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Time Transfer: Sideline or Geodetic Objective

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Abstract. *The evolution of timekeeping is the most impressive technical development in the recent past culminating in the concept of optical clocks. Having a relative stability of up to* 10^{-18} *these clocks are getting interesting for fundamental physics applications, testing the theory of relativity. With the need of carrying out these tests in space, the development of space clocks is pushed forward. The ESA mission ACES will be the next step in this evolution and future ESA studies aim on the establishment of a universal time scale in space. On the other hand, the development of free space time transfer techniques has to come along with the evolution of space clocks. Having a "space time scale" in mind, the importance of accuracy of time transfer is a major aspect in this subject. Laser ranging is the geodetic space technique mostly trimmed for accuracy in measurement of distances in space. Using the synergy between ranging and time transfer, time can be transferred by a coupled two-way and one-way pulsed laser technique, whose principle and potential has already be shown by the T2L2 experiment onboard the Jason satellite and will be continued by the ELT experiment installed on the ACES mission.*

Introduction

With the redefinition of the second in 1967 based on the transition of the two hyperfine levels of the ground state of the ^{133}Cs atom, the "atomic age" of time standards began. Since then a dramatic increase in stability and accuracy of keeping time has made time "the most precise and reliable observation we can make at present" [Fukushima 1989]. As the new optical clocks are getting more stable and accurate than the cesium primary standards a further redefinition of the second is being considered by the international metrology community [ITOC website]. Fundamental physics has special interest in such precise clocks. With the fact that a unification of general relativity and quantum theory leads to deviations from standard physics, the limits of these theories are subject of intense studies [Lämmerzahl 2008]. With clocks two aspects of the theory of relativity can be verified: The gravitational redshift and the local Lorentz invariance of special relativity [Lämmerzahl 2008]. Gravitational redshift occurs when light leaves the gravity field of a massive body. As the photons escape the field they loose energy which results in a lower frequency. The possibility to realize large potential differences to verify this effect with high precision is one reason to bring clocks into space. Another application is the identification of velocity dependent changes of physical constants [Lämmerzahl 2008] such as the speed of light. The complex time variable gravity potential on the Earth's surface [Schiller 2007] and the possibility to tune atomic clocks in a microgravity environment to better precision [Salomon 2001] are additional reasons for considering to establish a future global time scale in space. The ACES mission will be ESA's first step in this direction.

Beside fundamental physics also navigation has an interest to have precise clocks in orbit [Hugentobler 2009]. Navigation satellites equipped with stable and well synchronized clocks allow to reduce the number of monitoring stations and to provide users with accurate predicted clock information required for precise positioning and navigation in real-time and single receiver mode.

With the trend to bring precise clocks into orbit there is also a need to compare and synchronize clocks in space and on ground with high accuracy.

Geodetic interest on time keeping

We mentioned already three points where geodesy has an interest in ground to space time transfer: gravitational redshift will allow to measure height differences with clocks, geodetic observing stations will have to be synchronized to a future global "space time scale" and navigation requires synchronized clocks. We may, however, not only think of synchronizing GNSS (Global Navigation Satellite System) clocks, but also of clocks of low Earth orbiting (LEO) satellites. Precise orbits of many of these satellites are determined using onboard GNSS tracking data. With synchronized GNSS and LEO satellite clocks the one way GNSS tracking data will no longer consist of pseudo ranges but in biased ranges. This will enhance a geodetic observation technique which plays an essential role for precise orbit determination [Schäfer 2013].

T2L2 and its precursor experiment have already shown that SLR can be used for precise time transfer by combining two ways and one way ranging technique [Exertier 2009]. To fully exploit the synergy between ranging and time transfer the stations need a tight link to a clock (see section **SLR station performance**) comparable stability to the space clock and a space segment which does not only reflect but also detect and time-tag the laser pulses sent to the spacecraft. Laser ranging, accompanied with frequent calibration and well-established knowledge of detector delays is a ranging technique trimmed for accuracy and stability. These two qualities are needed for time transfer, too, for comparing time scales and synchronizing clocks. Exploiting the synergy between ranging and time transfer, requiring some effort, allows SLR to contribute significantly to the precise comparison of time scales. SLR as a two-way ranging method is limited to distances up to the moon [Degnan 2002]. This is evidently also true for the combined two-way and one-way time transfer. For larger distances a combined one-way up- and down-link can be used instead, known as transponder technique. For this purpose two clocks are needed, one at the station and one onboard the spacecraft. Ranging is thereby directly linked with time transfer. The first transponder experiment was carried out to the Messenger spacecraft at an Earth fly-by [Smith 2006], it is successfully used for one-way ranging to the LRO spacecraft [Abshire 2006], and it is intensively studied for further missions and experiments (see for example [Oberst 2012, Turyshev 2010]). The preparation of SLR stations for laser time transfer is thus at the same time a preparation for the participation in transponder applications. Last but not least it is important to note that with the increasing accuracy of clocks the need arises to treat space and time as a common concept [Mai 2013]. Time keeping will then definitively become a geodetic task.

Synergy between ranging, data- and time transfer

The constant and finite speed of light explicitly couples the range of a travelling electromagnetic signal to the time of propagation. Therefore time can be transmitted by means of ranging signals referred to one time scale and registered with reference to another time scale. On the other hand, modulated continuous signals can be used to transmit information. All three applications of electromagnetic signals – ranging, time transfer, and data transfer - are related and bear the synergy to use one signal for more than one application. Figure 1 illustrates this synergy. Precise timing information is needed if a ranging application is also used for time transfer. Coding ranging signals offer the possibility for data transfer [Kirchner 2011]. Data transfer linked to a clock can be used for time transfer and ranging, if internal delays are calibrated. Combining data and time transfer thus offers geodesy the opportunity for a new ranging method [Schäfer 2013].

In the following discussion we relate the pulsed optical SLR signal to the ranging application and a phase modulated continuous signal in a combined one-way up-down link to the data transfer application. The later is currently done in the microwave domain (for example ACES [Cacciapuoti 2009]), but first experiments demonstrate the potential using optical signals [Nielsen 2002]. Comparing these different technologies, we have to confront a 2 kHz (limited due to sending/receiving overlap) optical pulsed signal with an up to 5Gbit/s modulated optical signal or a 100 Mbit/s signal on the microwave channel. The predicted precision for the ACES mission for one ISS pass is 4 ps for the ELT experiment and 0.4 ps for the microwave link (MWL). But as stated in the sections above before the advantage of SLR is accuracy. T2L2 has shown a repeatability of 45 ps in a common clock experiment, compared to the MWL to ACES provided an accuracy of 100 ps (not optimized for that purpose). A transponder like configuration with LLR systems working in single photon mode allows for time transfer in the whole solar system, whereas optical data transfer would need extreme laser power for interplanetary applications. Last but not least the SLR community is organized in the International Laser Ranging Service (ILRS). Tasks can thus be spread over the community depending on visibility or weather condition. The pulsed and continuous measurement principles have different strengths and LRO showed for instant, that a combination of optical pulsed and microwave tracking leads to the best results [Mao 2012].

T2L2: measurement technique and results

The Time Transfer by Laser Link (T2L2) instrument is passenger of the oceanographic space mission Jason2, and was launched in June 2008 at an altitude of 1335 km. T2L2 consists of an optical system (detection in the multi-photon regime) and an electronic device for timing. The principle of the experiment is based on the Satellite Laser Ranging (SLR) technique; thanks to the laser reflector array, in support of the precise orbitography, T2L2 benefits from the 2-way ranging. The Jason2 mission is using the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) technique, which oscillator (a quartz) is used by the T2L2 instrument as a reference. Its stability is of a few 10^{-13} Hz, that is of a few picosecond at 10 secondes and growing in $t^{3/2}$. At ground level, T2L2 relies on the ILRS network, whose stations are tracking the satellite Jason2 for 5 to 6 times per day maximum of 10 to 15 minutes each. Around 21 SLR stations of the ILRS network are participating to the T2L2 mission, providing Full Rate data in the CRD format regularly (see the website https//t2l2.oca.eu/). Some of them acquired a hydrogen maser as the reference clock of the station, since 2010 or before. Several field experiments implementing very different configurations have been realized to:

i) properly measure the performances of time transfer by laser link (short and long term stability),

ii) progress in the measurement of the ground links (delay, cables, etc.) including the time distribution of pulses between equipment: clock, SLR system, and GPS antenna,

iii) comparing T2L2 time transfer to existing microwave techniques such as GPS [Guillemot 2012, Samain 2011, Samain 2012]. We used the French Transportable Laser Ranging Station (FTLRS) to benefit from the quality of time and frequency laboratory SYRTE located at the Observatoire de Paris; the FTLRS has been deployed there for several months in 2010 and in 2013.

The SLR stations performances are very different, mainly due to the quality of the timing system and the detector. The error budget of the ground to space time transfer thus ranges from 45-65 ps for the best stations (equiped with an hydrogen maser) to 55 ns for the worse. The average stability achieved in today’s data processing at 75 seconds is of 4-8 ps and 2-3 ns, respectively. The ground to space time transfers are computed for all the SLR passes available on Jason2, that forms the basis to estimate the ground to ground time transfer between any couple of stations. As a consequence of the altitude of the Jason2 satellite, the field of view of the T2L2 optics, the unstability of the onboard oscillator over 1000 s, and the availability of SLR stations with a picosecond resolution of its dates, the common view (CV) provides the best results. For example over Europe, the stability of the time transfer between hydrogen masers ranges from < 1 ps at 30 sec. to 150 ps at 1000 sec. The main difficulty is to maintain a high quality of the different computation steps whereas the SLR does not provide data regularly in time due to technical, human, and meteorological reasons. A campaign dedicated to the study of the long term stability has been realized between the FTLRS and the MeO SLR/LLR station at the Grasse observatory by using the same clock for both systems. After one month of common passes, we established a repeatibility of the link of 45 ps. On the other hand, the stability of the time transfer between two h masers over 1,000 km has been estimated at 140 ps by comparing with the GPS technique. In that case on each geodetic site, the same clock system is distributing time (PPS and frequency) simultaneously to a GPS antenna and to the SLR station. Now considering accuracy, the space techniques should be referenced to a given point located near to the time and frequency laboratory. The goal is to avoid having long distances on the ground, to be able to measure the delays accurately, that is at the sub-nanosecond level. We made a campaign of time transfer in September and October 2013, betwen Herstmonceux (UK), Wettzell (G), Grasse and the Observatoire de Paris (equiped with the FTLRS). These sites have been calibrated both for the GPS and the laser techniques, relatively to the reference point selected on each site. The preliminary results show the difficulty to maintain a high level of accuracy for all the delays measured on ground, at the sub-nanosecond level. But they are encouraging.

ELT: What is different?

The differences between T2L2 and ELT are in the space segment. ELT will be a payload of ACES, a module which will be mounted on the ISS. ACES establishes a precise time scale in space. The basis is an active hydrogen maser for short and medium-term stability and a laser-cooled cesium clock for long-term stability [Cacciapuoti 2009]. With such a precise time scale not only space to ground and common view ground to ground time transfer is possible, but also non-common view ground to ground comparison of clocks. For that comparison two methods will be available: MWL with 100 Mbit/s modulation and ELT as the optical pulsed method carried out by different stations of the ILRS network. The ELT space segment is also totally different, as the detection principle of laser pulses is changed. Whereas in T2L2 the complexity of one-way tracking is totally moved to the space segment, leading to the above explained double detection, the responsibility for ELT’s detection accuracy is entirely in the observer’s hand. ELT will only work in single photon mode. The tracking station will have to ensure the single photon mode by regulating the laser power or the divergence of the laser beam. A simultaneous two-way and one-way tracking is only possible because the total attenuation between ground and space is 10^{13} at standard weather conditions. The gating of the SPAD detector is synchronized to on board time and has an offset less than 50 ns to UTC. The SLR signal should reach the detector within about 200 ns after gate open. The stations therefore have to control laser fire time to the predictions and correct for their own offset to UTC which uncertainty should not be greater than 50 ns. From the two-way ranging a real-time calculation of the ISS time bias would be helpful to further correction of the predictions. For symmetry reasons of one-way and two-way tracking single photon mode detection on ground or the use of a compensated SPAD diode will enhance accuracy of time transfer. The displacement of the complexity to the SLR stations has the tremendous advantage that the space segment can be kept light with low power consumption, an essential requirement to get the detector on future missions.

SLR station performance for time transfer

In section **Geodetic interest in time keeping** we noted, that stations need a clock with stability comparable to the onboard clock. For the ACES mission this is only possible on a short time scale if the station has a hydrogen maser. Ground and space clock can then be compared over one ISS pass (300 s). No ILRS station has today access to a frequency standard with a long-term stability like the ACES clock. For future experiments it will be necessary to get access to precise clock information. The rapid rising development in the stability of clocks makes it impossible for the stations to operate an up to date frequency standard at any time, so the possibility to get connected to metrology institutes by fiber link has to be considered. The ground network for time and frequency comparison is planed today and the station operators should declare their interest now, to be considered in these plans. After having access to precise timing information a reference point in time has to be defined and all timing information on the station has to be related to that point. Calibrating and monitoring cable delays from the reference point to the GNSS receiver and the SLR event timer will be necessary. The calibration from the event timer to the reference point of the telescope has to be done separately. This procedure is explained in detail in the article of Prochazka et al. in this proceeding.

As mentioned before there are special requirements for the stations participating in ELT. The one due to single photon mode and detector triggering are enumerated above.

Tuning laser power for single photon detection with 532nm wavelength at the space segment, programming laser trigger in respect to receive time in steps smaller 50 ns, programming correction algorithm due to real-time observed time bias, offset to UTC, laser response time to trigger signal, calibrated biases. All uncertainties of biases together should be much smaller than 100 ns (on board offset to UTC smaller 50 ns): offset to UTC and bias to laser trigger. The mounting of the ACES module on the ISS make other requirements necessary: Having the capability to track low orbiting satellites, handling a go/nogo – flag, integrating predictions every 90 minutes and sticking to laser safety issues. For time transfer full-rate data is necessary in the ILRS crd-format with every start event recorded in picosecond resolution.

Summery

T2L2 is a very successful demonstration, that SLR can do time transfer as a coupled two-way and one-way ranging method. The high accuracy of SLR can be shown in common clock experiments, with 45 ps long-term repeatability. But T2L2, with its double detection of laser pulses needs a heavy and power consuming payload. To get on future missions a lighter payload would be appreciable. ELT will bring such a detector system on board of the ACES mission, changing to the principle of single photon mode detection. The complexity of time transfer is relocated from space to ground, and a greater effort has to be shouldered by the participating ILRS stations. But we showed that this investment is a great and worthwhile step for future SLR applications and a science objective for geodesy. If the ILRS can show, that time transfer in single photon mode can be done with the same accuracy as in corrected multi photon mode, the probability to get on future experiments will be much higher.

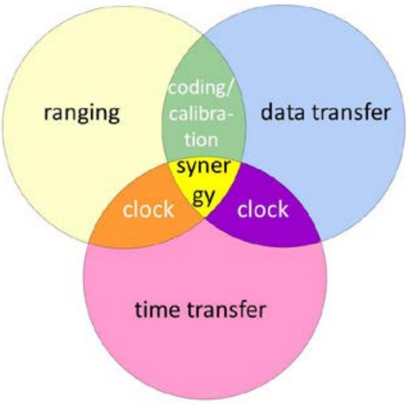

Figure 1. Synergy between ranging, data and time transfer

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