Summary of Ground Station Performance in 5 years of Laser Ranging Operation to Lunar Reconnaissance Orbiter

D. Mao[1], J. F. McGarry[2], M. H. Torrence[3], X. Sun[2], J. E. Horvath[4], C. B. Clarke[4], M. K. Barker[1], J. E. Golder[1], E. Mazarico[2], G. A. Neumann[2], D. E. Smith[5], and M. T. Zuber[5], [1]Sigma Space Corporation, Lanham, Maryland, USA, [2]Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, [3]Stinger Ghaffarian Technologies, Greenbelt, Maryland, USA, [4]Honeywell Technology Solutions, Inc. (HTSI), Columbia, Maryland, USA, [5]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

Since the beginning of the Lunar Reconnaissance Orbiter (LRO) mission in June 2009, ten satellite laser ranging (SLR) stations from the International Laser Ranging Service (ILRS) [1] have participated in the laser ranging (LR) operation to LRO [2] to obtain highly precise one-way, time-of-flight measurements by laser pulses to determine the distance between the transmitting Earth-based SLR station and LRO. NASA's Next Generation Satellite Laser Ranging (NGSLR) station at Greenbelt, Maryland has been serving as the primary LRO-LR station. In the last 5 years of operation, over 4000 hours of successful ranging data to LRO have been obtained, and simultaneous tracking data from 2, 3, or 4 participating stations have been collected routinely. Here we present a summary of the contributions from each participating station.

The LR measurement quality depends on the stability of the clocks at both the ground station and the spacecraft. All stations participating in the LRO-LR operation are equipped with oscillators to maintain a stable time base, such as rubidium (Rb), cesium (Cs) or hydrogen-maser clocks (the most stable). Since 2013, NGSLR has improved its time base to nanosecond precision and accuracy by employing the hydrogen maser clock of the nearby very long baseline interferometry (VLBI) site, via optical fibers [3]. Both the epoch time and the frequency of the hydrogen-maser are referenced to the United State Naval Observatory (USNO) master clock nearby via an All-View GPS receiver. LR data from NGSLR have been used to monitor the mid- to long-term characteristics of the LRO ultra-stable oscillator (USO). This oscillator is used as the clock source for the Lunar Orbiter Laser Altimeter (LOLA) [4], one of the instruments on LRO, to time-tag both the LOLA laser pulses and the LR laser pulses. After removing the oscillator frequency zero-point offset, the frequency aging and the frequency aging rate, which are derived from LR data, as well as the light time correction, the residual timing error over 5 years is less than 30 micro-seconds for the entire mission, which is much better than the 3-ms mission requirement for time reconstruction. Using the LRO USO as a common clock, here we show the behavior of each ground station clock with respect to NGSLR.

[1] Pearlman, M., et al (2008), *The International Laser Ranging Service*, AOGS Advances in Geosciences: Solid Earth.

[2] Zuber, M. T., et al (2010), *The Lunar Reconnaissance Orbiter laser ranging investigation*, Space Science Reviews, Vol. 150, pp. 63-80.

[3] Sun, X., et al (2013), 13-Po54, *Time Transfer between Satellite Laser Ranging Stations via Simultaneous Laser Ranging to the Lunar Reconnaissance Orbiter*, Proceedings of the 18th International Laser Ranging Workshop, Japan.

[4] Smith, D. E., et al (2010), *The Lunar Orbiter Laser Altimeter (LOLA) Investigation on the Lunar Reconnaissance Orbiter (LRO) Mission,* Space Science Reviews, Vol. 150, pp. 209-241.