NGSLR Performance in High and Low Energy Operation

Peter Dunn (1)**, Christopher Clarke** (2)**, Mark Torrence** (3)

(1) Raytheon Information Solutions
(2) Honeywell Technology Solutions Incorporated
(3) SGT Incorporated

peter.j.dunn@raytheon.com

Abstract

The Next Generation Satellite Laser Ranging System (NGSLR) has been designed to track targets at lunar distance as well as Earth-orbiting retroreflector-equipped satellites. NGSLR's eye-safe, single photon, high frequency observations of the closer targets exhibit characteristics of system and satellite signature which must be considered in an effective orbit determination in combination with data collected by other observatories in the global SLR network. To help isolate these features, observations taken by the instrument as the receiver in a two-station configuration with MOBLAS-7 at Goddard Geophysical and Astronomical Observatory (GGAO) have been used to calibrate the NGSLR event timer and processor.
High energy returns from available Earth orbiting satellites have now been used to calibrate the longer-pulse transmit system built into NGSLR to support the up-coming Lunar Reconnaissance Orbiter (LRO) Mission. Special efforts by stations in the tracking network will provide the timing required to construct the lunar observations from signals received at LRO. We will show the results of a continuing analysis of the accuracy and precision of each of the two NGSLR systems observing returns from geodetic satellites ranging in altitude from Larets to Etalon.

Introduction

NGSLR is a single photon multi-kilohertz eye-safe satellite laser ranging system (McGarry 2006).The instrument has conducted operations in several tracking modes, performing two-way ranging to ground targets and satellites, as well as three-way ranging to satellites in its low energy mode. In preparation for one-way ranging to LRO, it has operated in high energy mode and ranged to both ground targets and low and high earth satellites. This paper describes the analysis of the ranging observations to characterize the system and to calibrate it's operation when transmitting at both high and low energy.

Data Analysis for the low energy NGSLR 2 kHz system

The eye-safe laser (~100 micro-Joules at 2 kHz) has tracked targets ranging in altitude from Low Earth Orbiting (LEO) satellites to LAGEOS, and has successfully ranged to GLONASS-95 and GLONASS-l02. A tight laser divergence (4 arc-sec) is used and LEOs are often tracked at below 15 degrees elevation requiring no bias correction.

During the analysis period, a technique described by Degnan et al. (2008) and designed to accommodate the lack of overlap between the transmit and receive beams in the system, was implemented. In this method, the telescope is pointed behind, in the direction of the returning light from the satellite, and Risley Prism wedges are independently controlled to point the

laser ahead to anticipate the arrival of the laser pulse at the target.

NGSLR uses a Q-Peak laser with an output energy of about 50 micro-Joules per pulse at the telescope aperture in a 37 cm diameter beam. The current laser pulse width is about 300 picoseconds and the system generally receives multi-photon returns from the LEO satellites. The receiver system is a high quantum efficiency (32%) Hamamatsu four quadrant detector with a threshold discriminator nominally set to < 0.5 photoelectrons on each quadrant.

The low energy instrument has conducted satellite measurements in two tracking modes. Two-way, single station returns have been received from satellites up to LAGEOS altitude with a conventional SLR configuration using the 2 kHz laser transmitter. These measurements show the characteristics of the target satellite in the single photon regime, and RMS noise levels are limited to a minimum of about 30 mm by the convolution of the transmitter pulse width and the receiver impulse response.

The instrument has also taken measurements as the receiver in a two station (3-way) configuration with MOBLAS-7, a nearby high energy system. This configuration can be used for receiver testing; the higher power of the 4 or 5 Hz transmitting laser allows easier detection of returns from satellites at GPS and ETALON altitudes. The tighter transmitted pulse yields measurements with an RMS noise level closer to 20 mm. When the receiver stop time of the transmitter is considered as well as the transmit time, the 10 mm RMS noise level of the high energy transmitter can be matched, demonstrating the integrity of the eye-safe system's event timer and processor.

The increased number of returns per second from the NGSLR system produces normal points comparable in precision to the higher energy transmitter system and allows the station to autonomously close the tracking loop. Data taken at kilohertz resolution can also be used improve the definition of signals in the returns from satellites which have a strong satellite signature.

Sharing returns from a high energy transmitter

NGSLR receiver performance was calibrated using MOBLAS-7 which transmits shorter multi-photon pulses, with cables connecting the systems. For the case in which MOBLAS-7's own two-way measurements were monitored, the NGSLR Event Timer was triggered on the transmitting systems start and stop pulses. The RMS noise levels of returns detected by NGSLR amounted to 8 mm for ERS-2, 10 mm for Starlette and LAGEOS, and 15 mm for Ajisai.

These levels were consistent with those expected from MOBLAS-7's own system and confirmed the integrity of NGSLR's timing and software. In 3-way configuration, MOBLAS-7 fires and NGSLR only receives, and its threshold discriminator gave a higher detection noise level than MOBLAS-7. In this case the RMS noise levels were found to be 21 mm for ERS-2, 26 mm for Starlette, 21 mm for LAGEOS and 35 mm for Ajisai.

In the conventional 2-way configuration, NGSLR transmits longer pulses than MOBLAS-7, and the RMS noise levels were 30 mm for ERS-2 and Starlette, 35 mm for LAGEOS and 42 mm for Ajisai. The characteristics of a 72 degree elevation Ajisai pass are shown in the Figure 1, which also gives the contribution to the tracking signal from each of the four receiver quadrants. Evidence of both satellite and system signature can be seen in the full-rate

observations, and the normal points, shown in yellow and computed according to ILRS standards, demonstrate precision at the millimeter level.
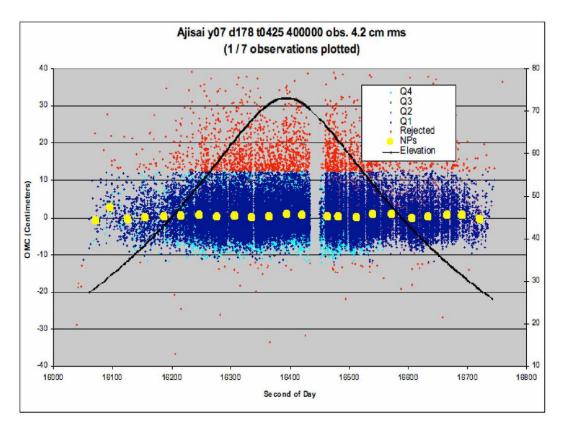

Figure 1. Normal point data compression residuals for an Ajisai pass from NGSLR/2K

In the first three quarters of this year NGSLR has tracked nearly 100 passes, including AJISAI, BEC, JASON, JASON-2, LARETS, STARLETTE, LAGEOS 1 and 2, and GLONASS-102 (McGarry et al., 2008a). Many of these passes were tracked simultaneously with MOBLAS-7, allowing for a calibration of system accuracy.

The following table lists the details of those co-located passes and includes the number of normal points, the RMS of those normal points and statistics associated with the overlap with the data from MOBLAS-7. The mean pass bias between the two systems is seen to be -9.5 mm +/- 4.5 mm for 27 passes of BE-C, Starlette, LAGEOS-1, Ajisai, Jason, Larets, LAGEOS-2, ERS-2 and Envisat. The receiver system was found to exhibit a dependence on the return signal strength which was monitored from ground target calibrations as a function of return rate.

When this system signature was accommodated in the NGSLR data processing, the mean pass bias between the two systems was reduced to 2.5 +/-3.5 mm. Otsubo and Appleby (2003) show that the Ajisai satellite exhibits a large bias of 20 to 30 mm when data from systems receiving low energy returns are compared with those from high energy instruments. When this satellite signature is accounted for, the mean pass bias between the two systems is reduced to -1.1 +/- 3.3 mm. Inter-comparison tracks thus confirm average agreement of a few millimeters between NGSLR and MOBLAS-7 for a number of LEO satellites and LAGEOS.

Satellite	DOY	Accepted Obs.	RMS(mm)	NPTs	NPT RMS (mm)	Mean Pass Bias (mm)	NPT over lap	Peak to Peak (mm)	Mean Pass Bias (mm)	Bias with system function (mm)	Bias with system/ satellite function
BEC	220	63161	35.9	30	1.1	-20.2	7	17	-20.2	4.8	4.8
Starlette	164	7716	32	20	1.8	4.3	19	15.8	4.3	29.3	29.3
Starlette	165	4946	33.1	8	1.6	-56.1	6	28	-56.1	-31.1	-31.1
Starlette	177	70201	31	24	1	-25.4	4	18.1	-25.4	-0.4	-0.4
Starlette	178	93276	32	19	0.6	-33.1	18	42.7	-33.1	-8.1	-8.1
Starlette	234	133693	28.8	17	1	-4.2	10	26.5	-4.2	20.8	20.8
Lageos-1	234	134	40.1	4	5.9	23.2	3	2.3	23.2	-1.8	-1.8
Lageos	247	3959	43.9	23	4.7	45.1	5	15.5	45.1	20.1	20.1
Ajisai	165	601211	43.7	28	0.5	-16.2	4	14.4	-16.2	8.8	-16.2
Ajisai	178	32431	44.4	24	2.7	1.4	17	32.8	1.4	26.4	1.4
Ajisai	193	413332	46.7	28	0.8	4	3	11.3	4	29	4
Ajisai	268	202346	47.5	30	1.1	-18.9	30	53.8	-18.9	6.1	-18.9
Jason	177	24033	30.4	42	2.6	-12.9	21	29.7	-12.9	12.1	12.1
Larets	184	16393	33.9	13	3.2	-48.6	7	51.6	-48.6	-23.6	-23.6
Larets	234	33972	25.3	10	1.1	-24.2	2	20.2	-24.2	0.8	0.8
Larets	268	89535	36.3	16	1.5	-15.4	9	32.3	-15.4	9.6	9.6
Lageos-2	164	4846	32.1	15	2.3	9.6	3	11.7	9.6	-15.4	-15.4
Lageos-2	165	15580	34	18	1.9	22.4	9	20.1	22.4	-2.6	-2.6
Lageos-2	177	2061	49.6	15	3.8	-9.9	14	18.5	-9.9	-34.9	-34.9
Lageos-2	178	1666	47.2	17	5.3	23.5	12	23.8	23.5	-1.5	-1.5
Lageos-2	193	5648	36.8	17	2.5	5.4	12	15	5.4	-19.6	-19.6
ERS-2	177	71341	32.7	24	1.9	-28.4	1	0	-28.4	-3.4	-3.4
ERS-2	184	29398	43.5	17	2.6	-38.9	5	20.8	-38.9	-13.9	-13.9
Envisat	212	8202	30.5	14	2.1	-21.4	5	45.6	-21.4	3.6	3.6
Envisat	226	983	31.5	10	3.8	-31.4	7	15.1	-31.4	-6.4	-6.4
Envisat	234	1458	29.2	14	3.9	8	6	10.3	8	33	33
Envisat	247	2537	33	12	3.9	1.4	3	2.5	1.4	26.4	26.4
									Mean	-9.5	2.5	-1.1
									Std Err.	4.5	3.5	3.3
									Std Dev	23.6	18.5	17.5
									Count	27	27	27

Figure 2. Statistics of passes tracked simultaneously with NGSLR and MOBLAS-7

Data Analysis for the NGSLR/LR system

The NGSLR system can switch from eye-safe laser ranging to high energy transmitting, in order to perform uplink-only ranging to the Lunar Reconnaissance Orbiter (LRO-LR). In this application the laser fire must be controlled to ensure that the pulses arrive at the spacecraft when the Range Window is open. Ground laser fire times are recorded and transmitted to a central facility where they are matched with the spacecraft events to form ranges (McGarry et al., 2008b).

226

Laser ranging to LRO employs a 28 Hz 30 mJ laser with a wavelength of 532.2 nm, which is matched to the center of the spacecraft's 3 Angstrom LR bandpass filter, and with a pulse width of 5.5 nanoseconds. In this mode, the width of the range gate generator output pulse is modulated to provide an approximately 28 Hz frequency to the laser.

In the first three quarters of this year NGSLR/LR has tracked 26 passes of satellites ranging in altitude from Low Earth Orbit targets to ETALON. Three of these passes were tracked simultaneously with MOBLAS-7, and showed an average difference between the two systems of -11 cm. This level of accuracy will allow the system to improve the orbital knowledge of LRO to support lunar gravity model development.

Satellite	SIC	DOY	Start Time	Accepted Obs.	RMS(mm)	NPTs	Obs/NPT	Skew	Kurtosis	NPT RMS (mm)	Mean Pass Bias (mm)	Overlapping NPTs	Peak to Peak (mm)
Larets	5557	5	2:31	2214	279.5	10	221	0.3	2.62				
Ajisai	1500	5	3:17	5542	266.8	15	369	0.34	2.76				
Etalon-1	525	5	3:30	276	322.3	6	46	0.12	3.07				
Starlette	1134	5	4:26	4141	240.6	7	591	0.29	2.82				
BEC	317	21	1:30	5170	282.3	27	191	0.38	2.9				
Etalon-1	525	21	1:44	18	316.2	7	2	0.08	4.4				
Ajisai	1500	21	2:59	5388	247.2	21	256	0.25	2.9				
Jason	4378	73	2:02	2109	310.5	17	124	0.43	2.84	37.5			
ERS-2	6178	73	2:54	8701	274.3	27	322	0.31	2.8	18.1			
Jason	4378	74	0:26	27011	296.1	46	587	0.43	2.91	16.4			
Lageos-2	5986	81	3:14	200	357.1	9	22	0.22	2.76	71.8			
Starlette	1134	107	1:38	10459	310.6	10	1045	0.24	2.89	10.5			
Lageos-2	5986	107	1:45	25601	294.1	8	3200	0.42	2.83	14.8			
ERS-2	6178	116	2:06	2093	287.6	17	123	0.31	2.97	30			
Larets	5557	116	3:02	4334	297.6	9	481	0.29	2.8	23.6			
Etalon-2	4146	170	0:39	299	477.4	10	29	0.12	2.5	77.5			
Envisat	6179	170	1:36	2019	341.4	22	91	0.51	2.89	38.8			
Ajisai	1500	170	1:57	23941	266.8	30	798	0.51	3.01	10.1			
Lageos-2	5986	170	3:00	12739	306.6	29	439	0.37	2.84	19.5			
Larets	5557	207	2:29	1217	288.1	9	135	0.27	2.88	26.4	-65.5	5	245.4
BEC	317	207	3:15	34684	241.9	44	788	0.17	2.87	8.5	-165.1	34	385.6
Etalon-2	525	207	3:22	3179	237.9	1	3179	0.11	2.71	3.6			
ERS-2	6178	207	2:42	9738	259.3	24	405	0.31	2.82	16.5	-97.4	19	385.1
Lageos-1	1155	207	3:48	1688	303.3	17	99	0.41	2.76	33.8			
Lageos	1155	248	0:53	294	256.1	8	36	0.39	2.82	44.8			
Envisat	6179	248	2:24	3184	240.6	11	289	0.28	2.83	21.2			

Figure 3. Statistics of passes tracked by NGSLR/LR

References

Degnan, J., McGarry, J., Zagwodzki, T., Varghese, T., *Transmitter Point-Ahead using Dual Risley Prisms: Theory and Experiment,* in this Proceedings, 16th International Workshop on Laser Ranging, Poznań, Poland, October 2008.

McGarry, J., Zagwodzki., T., *SLR2000: The Path Toward Completion,* Proceedings of the 15th International Workshop on Laser Ranging, Canberra, Australia, October 2006.

McGarry, J., Zagwodzki, T.,Varghese, T., Degnan, J., et al, *NGSLR: Sharing Eyesafe Kilohertz SLR with Transponder Ranging,* in this Proceedings, 16th International Workshop on Laser Ranging, Poznań, Poland, October 2008a.

McGarry, J., Zellar, R., Neumann, G., Noll, C., Torrence, M., et al, *Laser Ranging to the Lunar Reconnaissance Orbiter: a Global Network Effort,* in this Proceedings, 16th International Workshop on Laser Ranging, Poznań, Poland, October 2008b.

Otsubo, T , Appleby, G., *System-dependent centre-of-mass correction for spherical geodetic satellites,* Journal of Geophysical Research, 108, B4, 2201,10.1029/2002 JB002209,2003.