Processing Single Photon Data for Maximum Range Accuracy

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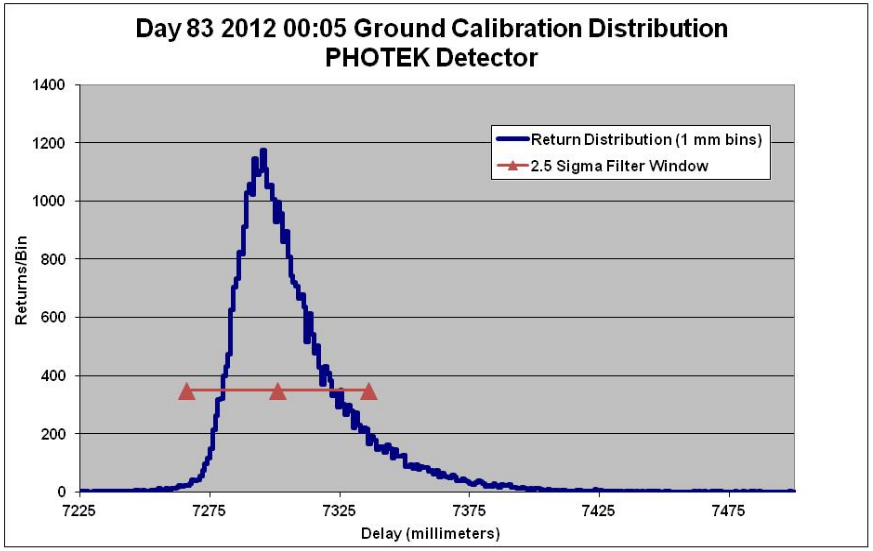
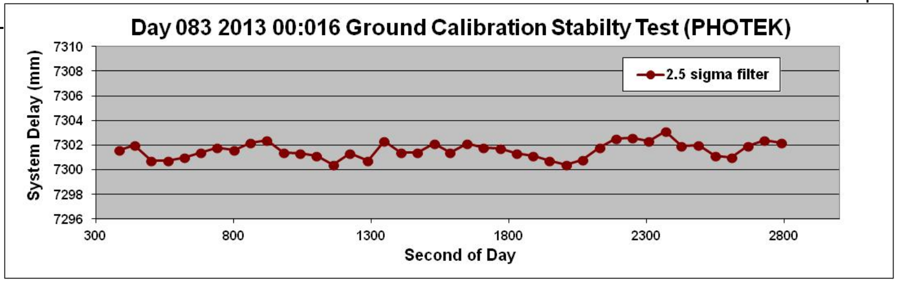
Abstract

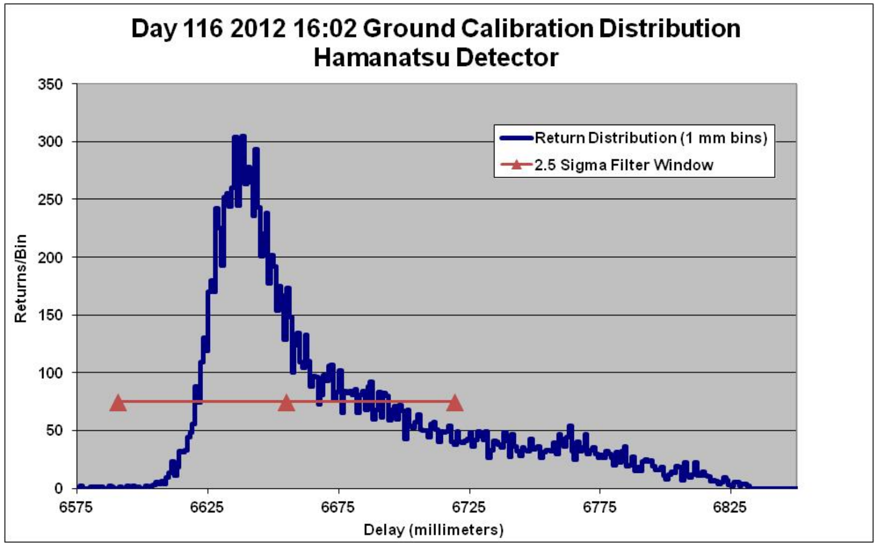
When ranging with single photons, the probability distribution for photon returns is given by the convolution of the laser pulse, receiver response, and the target signature. Even for picosecond laser pulses and single cube calibration targets, the probability distribution for NGSLR returns will be dominated by the non-Gaussian PMT/receiver response. For dynamic satellites, the target contribution is represented by an average response over the duration of a satellite normal point. The target range is best estimated by the centroid of the distribution, which generally falls well behind the peak. Thus, choosing a tight RMS cutoff from the peak during data editing will bias the range measurement toward shorter values. This effect was clearly demonstrated during the recent collocation of NGSLR with MOBLAS-7, where standard processing rejected all photon events outside a chosen RMS distance from the peak. For a 1.8 sigma RMS, both short arc collocations and global orbital fits of LAGEOS and LEO satellites showed an 10 to 12 mm bias between NGSLR and MOBLAS-7. However, when a 3 sigma RMS filter was applied, the LEO biases were reduced to about 2.5 mm while the LAGEOS bias was still about 12 mm, in good agreement with prior theoretical predictions.

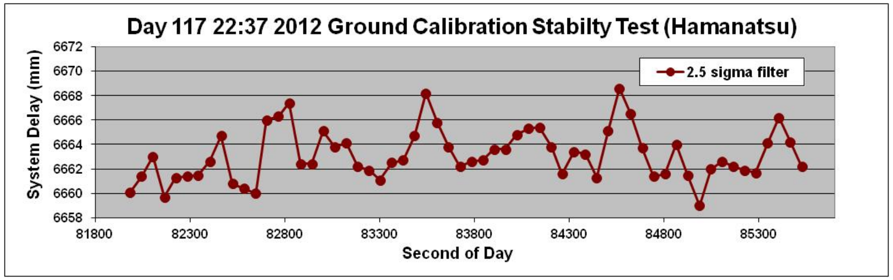
Processing History

- March 2012, PHOTEK detector is degrading, only acquiring very weak night time GNSS data and no day time GNSS data.
- PHOTOEK is replaced by Hamamatsu detector. Stronger returns, tracking GNSS satellites day and night.
- Calibration stability is not as good, +/- 3 mm, some larger pre-post calibration shifts
- Distribution of returns from single cube calibration targets are non-Gaussian and skewed long



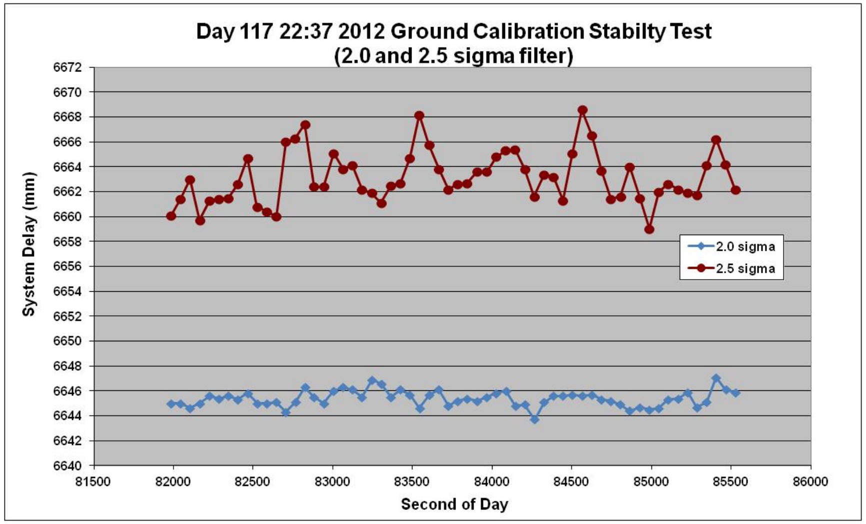


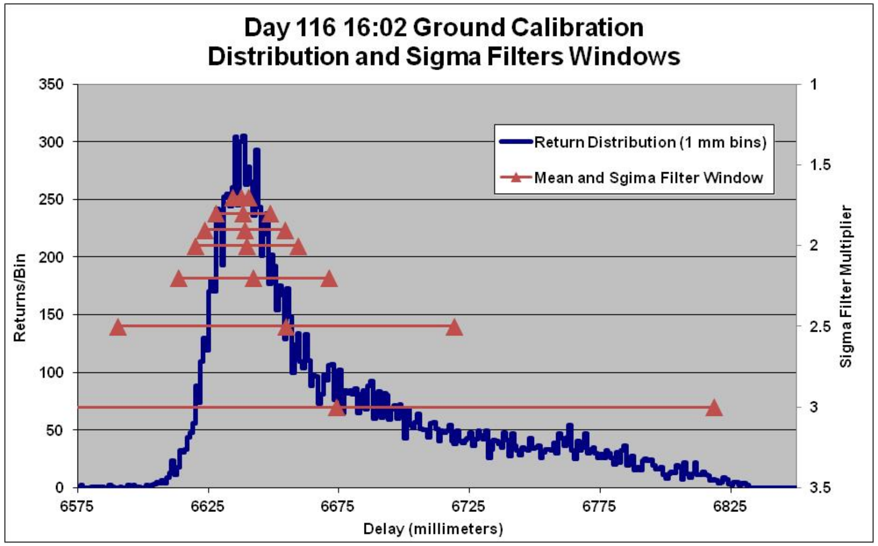




Processing History (continued)

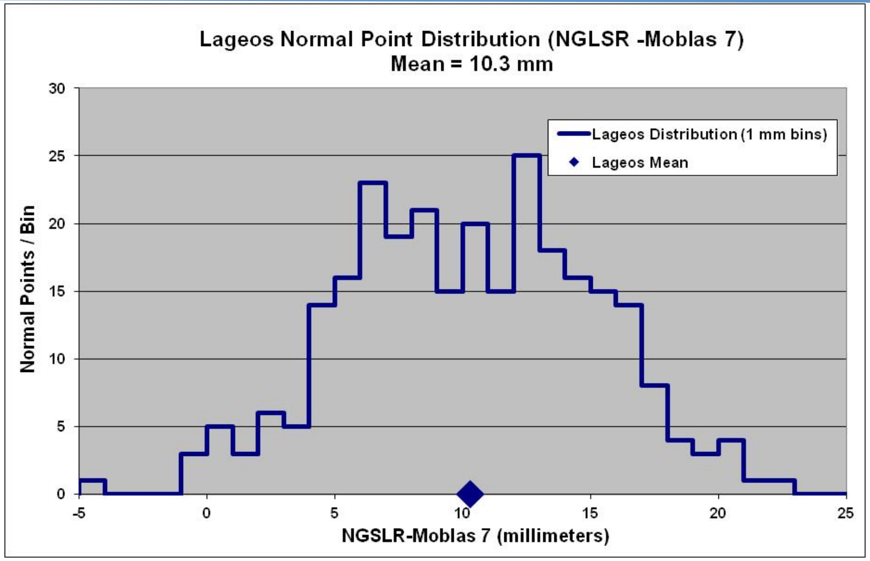
- Distribution of returns from single cube calibration targets using Hamamatsu was skewed longer with a larger tail than returns from PHOTEK. Range envelope was ~200 mm for Hamamatsu and ~100 mm for PHOTEK.
- Iterative 2.5 sigma filter incorporated much of the tail of the distribution.
- In order to increase measurement stability, began testing with tighter iterative sigma multiplier filters
- Tighter iterative sigma filters that found the "peak" of distribution rather than "centroid" were more stable.
- Tighter sigma filter processing of Hamamatsu data produced similar calibration stabilities to data from PHOTEK.
- Tested multiple sigma filters (1.7-3.0), 1.8 appeared to best represent peak and became the standard processing procedure.

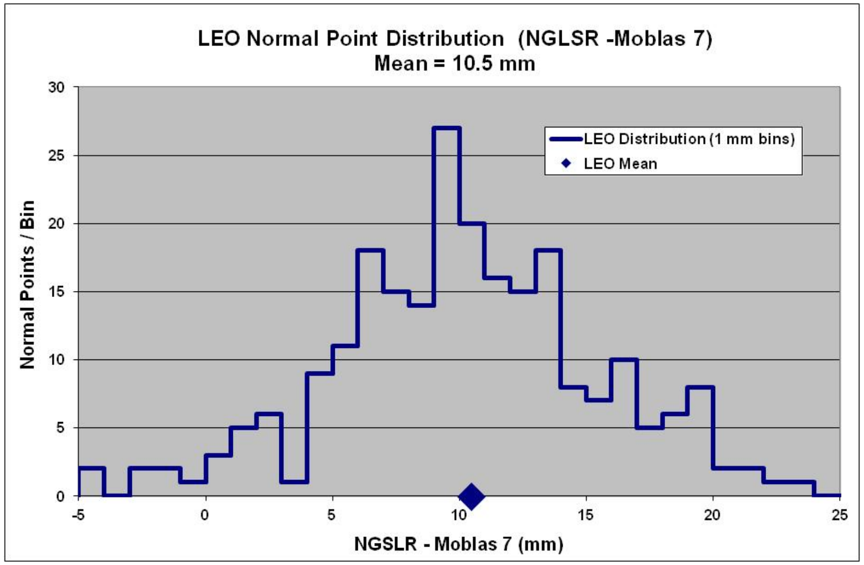




Collocation Analysis (1.8 Sigma Filter)

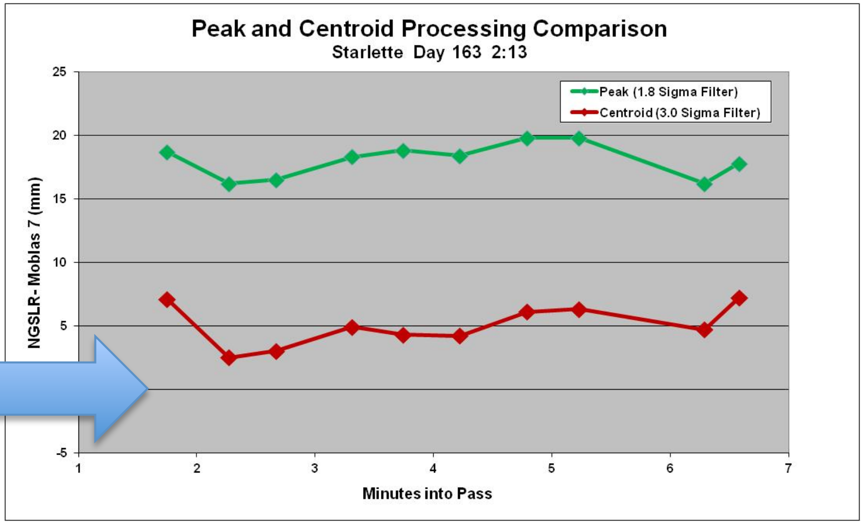
- Simultaneous data tracked by MOBLAS-7 and NGLSR between May 29 and July 5, 2013 was analyzed.
- NGSLR ground calibrations and satellite data processed using an iterative 1.8 sigma multiplier filter. (Moblas-7 processed using 3.0 sigma filter)
- Collocation Analysis was performed using POLYQUICK software.
- Analysis performed on simultaneous normal points. Separate analysis was performed for Lageos 1/2 and LEO (excluding BEC and Ajisai) satellites.
- The mean normal point bias (NGLSR-Moblas 7) was 10-11 millimeters for both Lageos 1/2 and LEO satellites.
- Biases were larger than expected. Lageos 1/2 , ,with a 1.8 sigma filter edit, biases were expected to be a few millimeters. LEO biases were expected to be a few millimeters or less.

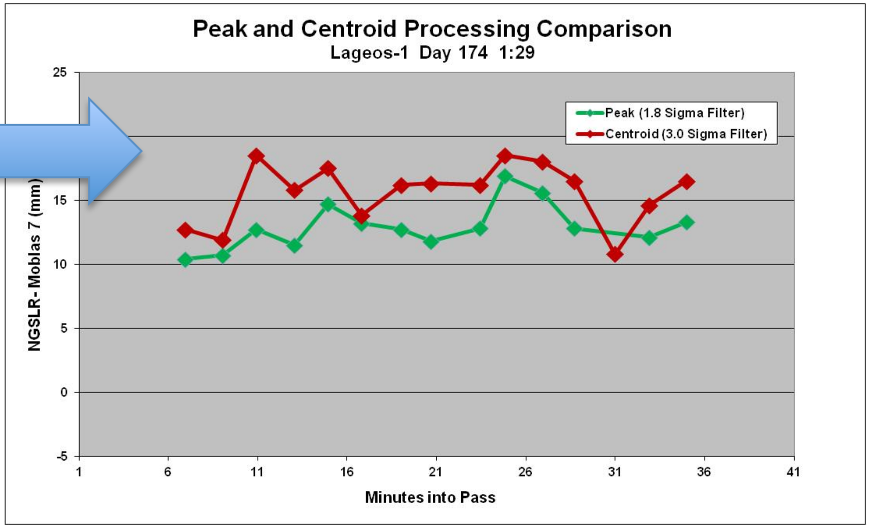




Individual Pass Peak and Centroid Analysis

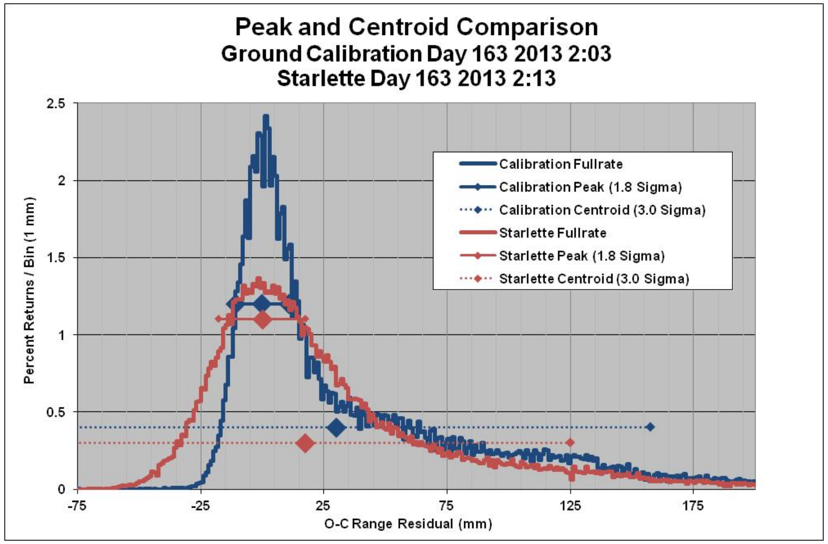
- Began comparing "peak" and "centroid" detection for individual passes. Ground calibrations and satellite passes processed at 1.8 and 3.0 sigma filter levels.
- Normal point differences from Moblas-7 were plotted for each pass.
- Starlette pass: NGSLR – Moblas 7 normal point bias was reduced by about 10 mm when using 3.0 sigma processing compared to 1.8 sigma processing.
- Similar pattern repeated for all LEO passes processed.
- Lageos pass: NGSLR – Moblas 7 normal point bias was increased by 1-2 mm when using 3.0 sigma processing compared to 1.8 sigma processing.
- Similar pattern repeated for all Lageos -1/2 passes.

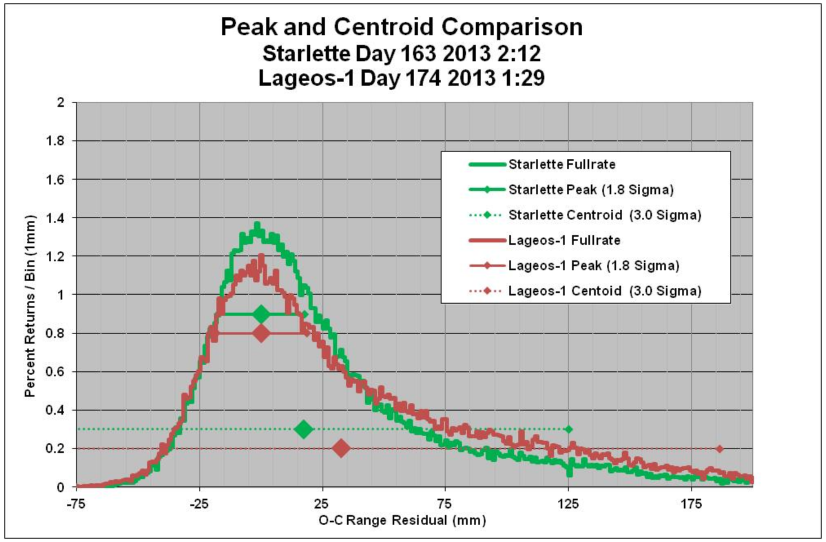


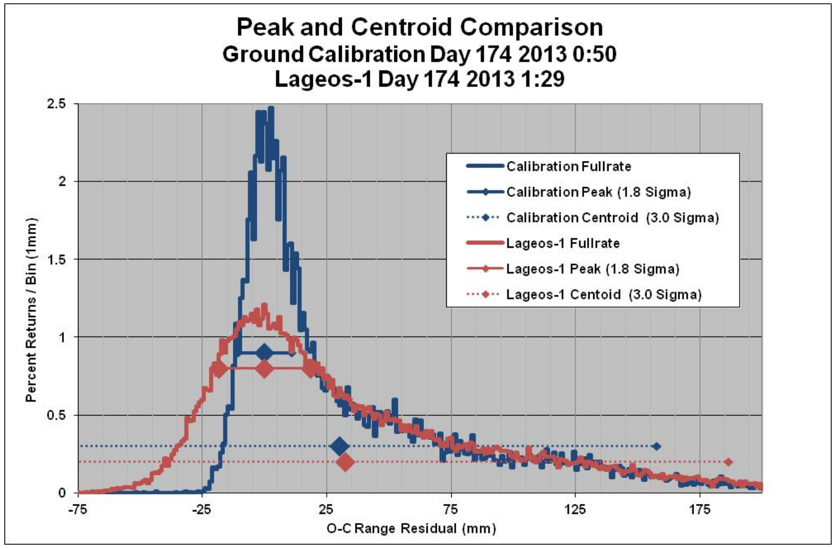


Satellite and Calibration Distribution Comparison

- Lageos and Starlette O-C range residual distribution were plotted with the calibration distribution.
- Peak and centroid detection displayed on each distribution.
- Starlette and Lageos are compared. The narrower impulse respone from Starlette caused the centroid to move 5-10 mm closer to peak when compare with Lageos.

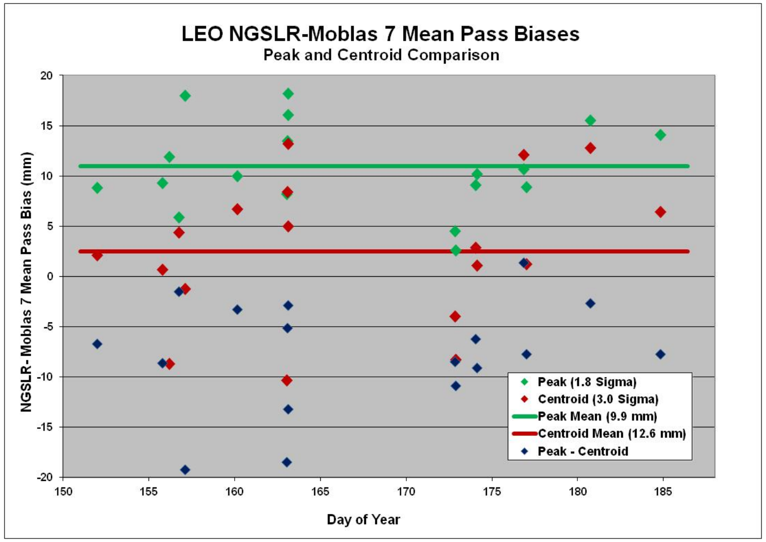


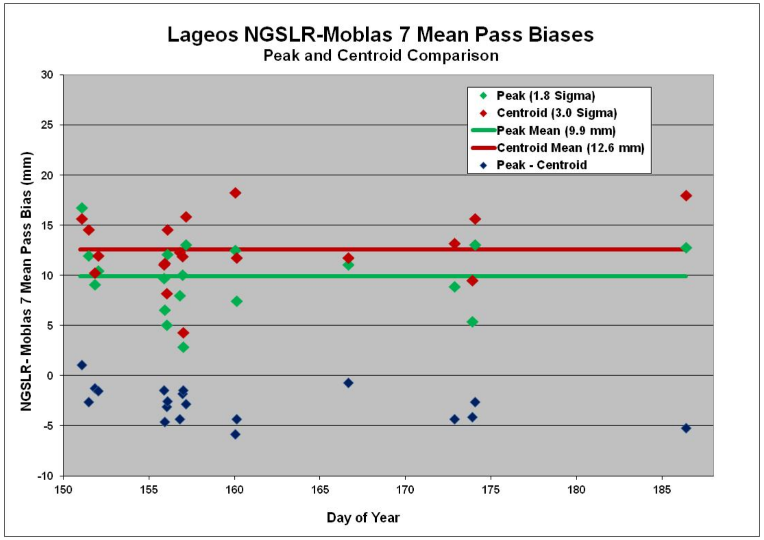




Cumulative Peak and Centroid Analysis

- Simultaneous NGSLR and Moblas 7 tracked between May 30 and July 5, 2013. Sub-set of final collocation data set.
- Ground calibrations and 37 satellites (19 Lageos, 18 LEO) passes processed at 1.8 (peak) and 3.0 sigma filter (centroid) levels.
- An overall mean pass bias was calculated for Lageos and LEO satellites using peak and centroid detection. Individual pass biases for plotted for each method along with differences between the two methods.





	LEO (NGSLR - Moblas 7) Mean Bias (mm)	Lageos (NGSLR - Moblas 7) Mean Bias (mm)
1.8 Sigma Filter	11 +/-1.0	9.9 +/-0.8
3.0 Sigma Filter	2.5 +/-1.7	12.5 +/- 0.8

Theory

- Threshold detection is modeled as a two state Markov process.
- The transition between states occurs when the received signal exceeds the detection threshold.
- The single cube calibration target can be modeled as a delta function.
- The 50 psec FWHM NGSLR laser pulse is sufficiently short compared to the satellite, s(t), and receiver , *r(t)*, impulse responses that it can also be represented by a delta function.

The photoelectrons generated at the photocathode by the satellite at range R_s and the calibration target at range R_c is then given by:

$$\lambda_s(t) = n_s \int_{-\infty}^{t} dt' r(t') s\left(t' - \frac{2R_s}{c}\right)$$

Satellite

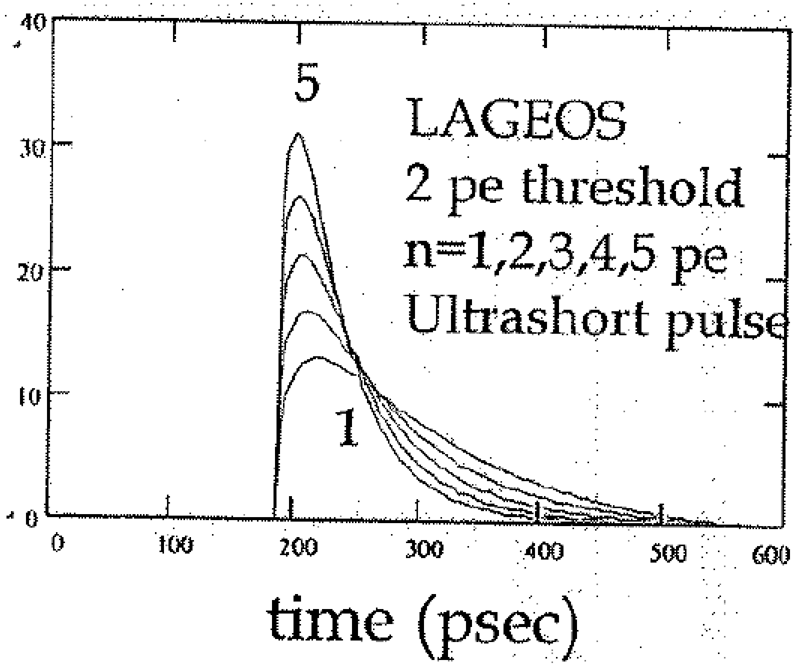
$$\lambda_c(t) = n_c \int_{-\infty}^{t} dt' r(t') \delta\left(t' - \frac{2R_c}{c}\right) = n_c r\left(t - \frac{2R_c}{c}\right)$$

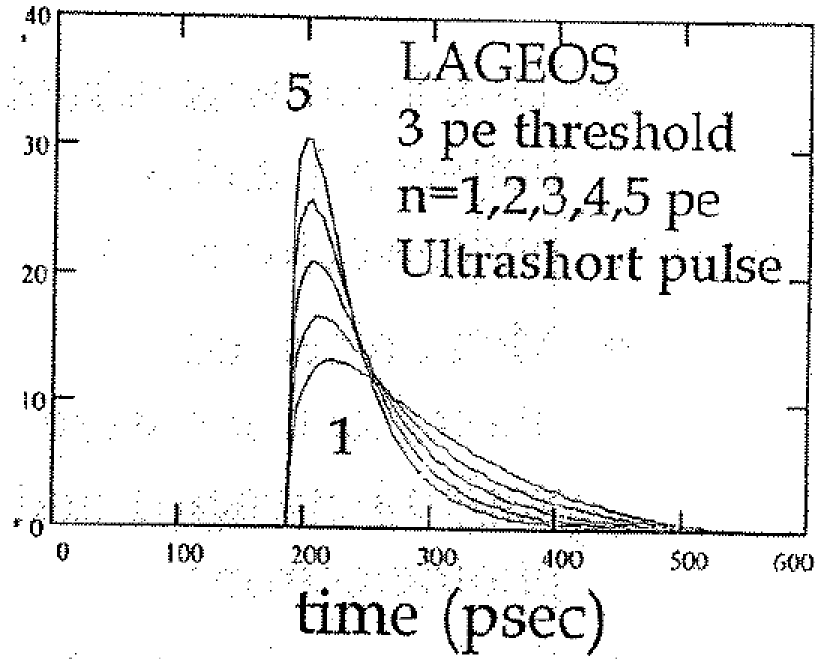
Single Cube Calibration Target

where n_s and n_e are the mean signal strengths generated during satellite tracking and calibration respectively. Thus, for an ultrashort pulse, the photoelectrons generated at the detector by the calibration target have a probability distribution given by receiver impulse response while the satellite return is the convolution of the satellite and detector impulse responses.

Poisson Distribution Effects of Threshold and Mean Signal Strength*

Plots show the probability distribution for threshold detection times as a function of threshold setting (2 or 3 pe) and signal strength (1 to 5 pe), taking into account Poisson statistics of exceeding the detection threshold. For signal strengths greater than about 2 pe, the distributions were found to be virtually independent of the threshold setting. As the signal strength increases, the distribution becomes more sharply peaked and the centroid of the distribution moves farther outward from the LAGEOS centroid.

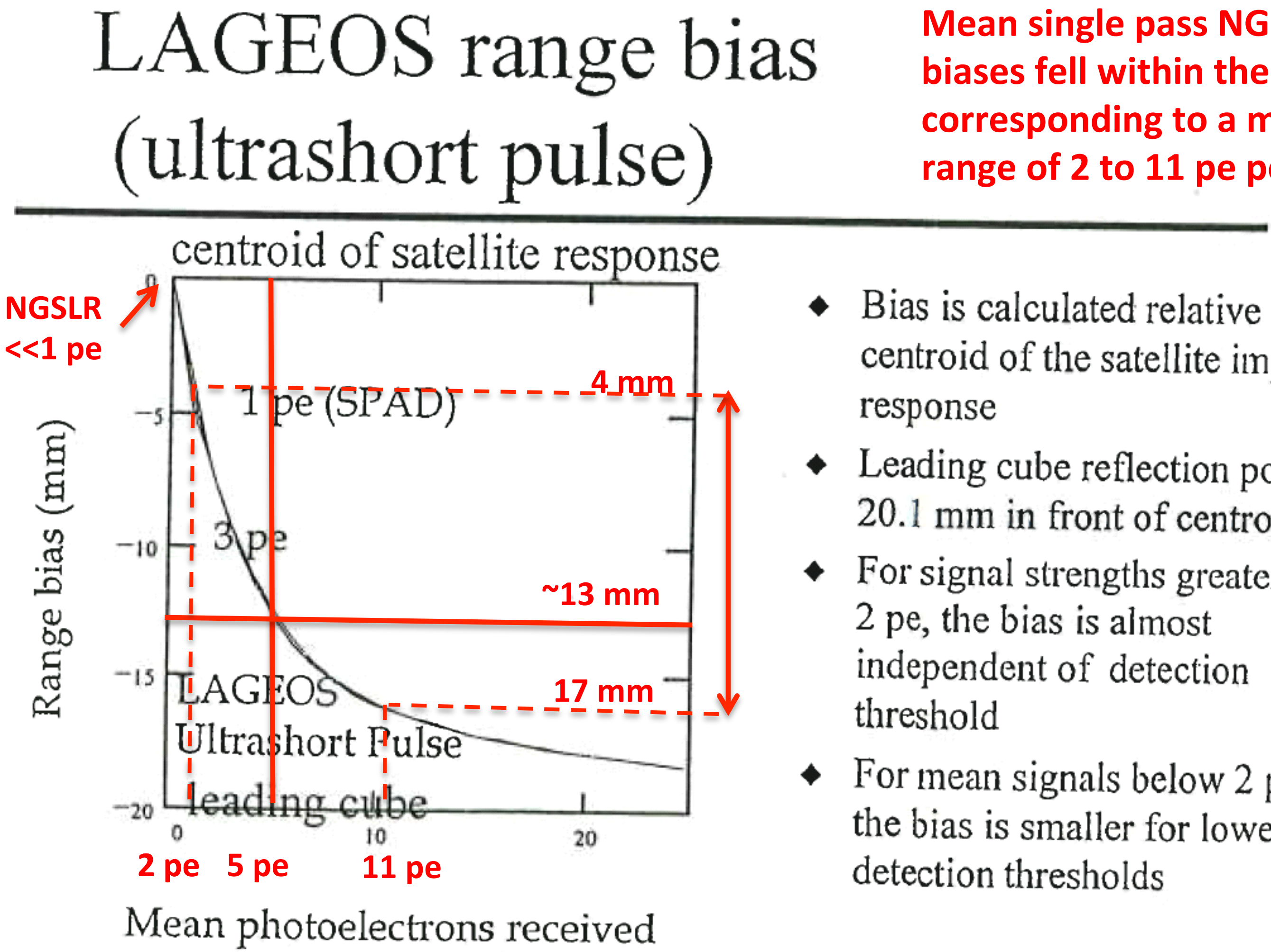




* From J. Degnan, "Effects of detection threshold and signal strength on LAGEOS range bias", 9th Intl. Workshop on Laser Ranging, Canberra, Australia, 1994. Plot assumed a SPAD delta function receiver impulse response.

Theoretical Results from Degnan*

Mean single pass NGSLR-MOBLAS7 collocation biases fell within the range 4mm and 17 mm, corresponding to a mean MOBLAS7 signal range of 2 to 11 pe per pass (from Slide 8).



- Bias is calculated relative to centroid of the satellite impulse response
- Leading cube reflection point is 20.1 mm in front of centroid
- For signal strengths greater than 2 pe, the bias is almost independent of detection threshold
- For mean signals below 2 pe, the bias is smaller for lower detection thresholds

* **From J. Degnan, "Effects of detection threshold and signal strength on LAGEOS range bias", 9th Intl. Workshop on Laser Ranging, Canberra, Australia, 1994. Plot assumed a SPAD delta function receiver impulse response.**

Theoretical Results of Fan et al *

In their calculations, Fan et al assumed an additional peak-to-peak detector time jitter ranging from -18 mm to 18 mm with a mean of 0 mm.

Table 1 The CoM corrections and RMS values of Lageos in consideration of retro-reflector array

	CoM1/mm	RMS(x_1)/mm	RMS(ξ)/mm	RMS(x_2)/mm
NGSLR	242.26	1.91	6.71	6.98

Table 2 The CoM corrections and RMS values of Lageos in consideration of returned signal strength and signal detection

	Q/pe	CoM2/mm	RMS(x_3)/mm	RMS(x_4)/mm	RMS(total)/mm
	0.1	242.64	6.92	7.54	9.19
	0.5	244.12	6.67	7.32	9.00
	1	245.88	6.31	6.99	8.74
	2	248.96	5.50	6.27	8.17
MOBLAS	4	253.25	3.93	4.94	7.21
	10	257.89	1.93	3.57	6.35
	20	259.99	1.43	3.32	6.21

From Table: NGSLR/MOBLAS BIAS (5 pe) ~12 mm

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

Summary

•Processing single photon NGSLR single cube calibration data produces a range distribution that correlates well with the impulse response of the MCP/PMT detector, i.e. a risetime of ~200 psec (~30 mm) and a FWHM of ~300 psec (~45 mm), and a long tail. This is in agreement with theoretical expectations for a relatively short laser pulse (50 psec FWHM) and a delta function, single cube, calibration target response. **For NGSLR, the best estimate of calibration range (and satellite range) is given by the centroid of the range distribution and not the peak, provided the system is operating at single photon levels (P_d ~n_s <<1)).**

•Collocation analysis with Moblas-7 indicates that processing single photon NGSLR data with a tight iterative sigma multiplier filter, effectively detects the peak of the distribution of returns and produces a large bias between NGSLR and Moblas-7 for Lageos, which has a wider target signature than the smaller LEO arrays. This is attributed to a higher mean MOBLAS signal strength which strongly skews the data toward shorter range values.

•Processing NGSLR date with a three sigma filter better detects the centroid of the distribution of returns and produces a 12.5 millimeter mean bias between NGSLR and Moblas-7 for Lageos, which is in good agreement with prior theoretical values (Degnan and Fan et al), and a relatively small 2.5 millimeter bias for the LEO satellites**. Since NGSLR signal strengths from LAGEOS are always 0 or 1 pe with only a few percent return rate, Poisson statistics can never skew the normal point data more than about 3.5 mm. Thus, the observed variation in bias (4 mm to 17 mm) from pass to pass is most likely due to changes in MOBLAS mean signal strength resulting from changing atmospheric conditions, mean satellite range at different pass elevations, random pointing errors, or inconsistent signal strengths during ground target calibrations. This possibility should be investigated further.**