NGSLR's measurement of the retro-reflector array response of various LEO to GNSS satellites

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NGSLR Current Status

- New Photonics Industries laser installed in system recently:
  + Capable of 2.8 mJ per pulse transmit energy at 2 kHz
  + 50 picosecond pulsewidth

- Redesigned and upgraded optical bench:
  + Cleaned up optical paths – provided more isolation between xmit & recv
  + Added alignment aids
  + Increased space where needed to automate optics

- Ground calibrations performed with new configuration (satellites soon):
  + New PI laser RGL532-2.5
  + Hamamatsu model R5916U-64 MCP-PMT with 40% Q.E.
  + Ground calibration stability looks good (+/- 1 mm) after warm-up

- Satellite passes tracked in older configuration in early 2012:
  + 1 mJ in-house laser (2kHz) with same detector as new configuration
  + Turned in prelim set of 50+ LEO to GNSS passes to E. Pavlis for analysis
  + Several daylight GNSS passes tracked
  + Our internal analysis showed fairly consistent 1-2 cm long from MOBLAS-7

SATELLITE PASSES TRACKED BY NGSLR APRIL TO JUNE 2012
SUBSET SELECTED FOR PRELIMINARY PERFORMANCE ANALYSIS

SATELLITE	# passes NIGHT	# passes DAY
GLONASS (GNSS)	5	1 **
GALILEO (GNSS)	1	0
ETALON (GNSS altitude)	1	0
LAGEOS (1/2)	7	5
LARES	4	1
STARLETTE/STELLA	4	5
Other LEO	17	6
TOTAL	39	18
Passes tracked with NASA 1 mJ laser and Hamamatsu detector		

** Several daylight GNSS tracked but only 1 submitted

Erricos Pavlis: The NGSLR data "… look good and fit well with the rest of the (network) data, but these are too few to draw firm conclusions."

Theoretical Retro Array Response Calculations

$$n_{pe} = \eta_q \left(E_T \frac{\lambda}{hc} \right) \eta_t G_t \sigma \left(\frac{1}{4\pi R^2} \right)^2 A \eta_r T_a^2$$

where:

n_{pe} = expected photoelectrons received per fire

η_q = detector quantum efficiency

E_T = per pulse transmit energy

λ = wavelength (532nm)

η_t = transmit path transmission

G_t = transmitter gain (function of divergence and mispointing)

σ = array cross section

R = range to satellite

A = area of telescope

η_r = receive path transmission

T_a = atmospheric transmission (1-way)

and where:

$$G_t = \frac{8}{\theta_t^2} exp \left[-2 \left(\frac{\theta}{\theta_t} \right)^2 \right]$$

J. Degnan, "Millimeter Accuracy Satellite Laser Ranging: a Review," Contributions of Space Geodesy to Geodynamics: Technology, Volume 25, 1993.

NGSLR Configuration for Array Response Comparisons

- Configuration:
  - NASA in-house built 1 mJ laser (actual output energy somewhat less)
  - Hamamatsu model R5916U-64 MCP-PMT with 40% Q.E.
  - Old optical bench layout, optics and equipment
  - Automated closed loop tracking not yet implemented

- Parameters used:
  - Telescope diameter = 40 cm
  - Per pulse transmit energy (out of laser): 800 microJoules
  - Laser repetition rate: 2 kHz
  - Laser divergence full angle: 3.5 arcsec
  - Detector counting efficiency (not QE) used: 0.28
  - Transmit throughput: 0.514
  - Receiver throughput: 0.572 (night), 0.388 (day)
  - Beam pointing error used: none (min), 7 arcsec (max)
  - Atmospheric transmission: clear atmosphere → 0.5 tranmission 1-way

Parameters for Array Response Comparisons

- Determination of parameters:
  - Detector counting efficiency (QE x active area).
  - Per pulse transmit laser energy: measured at laser output with Scientech Power Energy Meter model 364.
  - Laser divergence: measured after T/R switch using a Photon Inc Beam Profiler. The imaging head was placed in the image plane of a 750 mm FL lens and the far field spot size recorded.
  - Transmit & receive transmission: calculated.
  - Beam pointing error: educated guess from operating the system.
  - Lidar cross section: used ILRS report (D Arnold) for current values.
  - Atmospheric transmission: assumed no better than clear.

- Cross section values used (Million meters squared):
  - BEC: 3.6
  - STARLETTE: 0.65
  - LAGEOS 1&2: 7.0
  - AJISAI: 12.0
  - GALILEO-101: 60.0
  - GLONASS 122&123: 80.0

How Actual Return Rate Was Calculated

- Polynomial fit to the OMC residuals of all returns:
  (range – predictions – systemdelay – refraction).

- Because all of these passes has fairly strong signal we could do this. Operationally the data is filtered using a time and range window about the signal determined by the real-time software.

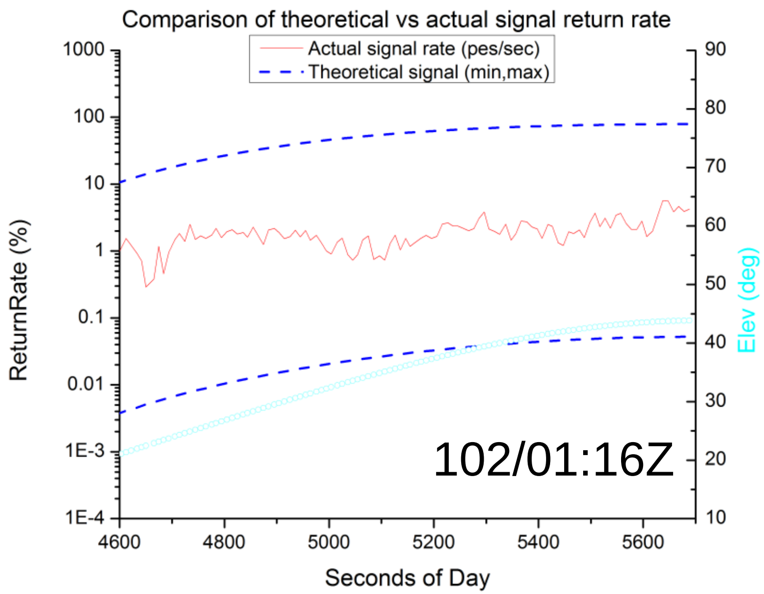
- 3.5 to 4.0 sigma filter was used to reject the noise.

- Data was binned in 2.5 sec intervals for LEO, 10 sec intervals for LAGEOS and 30 sec intervals for GNSS.

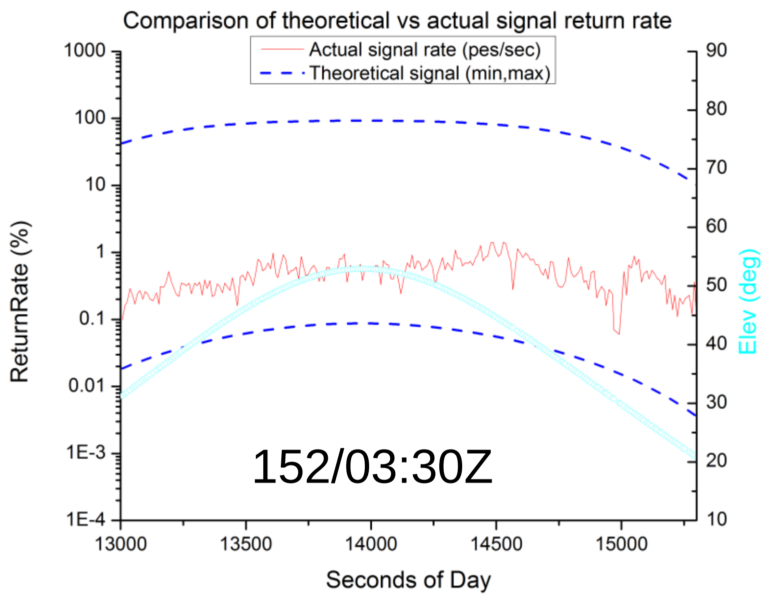
- Return rate calculated for each signal bin.

- To produce an equivalent theoretical value corresponding to the return rate per bin, the probability of detection was calculated from the theoretical expected number of photoelectrons: Prob(det) = 1 – exp(-n_{pe})

LAGEOS 1

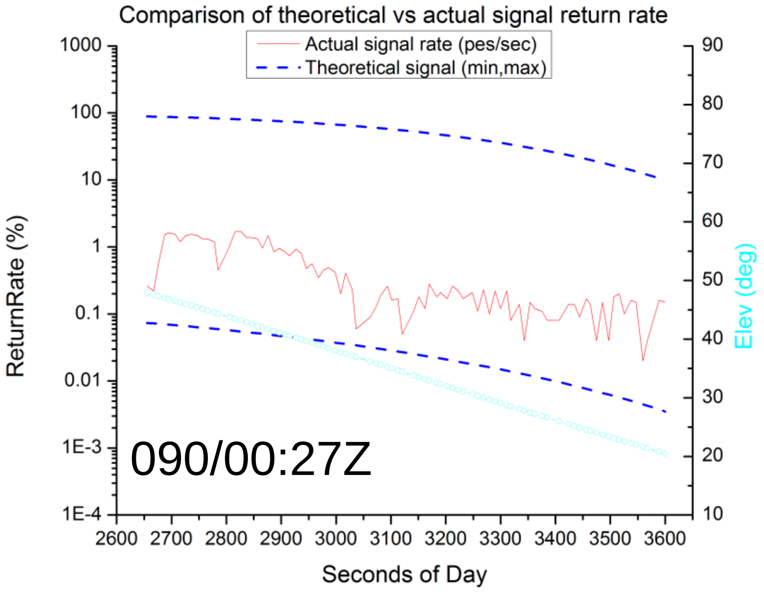


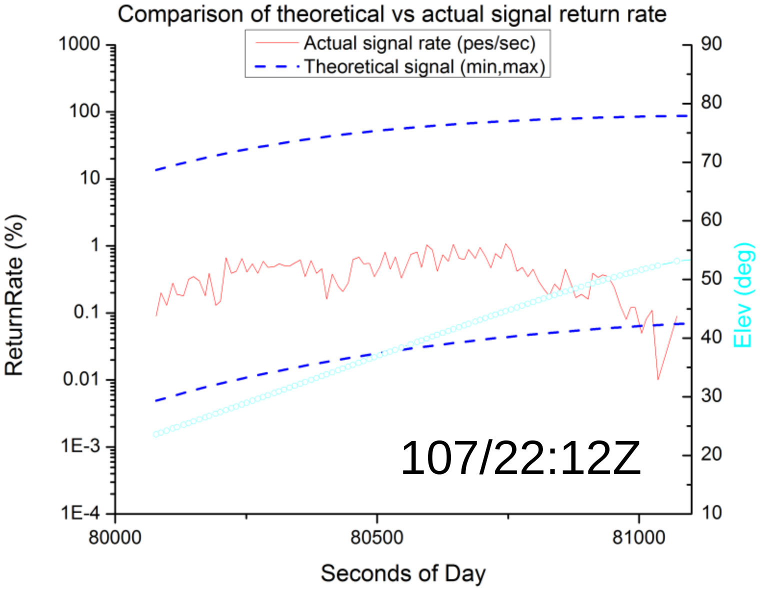
Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
Elev (deg)
Seconds of Day
102/01:16Z

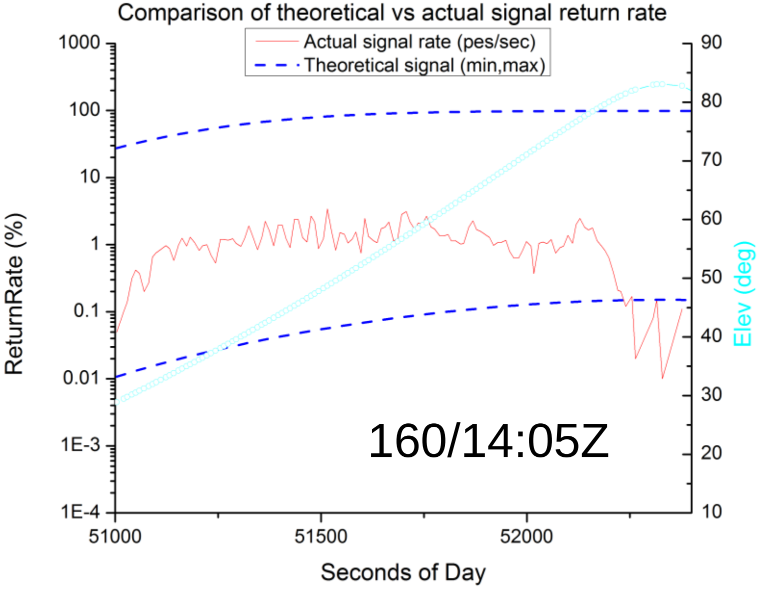


Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
Elev (deg)
Seconds of Day
152/03:30Z

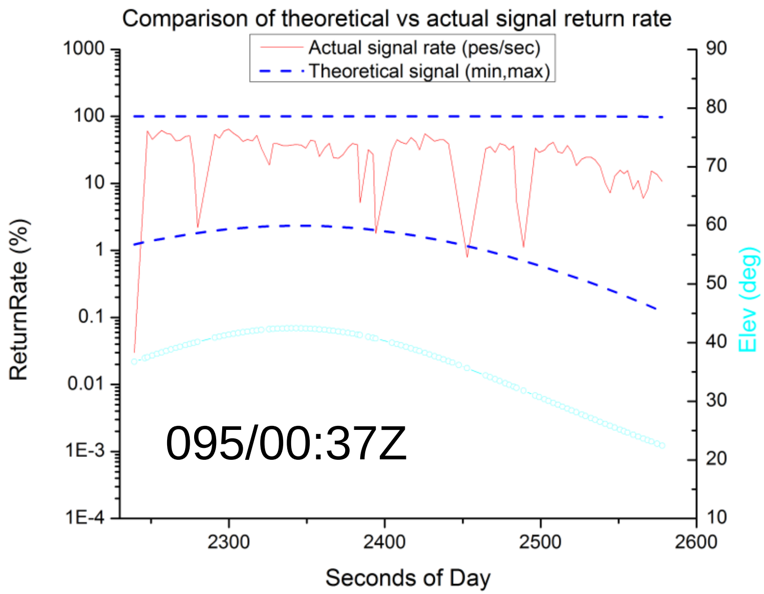
LAGEOS 2


Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
Elev (deg)
Seconds of Day
090/00:27Z

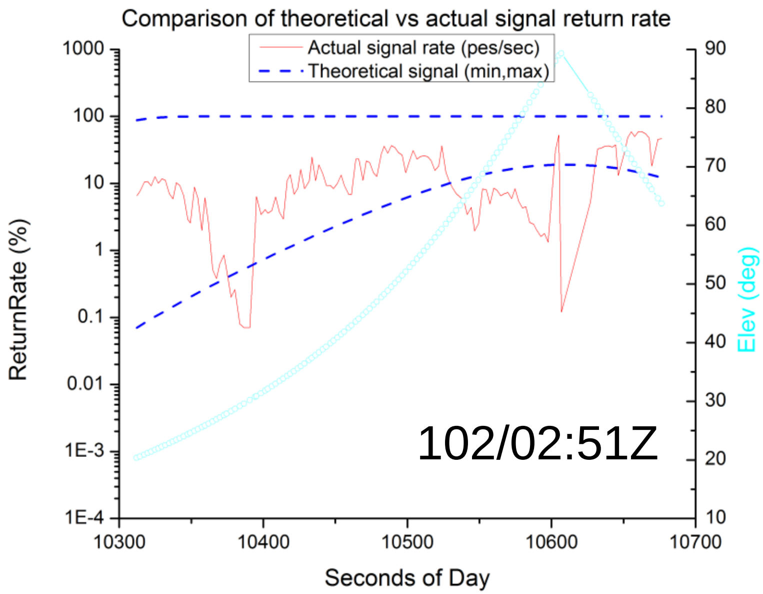

Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
Elev (deg)
Seconds of Day
107/22:12Z


Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
Elev (deg)
Seconds of Day
160/14:05Z

STARLETTE

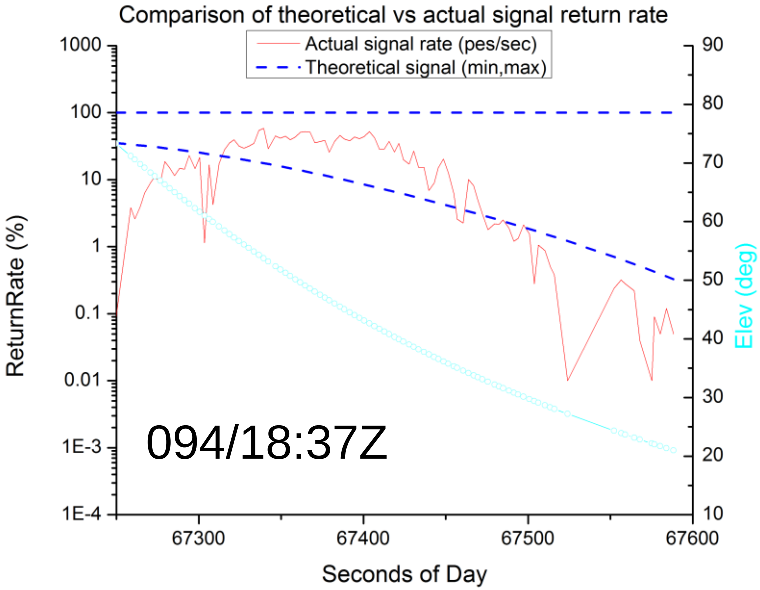


Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
1000
100
10
1
0.1
0.01
1E-3
1E-4
90
80
70
60
50
40
30
20
10
Elev (deg)
2300
2400
2500
2600
Seconds of Day
095/00:37Z

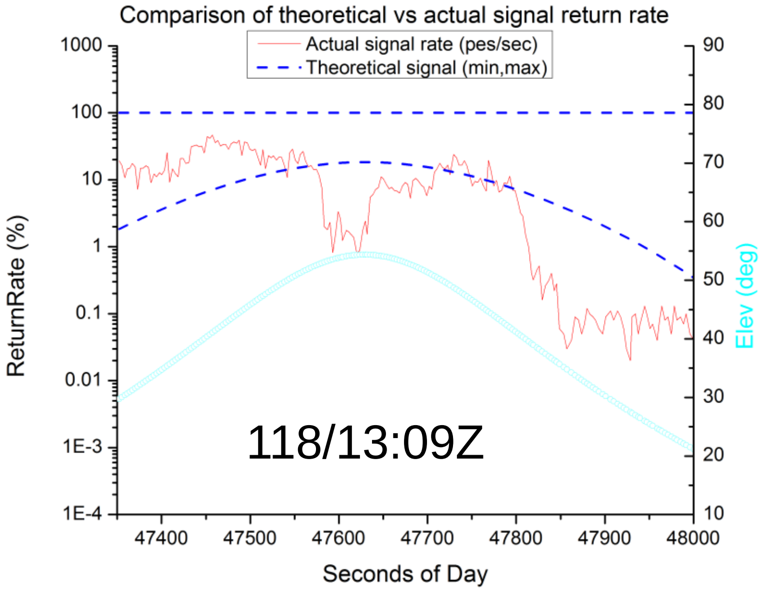


Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
1000
100
10
1
0.1
0.01
1E-3
1E-4
90
80
70
60
50
40
30
20
10
Elev (deg)
10300
10400
10500
10600
10700
Seconds of Day
102/02:51Z

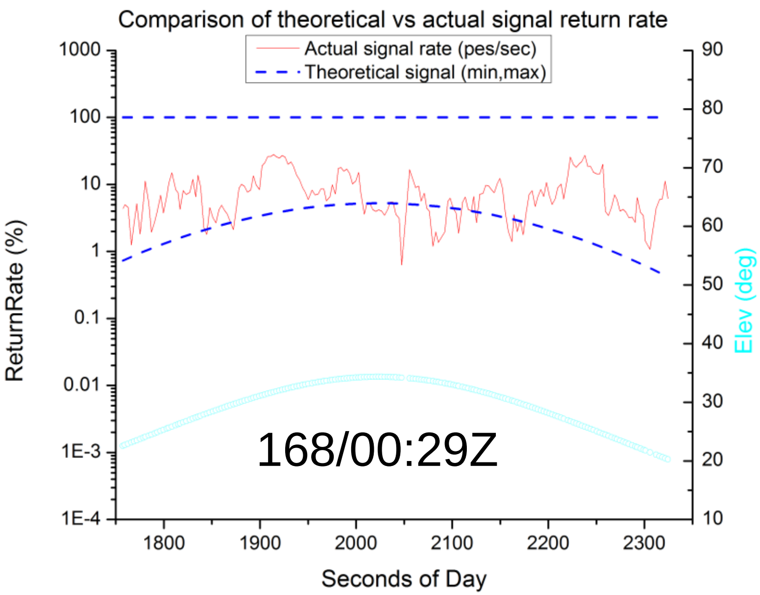
AJISAI



Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
1000
100
10
1
0.1
0.01
1E-3
1E-4
ReturnRate (%)
90
80
70
60
50
40
30
20
10
Elev (deg)
67300
67400
67500
67600
Seconds of Day
094/18:37Z

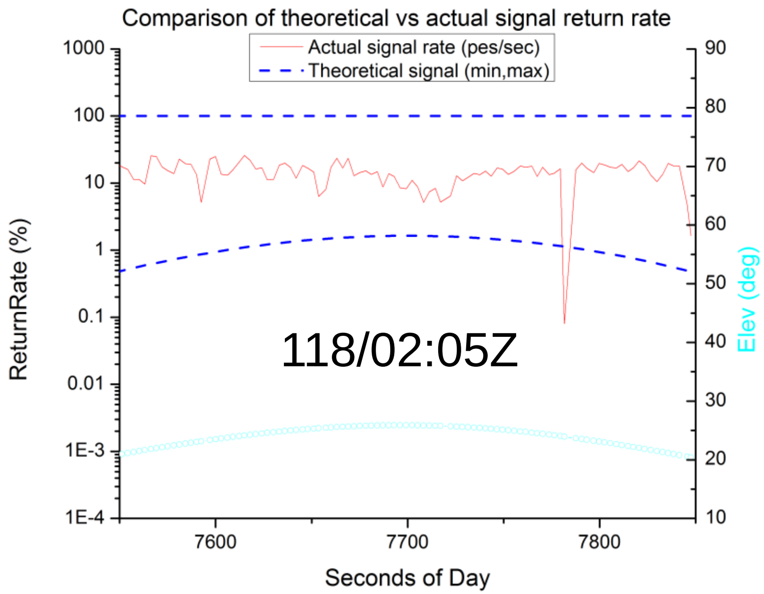


Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
1000
100
10
1
0.1
0.01
1E-3
1E-4
ReturnRate (%)
90
80
70
60
50
40
30
20
10
Elev (deg)
47400
47500
47600
47700
47800
47900
48000
Seconds of Day
118/13:09Z

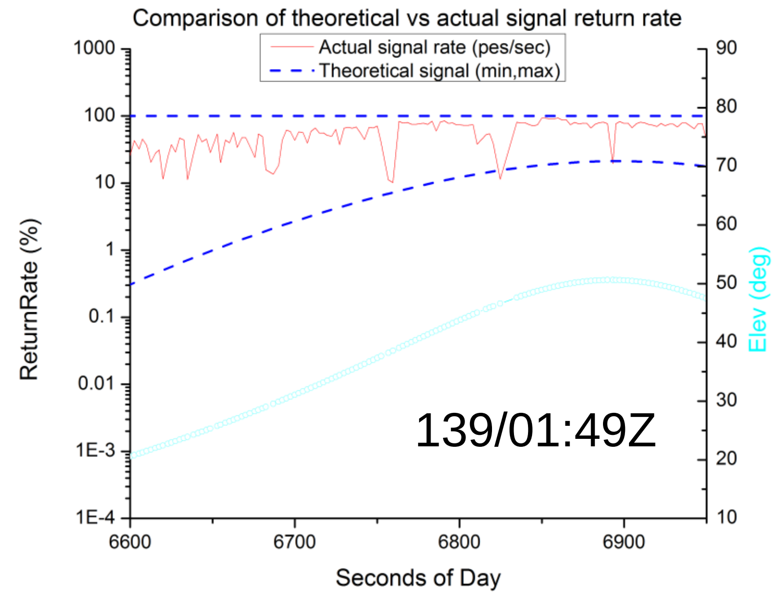


Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
1000
100
10
1
0.1
0.01
1E-3
1E-4
ReturnRate (%)
90
80
70
60
50
40
30
20
10
Elev (deg)
1800
1900
2000
2100
2200
2300
Seconds of Day
168/00:29Z

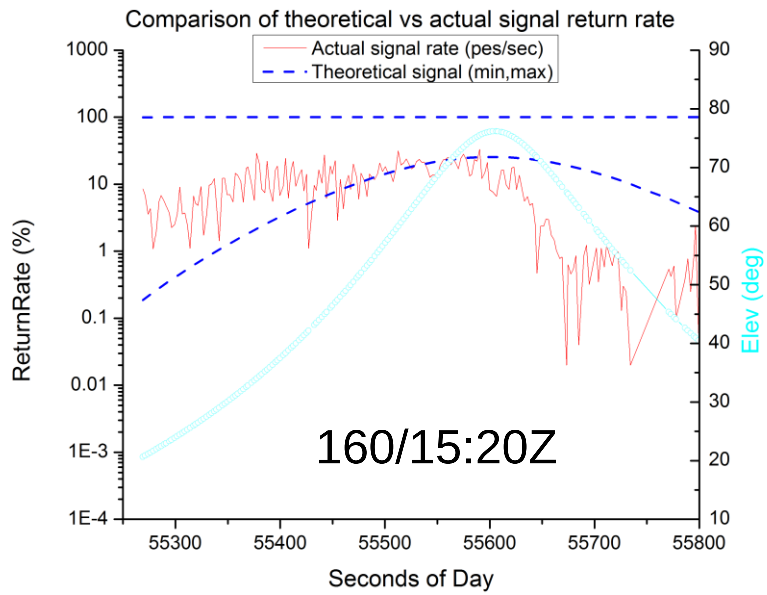
BEC



Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
1000
100
10
1
0.1
0.01
1E-3
1E-4
90
80
70
60
50
40
30
20
10
Elev (deg)
118/02:05Z
7600
7700
7800
Seconds of Day

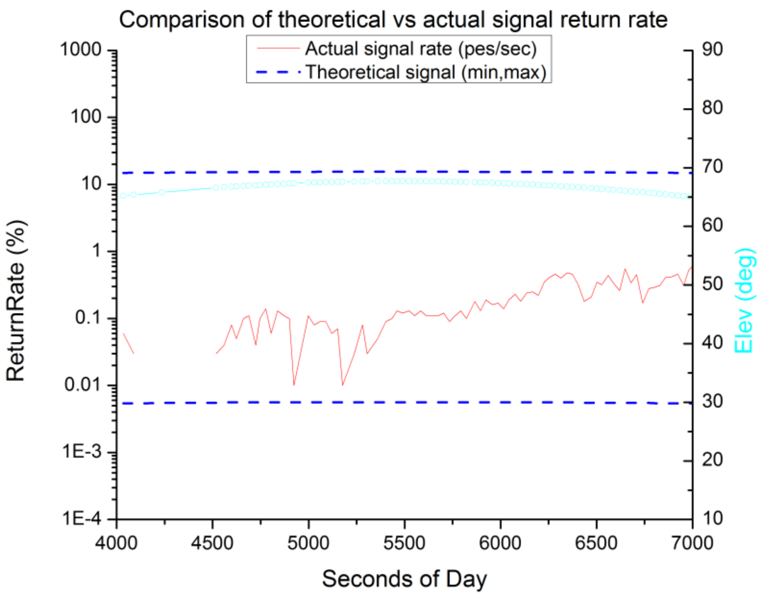


Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
1000
100
10
1
0.1
0.01
1E-3
1E-4
90
80
70
60
50
40
30
20
10
Elev (deg)
139/01:49Z
6600
6700
6800
6900
Seconds of Day

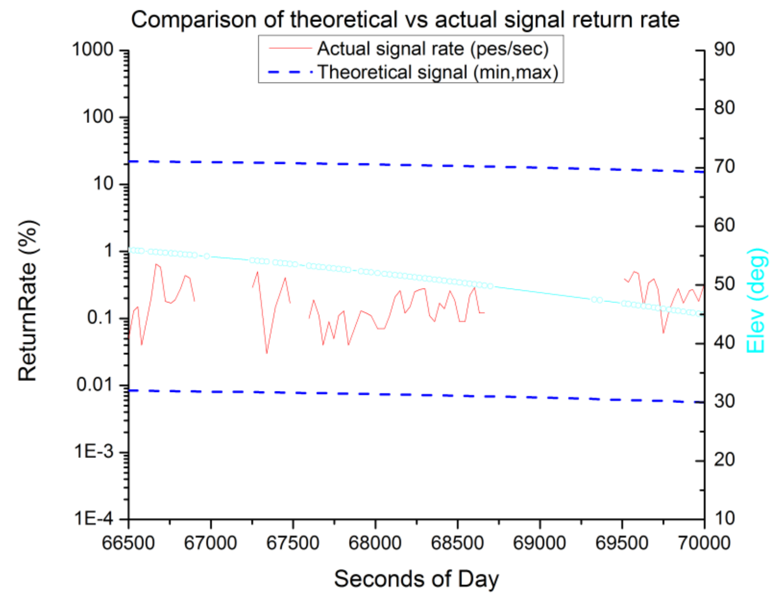


Comparison of theoretical vs actual signal return rate
Actual signal rate (pes/sec)
Theoretical signal (min,max)
ReturnRate (%)
1000
100
10
1
0.1
0.01
1E-3
1E-4
90
80
70
60
50
40
30
20
10
Elev (deg)
160/15:20Z
55300
55400
55500
55600
55700
55800
Seconds of Day

GNSS

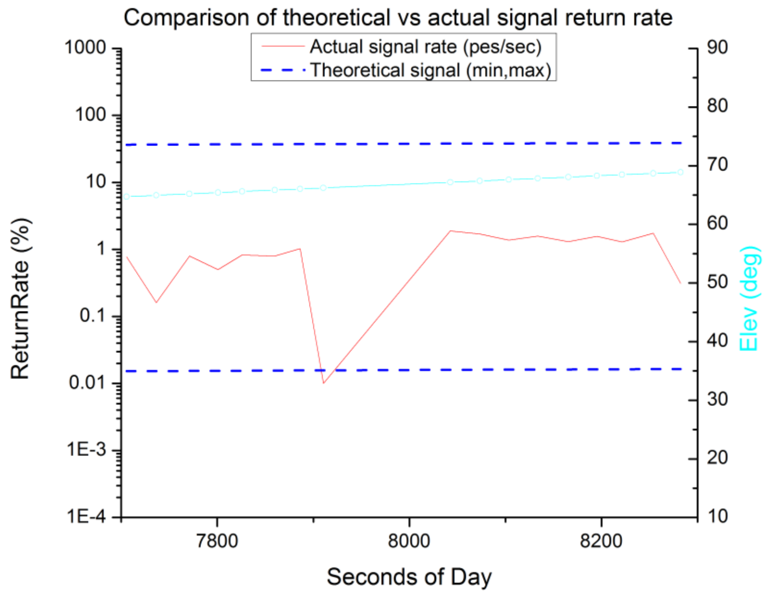


Galileo-101 090/01:04Z

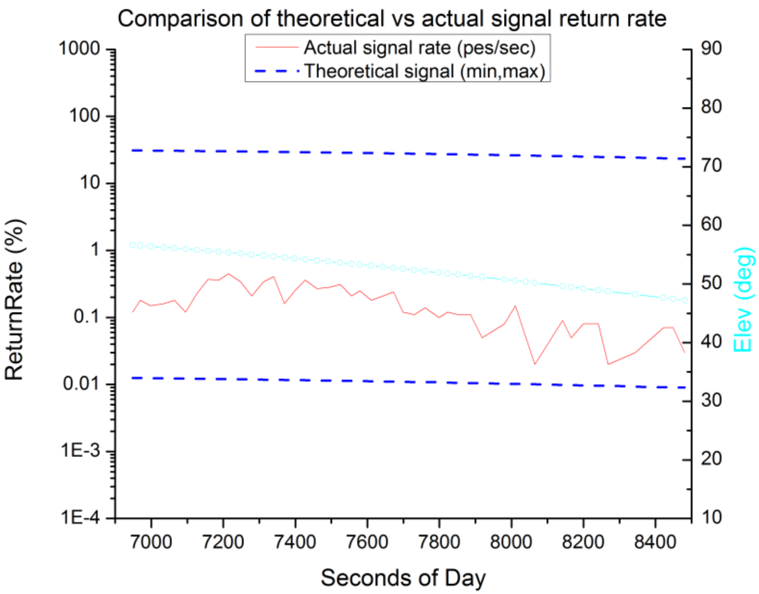


GLONASS-123 150/18:28Z

GNSS



GLONASS-122 090/02:08Z



GLONASS-122 152/01:55Z

Summary and Conclusions

- Narrow divergence coupled with pointing errors causes our return signal strength to be an order of magnitude or more down from what it could be.

- Automated closed loop tracking has not yet been implemented at NGSLR. This should dramatically increase our return signal strength.

- Atmosphere was not well known and pointing errors were not known exactly, but everything else was well calculated or measured.

- Lidar cross sections used were a single fixed number for each satellite. Probably should do this calculation with Dave Arnold's minimum and maximum values.

- Some of the passes do come close to achieving their theoretical maximum rates.

- We will revisit this when we have collected data with our new PI laser.