NGSLR / MOBLAS-7 Collocation Analysis

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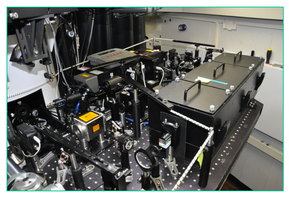
Poster - 13Po30

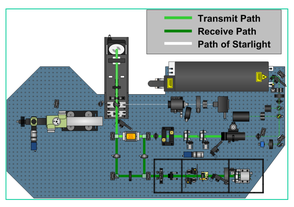
Abstract: After 2 years of intensive engineering development, NASA's Next Generation Satellite Laser Ranging System (NGSLR) was collocated against the NASA Network standard, MOBLAS-7. Collocation, a method of direct comparison testing developed by NASA and Honeywell in the 1980's, is used to identify 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.

NGSLR: NASA's Next Generation Satellite Laser Ranging (NGSLR) system, located at NASA Goddard Space Flight Center, was designed in the mid-1990's by Dr. John Degnan, and was originally intended for completely automated eye-safe SLR operations. As the eye-safe ANSI standards changed to a requirement for significantly less laser power in the late 90's, and as NASA evolved the NGSLR GNSS tracking requirements for daylight, it was necessary to modify the NGSLR system design. In 2011, NASA developed the Space Geodesy Project (SGP) that ensured the completion of the NGSLR prototype system.

While much of the original NGSLR design remained the same, several large components that affected the automated operations capability were redesigned and modified. The entire optical bench was modified, a new higher power, shorter pulsewidth laser was chosen, and operations software was modified for future automation (Further information can be found in H. Donovan's presentation "UPGRADE OF THE NGSLR OPTICAL BENCH AND RESULTING PERFORMANCE IMPROVEMENTS").





Pre-Collocation Readiness: In April and May 2013, the NASA NGSLR team made final preparations for a NGSLR / MOBLAS-7 collocation that would prove the performance of the NASA's NGSLR 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" (ILRS web page). Orbital analysis is used as an independent collocation verification, and is the long standing determination for a system with no bias.

NASA and Honeywell have had a long history of performing collocations, and in fact, each NASA system has been collocated (usually against the NASA standard, MOBLAS-7) to verify the system performance prior to deployment and approval for operational status. This collocation, however, is different in that it directly compares two systems with very different configurations, most significantly a single photon vs. multi-photon configuration. Theory and 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. The satellite Center of Mass correction should be different for the different 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)

See J.McGarry's presentation "THE COLLOCATION OF NGSLR WITH MOBLAS-7 AND THE FUTURE OF NASA SATELLITE LASER RANGING"

Collocation Requirements: A detailed collocation test plan was written to document collocation requirements.

Requirement	Collocation Specification
Pre / Post-collocation Survey	• A pre and post-collocation survey must be performed • DX, DY and DZ components between the two stations must be known with an accuracy of 1mm in each component
Meteorological (MET) comparison	NGSLR and MOBLAS-7 MET Sensors must 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, bias, 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 +/-2.5mm
Simultaneous Satellite Tracking (quantity, quality, bias, dependencies)	• Mean bias 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 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

COORDINATES – ITRF2008 (epoch 2005)

Station	Latitude (d,m,s)	Longitude (d,m,s)	Height (m)
MOBLAS-7	39° 01' 14.17858" N	76° 49' 39.70267" W	19.184
NGSLR	39° 01' 12.96987" N	76° 49 38.81418" W	18.496

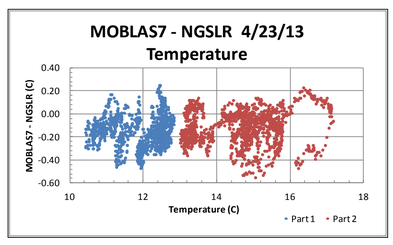
MOBLAS-7 Eccentricities

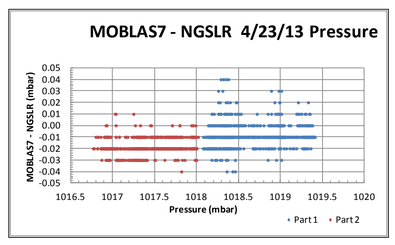
DN (m) -00.009	DE (m) -00.032	DU (m) +03.138

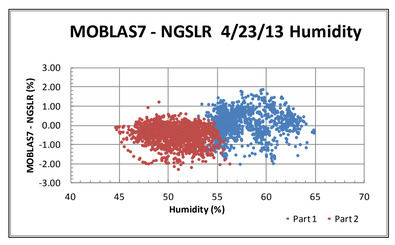
NGSLR Eccentricities

DN (m) -00.081	DE (m) -02.814	DU (m) +03.695

NGSLR / MOBLAS-7 Pre-Collocation Survey Results







NGSLR – MOBLAS-7 MET Sensor Comparison Results – All data within collocation specifications

Collocation: On May 28th, 2013, after all pre-collocation requirements were completed, the NGSLR and MOBLAS-7 station hardware and software were frozen for any configuration change during collocation testing. The NGSLR / MOBLAS-7 collocation test began on May 29th, 2013. The collocation was expected to take approximately 1 month due to the 30 valid simultaneous LAGEOS pass requirement. The MOBLAS-7 team and crew put all other station priorities on hold to make sure that the NGSLR test was successful. The systems operated simultaneously in good weather for 12 hours / day, 5 days a week until all data quantity requirements were fulfilled. The LAGEOS-1/-2 satellites were moved to the top priority on the system schedules, and full passes were tracked while above 20 degrees from horizon. On July 5th, 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 edit 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 (See Clarke/Degnan's presentation, "PROCESSING SINGLE PHOTON DATA FOR MAXIMUM ACCURACY") for a very close representation of the centroid of the data. Because of the large amount of noise, some of the weaker passes (which are viable with a 1.8*sigma edit) are no longer viable. Therefore, we did not fully achieve 30 valid simultaneous LAGEOS passes, however, a good data collocation dataset was achieved, and data quantity was deemed satisfactory for collocation analysis.

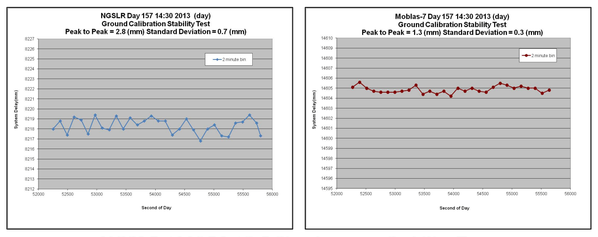
NGSLR and MOBLAS-7

NGSLR Collocation Dataset	
	# of Passes
All NGSLR Passes	**121**
LAGEOS-1/2	35
GNSS	16
LEO	34
Collocated LAGEOS	**28**
Collocated GNSS	**5**
Collocated LEO	**31**

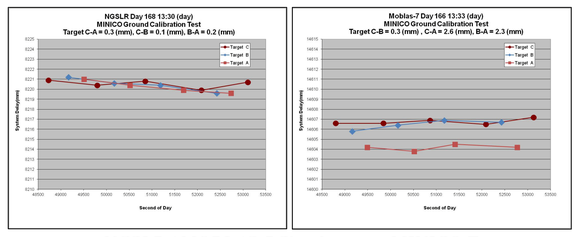
Total NGSLR Passes during Collocation period

Collocation Analysis: The NGSLR was directly compared to MOBLAS-7, examined for stability and precision, and scrutinized for any anomalies. Ground Tests (specifically stability and MINICO tests) are essential to detect any temporal variations, as well as a test for angular or range dependent biases in the system.

	Stability Tests Results	**MINICO Test Results**
NGSLR:	+/- 1.5mm (standard deviation =/< 0.7mm)	+/- 1.0 mm (all 3 targets)
MOBLAS-7:	+/-1.0mm	+/- 1.0 mm (2 targets, 1 target 2mm short)



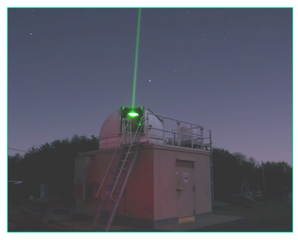
NGSLR / MOBLAS-7 Simultaneous Stability Test



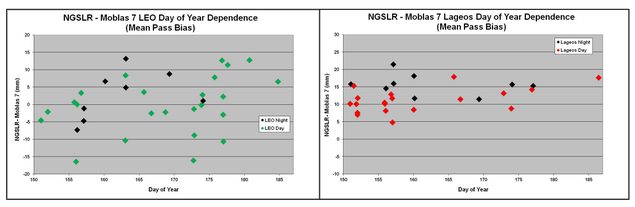
NGSLR / MOBLAS-7 Simultaneous MINICO Test

Satellite data comparison is completed using POLYQUICK software by directly comparing all simultaneous normal point data. The satellite data is used to detect direct biases between the two systems. The bias tests that were performed during collocation included tests for:

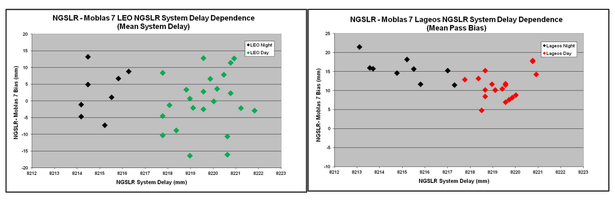
- Range-Dependent Range Bias
- Range-Rate Dependent Bias
- Elevation Dependent Range Bias
- Azimuth Dependent Range Bias
- Energy Dependent Range Bias
- Test for Long Term Mean Range Bias Stability
- Test for Diurnal Effects
- System Delay Range Bias
- Sky Coverage



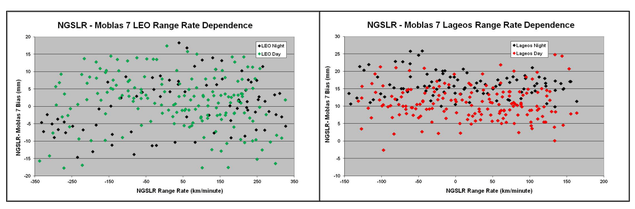
The analysis was conducted for all satellites (except for BEC and Ajisai due to the retroreflector configurations), however the LAGEOS satellite analysis has been separated because of the expected CoM correction differences with single and multi-photon systems. These charts clearly show that NGSLR measures long to MOBLAS-7 due to the differences with the single and multi-photon configurations. The following charts represent the analysis performed during collocation:



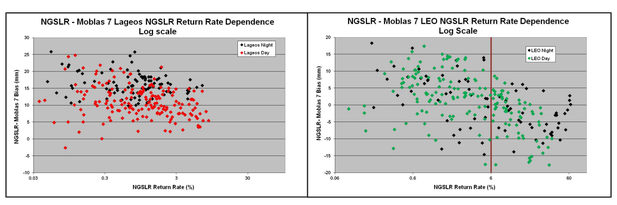
NGSLR / MOBLAS-7 Day of Year Dependence



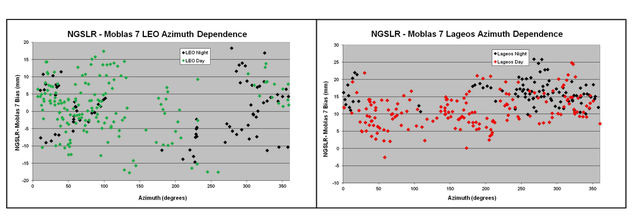
NGSLR / MOBLAS-7 System Delay Dependence



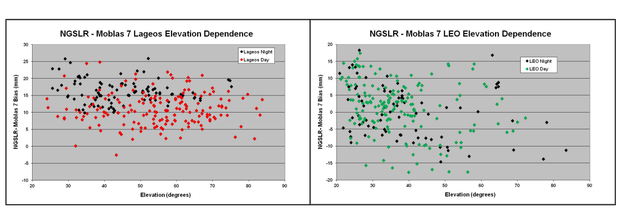
NGSLR / MOBLAS-7 Range Rate Dependence



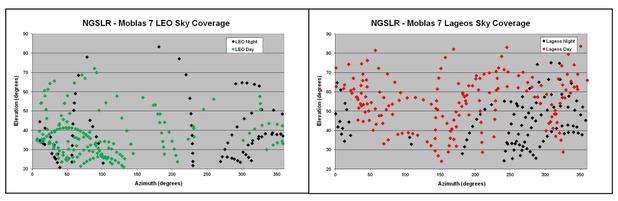
NGSLR / MOBLAS-7 Return Rate Dependence



NGSLR / MOBLAS-7 Azimuth Dependence



NGSLR / MOBLAS-7 Elevation Dependence



NGSLR / MOBLAS-7 Sky Coverage

Two sub-centimeter trends were identified during the parameter dependency testing, however neither were deemed significant problems:

- Bias difference between lower (<6%) and higher (>6%) return rates was about 7.5 mm.
  - Effect is probably due to the difference in single photon returns and multiple photon returns
  - Future modifications for automated to control higher return rate
- Day/Night time LAGEOS bias of about 5 mm (daytime data shorter than the night time data)
  - Failure of NGSLR laser has delayed investigation
  - Tests currently being devised for further diagnosis

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. The mean bias for the LAGEOS-1/LAGEOS-2 passes were 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 1mm.

			MOBLAS7- NGSLR Mean (mm)	
Satellite Type	**Collocated passes**	**Simultaneous Normal Points**	**Normal Point Bias**	**Pass Bias**
LAGEOS-1/2	28	270	12.81	12.89
Low Orbital	31	246	0.97	0.52
High Orbital	5	18	15.32	15.44

Final NGSLR / MOBLAS-7 Collocation Bias Results

The NGSLR / MOBLAS-7 collocation was a highly successful verification of the performance of the NGSLR system. The final comparison results followed the expected differences between single and multi-photon systems and proved that the NGSLR system is a viable SLR system that meets the next generation SLR standards.