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Time Transfer between Satellite Laser Ranging Stations via Simultaneous Laser Ranging to the Lunar Reconnaissance Orbiter

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Abstract. *A new technique is described to transfer time between distant satellite laser ranging stations via simultaneous one-way laser ranging to the Lunar Reconnaissance Orbiter. The time standard of the primary station is referenced to a nearby Master Clock using an All-View GPS receiver. A ground-based experiment has been conducted to validate the technique. Sub-nanosecond precision and accuracy is shown to be achievable.*

Introduction

Satellite laser ranging (SLR) has long been used to measure the distance from ground fiducial points to satellites to determine the spacecraft position in orbit, to detect tectonic movements on Earth, and to conduct other geodetic measurements (Degnan 2013). The SLR technique may also be used to compare times of the ground station to satellite clocks (Fridelane 1995). The satellite in this case not only retro-reflects the incoming laser pulses but also detect and time-tag them with respect to its own time base. The ground station measures the time-of-flight of the laser pulses as well as transmits its time code to the satellite. The accuracy of laser time transfer is not sensitive to the daily and seasonal variation of the ionosphere delay, which is a major source of error for the radio frequency (RF) techniques and the Global Position System (GPS). The Laser Time Transfer (LTT) project first demonstrated laser time transfer to the Compass M1 satellite at sub-nanosecond precision (Yang 2008). The Time Transfer by Laser Link (T2L2) project by the Centre National d'Etudes Spatiaes (CNES) and Observatorire de la Cote d'Azur (OCA) expanded the technology to not only transfer time to the satellite but also compare the station times of remote SLR sites at 0.1 ns precision and accuracy (Samain 2009, Prochazka 2011). Here we report a new technique of transferring time between remote SLR stations by simultaneous one-way Laser Ranging (LR) to the Lunar Reconnaissance Orbiter (LRO) at lunar distance. The major objective is to establish accurate ground station times and improve LRO orbit determination via simultaneous LR measurements.

One-way laser ranging is used on LRO to assist in orbit determination (Zuber 2010). Laser pulses are transmitted from the ground station and time-tagged at both the ground station and LRO. The difference of the time tags for each laser pulse gives a measure of the one-way time-of-flight plus an offset. The time bases at ground and LRO are sufficiently stable so that the one-way time-of-flight measurement is sufficient to capture all the orbit dynamics plus a slow varying time offset. The ground station time and the LRO clock time can be solved independently using other means. The major advantage of one-way laser ranging is the low signal propagation loss, which increases as the square instead of the fourth power of the distance. A 22-mm diameter LR telescope on LRO is sufficient for LRO to detect laser pulses from most of the SLR stations with ample link margin. The LR receiver telescope is mounted on and co-aligned with the high gain RF antenna which is pointed to Earth whenever LRO is in the near side of the Moon. The LR receiver field of view is wide enough to cover the entire Earth so that SLR stations at different parts of the world can range to LRO simultaneously.

Although LRO LR system was originally designed for single ground station ranging at a time, it was found that it could easily detect and record laser pulses from multiple ground stations simultaneously. The results of these simultaneous LR measurements can be used to compare the SLR station times or transfer time from one to the other using times-of-flight estimated from RF tracking. The accuracy of the time transfer depends only on the difference of the times-of-flight from each ground station to the spacecraft. Since LRO is much further away compared to near Earth satellites, we can tolerate a much larger uncertainties in the times-of-flight from each SLR station to LRO than those required in the T2L2 measurements. We will show in the subsequent sections that the times-of-flight estimated from conventional RF tracking are sufficient for time transfer at sub-nanosecond accuracy without the need for a 2-way laser ranging as in the T2L2 project.

The Next Generation Satellite Laser Ranging (NGSLR) station at Greenbelt, Maryland, serves as the primary LRO LR station. Its time base has recently been improved to nanosecond precision and accuracy by employing the hydrogen maser clock at the nearby Very Long Baseline Interferometry (VLBI) site via optical fibers. An All-View GPS receiver is used to monitor the hydrogen maser time against the GPS time. The United State Naval Observatory (USNO) in Washington, DC, also provides its All View GPS receiver data in reference to the master clock. The NGSLR time can thus be referenced to the USNO master clock by differencing the results of the two All-View GPS receivers. Because of the proximity of the two sites, the ionosphere effects on the GPS signals are similar and the effects are largely canceled out. As a result, one can transfer the time of the USNO master clock to a distant ground station via simultaneous LRO LR with NGSLR, as depicted in Figure 1.

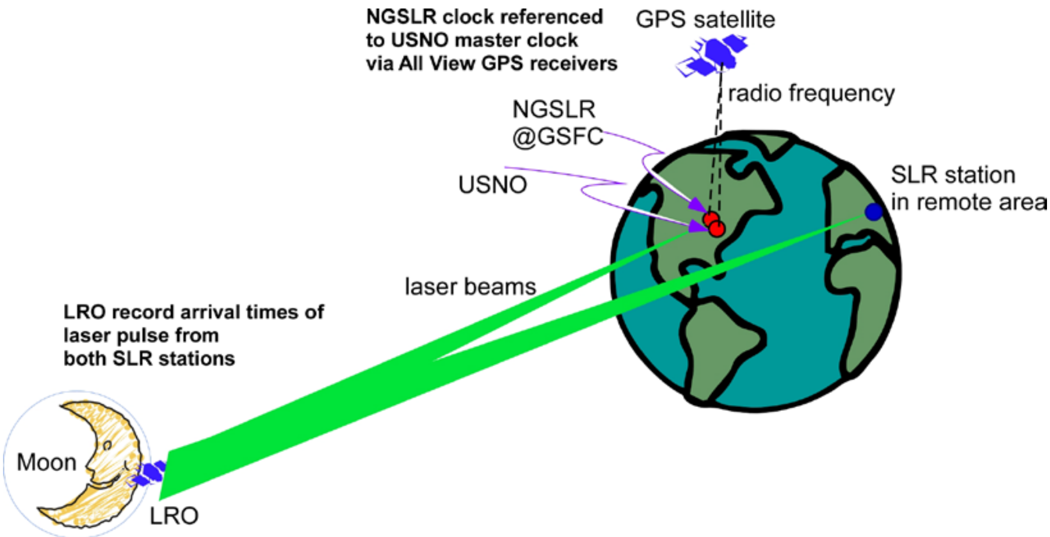

Figure 1. Concept of laser time transfer via simultaneous LRO LR measurements.

The concept of LRO LR time transfer has been verified on ground between NGSLR and the nearby Mobile Laser System (MOBLAS-7) at NASA Goddard Space Flight Center (GSFC) by ranging to a fixed target and recording the laser pulse arrival times at the target as in LRO. Several simultaneous LRO LR measurements were conducted from NGSLR and MOBLAS-7 in the past year and data analysis is on-going. In this paper, we will describe the principle of operation, error analysis, and the ground test results.

Comparing SLR Station Times via Simultaneous Laser Ranging to LRO

In LRO LR operation the ground station transmits laser pulses and time-tags the pulses with respect to its own time base. The LR receiver at LRO time-tags all the received laser pulses in reference to its own time base and sends these time tags to Earth for post data processing. The time tags from LRO and the ground station are then paired up based on estimated ranges and the station pulse train patterns. The difference of the two time tags in a pair measures the one-way laser pulse time-of-flight. In simultaneous LR operation, LRO records laser pulse arrival times from all participating ground stations. These laser pulse arrival time tags from LRO are paired up with the corresponding ground station laser emission time tags in post data processing according to the unique laser characteristics of the station. Figure 2 shows the geometry and timing diagram of a two-station simultaneous LRO LR operation.

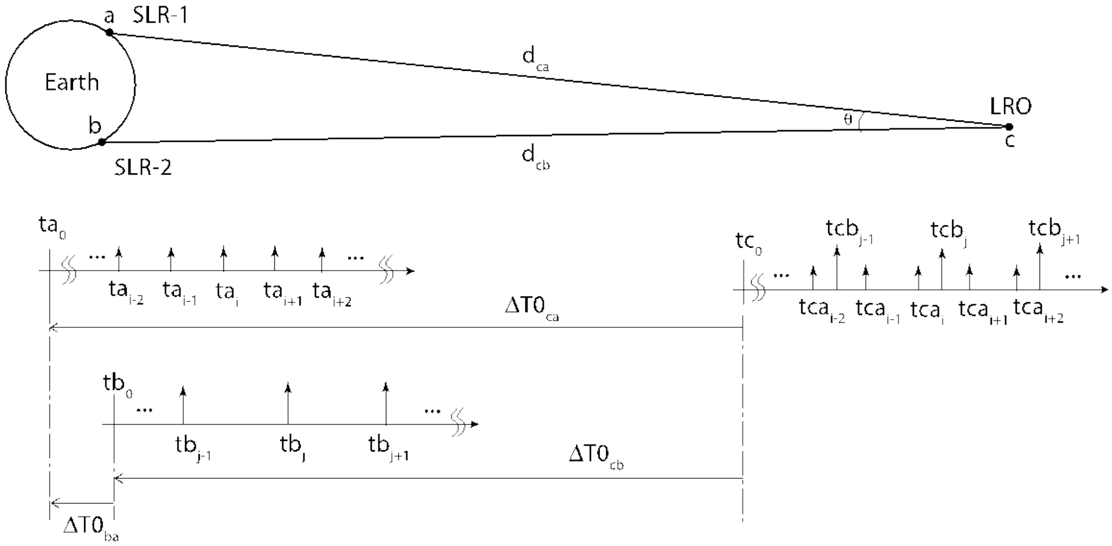

Figure 2. Geometry and timing diagrams of a two-station simultaneous LRO LR operation. The mathematical symbols are all defined in the subsequent equations in this section.

In the absence of measurement error, the times-of-flight of laser pulses from the ground station SLR-1 to LRO can be expressed as

$$t_{Lca}(i) = \left(tca_i - t_{c0}\right) - \left(ta_i - t_{a0}\right) = \left(tca_i - ta_i\right) - \left(t_{c0} - t_{a0}\right) \tag{1}$$

where $t_{Lca}(i)$ is the time-of-flight of i^{th} laser pulse in the sequence, tca_i is the time-tag of the laser pulse received at LRO, ta_i is the time-tag of the corresponding laser pulse transmitted from the ground station SLR-1, t_{a0} is the origin, or the reference time, of the SLR-1 clock, and t_{c0} is the reference time of the LRO clock.

Similarly, the times-of-flight of laser pulses from the second ground station, SLR-2, to LRO, $t_{Lcb}(j)$, can be written as

$$t_{Lcb}(j) = \left(tcb_j - t_{c0}\right) - \left(tb_j - t_{b0}\right) = \left(tcb_j - tb_j\right) - \left(t_{c0} - t_{b0}\right) \tag{2}$$

where tcb_j is the time-tag of the j^{th} laser pulse received at LRO, tb_j is the time-tag of the corresponding laser pulse transmitted from the ground station SLR-2, and t_{b0} is the reference time, of the SLR-2 clock.

The difference of the reference times of the clocks at LRO and the ground stations are given by

$$\begin{aligned} \Delta T0_{ca} &= t_{c0} - t_{a0} = \left(tca_i - ta_i\right) - t_{Lca}(i) \\ \Delta T0_{cb} &= t_{c0} - t_{b0} = \left(tcb_j - tb_j\right) - t_{Lcb}(j) \end{aligned} \tag{3}$$

and

$$\begin{aligned} \Delta T0_{ba} &= t_{b0} - t_{a0} = \Delta T0_{cb} - \Delta T0_{ca} \\ &= \left[\left(tcb_j - tb_j\right) - \left(tca_i - ta_i\right)\right] - \left[t_{Lcb}(j) - t_{Lca}(i)\right] \\ &= \Delta Tcb_j - \Delta Tca_i - \Delta TL_{i,j}. \end{aligned} \tag{4}$$

where ΔTcb_j and ΔTca_i are the raw LRO LR times-of-flight for SLR-2 and SLR-1, respectively, and $\Delta TL_{i,j}$ is the difference of the two times-of-flight at the sampling times.

Therefore, time offset between the two ground stations can be solved as long as the difference of the two times-of-flight can be obtained from the RF tracking results. Although these times-of-flight estimates are not as accurate and precise as those from two-way laser ranging, the errors in the differences of the two times-of-flight are small. When one of the ground station clocks is calibrated to a standard time, such as the Coordinated Universal time (UTC), it can effectively transfer its time to the other ground station through such a simultaneous LRO LR operation.

The accuracy and the precision of the time transfer depend on the quality of the LRO LR measurements and the time-of-flight estimates from the RF tracking. The LRO LR measurements typically have a standard deviation of about 0.5 ns for a single detected laser pulse and can be reduced by averaging over the results from many laser pulses. The uncertainties of the time-of-flight estimates for LRO from the RF tracking data analysis is <100 m. We will show next that the error in the time transfer due to these range uncertainties can be <<1 ns.

Considering the case shown in Figure 3, the error in the difference of the ranges from the ground stations to LRO, δr, due to an error in LRO orbit position estimation, ε, can be expressed as,

$$\delta r = \left(r_b' - r_a'\right) - \left(r_b - r_a\right) = \left(r_b' - r_b\right) - \left(r_a' - r_a\right). \tag{5}$$

Since

$$\begin{aligned} r_a' &= \left(r_a^2 + \varepsilon^2 + 2 r_a \varepsilon \cos\alpha_a\right)^{1/2} \approx r_a\left(1 + 2\frac{\varepsilon}{r_a}\cos\alpha_a\right)^{1/2} \approx r_a\left(1 + \frac{\varepsilon}{r_a}\cos\alpha_a\right), \\ r_b' &\approx r_b\left(1 + \frac{\varepsilon}{r_b}\cos\alpha_b\right) \end{aligned} \tag{6}$$

the difference of the ranges for small angles can be approximated as

$$\delta r = \varepsilon\left(\cos\alpha_b - \cos\alpha_a\right) \approx \varepsilon\left(\alpha_a^2 - \alpha_b^2\right). \qquad (6)$$

Consider the worst case when $\alpha_b = 0$ and the two ground stations are half the globe away, then $\alpha_b \le 0.0168$, $|\delta r| \le 2.8 \times 10^{-4}|\varepsilon|$. For a 100-m LRO orbit determination uncertainty, the resultant error in the difference of the two light paths is <2.8 cm, or <0.1 ns in time.

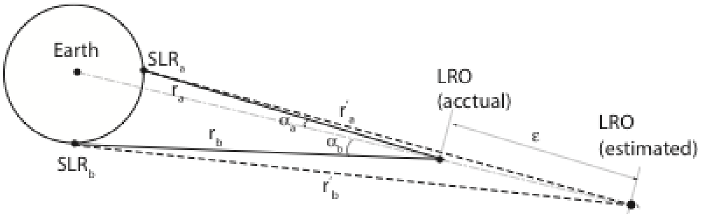

Figure 3. Geometry of a two-station simultaneous LRO LR operation and the effects of the spacecraft range estimate error.

(6)

The LRO orbit position uncertainties post data processing is usually about 10 m and its effect on time transfer should be negligible compared to other source of errors.

Validation of the Time Transfer Technique Using a Ground Target

Ground tests were performed from NGSLR and MOBLAS-7 to two calibrated targets. The time offsets from the event timer to the telescope invariant points at both of the stations had been calibrated to within 1 ns. The laser emission timing pulses, or the start pulses, from MOBLAS-7 were also transmitted to NGSLR over a coax cable and time-tagged with the event timer at NGSLR. An optical receiver and an event timer were setup at the target to detect and time-tag the laser pulses as in LRO. NGSLR and MOBLAS-7 transmitted and time-tagged laser pulses as in a simultaneous LRO LR operation for about an hour. The test was repeated to a different ground target separated by10° in azimuth. Figure 4 shows the test results.

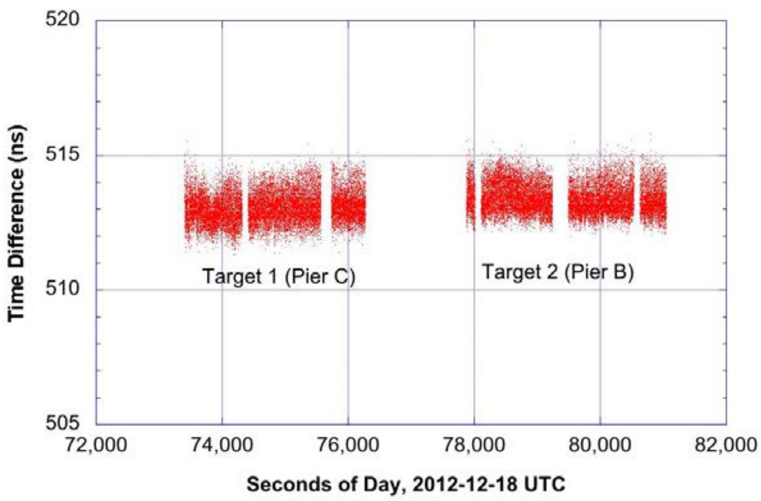

Figure 4. Time offset between NGSLR and MOBLAS-7 solved from the simultaneous one-way laser ranging.

The time offsets solved from these one-way laser ranging tests were nearly constant over the course of two and half hours. The time offsets solved from Targets 1 and 2 measurements were 513.00 and 513.30 ns, respectively. The time offset consisted of mostly the coax cable delay between the two stations. The time offset from the preliminary test about a year ago to Target 1 was 513.27 ns. The three tests yielded the same results to within 0.3 ns for two different targets over a year time span.

Simultaneous LR measurements from NGSLR and MOBLAS-7 to LRO have also been conducted with the MOBLAS-7 start pulses transmitted to NGSLR and time-tagged on the same time base as that for its own laser emission times. An All-View GPS receiver has monitored the hydrogen maser time at NGSLR since January 20, 2013. We are currently analyzing these data to reduce the effect of the spacecraft motion and minimize the timing error. The next step is to compare and transfer time with a far away ground station, such as the McDonald Laser Ranging Station (MLRS) and SLR stations in Europe.

Conclusions

We have demonstrated a laser time transfer technique via simultaneous one-way laser ranging to LRO. Ground-based experiments with NGSLR and MOBLAS-7 have been conducted to validate the technique with stationary targets. Sub-nanosecond precision and accuracy have been shown to be achievable. Simultaneous LR measurements from NGSLR and MOBLAS-7 to LRO have also been conducted and the data analysis is currently ongoing.

Acknowledgements

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