oscillator with a stability of 1.5×10^{-13} at 0.25 second[18] would still yield a common-view time transfer instability of 5×10^{-18} at 100 seconds, beyond which the residual noise of the time transfer should continue to average down below 1×10^{-19} level. With this low noise time transfer, the clock comparison will be limited by the instability of the ground-based optical atomic clocks themselves. For state-of-the-art clock instabilities of $10^{-16}/\tau^{1/2}$, the clocks could be compared to 2×10^{-19} in one week, corresponding to a fractional uncertainty in the red shift measurement of 2×10^{-7}, or two orders of magnitude improvement over the first stage I-SOC-PF mission. This comparison would improve in direct proportion to continued improvements in the stability and accuracy of ground-based optical atomic clocks.

The above comparison focused on the redshift due to the sun. There is a similar time dilation effect from the Moon, reduced by a factor of 175 due to the difference in mass and range. The peak-to-peak Moon effect on the comparison of ground clocks is thus approximately at the 6×10^{-15} level for a Europe-Tokyo and a Boulder-Tokyo comparison[8]. This moon-induced effect, again nulled to zero, has never been tested but would be accessible here, thanks to the high precision of the clocks and the links.

In addition to the gravitational redshift tests, the missions would support searches for topological dark matter by comparing time offsets between ground-based clocks[2–4]. For the I-SOC-pathfinder mission, the detected signal would be an imprint, or phase-shift, on one clock compared to a second clock that did not overlap the defect. For the Geo-OTT mission, the common view comparison could enable nearly real-time comparisons on the effect of a defect passing through earth. The global network of clocks created by these two missions would also enable tests of Local Position Invariance by comparing atomic clocks around the world[5,6]. Such comparisons now are generally limited to those in Europe, where there is a regional fiber network[19].

Clock-based geodesy is closely related to the gravitational redshift measurement except in this case the relative clock frequencies of a global network of clocks (averaged over ~ 1 day to remove the tidal effects) could help to establish a global reference frame for the Earth's gravitational potential[20]. The clock network would provide high spatial and temporal resolution, complementing space geodetic missions such as GRACE and GOCE. The measurements could be of great importance in understanding water table changes and ocean circulation effects.

Finally, at the most basic level, the staged missions would support the expected near-future redefinition of the International Atomic Time scale. Currently, it is challenging to compare, and therefore define, time around the world to better than 1 nanosecond[21,22]. The I-SOC-pathfinder mission could enable time synchronization at the 20-ps level, while the later Geo-OTT mission could, in principle, enable time synchronization at the 100-fs level, assuming systematic effects are controlled by maintaining the clock signals in the optical domain.

III. Staged Mission Implementation, Schedule and Cost

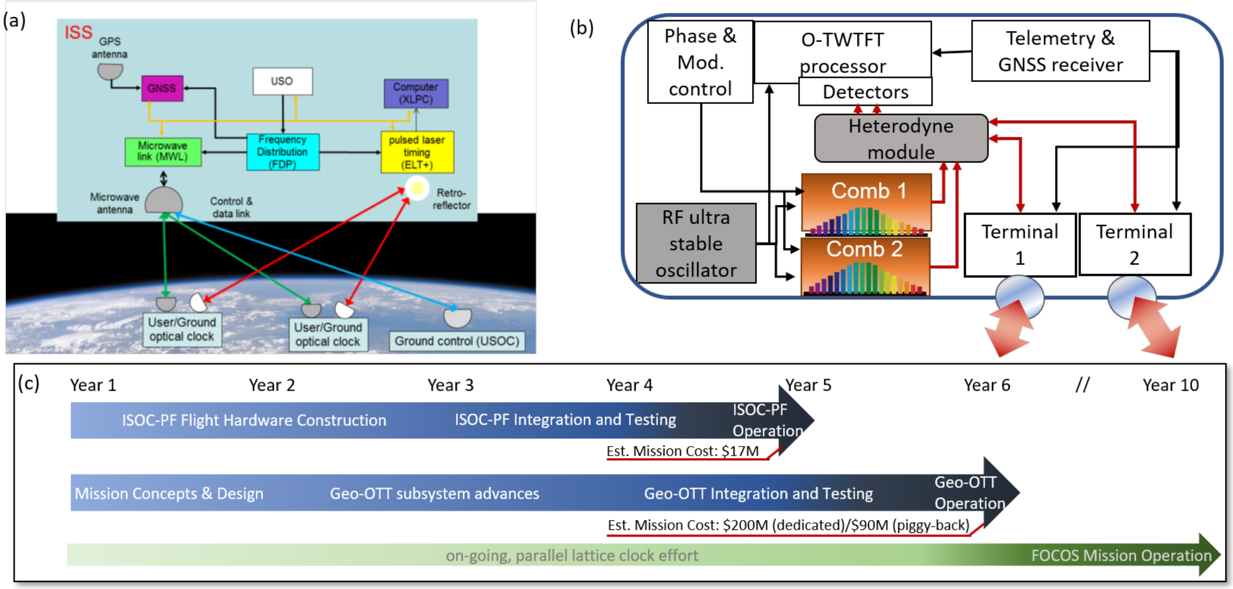

Figure 3: (a) Schematic of I-SOC-pathfinder showing the main subsystems. (b) Schematic of Geo-OTT showing main subsystems. Red lines indicate fiber-optic paths, or free-space paths from the terminals to/from the ground, for the transmitted comb light, which is at ~ 1.5 um. Black lines indicate RF/microwave paths. (c) Nominal schedule/cost for staged ISOC-PF and Geo-OTT missions with approximate mission costs given in USD. Their short time-to-launch allows for the de-risking and support of longer-term efforts such as the proposed FOCOS mission[7].

I-SOC-pathfinder: This mission concept has already been well developed for the ESA by a science team and is presented in detail in Ref. [8]. It would exist as an external payload on the ISS. It was designed to be relatively low cost by excluding an optical atomic clock and by use of subsystems with a strong space heritage, including a state-of-the-art Hydrogen maser from the Lebedev Institute of Moscow, an improved version of the ACES microwave link (HERO) and an improved version of the ACES pulsed optical link (ELT+), with respective TRL of 7, 5 and 6-9, currently. The total payload power, volume, and mass are 110kg/147 liters/240W. Figure 3a illustrates the basic components. The rough instrument cost is in the 15-20 M€ range. Given the high technical maturity of the design, this mission could be flying within five years.

Geo-OTT

Geo-OTT relies on *common-view* comb-based optical time transfer to achieve fs-level precision and thus only requires an RF ultra-stable oscillator as an onboard reference. Since fiber-optic frequency combs are closer in technology readiness than optical lattice clocks, this approach allows tests of fundamental physics outlined above in advance of space-qualified optical clocks. Frequency combs have been shown to operate with low power consumption[23–25], onboard a sounding rocket[24,26], and phase-slip free for greater than a month[27], so they will meet the critical phase coherence requirement as mentioned in Ref. ([8]).

In terms of feasibility for Geo-OTT, there are four separate issues to consider: (i) the impact of turbulence on the comb pulses, (ii) Doppler shifts of order 10's of MHz, (iii) breakdown in reciprocity due to the finite speed of light, and (iv) overall link loss due to diffraction and turbulence. Comb-based optical two-way time-frequency transfer (O-TWTFT) has been shown to operate with noise floors of 10^{-18} despite a horizontal, close-to-the-ground, 15-km air-path[12,14] -- more severe turbulence than all but the most aggressive of slant paths to a satellite. Separately, fs-level time synchronization has been maintained despite Doppler shifts due to 20 m/s closing velocities[16]. Both experiment[28] and theory[29,30] suggest that while the breakdown of reciprocity will result in imperfect cancellation of turbulence-induced fluctuations of the time-of-flight, this is bounded. The issue of latency was discussed earlier and should not limit the comparison. Finally, Geo-OTT must be able to operate with link losses of 70 – 90 dB, depending on telescope apertures. Initial demonstrations of O-TWTFT with few milliwatts of launch power and few-centimeter telescope apertures supported link losses up to 60 dB[13–15,17]. Recent work of Ref. ([11]) estimated a link loss of 72 dB would be sustained for a ground-to-geo link and demonstrated amplification of frequency combs for optical time transfer to overcome such losses. Another approach is to maintain modest launch powers and apertures but choose a different corner of the complex parameter space of O-TWTFT, e.g. a lower update rate that is still compatible with the longer lagency of ground-to-geo[12].

Based on current state-of-the-art fiber-optic frequency combs, we anticipate that a time-transfer payload (See Fig. 3b.) will have a mass of 10 kg, volume of 10 L and a power draw of 60 W, excluding the two free-space optical telescopes with their associated gimbals and tracking electronics, which are expected to make up the majority of the total payload SWAP. To establish a credible cost for the Geo-OTT mission including the free-space telescopes, we follow a similar analysis to that used for the FOCOS mission concept[7], which modeled the total OTT payload cost, size, weight and power on the DSOC/OPALs missions yielding an $61M cost, 100 kg mass, and 200 Watts of power. Following the FOCOS costing, the total cost for a dedicated mission would be $200M. However, by piggybacking on another Geo mission, the cost could be significantly reduced to below $90M. The ground comb-based time and frequency transfer units could cost $0.5M per station including a ~15-cm telescope, frequency comb, and electronics, again leveraging advances in free-space optical communication terminals. Most of the subsystems for the Geo-OTT mission are almost as technically mature as those of the I-SOC-pathfinder, but some additional development of the frequency combs and transceiver electronics will be required. The mission could be flown about two years after the I-SOC-pathfinder, in a staged schedule. Again, as noted earlier, the ground-based development of a space-based optical lattice clock could take place during this period enabling a future higher cost dedicated mission, beyond the 5-year timeframe, that includes both OTT and the optical clock.

IV. References

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