13-Po30

NGSLR / MOBLAS-7 Collocation Analysis

Julie Horvath[1], C. Bart Clarke[1],
Jan McGarry[2], H. Donovan[1], J. Degnan[3], J. Cheek[3], A. Nelson[1],
D. Patterson[1], A. Mann[1], F. Hall[1], T. Zagwodzki[4]

[1]Honeywell Technology Solutions Inc., Lanham, MD 20706 USA
[2]NASA Goddard Space Flight Center, Greenbelt, MD
[3]SigmaSpace Corp, Greenbelt, MD
[4]Cybioms Corp, Greenbelt, MD

Abstract

After 2 years of intensive engineering development, NASA's Next Generation Satellite Laser Ranging System (NGSLR) was collocated against the NASA Network standard, MOBLAS-7. Collocation, a method of direct comparison testing developed by NASA and Honeywell in the 1980's, is used to identify laser system ranging anomalies by utilizing geometry to isolate station dependent, systematic ranging errors from other external sources of systematic errors. The completed collocation was the final step for the NGSLR system performance and design validation.

During collocation, the NGSLR and MOBLAS-7 systems operated in good weather simultaneously for 12 hours per day / 5 days a week, day and night, from May 29th through July 5th, 2013. The systems tracked a total of 81 simultaneous passes, including 28 simultaneous LAGEOS passes during the collocation. This comparison test was the first NASA Collocation conducted between a single photon system (NGSLR) and a multi-photon (MOBLAS-7) system. Because there are known differences with satellite CoM corrections between single photon and multi-photon detection systems, it was assumed prior to collocation that NGSLR would measure long to MOBLAS-7. We will provide details of the NGSLR / MOBLAS-7 collocation analysis and describe the processing methods used to show NASA's Next Generation SLR performance.

Introduction

NASA's Next Generation Satellite Laser Ranging (NGSLR) system, located at NASA Goddard Space Flight Center, was designed in the mid-1990's, by a team led by Dr. John Degnan, and was originally intended for completely automated, eye-safe SLR operations. As the laser eye-safe ANSI standards changed in the 1990's toward significantly less laser power, and as NASA evolved the NGSLR GNSS tracking requirements to include daylight ranging, it was necessary to modify the NGSLR system design. In 2011, NASA established the Space Geodesy Project (SGP) whose mission included the completion of the NGSLR prototype system.

While much of the original overall design of NGSLR remained the same, several large components that affected daylight ranging to GNSS, system stability, and automated operations capability were redesigned and modified. The entire optical bench was modified to include a higher power, shorter pulsewidth laser (required for daylight GNSS tracking), translation stages for automated configuration changes, and new optics to handle the higher power laser energy. Operational software was modified to account for hardware upgrades to prepare for full automation, including automated SLR and ground calibration features.

Pre-Collocation Readiness

In the spring of 2013, the NASA NGSLR team made final preparations for a NGSLR / MOBLAS-7 collocation that would prove the performance of the prototype system. Collocation is a method of direct comparison testing developed by NASA and Honeywell (formerly Bendix Field Engineering Corp) in the 1980's. Collocation analysis, a purely geodetic technique, is the process of comparing ranging data to the sub-centimeter level from two or more satellites laser ranging systems in close proximity (<600 meters, preferably <60 meters) by quasi-simultaneously ranging to common retro-reflector equipped satellites. [http://ilrs.gsfc.nasa.gov/network/system_performance/co-location_history.html] The collocation test provides a unique opportunity to identify laser ranging problems by utilizing the collocation geometry to isolate station-dependent systematic ranging errors from other major sources of systematic errors including atmosphere, orbit modeling, station location, etc.

The primary objective of this collocation test was to calibrate the ranging performance of the NGSLR system against that of MOBLAS-7 and to establish a documented benchmark of the NGSLR laser ranging capability. This collocation, however, was different than any other collocation performed by NASA, as it directly compared two systems with very different configurations, most significantly a single photon vs. multi-photon configuration. This provided a direct confirmation of the theoretical range differences between the two types of systems.

LAGEOS range bias theory between single photon & multi-photon systems :

John Degnan (1994):	**13 mm** (difference between 0.1 and 5 pe detection)
Fan Jianxing / Yang Fumin (2001):	**10 mm** (difference between 0.1 and 4 pe detection)
Otsubo / Appleby (2003 Koetzting):	**6 to 9 mm** (single photon and multi-photon difference)

Theory and orbital analysis tell us that the single photon system will measure long to the multi-photon system for satellites such as LAGEOS, due to the satellite signature. [Clarke et al. 2013] The figure above shows the expected differences from various theories.

Collocation Requirements

A detailed test plan was written to document requirements for both the pre-collocation subsystem testing and the quantity and quality of the collocation ranging data. Once all pre-collocation requirements were completed, station hardware and software configurations were documented and frozen for the duration of the collocation.

To eliminate potential sources of bias, pre-collocation requirements for subsystem testing include measuring precisely the vector between the systems' origins through survey; comparing the meteorological sensors and timing for each system; and capturing optical bench filter glass measurements and delays for post-processing system delay correction.

In October 2012, SGP personnel performed a survey measuring the NGSLR and MOBLAS-7 station positions, calibration pier ranges and the vector between the two systems. This pre-collocation survey result referenced to ITRF2008 was the set of coordinates that were used in the collocation analysis.

Pre-Collocation Survey Oct / Nov 2012						
Station	**Latitude (d,m,s)**	**Longtitude (d,m,s)**	**Height (m)**	**DN (m)**	**DE (m)**	**DU (m)**
MOBLAS-7	39° 01' 14.17858" N	76° 49' 39.70267" W	19.184	-0.009	-0.032	3.138
NGSLR	39° 01' 12.96987" N	76° 49' 38.81418" W	18.496	-0.081	-2.184	3.695

In April of 2013, the MOBLAS-7 and NGSLR spare MET4 meteorological measurement units were placed side by side for direct comparison. The NGSLR spare had been recently calibrated, and had been verified against the NGSLR operational MET4 unit. The offsets of NGSLR's MET data from MOBLAS-7's are shown here.

MET Data Offsets	
Pressure Mean Offset (mbars)	0.0144
Temperature Mean Offset (C degrees)	0.1350
Humidity Mean Offset (%)	0.2133

All collocation requirements and specifications are listed in the following table:

Requirement	Collocation Specification
Pre / Post-collocation Survey	• A pre and post-collocation survey must be performed
Meteorological (MET) comparison	• NGSLR and MOBLAS-7 MET Sensors will be compared Pre and Post Collocation Differences will be within: • Temperature: +/- 0.5 deg • Pressure: +/- 0.2 mbars • Humidity: +/-10%
Timing System Comparison	• The time offset between the NGSLR and MOBLAS-7 systems will be determined with an accuracy of +/- 1.0 microseconds
Collocation Pass and Normal Point Acceptance	• Pass must contain at least 2 valid collocated normal points • NGSLR Normal Pts - Must have 50 fullrate observations in normal point bin • MOBLAS-7 Normal Points: Must contain at least 25 fullrate observations (This may be reduced if there are valid, but weaker returns throughout the pass)
Simultaneous Ground Calibration Testing *(quantity, quality, range difference, stability)*	• 1 Daylight and 1 Nighttime MINICO and Stability • Stability should be within +/-2.5 mm • System Delays for all 3 targets will be within +/-2.5 mm
Simultaneous Satellite Tracking *(quantity, quality, range difference, dependencies)*	• Mean range difference between 2 systems should be within 1cm of theory • Pass quality criteria for both stations must conform to the ILRS standard RMS • ~30 LAGEOS, 20 LEO, and 5 HEO valid simultaneous Passes • Data should show no unexpected dependencies
Collocation Duration	• At least 1 month or until all SLR data quantity requirements have been met
System Configuration Freeze	• System hardware and software configurations will be frozen during the entire collocation period

Collocation

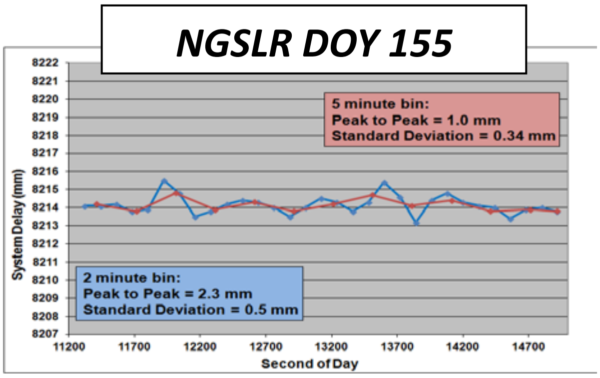
On May 28, 2013, the NGSLR and MOBLAS-7 station hardware and software were frozen and the NGSLR / MOBLAS-7 collocation test began on May 29, 2013. It was expected to take approximately one month to obtain the required 30 valid simultaneous LAGEOS passes. The MOBLAS-7 team put all other station priorities on hold to ensure a successful NGSLR test and the systems operated simultaneously in good weather for 12 hours / day, 5 days a week until all data quantity requirements were fulfilled. The LAGEOS satellites were moved to the top priority on the system schedules, and full passes were tracked while above 20 degrees from horizon. On July 5, 2013 the collocation was completed after the final simultaneous LAGEOS pass was achieved.

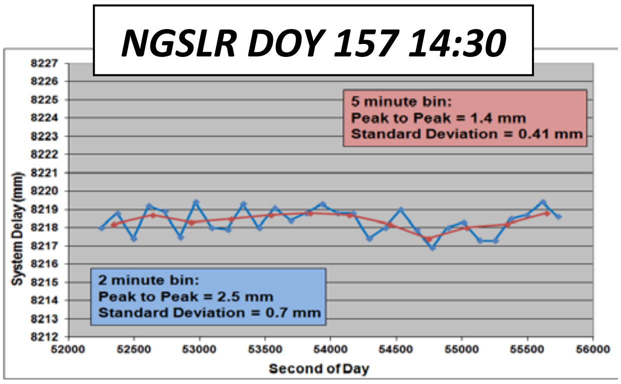
The NGSLR collocation data was originally post-processed with a 1.8*sigma filter to use the peak of the data distribution. After collocation analysis revealed that this sigma editing filter caused a bias in the data, the data was then processed with a 3*sigma edit [Clarke et al. 2013] for a very close representation of the centroid of the data. Because of the large amount of noise inherent in the NGSLR single photon detection, some of the weaker passes (which are viable with a 1.8*sigma edit) were no longer viable. Therefore, 30 valid simultaneous LAGEOS passes were not fully achieved, however, a good data collocation dataset was acquired, and data quantity was deemed satisfactory for collocation analysis.

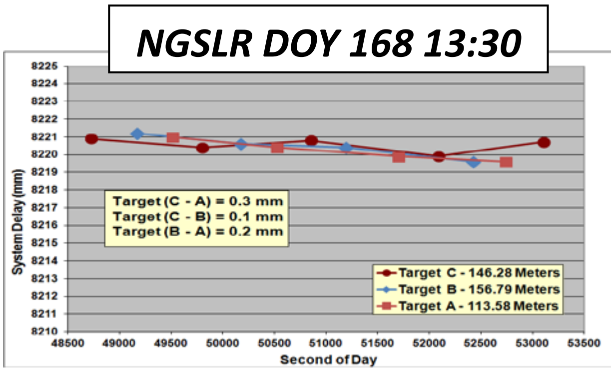
Collocation Analysis

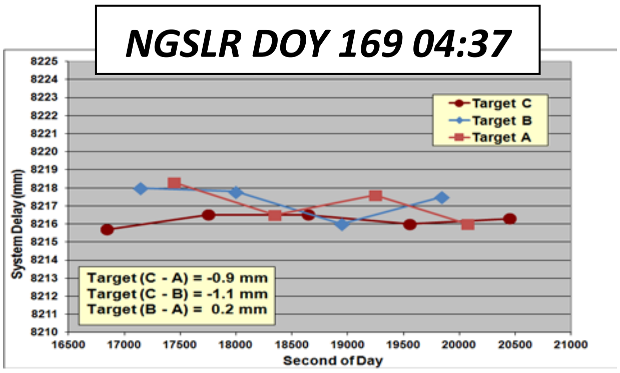
Ground Test Analysis: The NGSLR system was directly compared to MOBLAS-7, examined for stability and precision, and scrutinized for any anomalies. Ground Tests (stability and MINICO tests) are essential to detect any temporal variations, as well as test for angular or range dependent biases in the system. The following charts show NGSLR's very good stability, and that no angular or range biases were detected.

Ground Test	Stability Test Results	MINICO Test Results
NGSLR	+/- 1.5mm (standard deviation <= 0.7mm)	+/- 1.0 mm (all 3 Targets)
MOBLAS-7	Typically within +/- 2.5 mm	+/- 1.0 mm (2 Targets), 1 Target 2mm short





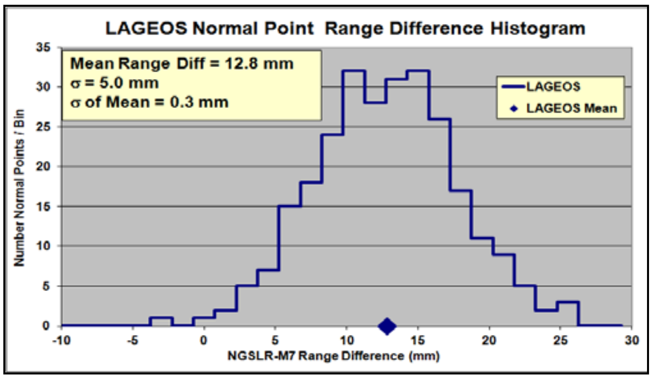




Satellite Data Analysis: Satellite data is analyzed using POLYQUICK software [ilrs.gsfc.nasa.gov/network /system_performance/polyquick .html] which directly compares all simultaneous normal point data. The satellite data is used to detect biases between the two systems.

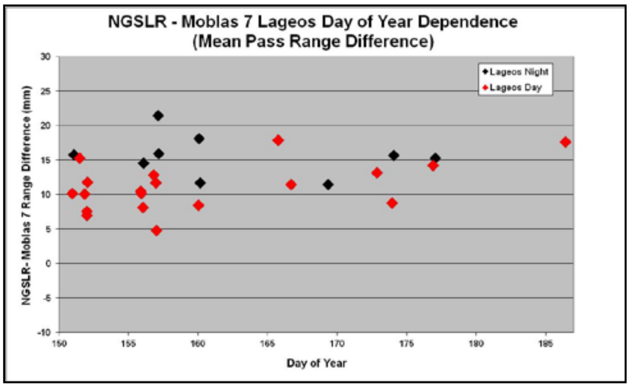
Bias Tests Performed During Collocation	
Range-Dependent Range Bias	Range-Rate Dependent Bias
Elevation Dependent Range Bias	Azimuth Dependent Range Bias
Energy Dependent Range Bias	Test for Long Term Mean Range Bias Stability
Test for Diurnal Effects	System Delay Range Bias
Sky Coverage	

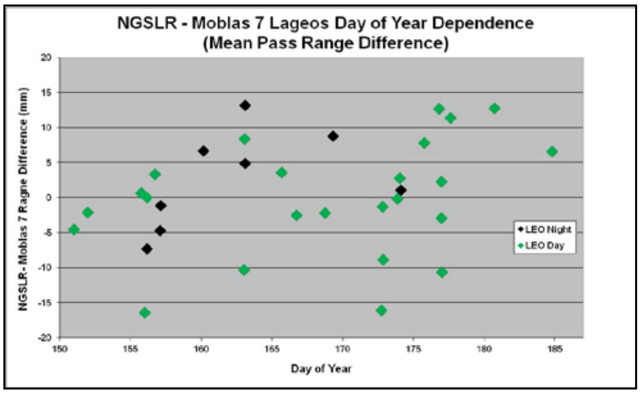
POLYQUICK analysis was conducted for all satellites except for BEC and Ajisai due to their retroreflector configurations. No significant or unexplained dependencies were found during analysis. The following plots are examples from the analysis performed during the collocation.



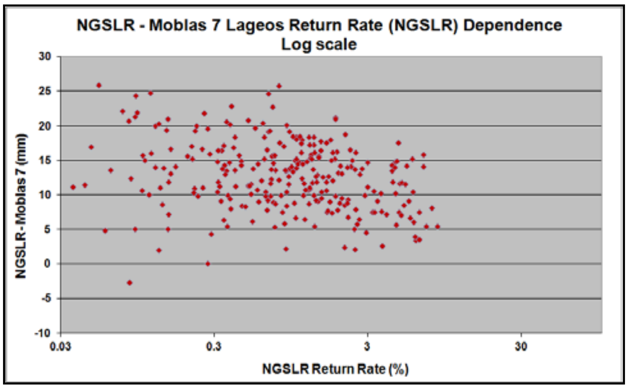
This histogram shows a symmetric distribution of the NGSLR / MOBLAS-7 collocated LAGEOS normal point range differences. The distribution of the normal point differences is consistent with previous MOBLAS-7 collocations with other systems, and the mean range difference of 12. 8 mm is in agreement with theoretical values.

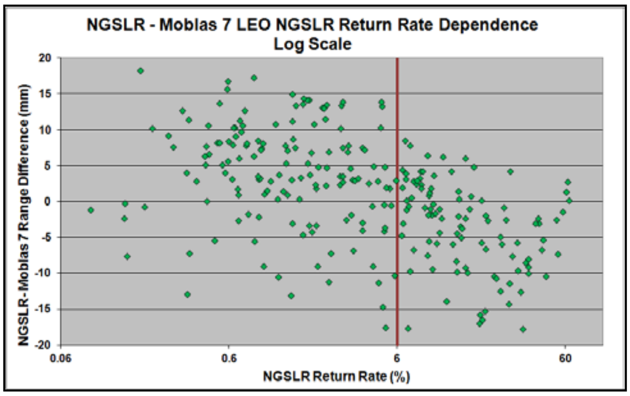
The following charts represent all of the pass mean range differences throughout the collocation period for both LAGEOS and LEO satellites. This analysis can show potential dependencies that occur over time. The collocation dataset showed no time dependence bias, however the LAGEOS chart does show a difference in day and night passes. This difference only occurs for a small number of passes at the beginning of the collocation, and is not evident in the LEO passes. After day 160, the night pass range differences agree with the daytime passes. The collocation team continued to investigate this issue after the collocation was completed, and found that there were no longer differences between the day and night passes. The early day/night difference is now considered a non-problem.





The following charts, showing normal point range differences, are designed to find potential dependencies in satellite return rate. The NGSLR Return Rate (log scale) LAGEOS dependency plot displays no significant trends. The LEO range differences are biased at higher return rates as expected when comparing single and multi-photon returns. The mean range difference at lower





return rates (< 6%) is 4.0 mm, while at higher return rates (>6%) is -3.4 mm. The higher signal strength is producing multi-photon returns causing the single photon detector to bias the data short.

Future NGSLR operations will automatically control the signal strength using divergence to limit the number of multi-photon returns.

In summary, collocation analysis showed no NGSLR range bias dependencies with two exceptions. These two sub-centimeter trends were identified, but proved to be non-problems:

1. The bias difference between lower (<6%) and higher (>6%) return rates was about 7.5 mm.
   - Effect is due to the difference in single photon returns and multiple photon returns
   - Future modifications to NGSLR for automated control of higher return rates are planned
2. Day/Night LAGEOS bias of about 5 mm (daytime data shorter than the night time data)
   - The nighttime LAGEOS data occurs all in a very concentrated timeframe at the very beginning of the collocation period. After the first few days of collocation tracking, the day and night range differences agreed and mean pass range differences were more stable.

Collocation Results

The NGSLR / MOBLAS-7 mean bias for LAGEOS and the LEO satellites were well within 1 cm of the expected biases between single photon and multi-photon systems, and all results are shown in this chart. The mean bias for the LAGEOS passes was about 12.8 mm. The theory indicates it should be between 6 and 13 mm. The mean bias for all LEO satellites combined was between 0.5 and 1 mm, but approximately 4 mm when all returns were single photon. This was expected due to the small satellite signature of the LEO satellites.

Satellite Type	Collocated passes	Simultaneous Normal Points	NGSLR - MOBLAS7 Mean (mm)	
			Normal Point Range Difference	Pass Range Difference
LEO	31	246	0.97	0.52
LAGEOS-1/2	28	270	12.81	12.89
GNSS	5	18	15.32	15.44

Conclusions:

The NGSLR / MOBLAS-7 collocation was a highly successful verification of the performance of the NGSLR system. The NGSLR showed good system stability, no unexplained range bias dependencies, and range differences with MOBLAS-7 were within ~4 mm of the expected single photon and multi-photon theoretical values. The final comparison results proved that the NGSLR system is a viable SLR system that meets the next generation SLR standards.

References:

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- Fan J. et al. 2001. “Theoretical analysis and numerical solution of laser pulse transformation for satellite laser ranging”, Science in China (A), Vol. 44, No.7, July.

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- Clarke C., and J. Degnan. 2013. “Processing Single Photon Data For Maximum Accuracy”. 18th International Laser Ranging Workshop, Mt. Fuji, Japan. November 2013.