Footprint scale Surface Roughness from ICESat Pulse-Widths: Lessons learnt for Future Planetary Laser Altimeters. W.D. Poole[1,2] (william.poole.10@ucl.ac.uk), J.-P. Muller[1,2], P.M. Grindrod[2,3], and S. Gupta[4], [1]MSSL-UCL, Dorking, Surrey, RH5 6NT, UK, [2]Centre for Planetary Sciences at UCL/Birkbeck, Gower Street, London, WC1E 6BT, UK, [3]Dep. of Earth and Planetary Sciences, Birkbeck, University of London, Malet Street, London, WC1E 7HX, UK, [4]Dep. of Earth Science and Engineering, Imperial College, London, SW7 2AZ, UK.

Introduction: Secondary science goals for the MOLA and LOLA instruments included assessing laser footprint scale surface morphology (5 and 150 m respectively) from the width of backscatter laser pulses [1,2]. However, our previous work has shown that pulse-width data from these instruments is a poor indicator of surface slope and roughness as measured from high-rsolution digital terrain models (DTMs) [3,4]. To try to understand the cause of these findings and to test whether, on a practical level, surface roughness and/or slope can/cannot be determined from planetary laser altimeter pulse-widths, we explored the relationship between ICESat's Geoscience Laser Altimeter System (GLAS) backscatter pulse-width data and surface roughness and slope estimates from high-resolution DTMs over the McMurdo Dry Valleys, Antarctica [5].

After assessing pulse-width data from MOLA and LOLA we found the MOLA instrument to be unreliable at determining surface roughness and slope over smooth terrains, whilst the pulse-widths correlate well with footprint scale (~70 m) slope over rough terrain, such as Aureum Chaos [3,4]. On the other hand, LOLA pulse-width data was shown to correlate very well with footprint scale (5 m) slope, but only for a select number of orbits [4]. The remaining orbits showed no correlation, which results in this particular dataset being unusable on a global scale [4].

Unlike these instruments, ICESat/GLAS data contains the full backscatter waveforms (in 1 ns bins) as well as a variety of additional products which enable us to filter out shots affected significantly by atmospheric effects. Analysis of these full backscatter waveforms should allow us to identify the source of poor correlations in previous work or find new methods of extracting terrain characteristices from the backscatter profile data which may benefit the design of future planetary laser altimeter instruments.

Theory: Theoretically, the backscatter pulse-width of a laser pulse is as a product of: outgoing pulse-width, instrument effects, beam curvature, and terrain characteristics [6]. The first three are known, and can therefore be factored out, leaving behind the effects due to terrain, which can then provide an indication of the roughness or slope of the terrain within the footprint. If the background slope is also known, then this too can be factored out, leaving behind the effects due to small scale roughness from this slope [7].

Study Site: The primary science goal of ICESat/GLAS was to measure the change in elevation of terrestrial ice sheets and sea ice coverage by repeatedly taking elevation measurements in a 91-day fixed near-polar orbit (94° inclination) [5]. This orbit, which is similar to the orbits of both MOLA and LOLA, produces a higher concentration of shots near the poles. The McMurdo Dry Valleys region was chosen as a calibration site for the mission with this in mind, and because they contain extensive areas of permanently ice- and snow-free terrain, which means the region remains stable for the lifetime of the mission [5]. As part of the calibration the area was surveyed by NASA's Airbourne Topographic Mapper (ATM), the DTM's from which, were used in this study [5].

Method: As with previous studies, surface roughness and slope estimates from high-resolution DTM's were compared to backscatter pulse-widths to assess the relationship between them. The DTM data was available with 2-4 m post-spacing. In this study the geolocation and geometry of each footprint is known, so instead of assuming a circular footprint and producing surface roughness and slope maps, elevation data was extracted within each footprint before the following values were calculated for each footprint: the RMS height, range, slope of a best-fit-plane, and detrended RMS height calculated from the deviations from the best-fit-plane. These values were then compared to pulse-widths provided within NASA's GLAH05 dataset and those calculated from the backscatter profiles using different thresholds, so as to determine the method with the strongest correlation between pulse-width and within-footprint roughness or slope. Pulse-shots which were taken in potentially cloudy conditions, or over ice rather than bare terrain were not considered here, so that of the 36,000 shots taken during the lifetime of the mission (2003-09), typically around 4000 were used here, of which ~200 adhere to strict quality control (SQC), discussed below. Additionally, one can also account for the Gaussian distribution of transmitted energy within the pulse, with peak energy (i.e. photons) concentrated towards the centre of the footprint rather than an even distribution.

Results: Pulse-widths calculated using the 5% and 10% of backscatter peak profile height produced the best correlations with surface roughness and slope estimate, with R^2 values between 0.74 and 0.79 using typical pulse-shots (Figure 1). When the SQC shots are used, an R^2 of 0.67 is observed between 5% peak pulse-widths and detrended RMS height, meaning that small scale deviations from background slope, as mentioned in [7] can indeed be found when the background slope is known (Figure 2). This only applies when shots that have been affected by atmospheric scattering have been removed, and shows that the process of finding detrended roughness is sensitive to atmospheric influences which may influence the pulse-width by a few ns; additionally, one must also account for the Gaussian distribution of transmitted energy within the pulse. We also found that different relationships exist between pulse-widths and surface characteristics for each Operational Period of the instrument, which due to failings in laser 1 shortly after launch, represent 33-day subsets of the 91-day repeat orbit, with downtime inbetween. The difference between these operational periods appears to be laser output energy, although no relationship was found between the output energy and the corresponding correlations and gradients of the best-fit lines.

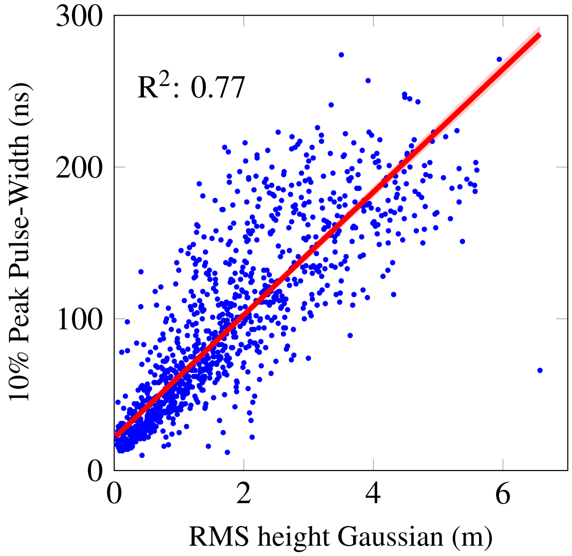

Figure 1. Pulse-widths calculated using a 10% Peak Energy threshold, plotted against RMS height taking into account of the Gaussian distribution of transmitted energy within the laser pulse.

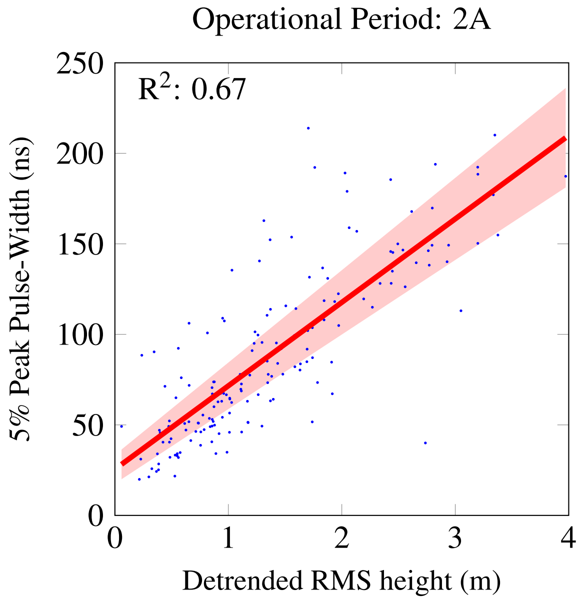

Figure 2. Pulse-widths calculated using a 5% Peak Energy threshold, plotted against detrended RMS height taking into account of the Gaussian distribution of transmitted energy within the laser pulse. This plot uses only the SQC shots in laser operational period 2A.

Disussion: A significant improvement in correlations between planetary laser altimeter pulse-widths and within footprint surface characteristics has been shown. This could be due to one or more of the following: an improvement in technology, transmission of full backscatter waveform, or better undersatanding of the Earth system, enabling better ancillary data needed to filter out poor data. Whilst atmospheric effects may be less of an obstacle some future laser altimeters, the extreme conditions in which they must operate may pose a problem [8]. And, whilst the method of obtaining footprint scale surface morphological characteristics is unlikely to have an influence on future mapping of Mars and the Moon, where high-resolution stereo imagery have enabled us to produce high-reolution DTMs, it may have an influence on terrains mapped only in low resolution, such as Mercury, or the icy moons of the Giant Planets.

Conclusion: The results presented here allow us to confirm that the theory behind derving footprint scale surface morphological characteristics from backscatter pulse-widths appears to be correct, and may work given the right conditions, the main one of which is to use the full backscatter pulse waveform. More interestingly, even small scale deviations from background slope can be found as proposed in [7] (assuming this is also known). Future work will now explore the resolution at which this background slope is required to be known, for this to be applicable, and whether the removal of backgroud slope can account for the poor results found using MOLA [3].

References: [1] Smith, D.E. et al., 2001, JGR, 106(E10), 23689–23722. [2] Smith, D.E. et al., 2010, GRL, 37(18). [3] Poole et al., 2012, 43rd LPSC, abstract: 1854 [4] Poole et al., 2013, 44th LPSC, abstract: 1511 [5] Schutz, B.E. et al., 2005, GRL, 32(21). [6] Gardner, C.S., 1992, IEEE Trans. on GRS, 30(5), 1061–1072. [7] Neumann G. et al., 2003, GRL, 30(11), 1561–1354. [8] Thomas, N. et al., 2007, PSS, 55(10).