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Space-Time Referencing: atomic clocks, laser links and applications

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A Space-Time Reference (STR) frame that has exceptional performance could be realized using an advanced atomic clock in a well-defined orbit that is periodically connected to the highest-performance atomic clocks on the ground using two-way Doppler-canceling laser links. The two-way laser links would also provide precise range information and thus precise orbit determination (POD).[i] With a well-defined orbit and a synchronized clock, the satellite could serve as a high-accuracy reference providing accurate Time[1] worldwide, an exceptional reference frame for geodesy, and independent high-accuracy measurements of Global Navigation Satellite Systems (GNSS) clocks. The STR would be able to deliver sub-picosecond timing worldwide with < 1 millimeter range determination and could serve as an enabling subsystem for other proposed space-gravity missions. That would represent an improvement over GNSS (e.g. GPS) by a factor of > 1000 in timing and > 100 in range.

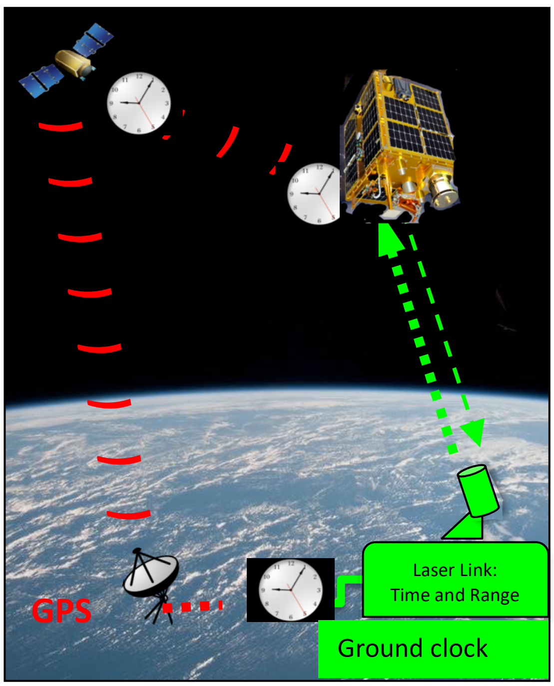

Fig 1. Illustration of the basic concept of the STR satellite system. State of the art optical atomic clocks on the ground would synchronize the orbiting clock via two-way Doppler cancelling laser links. Signals would include Time, frequency, range rate (Doppler), and absolute range determination between the ground station and the STR satellite. The STR and ground stations may optionally receive signals from the GNSS (GPS, GALILEO, BEIDOU, GLONASS), VLBI, and DORIS to interconnect the best reference frames and augment those systems with higher accuracy and validate performance.

The STR satellite would be compact and dense with a well-defined center of mass and located in a precisely determined orbit (MEO or above) that has low atmospheric drag and other disturbances. Phase-coherent optical links can be achieved with continuous wave (cw) lasers and/or femtosecond (fs) pulses and would provide high-precision range, range-rate (Doppler), and timing information. Optimal design of the system, space clock and laser links would depend upon mission objectives and performance requirements. For many mission concepts we would not require a high accuracy clock in orbit but would require sufficient stability over short time intervals that the clock can serve as a "frequency-flywheel" over time-scales of one to two hours. At that time interval the space clock would be synchronized via the laser links to the highest accuracy atomic clocks and Time scales maintained at national standards laboratories (e.g. NIST, NPL, BNM-SYRTE…).

[1] Capitalized herein to denote epoch in a defined reference frame, and distinguished from time offsets, intervals etc.

The basic approach for the STR, and the required technologies, will have broad applicability for future missions testing fundamental physics in space, such as clock and position-based tests of Einstein's Relativity, including Local Lorentz Invariance (LLI); gravitational red shift; local position invariance (LPI); Shapiro time delay and two-way speed of light measurements to constrain the curvature of space-time; tests of symmetry postulates (CPT invariance); and searches for new scalar or vector fields beyond the standard model as proposed for several future missions [ii,iii,iv,v,vi,vii,viii,ix,x,xi,xii]. With a stable clock in a well-defined low-drag orbit, the General Relativistic corrections to coordinate, proper time and light propagation intervals can be calculated and tested experimentally to high accuracy [xiii,xiv,xv,xvi]. From the scientific perspective there is strong motivation for more precise and accurate tests of gravity, where compelling experimental evidence for Dark Matter and Dark Energy show that our fundamental understanding of gravity and "matter" is especially lacking.

Clocks – atomic frequency references

The performance of the space atomic clock can be chosen to meet mission goals utilizing either advanced microwave or optical atomic clocks. Examples of advanced microwave atomic clocks for space include: NASA JPL Deep Space Atomic Clock (DSAC), EU GALILEO passive hydrogen maser, ESA-ACES mission atomic clocks PHARO cold-Cs and an active hydrogen maser, and China's demonstrated cold Rb atomic clock in space[xvii]. Programs working to develop advanced optical atomic clocks for space include ESA's Space Optical Clock SOC[xviii], and I_2,[xix] and China's cold-atom optical clocks[xx]. We are not aware of similar programs underway in the U.S., but there are proposals to begin the development of advanced optical clocks for space in the U.S. (e.g. FOCOS).[xxi]

Laser links

For the STR we would leverage existing programs within NASA, other agencies or the commercial sector that are developing high-performance laser communication links for space [xxii, xxiii, xxiv]. Much of the space laser communication technology can modified to enable accurate timing. Recent analysis and experiments show that the laser links can support the demanding performance of even the highest performance optical atomic clocks and timing uncertainties at the 1 fs level or less (See for example the complementary white paper "Frequency Comb Based Optical Time Transfer" and references therein that discuss both comb-based and cw-laser approaches to Doppler cancelled links.)

Atmospheric turbulence causes significant scintillation and fading of laser beams between the ground and space but can be mitigated with receiver design, modeling, and control. The various limitations imposed on time transfer related to "piston" effects, point-ahead and refraction do not appear to limit the time transfer down to the 100 fs level and below[xxv].

Because of the short wavelengths of laser light, small apertures (e.g. 10 cm) can be used to enable compact transportable ground terminals that can be located at benchmark locations for geodetic measurements, PNT at remote locations, and/or secure data transfer. As noted above, these FSO terminals share many of the same requirements as future FSO for coherent communications, but notably time transfer is less affected than high-speed communications by the many, short turbulence-induced signal fades and furthermore requires less received power than a high-speed communication link. For both these reasons, it may be possible to locate the

FSO terminals closer to national laboratories or the benchmark locations for geodetic measurements where the turbulence-induced link loss might exceed that tolerable for communications.

One-way links for range and deep space navigation:
Two-way Doppler-cancelling laser links are the preferred approach and provide the highest performance, but even a single one-way link can be useful and provide valuable range information with a simpler architecture. One-way links have reduced performance but provide value to a wider range of potential users as is the case for GNSS which are one-way PNT signals. One-way is particularly interesting for deep-space missions where the latency in the transit time limits knowledge of satellite position and navigation control bandwidths (e.g. the time delay of light between Earth and Mars ranges from 4 to 24 minutes). An excellent example is the development of DSAC clock for deep space mission navigation with one-way ranging[xxvi]. One-way time transfer from space-to-ground is coupled tightly with absolute ranging and measurements of the atmosphere, as noted below.

STR for Position Navigation and Time (PNT)
To provide a comparative context, we can estimate the performance achievable with an example optical STR compared to GNSS. Accurate knowledge of position on Earth comes primarily from precise geodetic surveys combined with GNSS measurements that are used to create the best model for an International Terrestrial Reference Frame (ITRF) [xxvii,xxviii]. The current TRFs can determine relative base station positions on the Earth to about 1-mm precision at 100-km distances, and relative to the center of Earth with an uncertainty of a few millimeters. But naturally those benchmark locations are moving due to plate tectonics, solid Earth tides, sea loading etc. Measurements from space are essential. Position determination from GNSS (e.g. GPS) combined with augmentation systems (e.g. WAAS, PPP, STK) can under favorable conditions provide position information on Earth with uncertainty of $\approx$ 10 cm and Time uncertainty in the UTC frame of 0.5 to 3 ns at best.[xxix] As discussed in many references establishing TRFs that can be tested validated is a long involved complex problem with many inputs and constraints; we believe that high accuracy range and time data from a STR (high performance atomic clock, accurate orbit, and two-way laser links) can provide valuable new information to augment other data and the overall process.

Absolute range and total group delay.
The performance of the new optical atomic clocks and two-way laser links will support fractional frequency uncertainties of $\approx 1\text{x}10^{-16}/\sqrt{\tau}$ for averaging times τ in seconds. That means that optical phase fluctuation and hence length fluctuations must be compensated and cancelled to a corresponding level for determination of frequency offsets and time intervals between clocks. However, to determine the absolute range and Time (epoch) requires knowledge of the total propagation delay. For a laser link between Earth and a satellite at zenith the atmosphere contributes an additional group delay of about 6 ns, equivalent to $\approx$2 meters. Modeling of the dry and wet atmosphere with input from meteorological data can calculate the atmospheric delay with an uncertainty of about 1 mm. That is achieved routinely for Satellite Laser Ranging (SLR) stations and Lunar Laser Ranging using single laser wavelengths (e.g. 532 nm pulses). [xxx,xxxi,xxxii,xxxiii,xxxiv] It will be possible to reduce that uncertainty to < 1 mm by including additional wavelengths with cw lasers or broadband fs pulses, but ultimate performance needs to

be demonstrated and verified. For the most precise measurements, it might be possible to couple comb-based time transfer with dual-comb spectroscopic measurements of the atmosphere. The same frequency comb transmitted signal could provide both timing information and probe the atmospheric content along the path to determine total air mass (from oxygen measurements), water vapor, carbon dioxide content etc.[xxxv]. Based on these spectroscopic data, one could apply real-time corrections for the total air index of refraction providing even more accurate range and timing from space to ground.

Accurate range determination also requires detailed modeling of solid Earth tides, sea and ice loading, and crustal plate motion, etc. For that we would leverage the extensive capabilities within the geodesy, geodetic, SLR communities. STR would bring valuable high-accuracy range data to Earth sciences and new input for models, TRFs, sea level rise, and Earth gravity mapping. We anticipate strong synergism of the STR concepts with Earth science programs and missions within NASA and other agencies. Adding a second two-way laser link operated simultaneously as illustrated in figure 2 will enable stiff constraints on distances between remote sites and thus TRFs.

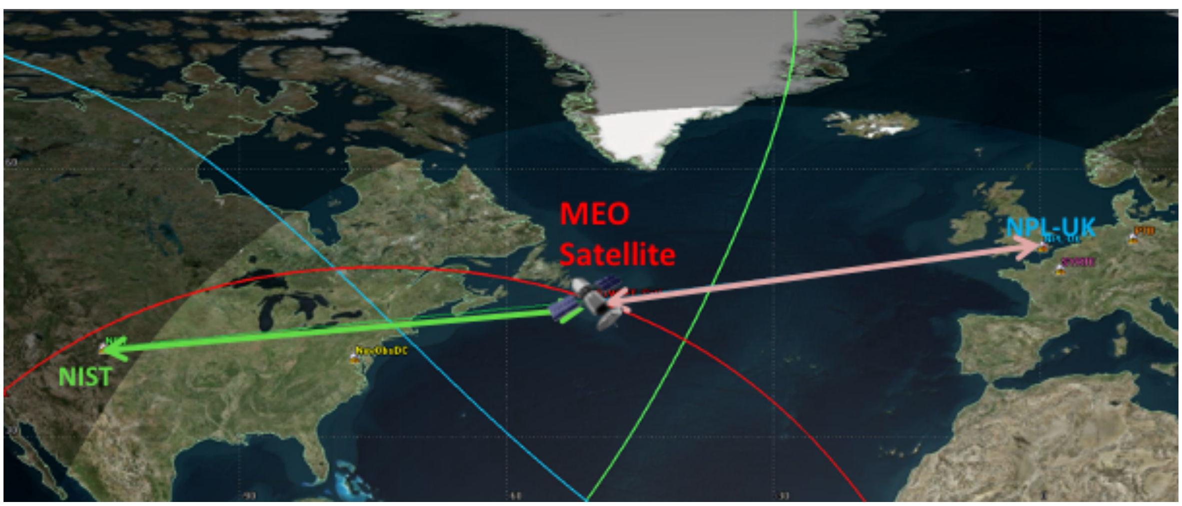

Fig. 2. Concept of two two-way laser links simultaneosly connecting standards labs in the U.S. and Europe. Accurate ranging on the links determines the distance between the ground terminals. As an example, sub-millimeter uncertainty on the range between NIST and NPL seems feasible and in real time. The red trace represents the satellite orbit and area between the visibility curves from NIST (green) and NPL (blue) is the region where the satellite in a circular MEO orbit (approx. 5 hr with inclination 50 degrees) is visible at both sites.

Existing GNSS systems combined with advanced analytical methods do amazingly well in monitoring ground motion and elevation changes at the mm/yr level [xxxvi, xxxvii, xxxviii, xxxix]. Such measurements are critical to Earth sciences and hydrology. Related studies and ideas for improved satellite geodetic references include GETRIS, GRASP, E-GRASP and KEPLER that would be new satellites in well-defined orbits whose position is determined by existing GNSS, DORIS, and VLBI and SLR systems combined with modeling [xl, xli, xlii, xliii].

Recent reviews of TRFs [xliv] by the National Academies point to compelling needs for improved geodesy and satellite-based geodetic references. Motivation includes critical issues in Earth science resulting from climate change and global warming that will increasingly impact safety, health, agriculture, and economies. A key example is the uncertainty in the measured rates of sea level rise (≈+2 +/- 0.6 mm/yr) that are due in part to uncertainties in the orbit of the geodetic and laser ranging satellites that measure sea level from space.[xlv] The best reference frames have uncertainties of the position of the center of the earth and our terrestrial reference frames at the critical few mm level.

The preferred reference frame depends upon mission objectives and applications. For deep-space missions and high-accuracy tests of General Relativity or searches for new physics a Helio-centric, or galactic reference frame may be required. For accurate space-time measurements on the rotating earth, the preferred reference frame is an Earth Centered Inertial (ECI) frame, as chosen for time scales, such as TAI, UTC, GPS time. In all frames careful attention must be paid to relativistic effects of moving clocks and earth's gravity [xiii,xv,xvi,[xlvi],[xlvii]]. As pointed out in these references and elsewhere, at the levels of timing precision (ps) and range uncertainty (mm) that are of interest for STR the relativistic corrections will be significant and will require calculations to higher order in velocity (v/c) and gravitational potential ($\Delta U/c^2$) than in current GNSS systems.

STR: enabling science missions and applications

A STR in a nearly inertial MEO orbit, with a stable atomic clock and a laser two-way timing link would provide an exceptional reference frame for geodesy, Earth sciences and navigation systems and Time transfer at unprecedented levels from space providing worldwide coverage. Using the same technologies in a highly elliptic orbit or on the longer-term flying closer to the sun would enable accurate measurements to test the foundations of General Relativity and our understanding of space-time to higher orders in velocity (v/c) and with larger gravitational potential differences than can be done near the earth. Related concepts have been proposed for several space science missions, e.g. EGE, SAGAS, STE-QUEST, GRESE, LARASE, etc.) [xi,[xlviii],[xlix,l],[li],**Error! Bookmark not defined.**], and more recently for a NASA mission FOCOS.[xxi] Here we have focused on how the STR concepts can be enabling for accurate Position, Navigation and Timing on Earth and in space, and new capabilities (e.g. optical atmospheric science, geoscience, geodetic referencing. The underling technologies exist today and some subsystems (such as laser links and advanced microwave atomic clocks) are already space-qualified or soon to be deloyed in space.

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