

Time-transfer experiments between satellite laser ranging ground stations via one-way laser ranging to the Lunar Reconnaissance Orbiter

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Introduction

Satellite laser ranging (SLR) has long been used to measure the distance from a ground station to an Earth-orbiting satellite in order to determine the spacecraft position in orbit, and to conduct other geodetic measurements such as plate motions[1]. This technique can also be used to transfer time between the station and satellite, and between remote SLR sites, as recently demonstrated by the Time Transfer by Laser Link (T2L2) project by the Centre National d'Etudes Spatiales (CNES) and Observatoire de la Côte d'Azur (OCA) [2,3] as well as the Laser Time Transfer (LTT) project by the Shanghai Astronomical Observatory[4], where two-way and one-way measurements were obtained at the same time. Here we report a new technique to transfer time between distant SLR stations via simultaneous one-way laser ranging (LR) [5] to the Lunar Reconnaissance Orbiter (LRO) spacecraft at lunar distance. The major objectives are to establish accurate ground station times and to improve LRO orbit determination via these measurements.

One-way laser ranging to LRO has been in operation for five years from June 2009, when the spacecraft was launched, to the end of September, 2014. The one-way time-of-flight LR measurements are to be used in the orbit determination process to help achieve high precision LRO orbit solutions. The laser pulses are time-tagged when transmitted from the ground station. When the pulses arrive at LRO and are received by the LR telescope mounted on the High Gain Antenna, the received signals are time-tagged by the Ultra Stable Oscillator onboard LRO. The time difference between the transmitted and received signals determines the distance between the ground station and the spacecraft. The LR telescope is pointed to the Earth whenever LRO is at the near side of the Moon. The LR receiver has a large enough field of view to cover the entire Earth, so that ground stations at different locations can range to LRO at the same time. Ten SLR stations from the ILRS network[6] have been participating in the LR operation. Each station has equipped with its own stable time source, such as Cs clocks, Rb clocks, and Hydrogen masers, to ensure an accurate timing measurement at the station. Regular simultaneous passes from multiple stations, up to 4, have been obtained. LRO-LR has thus provided a new platform for time transfer, and can use the time transfer technique to improve the spacecraft orbit determination via more precise measurements and regular simultaneous passes.

The results of the simultaneous LR measurements can be used to compare the SLR station times or transfer time from one to the other via the times-of-flight estimated from the conventional radio frequency tracking of LRO. The accuracy of the time transfer depends only on the

difference of the times-of-flight from each ground station to the spacecraft, and is expected to be at sub-nano second level[7].

Monitoring the station time with an All-View GPS receiver

The primary LRO-LR station is NASA’s Next Generation Satellite Laser Ranging (NGSLR) station at Greenbelt, MD. Since January, 2013, the time base at NGSLR has been improved by switching from an Cs clock to a Hydrogen maser clock at the nearby Very Long Baseline Interferometry (VLBI) site via optical fibers. The time of this maser has been monitored against the GPS time via an All-View GPS receiver. The United States Naval Observatory (USNO) in Washington DC, about 20 miles south-west to NGSLR, also provides its All-View GPS receiver data referenced to its master clock. By differencing the GPS receiver data from NGSLR to those from USNO, the Hydrogen maser clock can be referenced to USNO’s master clock. Given that USNO and NGSLR are close in location, the ionosphere effects on the GPS signals are largely canceled. Hence, the USNO master clock time can be transferred to a distant SLR station as it ranges to LRO simultaneously with NGSLR.

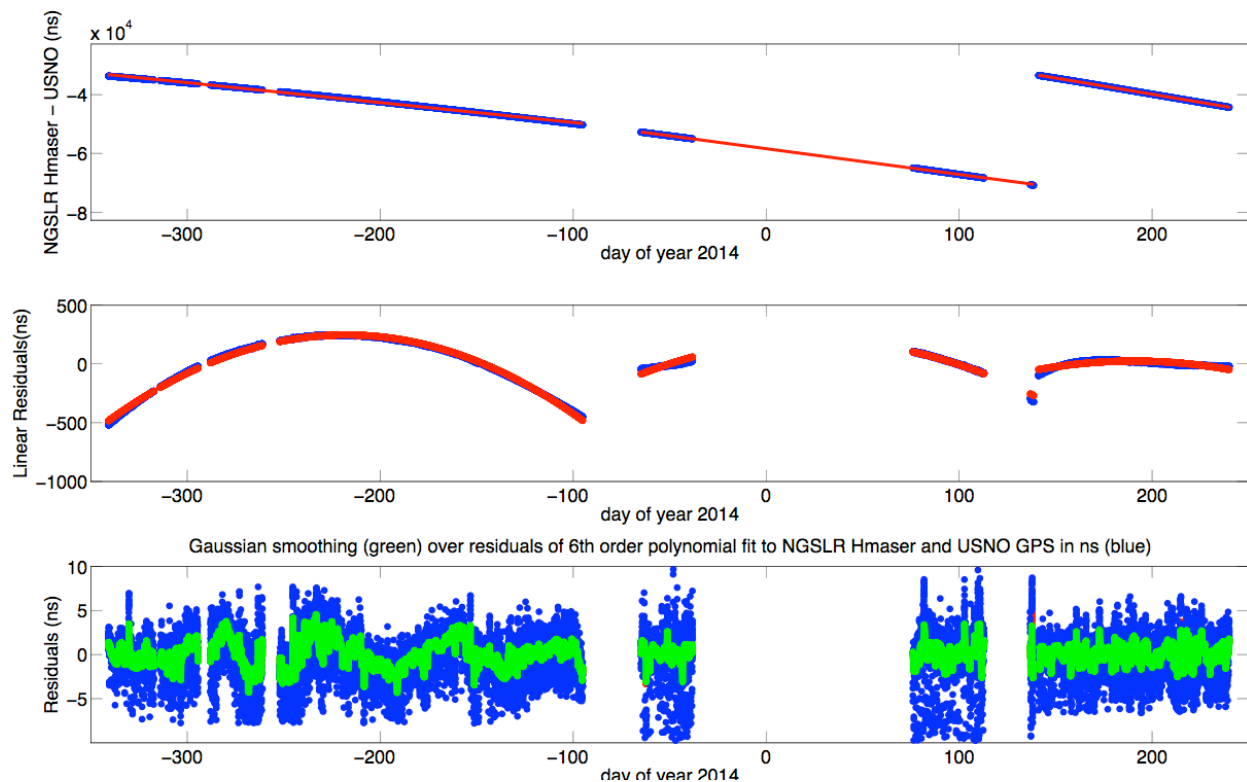


Figure 1. Difference between NGSLR Hydrogen maser time and USNO master clock time (top), residuals of the time differences after removing a linear fit (middle), and residuals of the time differences after removing a 6th order polynomial fit (in blue, bottom) with Gaussian smoothing (in green, bottom). All time differences and residuals are in ns.

The time difference between the NGSLR maser and the USNO master clock from January, 2013 to September, 2014 is shown in Figure 1. The gaps in the figure are due to either the lack of maser data, e.g., at the beginning of 2014, or maser power down incidents, e.g., around day 140 of 2014. The top panel in Figure 1 shows that the NGSLR maser has an obvious long-term drift. After removing a 6th order polynomial fit to the direct time difference shown in the top panel of

Figure 1, the residuals over 20 months are generally less than 10 ns. By adding a Gaussian smoothing function to the residuals, the long-term rms can be reduced to about 1 ns.

Verification and validation with ground targets

The concept of the time transfer between distant SLR stations via simultaneous laser ranging to LRO was first tested and verified on the ground. The testing experiments were performed by NGSLR and the Mobile Laser System-7 (MOBLAS-7), both located at the Goddard Geophysical and Astronomical Observatory (GGAO). The laser pulses transmitted from MOBLAS-7 were transferred to NGSLR via a coax cable and time-tagged by NGSLR's event timer, which also time-tagged NGSLR's outgoing laser pulses. The time offsets between the event timer and the telescope invariant point at both stations have been calibrated to less than 1 ns. An optical receiver and an event timer were set up at the ground target to detect and time-tag the incoming laser pulses as in LRO.

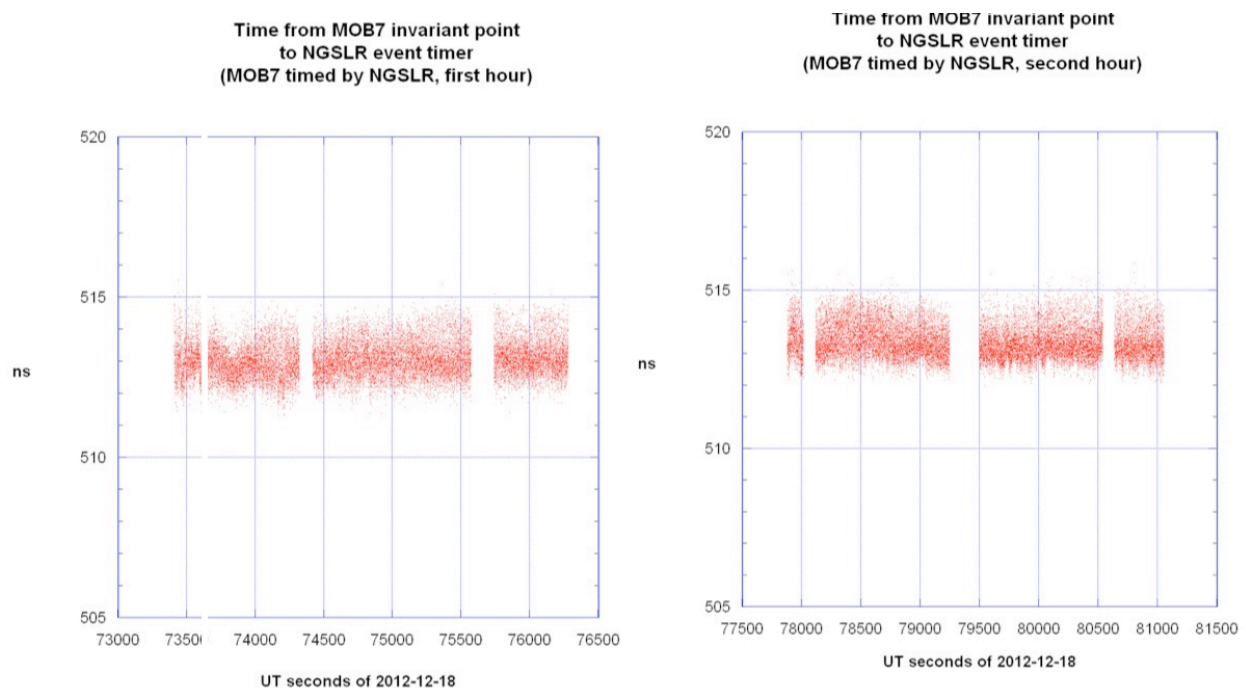


Figure 2. Time offsets between NGSLR and MOBLAS-7 to Pier C (left) and Pier B (right) solved from the simultaneous one-way laser ranging on December 18th, 2012.

The full-length test was performed to two calibrated ground targets at GGAO, Pier C and Pier B, 10 degrees apart in azimuth. NGSLR and MOBLAS-7 ranged to the targets simultaneously as in LRO-LR operation about an hour each. The time differences between NGSLR and MOBLAS-7 from this test were shown in Figure 2. The time offsets solved from this test between the two stations were 513.00 ns for Pier C, and 513.30 ns for Pier B, which were mostly the cable delay between the stations. A preliminary 10-minute long test was performed a year before this test on November 30th, 2011 to Pier C, which yielded a time offset of 513.27 ns. Results from both ground tests agree with one another to within 0.3 ns for two different targets over one-year time span.

Results of time transfer via LRO between ground stations at GGAO

The time transfer tests between NGSLR and MOBLAS-7 via simultaneous ranging to LRO first took place in February 4th, 2013. As in the ground test, the laser pulses transmitted from MOBLAS-7 were sent to NGSLR via a coax cable to be time-tagged by the NGSLR event timer, which was referenced to the Hydrogen maser monitored with respect to the USNO master clock. The cable delay has been measured and applied in the data analysis when solving for the time offset between the stations. Four consecutive hour-long simultaneous LRO-LR passes on February 4th, 2013, and then 3 more on the next day were obtained from both stations. The time offsets solved from these passes are within 4 ns, all with rms values about 1 ns. The same test was repeated 6 months later in August, 2013, then again a year later in September 2014. Figure 3 shows the results from all these tests, and the time offsets between the two stations agree very well with one another.

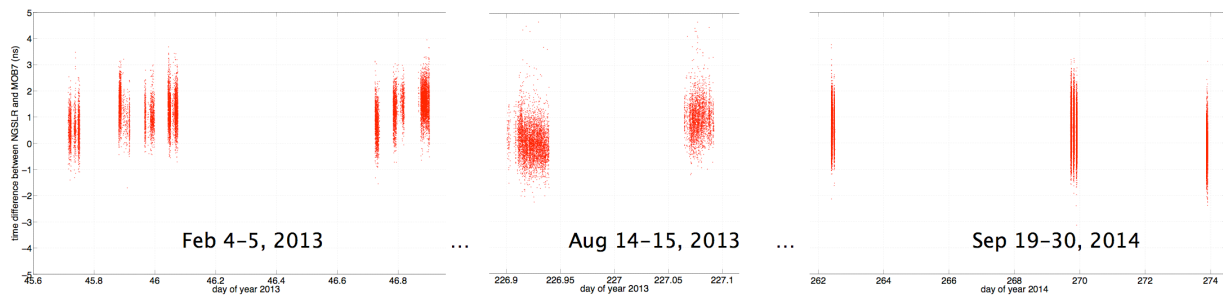


Figure 3. Time offsets (in ns) between NGSLR and MOBLAS-7 to LRO solved from the simultaneous one-way laser ranging passes on February 4th and 5th, 2013, August 14th and 15th, 2013, September 19th to 30th, 2014, respectively. The y-axis here is set from -5 ns to 5 ns.

Summary

Time transfer between ground stations via one-way simultaneous ranging to LRO has been demonstrated, and verified on the ground and to the spacecraft. Results from NGSLR and MOBLAS-7 showed that nano-second accuracy and precision are achievable, and can be stable for more than a year.

Another SLR station at McDonald Observatory, in Ft. Davis, Texas, has also participated in the time transfer test with NGSLR started in 2014. A Cs clock has been used at McDonald as time source. Like the NGSLR Hydrogen maser, this Cs clock has been monitored and referenced to the USNO master clock. Data from simultaneous ranging to LRO between McDonald and NGSLR are currently under analysis.

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