Free space laser communication experiments from Earth to the Lunar Reconnaissance Orbiter in lunar orbit

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Abstract: Laser communication and ranging experiments were successfully conducted from the satellite laser ranging (SLR) station at NASA Goddard Space Flight Center (GSFC) to the Lunar Reconnaissance Orbiter (LRO) in lunar orbit. The experiments used 4096-ary pulse position modulation (PPM) for the laser pulses during one-way LRO Laser Ranging (LR) operations. Reed-Solomon forward error correction codes were used to correct the PPM symbol errors due to atmosphere turbulence and pointing jitter. The signal fading was measured and the results were compared to the model.

OCIS codes: (060.2605) Free-space optical communication; (280.3400) Laser range finder.

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1. Introduction

Laser systems can be used to track and communicate with spacecraft in deep space to achieve better performance at lower power and with smaller size apertures than conventional microwave systems. A single laser system can be used for both communication and tracking, similar to the conventional microwave communication and tracking systems. Lasers have been used to track Earth orbiting satellites and lunar retro-reflective arrays on the lunar surface for over 40 years [1]. Free space laser communication technologies have been under development over the past 30 years and several experiments have been successfully conducted [2–4]. The Lunar Laser Communication Demonstration (LLCD) will be launched in 2013 on board the Lunar Atmosphere and Dust Environment Explorer (LADEE) and will be the first two-way high speed (622 Mbps) lunar laser communication demonstration [5]. The Laser Communication Relay Demonstration (LCRD) at 1.25 Gbits s^{-1} to geosynchronous satellites is currently under development at NASA GSFC with an anticipated launch date in 2016 [6]. There are many common attributes between laser ranging and communications, such as pointing, timing, and atmosphere effect corrections. The two can be combined into one system with a single laser transmitter and receiver. The ranging signals are slow varying and one measurement every few seconds is sufficient to track a spacecraft in deep space. The communication signals are fast transitioning between discrete levels and at discrete time. The two signals can be unambiguously separated at the receiver because they occupy different frequency spectra. There have been several experiments to transfer times from SLR stations to spacecraft while ranging [7–9]. A laser ranging experiment at quantum (single photon) signal level between a near earth satellite and an SLR station has been demonstrated [10]. Laser ranging and communication using a PPM signal format has been proposed and some elements of the concept have been demonstrated [11]. A two-way laser ranging measurement will be carried out by LLCD on the LADEE mission as a byproduct of the timing recovery for the data communication [5].

We have recently demonstrated simultaneous laser ranging and communication experiments with existing infrastructure and minor modification to the ground station timing equipment. We successfully transmitted digital data from the Next Generation Satellite Laser Ranging (NGSLR) station in Greenbelt, Maryland, to LRO in lunar orbit over a 380,000 km distance at 200-300 bits s^{-1} error free with Reed Solomon forward error correction coding. The experiments also provided direct measurements of laser signal fading due to atmospheric turbulence and laser pointing jitter. Although the data rate was relatively low, the experiment demonstrated a useful technique for simultaneously laser tracking and data communication to a spacecraft in deep space from existing SLR stations as an alternative to the conventional microwave links.

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2. Test setup

2.1 Space terminal

The LR subsystem [12] on LRO is a one-way laser ranging system which consists of a 2.2-cm diameter optical receiver on the high gain antenna (HGA) and an optical fiber bundle that sends the optical signal through the HGA gimbals and boom to the Lunar Orbiter Laser Altimeter (LOLA) [13] on the instrument deck for time-tagging. The LR receiver is bore-sighted with the HGA, which is pointed to the ground station for data transmission whenever LRO is in view from Earth. The LR receiver can detect and time-tag laser pulses from Earth at 532-nm wavelength from any SLR station around the globe. The clock oscillators on LRO and at the ground stations are stable to $<<10^{-12}$ (a few ns over an hour). The LR receiver has an 8-ms range window that opens at 28 Hz and synchronized with the LOLA laser pulse emission times and the spacecraft mission elapsed time (MET). The timing precision of the LR receiver is about 0.3 ns. The detection threshold is adjusted automatically to achieve the highest receiver sensitivity while keeping the false detection rate below 1%. The LR receiver also measures the received pulse energy by integrating the received pulse waveforms. LRO LR has been in operation since June 2009 and the prediction of the spacecraft MET and light travel time from NGSLR to LRO has been improving steadily, and has become more than sufficient for communication experiments like those described herein. The regular LR operation and range measurements were not affected by these laser communication experiments since the ground stations and LRO time-tagged the laser pulses in pairs and determine the range from the difference of the two time-tags in the pair.

2.2 Ground station

The laser from NGSLR telescope had a 30-cm beam diameter and 50-μrad (~10-arcsecond) divergence angle. The laser transmitter was a diode pumped Q-switched Nd:YAG laser and frequency doubled to produce 6-ns laser pulses at 532-nm wavelength. The laser pulse could be externally triggered at up to 50 Hz (20-ms recovery time after each laser pulse emission) and could accommodate the 28-Hz PPM trigger signal.

The pointing of the telescope was controlled by the azimuth and elevation gimbals with a 50-Hz velocity drive servo control loop and the tracking jitter was at 1-arcsecond level for a slew rate ranging from sidereal rates to several degree s^{-1}. The telescope pointing was calibrated by co-bore sighting a camera with the laser beam and pointing the telescope to a nearly uniform grid of about 50 bright stars in the FK5 star catalog. A least square fit of the pointing biases was performed to a 22-term trigonometric model, which was then used to correct the pointing offsets of the telescope. The calibration was periodically performed to maintain a pointing accuracy of about 1 arcsecond.

The laser beam pointing was programmed to follow the LRO orbit position predictions provided by the Goddard Flight Dynamics Facility in the form of Consolidated Prediction Format vectors. The accuracy of the LRO orbit prediction was <3 arcseconds based on our LR experiences. There was also a near-real time low-data-rate telemetry feedback from LRO to the ground station to indicate LR signal detection at LRO, which was used to fine-tune the pointing. The laser beam refraction by the atmosphere was calculated and corrected using a long established model [14] with the temperature, barometric pressure, and humidity data from a small weather station next to NGSLR. The system epoch time was provided by a GPS receiver, which was accurate to ± 100 ns with respect to UTC. The light travel time for each laser shot was calculated from the ground station coordinates to that of LRO at the time.

For eye safety, a radar co-bore sighted with the laser beam was used to detect airplanes and automatically block the laser beam via a relay switch when an airplane came within 3° of the laser beam. The airplane avoidance action causes data outages for a few to tens of seconds.

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2.3 Data encoding and decoding

A 4096-ary PPM signal format was used with 1-μs slot time in our experiments. Each laser pulse from NGSLR was transmitted in one of the 4096 (12 bits) possible time slots at 28 pulses per second, which gave a raw data rate of 336 bits s^{-1}. Figure 1 shows a timing diagram of the PPM signal, the range window, and the duty cycle. The size of PPM time slots was limited by the ground station laser pulse emission time jitter and trigger control (150 ns peak to peak) and the digital data timing recovery at the receiver. The number of PPM slots on each laser pulse was limited by the LR range window width and uncertainties in the prediction of LRO position and MET.

Reed-Solomon codes were chosen because they could match the 4096-ary PPM symbol size and were much more effective than binary codes. The time between laser pulses, ~36 ms (1/28Hz), was considerable longer than the time scale of atmosphere fading effects [15], so that the channel could be considered as "memoryless" and the transmission errors as independent. The dominant errors were missed detections, or erasures, as in a typical free-space communication system. Reed-Solomon codes were better at correcting erasures than falsely detections and suitable for correcting burst errors resulted from brief gaps in the signal without the need to interleave the source data. The data was transmitted in code blocks of 4095 PPM symbols, of which the first k symbols were data and the rest were parity checks. The code was capable of correcting up to (4095-k)/2 falsely detected PPM symbols or twice as many erasures in a code block. The rate of the code was defined as the ratio of the number of the data symbols to the block size. Each code block was 146.25 seconds, which was sufficiently long to correct occasional signal outages due to airplane avoidance actions. Each laser communication test session was about one hour long as LRO emerged from behind the moon and traveled from pole to pole. A total of 15-22 code blocks (740 to 980 kbits) could be transmitted in each test session.

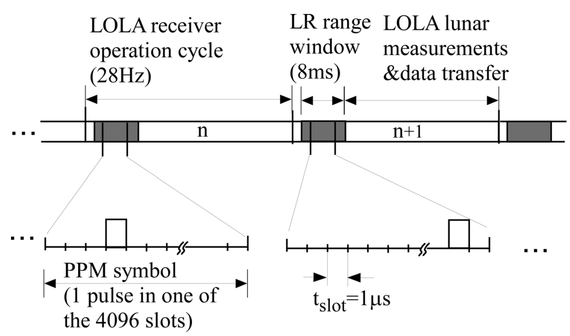

Fig. 1. LRO LR laser pulse position modulation. The approach allows simultaneous laser ranging and data transmission. Each laser pulse is delayed to one of the 4096 time slots (12 bits) within the 8-ms LR range window. At the 28-Hz LOLA laser pulse rate, the raw data transmission rate is 336 bits s^{-1}, mainly limited by the LRO LR operating duty cycle.

The PPM symbol sequences were generated with the use of a digital pattern generator driven by the PPM slot clock and triggered by the PPM symbol clock. A 31-symbol time synchronization patterns were inserted in between code blocks. Reed Solomon encoding and decoding were carried out using the built-in functions from MATLAB Communication Toolbox.

2.4 Time prediction and synchronization

The LRO clock oscillator frequency and the drift rate of MET were estimated from the long-term trend of the one-way LRO LR range measurements. The LR range window time, which is synchronized with LRO MET, could be predicted to well within 1 ms with respect to UTC. The light travel time from NGSLR to LRO varied by up to 6 ms during a one-hour LR session

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as the spacecraft traveled from pole to pole of the moon. The light time for each shot had to be pre-compensated by adjusting the delay of the pattern generator output so the PPM laser pulse could arrive in the LR range window. Both the PPM slot time and symbol clocks were generated from a GPS based clock source. The time drift between the GPS clock and the LRO MET was 10's μs over a one-hour LR session. The residual errors of the spacecraft orbit prediction also caused a baseline time drift for the PPM signal. These time drifts were estimated from the times of the synchronization patterns and removed during PPM signal processing.

The time tags of the received laser pulses at LRO were sent back to Earth for the routine one-way LR measurements. For the laser communication experiments, the received laser pulse time tags were first divided into 28-Hz PPM symbols by modulo division of the nominal laser pulse time interval $(28\ \text{Hz})^{-1}$. The time synchronization patterns were located and the residual time bias was estimated. The resultant timing jitter was found to be 300 ns peak to peak, which was much smaller than the 1-μs PPM slot time. The PPM symbols were reconstructed by subtracting the time bias from the pulse arrival times and rounding these times to the nearest integer number of PPM slot times. Missed detections, or erasures, were filled in with a zero and a file of erasure flags was generated. The data was then divided into code blocks for the Reed Solomon decoder.

3. Results

We first transmitted random PPM symbols with Reed-Solomon code at Rate $7/8, 3/4$ and $1/2$, respectively. The tests were repeated a number of times over a four-month period. The transmitted laser pulse energy was constant during these tests while the weather conditions at NGSLR naturally attenuated the signals to allow us to assess the PPM symbol error rate (SER) vs. the average received signal pulse energies. The results are shown in Fig. 2. As expected, the Reed-Solomon codes completely restored the data when the error rate was less than the number of parity check symbols. It was difficult to quantify the coding gain, which is defined as the reduction in average signal pulse energy to achieve a given low error rate (e.g. SER $<10^{-6}$), because the raw data SER were at best 10% due to the atmosphere effects.

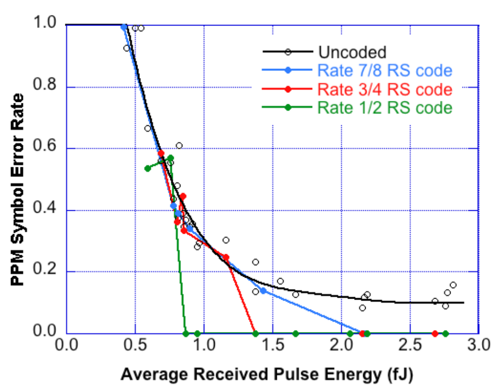

Fig. 2. Data transmission error. Plotted in terms of PPM symbol error rate vs. average received laser pulse energy with and without Reed-Solomon coding for data collected from November 2011 to March 2012. The transmitted data consisted of pseudo random numbers uniformly distributed over the 4096 PPM slots. The symbol error rate for the raw data leveled at ~10% even at strong input signal level due to signal fading by the atmosphere turbulence and laser beam pointing jitter. Reed-Solomon coding was effective in bring the error rate to zero when the raw error rate fell below the maximum correctable of the code.

A normalized histogram of the received pulse energy is shown in Fig. 3 with the data collected during the LR session on 4 November 2011, 17:57 local time, under clear sky

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conditions. A log-normal probability distribution function was fitted to these data using a least mean square method. A sample autocovariance function was also calculated for the same set of data and the results are plotted in Fig. 4. There was no apparent correlation in the atmosphere effects from one laser shot to the next at ~36-ms interval. The weak correlation up to 20 sec was possibly due to telescope pointing errors and gaps in the data from airplane avoidances. This confirmed that communication channel could be considered as memoryless.

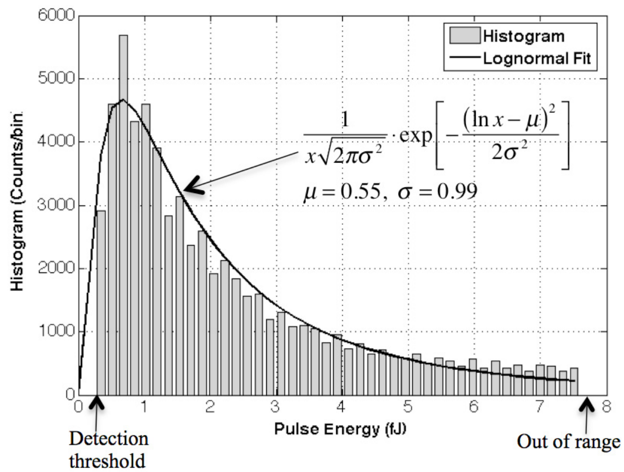

Fig. 3. Histogram of received pulse energy. Data from LRO LR session on 4 November 2011, 17:57 local time with a 73% sun-illuminated Moon at 70° above the horizon. The local weather conditions were temperature 11-13°C, wind speed 1-3 m/s SE, relative humidity 45%, pressure 1012 mbar, and the visibility 50 km, as indicated by the precipitation sensor next to the ground station.

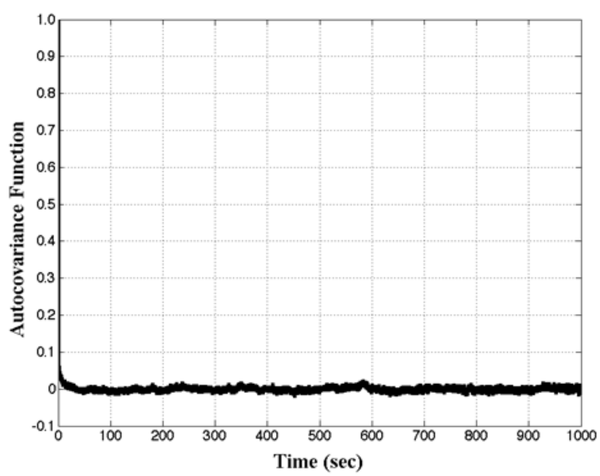

Fig. 4. Sample autocovariance of received pulse energy. Data from LRO LR session on 4 November 2011, 17:57 local time, same as in Fig. 3. The weak correlation up to 20 sec was possibly due to telescope pointing errors and gaps in the data from airplane avoidances.

Finally, we transmitted a gray-scale image of the Mona Lisa to LRO. The image was first cropped to 152x200 pixels and then normalized to 4095 (12 bits) gray-scale. Each pixel was coded into a PPM symbol and transmitted to LRO with a single laser pulse. Each image took about 30 minutes to transmit. Figure 5 shows the raw and corrected image transmitted on 26

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March 2012, 15:38 UTC with a Rate 2/3 Reed Solomon code. The transmission errors appeared randomly distributed with 15% erasures (white pixels) and 0.2% false detections (black pixels). The long strip of white pixels was from a signal outage for an airplane avoidance action. The Reed-Solomon code was able to completely restore the original image.

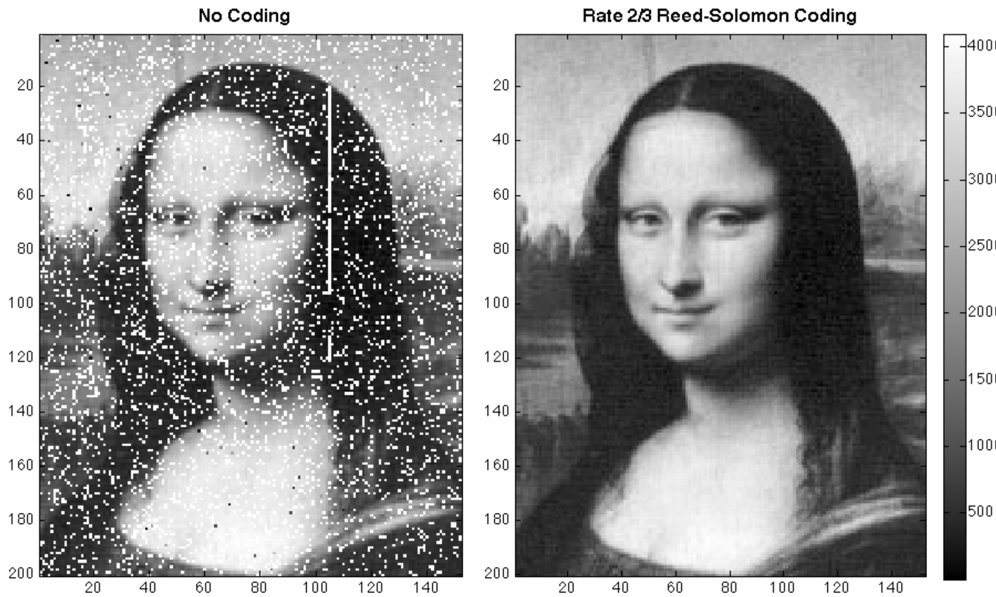

Fig. 5. Mona Lisa images received by LRO without and with Reed Solomon coding. Data obtained on 26 March 2012, during the LR session starting at 11:38 local time. The image consisted of a 200×152-pixel 12-bit (4096) gray scale intensity map and each pixel was transmitted with one laser pulse in 4096-ary PPM signal format. The image on the left was constructed from the raw data without coding. The black dots represented false triggers and the white spaces represent misses (erasures). The white streak across Mona's left ear was caused by the blockage of the laser beam for airplane avoidance. The PPM symbol error rate of the raw data was about 15%, mostly in the form of erasures. The image on the right was constructed from data with Rate 2/3 Reed-Solomon linear block error correction coding.

4. Conclusions

We have successfully demonstrated simultaneous laser ranging and communication from an Earth station to LRO in lunar orbit with 4096-ary PPM modulation and Reed Solomon coding at about 300 bits/s. Signal fading due to atmosphere effects and laser pointing jitter was directly measured and appeared to follow the commonly assumed log-normal distribution. Reed Solomon error correction coding was shown to be very effective in correcting erasure dominated transmission errors.

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