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SLR energy density estimations and measurements for the Herstmonceux station

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Abstract. *To estimate the energy of a returning laser pulse a satellite laser ranging station must take in to account system losses, atmospheric transparency and turbulence, target reflectivity and laser and detector characteristics. At the SLR station at the Space Geodesy Facility (SGF), Herstmonceux, close attention is given to all aspects of the link budget equation, using real measurements where possible, to give the best possible energy estimations. For comparison, SLR return energy densities were obtained from return rate measurements for a series of ILRS targets using the 12Hz and 2kHz systems. In-orbit energy densities and estimations are also investigated for the Jason-2 and Lunar Reconnaissance Orbiter (LRO) satellites. The motivation of this work is for the comparison of the theoretical and observed return energies to inform both on system performance and link budget accuracy.*

Introduction

A short laser pulse for satellite laser ranging (SLR) diverges as it travels through the Earth's atmosphere, out in to space and towards the satellite target. Its energy density is consequently inversely proportionally to the square of the distance travelled and once it is retro-reflected this factor becomes the fourth power of the range, R^4. The return energy is further reduced by optical losses, the reflectivity the corner cube target and the detector efficiency. Each transmission through the atmosphere reduces the energy by scattering and absorption and turbulence distorts the beam quality and pointing.

Taking all of these factors into account, accurately estimating the impact of each and measuring the real-world values ideally would result in close agreement between the estimated and recorded energies. The actual level of agreement observed will indicate how accurately the factors involved in the calculation are known, as well as being a test of the models employed.

Return Energy Measurements

The SLR station at the SGF, Herstmonceux measures return signal strength in real time as return rate, which is the number of satellite returns over the number of opportunities for detection. This value is used to control the signal intensity on to the SPAD detector to single photon levels by reactively adjusting a ND filter wheel. This value is again calculated at the data extraction stage so that all high energy level data is discarded.

For this study, return rates were recalculated by comparing the full rate data files with the raw files archived at the facility along with the records of applied filters. This method had the advantage of the satellite tracks being well defined in advance in the full rate data files which were formed by the SLR observer in a consistent manner using orbit fitting and Gaussian filtering software. The data set begins in June 2009 when the narrowband oven filter was last retuned. This period is not without events and included laser services, SPAD swaps and optic changes. Energy densities were calculated for both SLR systems, although the kHz laser was operational for less than half of the period.

The resulting return rates, equivalent to detection probabilities, were converted to number of photoelectrons using photon detection statistics, which are appropriately described by a Poisson distribution. This was then scaled for detector quantum efficiency and converted to joules using the Planck constant and the wavelength of the laser, 532nm. Further corrections were made for the telescope receive efficiency, the semi-train in the case of the 12Hz laser and applied filters (ND and spectral). Finally the values were scaled for the area of the telescope to give energy density in J/m^2.

Estimating Energy Density

A multitude of factors must be taken into account to model the energy budget between the emitted and received laser pulses (Degnan, 1993) and close attention to detail is necessary to simulate real world results. In order to perform the calculations presented here, a review of the SLR system was made, identifying all the known values, measurements and best estimates relevant to the performance of the different station components.

The divergence of the emitted laser beam was measured using a satellite scanning method (Burris et al., 2013). Pointing errors were estimated as an average bias based on observer experience plus random pointing errors modelled as a Gaussian distribution. Atmospheric transmission was estimated from local visibility measurements and the values were tested with photometry star calibrations. Retro-reflector array cross sections were computed from diffraction theory in combination with the velocity aberration of each satellite. For spherical LRA targets, the retro-reflectors were simply assumed to be evenly distributed. For Jason-2, actual retro-reflector positions and spacecraft attitude law were considered.

The simulations shown here are the result of performing link budget calculations for a number of satellites for all the passes visible from SGF for a period of several months, in an attempt to reproduce the empirical data available from actual laser ranging operations.

Results

For each satellite, the energy densities were plotted against range and averaged in bins. These averages for Lageos1 and Lageos 2 are shown on the left in figure 1 for the 12Hz and 2kHz systems. At a range of 7000 km for the 12Hz system the energy density from the Lageos satellites is between 0.003 and 0.004 femtojoules per m^2. For the 2kHz system this value is lower at approximately 0.00045 fJ/m^2. On the right hand side are plotted the corresponding energy densities estimated using the link budget. At 7000km range for the 12Hz and 2kHz systems the energy densities are estimated at approximately 0.035 fJ/m^2 and 0.0014 fJ/m^2 respectively. The energy densities estimations are larger by factors of about 10 and 3 respectively.

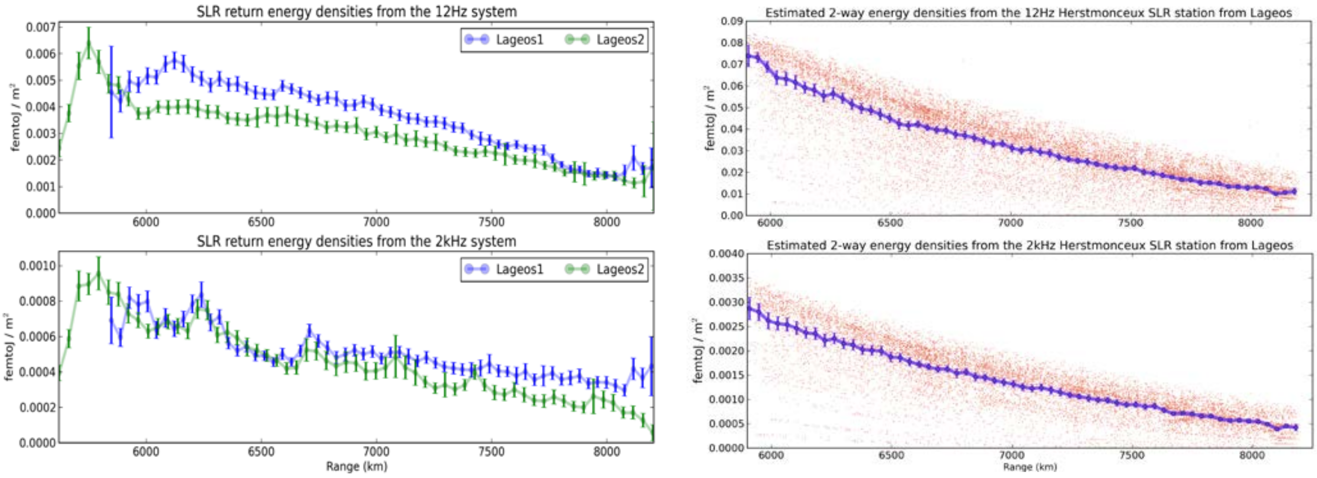

Figure 1. Return energy densities binned in range for the Lageos satellites for the 12Hz and 2kHz SLR systems. The left hand plots show the measurements made at the SGF, Herstmonceux and the plots on the right contain the link budget estimations.

Figure 2 contains the equivalent plots for the Starlette and Stella satellites. These satellites are similar in size and shape but have different orbital properties with Starlette having a larger eccentricity and Stella an inclination of 98.6 degrees. At 1200 km the 12Hz and 2kHz return energy densities are 0.03 fJ/m^2 and 0.0035 fJ/m^2 respectively. The estimated energy densities are 7 fJ/m^2 and 0.3 fJ/m^2. The agreement is significantly poorer with the estimated values being far greater than those measured at the station for these satellites.

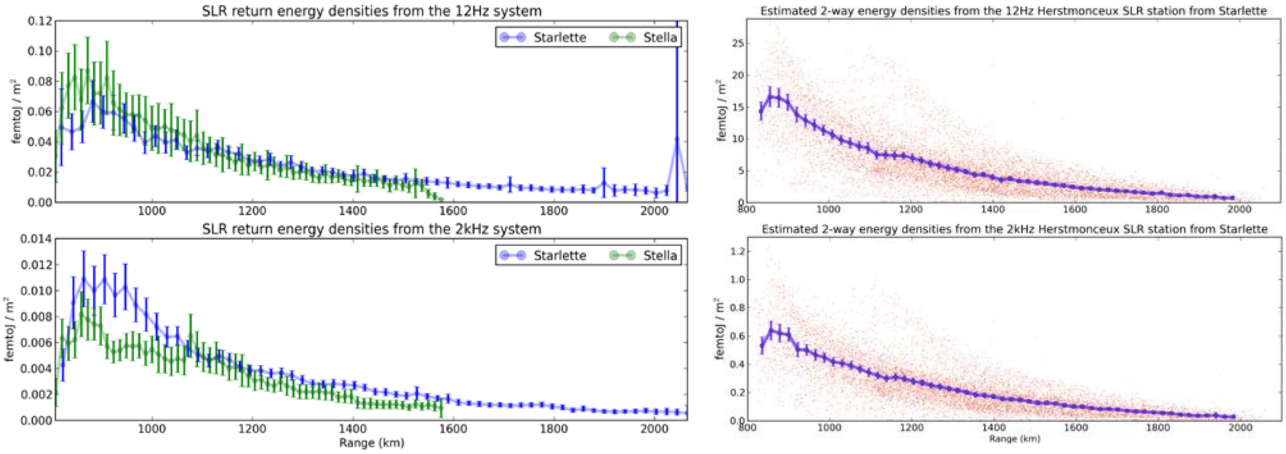

Figure 2. Return energy densities binned in range for the Starlette and Stella satellites and the 12Hz and 2kHz SLR systems. The left hand plots show the measurements made at the SGF, Herstmonceux and the plots on the right are the Starlette link budget estimates.

Figure 3 shows the measurement and link budget estimations for Jason-1 and Jason-2. At a range of 1800km the 12Hz system measured average energy densities between 0.015 and 0.02 fJ/m^2. The 2kHz system recorded between 0.002 and 0.003 fJ/m^2. The 12Hz and 2kHz estimates are approximately 0.6 fJ/m^2 and 0.025 fJ/m^2 respectively. Again, the energy density estimations are greater than the measured values.

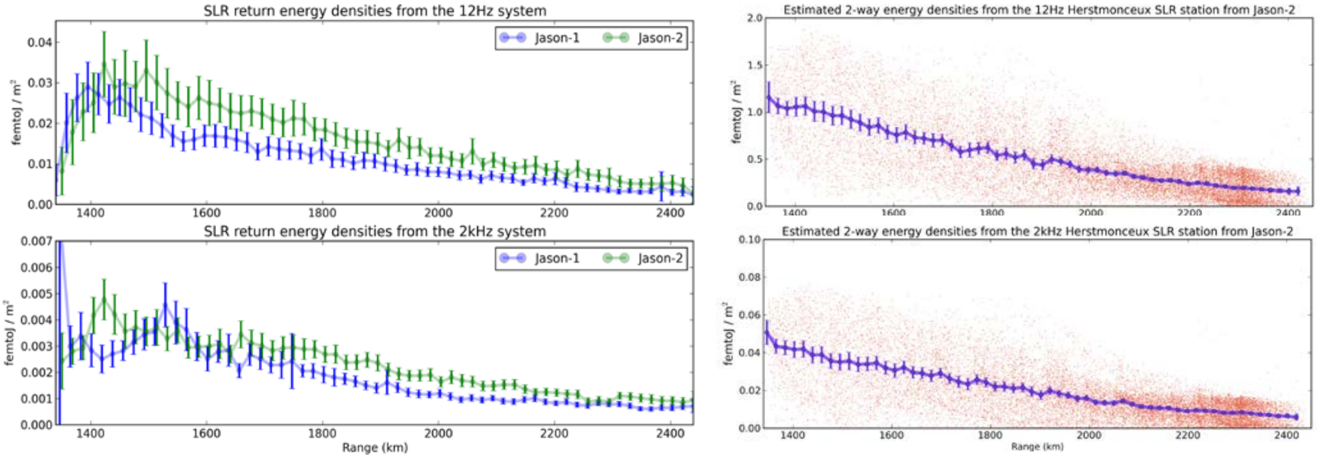

Figure 3. Return energy densities Jason-1 and Jason-2 for both SLR systems. Measured energies are plotted on the left and link budget estimates on the right.

Measurements in Orbit

Jason-2

Jason-2 was launched in the summer of 2008 to follow on from the TOPEX/Poseidon and Jason-1 missions. It monitors global ocean circulation, the tie between the oceans and the atmosphere, events such as El Nino conditions and ocean eddies. In addition, Jason-2 carries the Time Transfer by Laser Link (T2L2) payload which offers the capability to compare ground clocks at different stations (Exertier et al., 2010), particularly those in common view, with an accuracy of better than

100ps. The T2L2 unit uses two photo detectors. The first is linear and records the incident energy of incoming laser pulses and the background from the Earth's albedo. It is used to provide a gate to the second non-linear detector in geiger mode which is used to trigger the event timer and make the T2L2 measurement. In front of each detector is a graded neutral density filter with a profile that accounts for the distance to the satellite and the atmospheric attenuation. This is used to minimise the dynamic energy received during a pass. The raw energy density data is corrected to account for this filter to give a measurement in J/m^2, in the plane perpendicular to the line of sight.

Figure 4 shows energy densities at Jason-2 for the 12Hz system. The first upper plot shows 4 second averages of the values recorded which are plotted in range and binned to give averages. The lower plot contains the estimated values using the uplink link budget. At 1800km the recorded values and estimated values are approximately 0.6 $\mu J/m^2$ and 0.25 $\mu J/m^2$. The averaged recorded values are greater than the estimations.

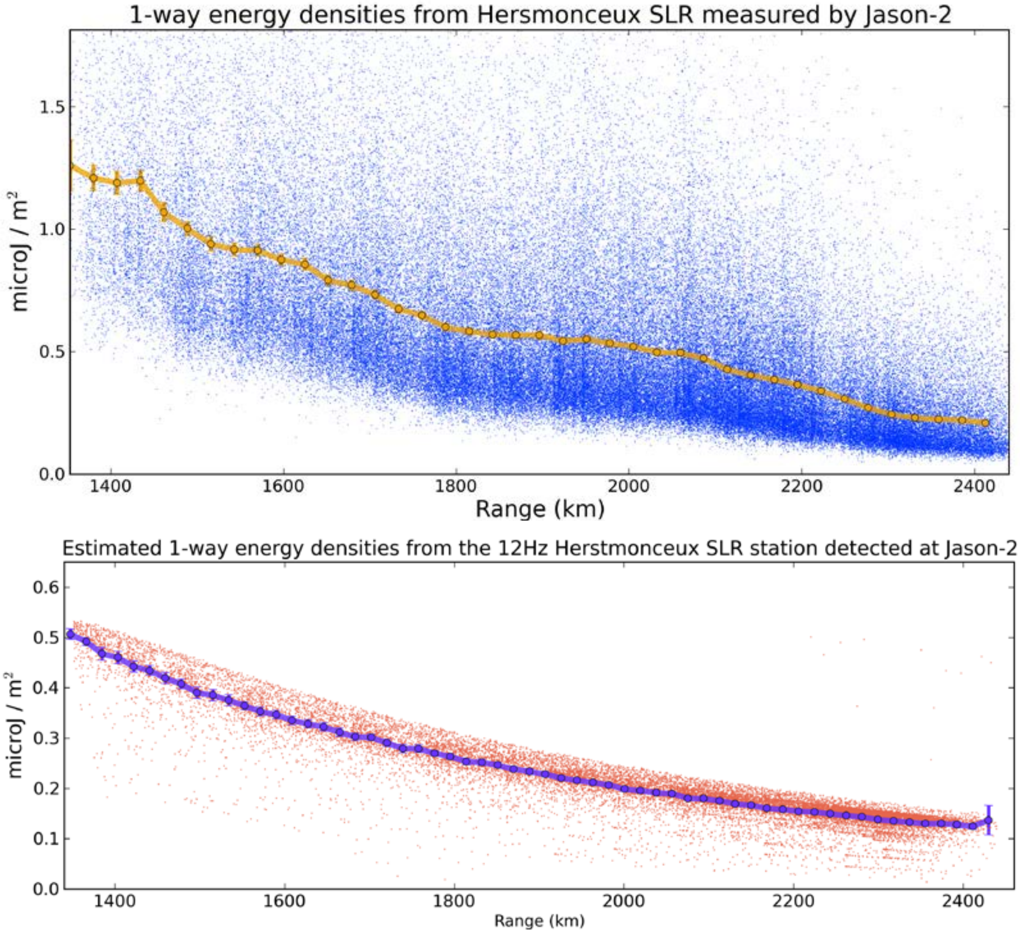

Figure 4. Energy densities recorded at the Jason-2 satellite plotted against range in the upper plot and the corresponding uplink estimations in the lower plot.

The values in the upper plot in figure 4 are spread in energy and reach large values above the plotted y-axis at lower ranges. It is believed that this is due to atmospheric turbulence causing scintillation, which can be characterised by a log-normal distribution. Figure 5 shows a histogram of Jason-2 data and a log-normal function describing the distribution very well.

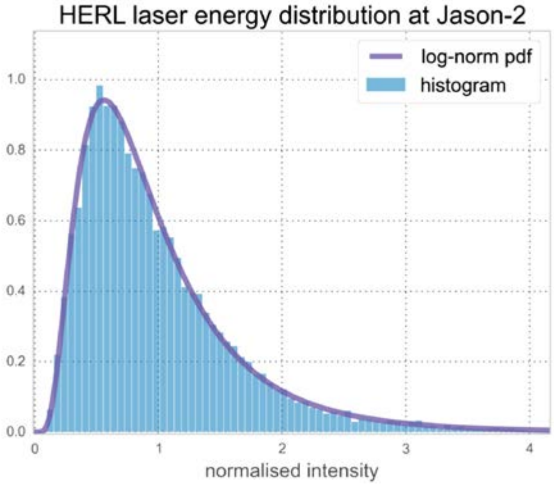

Figure 5. A histogram of energy densities recorded at Jason-2 and a log-normal probability density function giving a good fit to the asymmetric spread of the data.

LRO

The LRO mission was launched in June 2009 and orbits the lunar surface at a heights of approximately 50km. Laser ranging to the LOLA instrument on board LRO provides relative range measurements to the spacecraft at better than 10cm precision per shot. The SGF synchronises its laser fire with the gating of the LOLA detector at a rate of 14Hz. Each detected incoming pulse is recorded and a measurement of energy is made. The clear aperture of the receive telescope is 1.9 cm in diameter.

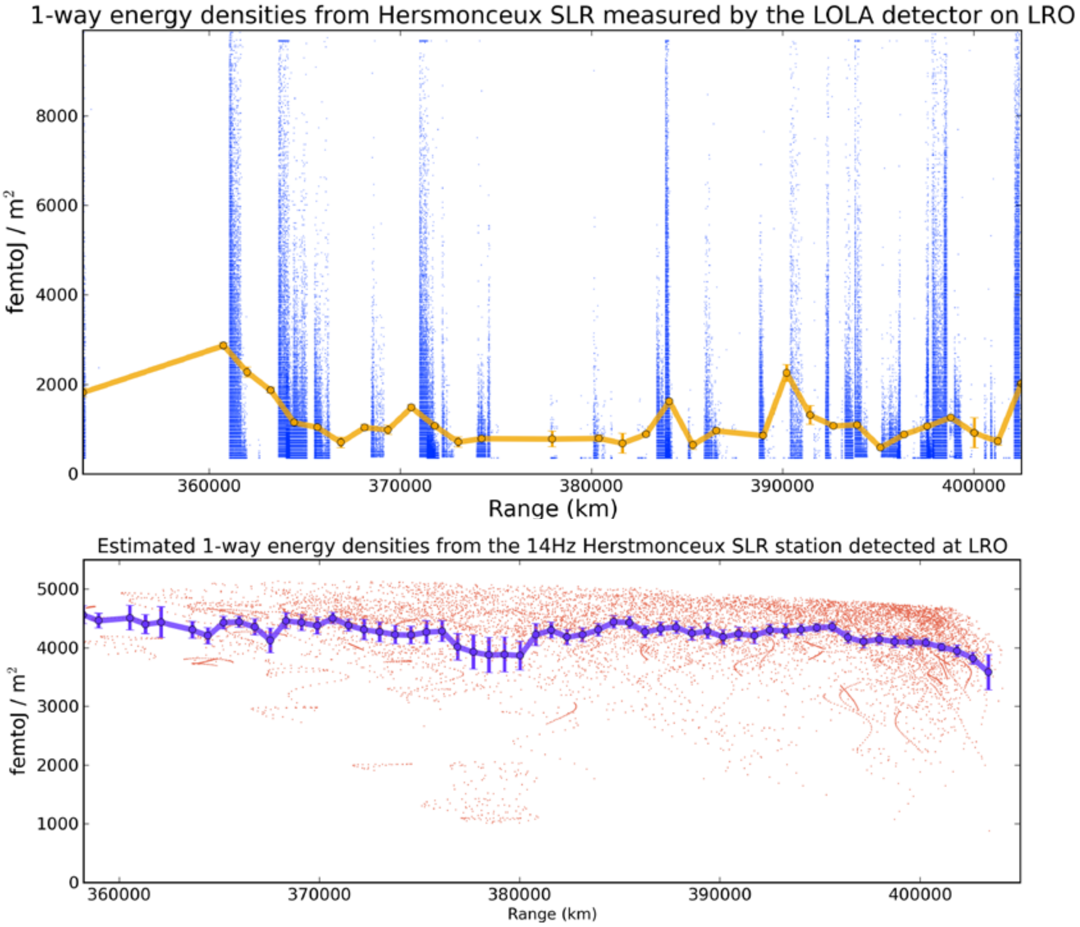

Figure 6. Energy densities recorded by the LRO satellite orbiting the Moon plotted against range. Uplink estimations are plotted in the lower plot.

The upper plot in figure 6 shows the energy densities of SGF laser pulses detected at LRO plotted against range. Averages are taken in range bins and are also plotted. There again seems to be an uneven spread in recorded energies but the averages are between 1000 and 2000 fJ/m^2. The lower plot in figure 5 contains the estimated energies from the uplink link budget and the averages are between 4000 to 5000 fJ/m^2. The estimations are, unlike as with Jason-2, larger than the averaged recorded energy densities.

Conclusions

The SGF, Herstmonceux has a variety of laser pulse energy density measurement data sets in its possession. These consist of the 2-way return energy density measurements made at the station for different SLR satellites at low and high repetition rates and the in-orbit measurements recorded by the Jason-2 and LRO satellites made available by our colleagues at OCA, CNES and NASA. In the case of the SGF energies, it was only possible to reproduce these data sets because of the on-site archive of raw SLR data and real-time logging of all the system variables related to SLR operations.

Detailed link budget calculations have resulted in high quality two-way estimations for a selection of satellites as well as one-way estimations for Jason-2 and LRO. These estimations will help to advance our understanding of the losses in out SLR system and to develop the models used. Comparisons between the averages of these datasets have shown some reasonable agreement between the estimated and observed values but remaining disagreement is significant and requires further explanation. The one-way estimations agree more closely with the values recorded at the satellites. The evident disagreement in the measured and estimated two-way energies suggests that either not all factors are being considered or that a more detailed treatment is needed for some of them.

Possible candidates to explain the differences between the empirical and simulated data include the LRA cross-section computation and non-modelled turbulence effects. It is also conceivable that accumulation or errors, lacking knowledge of some system performance variables and other unconsidered factors may explain a large fraction of the differences observed. Plans to improve the quality of the simulation and understanding of the system, as well as further analysis of the data sets available are considered as part of future work on this topic.

Acknowledgements

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