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European Laser Time Transfer (ELT) and Laser Safety for the ISS

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Abstract. *The methods of optical time transfer have been proposed and pioneered by the French group (Exertier, Samain et al.) in Grasse. As a result T2L2 was launched on Jason 2 and demonstrated the viability of this technique. With the Atomic Clock Ensemble in Space (ACES) a follow up mission for the exploitation of time transfer is in preparation at the European Space Agency (ESA). While the ultra-stable-oscillator (USO) of Jason 2 drifts significantly, ACES will provide a much more stable reference for non-common-view time comparison. The ILRS has been confronted with challenging tracking restrictions several times in the past. With ACES at the Columbus module of the ISS the challenge of guaranteed eye safety at all times during SLR laser activities is given. This paper reviews the requirements and the currently proposed procedure.*

Introduction

In recent years the methods of terrestrial frequency transfer via optical fiber links have improved enormously. In order to overcome variable phase fluctuations along the transmission line, a two-way interferometric compensation concept is now routinely employed. The optical frequency passes through the transmission line on an identical path twice before it beats with the oscillator near the point of origin. From this interferogram a phase delay compensation is obtained with high bandwidth, which is applied in order to keep the experienced delay constant at the remote end of the transmission line. This method has been successfully demonstrated between the national standards laboratory in Germany in Braunschweig and the Max-Planck-Institute for Quantum Optics near Munich corresponding to a distance of more than 900 km. Similar concepts have been employed in France around Paris and other locations in Europe and the USA, enabling a frequency transfer stability of $\Delta f/f < 10^{-17}$over many hours and days.

A frequency comparison in general provides access for the measurement of clock stability, but it cannot provide a comparison of time scales because of the unknown offset between the clocks at both ends of the narrow-band transmission line. Time transfer between two distant clocks requires a broad bandwidth transfer channel. Short laser pulses are very suitable for this type of application, however they are very unsuitable for fiber line transfer, because of the significant dispersion effects over long distance fibers. SLR on the contrary offers a broad bandwidth communication channel for time transfer and benefits from the fact that dispersion through the atmosphere affects microwave frequencies a lot more than optical frequencies. Furthermore, sub-centimeter satellite laser ranging has demonstrated a good control over atmospheric propagation delays.

The French T2L2 time transfer experiment has impressively demonstrated the suitability of SLR for optical time transfer (Guillemot et al., 2006) (Guillemot et al., 2009). The time transfer application differs from standard SLR operations in that it requires not only a cube corner retro reflector but also a well calibrated photonic detector on board of the satellite. T2L2 although it has achieved a time stability of 6 ps over 30 seconds of integration for a clock comparison between the hydrogen masers of the geodetic observatories in Grasse and Wettzell, is limited by the stability of the ultra-stable-oscillator of the Jason 2 satellite. The Atomic Clock Ensemble in Space (ACES) in preparation for launch in 2016 provides the next step in highly accurate clock comparison over large distances. ACES will be attached to the Columbus module of the International Space Station (ISS) and realizes a composite clock combined from a space qualified cesium fountain and an active hydrogen maser in a μ-g environment. A network of two-way microwave links allow a dense and precise clock comparison across the Earth and hence pushes the limits of fundamental physics, which is the main objective of this research project. The suitability of optical time transfer (Schreiber et al., 2009) has been shown in the past in a real world simulation experiment and since GPS measurements will provide a continuous and precise orbit for the ACES payload, two-way SLR measurements from various observatories on inter-continental distances will also allow to synchronize widely spaced apart ground clocks via the long-term stable time scale ($\Delta f/f \approx 10^{-15}$) in orbit. In comparison with the microwave link ACES will furthermore help to investigate the atmospheric signal delays to a much higher level than currently possible, which may lead to enhanced mapping functions over a wide range of frequencies.

Laser Ranging to the ISS

The application of SLR for a target located on the ISS has several implications. First of all there are severe limitations on power and weight for the additional SLR hardware, leaving room for a small detector package only, while the required timing unit serves two purposes. It is used for both the optical and the microwave link. In order to avoid systematic errors, the detection of the signal in space has to be done in the single photon regime. This requires an attenuation of the laser pulse of at least 6 orders of magnitude at the detector in space, while for the laser pulse an acceptance angle of more than 120 degrees is necessary at the spacecraft. Apart from technical issues, this project also touches a new regime in SLR laser safety requirements. Historically local operator safety considerations were the main concern. Hazards like high voltages, automatically slewing telescopes and laser eye safety (inside the laboratory) needed to be mitigated by defining appropriate procedures. Later, with increasing air traffic and more and more SLR stations coming on line, in-sky-laser-safety became progressively more important. Many SLR sites are now operating radar systems, which are providing a safe corridor around the laser beam in the sky. With growing orbit determination support for non-geodetic satellite missions, laser beam brightness became an issue for highly sensitive optical sensors onboard of satellites like ICESat or the Lunar Reconnaissance Orbiter (LRO). In order to provide precise orbit determination services to these missions, the ILRS has defined a set of procedures to accommodate tracking restrictions for example by defining ranging elevation masks, beam power limitations, session scheduling and the adherence to a go-/nogo- flag, controlled by the mission control. With the upcoming ranging to ACES the requirements for laser beam safety have also to be extended to cover the safety requirements of the astronauts working on the ISS (Schreiber, 2013). Since the Wettzell Laser Ranging System (WLRS) is using a rather collimated beam, a moderate repetition rate of 20 shots per second and a rather high laser power of up to 50 mJ, we consider it as one of the more challenging cases for the ranging to ACES. Table 1 lists the operational parameters of the WLRS, computes the energy density of the laser beam at the location of the ISS at minimum range and sets it against the maximum permissible energy level defined by ANSI Z136.1 for ultra-short laser pulses at the second harmonic wavelength of a Nd:YAG laser.

Table 1. Operational parameters of the WLRS

Parameter	**Quantity**
Wavelength	532 nm
Laser Energy per shot (at laser output)	0.1 – **50** mJ
Pulse Width	80 ps
Transmission through telescope	0.63
Transmission through atmosphere (max)	0.75
Minimum Range to ISS	380 km
Laser Beam Divergence (half angle)	**25** – 200 µrad
Atmospheric turbulence induced beam Divergence (half angle) typical	15 µrad
Diameter of Laser Spot at ISS	19 m
Total area illuminated at ISS	284 m^2
Energy Density	8.3e-9 J/cm^2
Interlock	go-/nogo- flag (as defined by the ILRS)
MPE (2^{nd} Harmonic Nd:YAG < 100 ps)	7.2e-8 J/cm^2

The given laser system is characterized by the transmitted beam power, the transmission efficiency of the station and the atmosphere and the beam divergence angle of the beam. The first and the latter are automatically chosen and preset specifically for each target by the WLRS system. For the maximum permissible energy (MPE) of a frequency doubled Nd:YAG laser system with a pulse width of less than 100 ps a value of 7.2e-8 J/cm^2 is specified by the ANSI standard Z136.1. The value per unit area is given by

$$E_{MPE} = \frac{\eta_t T_{atm} E_t}{(\vartheta R)^2 \pi},$$

with η_t the transmit path efficiency, T_{atm} the transmission of the atmosphere E_t the transmitted energy per pulse. ϑ is the divergence half angle and R the distance between ranging system and satellite. Figure 1 shows the energy density of the laser pulse at the location of the ISS for the 50 mJ case as a function of the divergence angle.

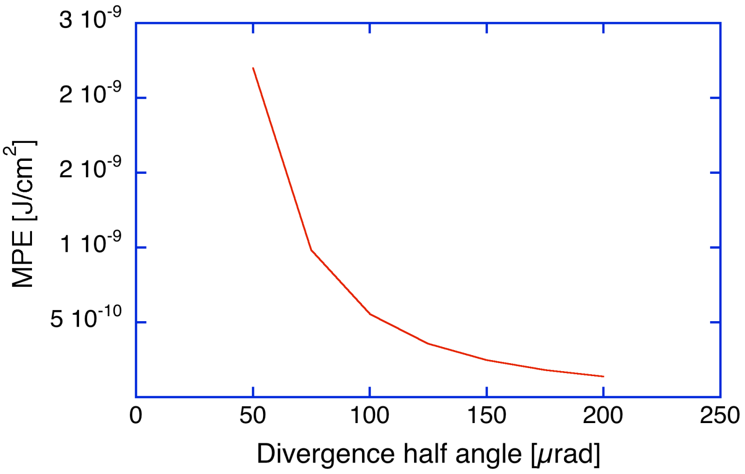

Figure 1: The computed MPE for the WLRS as a function of the divergence half angle. The system is safe to the naked eye at the minimum distance of the ISS (≈ 350 km) under all circumstances.

The time transfer functions of the ELT experiment are depending on a carefully balanced link budget for the optical ranging. The detector on the satellite has to be operated at the single photon detection level. The attenuation factor of the laser signal onboard the satellite is about 10^5. This requires a system setting according to table 2 for the WLRS in order to obtain the mission objectives.

Table 2: The relevant system parameters of the WLRS ranging to the ISS for nominal operation during the ELT experiment

Parameter	Quantity
Laser Energy per shot	0.1 mJ
Laser Beam Divergence (half angle)	200 µrad
Energy density at Columbus Module (TCA)	2.3e-13 J/cm^2
MPE (2nd Harmon. Nd:YAG < 100 ps)	7.2e-8 J/cm^2

The energy density value of table 1 corresponds to the high power setting (worst case scenario). The actual laser power operating level in order to comply with the mission requirements, i.e. the single photon detection level at the spacecraft, is required to be at 10^{-13} J/m^2, which is several orders of magnitude below the maximum permissible power setting and corresponds to the single photon signal level at the ISS.

For the tracking operations the ranging system will be programmed to set the necessary (low) power level of 0.1 mJ needed for the ACES tracking automatically. This is done under computer control prior to slewing the telescope into the position to point to the ISS. The instantaneous laser beam power is measured by a power meter on a shot by shot basis, while a beam block by default is orientated such, that it entirely blocks the entry of the laser beam to the telescope. Only if the required power setting is obtained, this beam block can be mechanically removed from the laser path under computer control to allow laser beam entry to the telescope. The gravity assisted default setting (no power applied) is when the beam dump blocks the laser beam. In order to reach the lower setting of the laser power, the time delay between amplifier pumping and oscillator fire is increased. Alternatively the system can be hard set to a lower power level by switching off the final amplifier stages. This will also increase the beam divergence because of the missing thermal lensing effect of the final amplifier crystal. A second redundant safety inhibit is that the telescope can only point and track the ACES Columbus module, when the beam divergence controlling mirror has reached the end position (corresponding to 200 µrad half angle beam divergence) and activates two micro switches wired up in series for added safety redundancy.

Discussion

The upcoming availability of modern atomic frequency standards in the µ-g environment of a free falling space station offers a great opportunity for unprecedented accurate clock comparisons over intercontinental distances. Accurate time transfer by means of an optical laser link has already been successfully demonstrated by the French T2L2 project on Jason 2, as well as the Chinese Beidou mission. The ELT project differs from the earlier missions by the fact that it requires a much higher level of detector and timer stability, because it is based on more accurate clocks in space. As a consequence the operation regimes of the applied photo-detectors have to be defined to a much tighter tolerance than for the detectors of the earlier projects. This requirement alone reduces the operating laser energy levels to a setting several orders of magnitudes below the maximum permissible energy threshold of the ANSI Z136.1 standard. However active safety measures at the ranging facility have to ensure that the required settings are properly invoked at any time during the ISS ranging. Several new functions within the WLRS provide the necessary redundant safety to achieve both, the mission objectives and the operational safety. This functionality is based on the existing ILRS restricted tracking procedures.

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