LASER PULSE CORRELATION: A METHOD FOR DETECTING SUBTLE TOPOGRAPHIC CHANGE USING LIDAR RETURN WAVEFORMS

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KEYWORDS: LIDAR, laser altimetry, waveforms, natural hazards, surface deformation

ABSTRACT

We present a technique for using the recorded laser return pulse as a raw observation to detect centimeter-level vertical topographic change from large footprint airborne and spaceborne laser altimetry. We use the correlation of waveforms from coincident footprints as an indication of the similarity in structure of the waveforms from epoch to epoch, and assume that low correlation is an indicator of vertical structure or elevation change. Thus, using vertically and horizontally geolocated waveforms as raw observables (i.e., waveforms tied to a common reference ellipsoid), we assess whether epoch-to-epoch vertical ground motion results in a decrease in the correlation of coincident waveforms over time, and whether this can be used to quantify the magnitude of the deformation. Results of computer models and an example over an area of eroded beachfront are described.

1 INTRODUCTION

Laser altimeters provide a precise and accurate method for mapping topography at fine horizontal and vertical scales. A laser altimeter provides range by measuring the round-trip flight time of a short pulse of laser light from the laser altimeter instrument to the target surface. This range is then combined with ancillary information describing the position and attitude of the laser at the time of each shot to derive the horizontal and vertical position of each laser footprint relative to a known reference surface (i.e., WGS-84) (e.g., Hofton et al., 2000b).

Newer generations of airborne (e.g., Blair et al., 1999) and spaceborne (e.g., Dubayah et al., 1997) laser altimeters measure the range by recording the shape and time of the outgoing and received laser pulses. The shape of the return pulse provides unique information about the vertical structure of material such as vegetation within each laser footprint. The shape of a return pulse can be as simple as closely resembling the shape of the outgoing laser pulse, or extremely complex (containing multiple modes) and temporally distorted. Distortion of the return pulse is caused by the time-distributed reflections from vertically distinct layers of material within the footprint. While extremely small diameter footprints typically return simple pulses, larger footprints (10 – 100m in diameter) can contain numerous vertically distinct target surfaces and thus provide the potential for producing complex return pulses.

Interpreting the return pulse from laser altimeters has evolved from methods involving real-time analog timing between thresholds, constant-fraction discriminators, multi-stop time interval units, and using post-processed range-walk corrections, to actual recording of the time varying return pulse intensity, i.e., the return waveform. Post processing of the waveform can involve thresholding the return pulse to identify timing points, calculating a centroid to find the "center", or fitting one or more gaussian pulses to the signal to separate the individual surface reflections (Hofton et al., 2000a). The laser derived elevations resulting from these interpreted laser ranges are used for a variety of purposes, from producing topographic data sets for scientific or commercial studies, to providing ground truth for the validation and calibration of other remote sensing data sets. Due to the inherent precision and accuracy of laser-derived topography, these data enable unique studies of topography including the detection of topographic change over relatively small horizontal scales and small vertical change over large areas.

2 DETECTING ELEVATION CHANGE

Natural hazard monitoring requires repeated measurements of surface topography whose change reflects some geologic or hydrologic process. A simple and direct method for detecting vertical topographic change is to sample the elevation at two separate epochs and difference the coincident measurements (dubbed spot comparison method). This method has been used successfully in regions of simple terrain, for example, to precisely detect vertical elevation changes at Mt. St. Helens (Garvin et al., 1996), Assateague Island, MD (Krabill et al., 1999), and on the Greenland ice cap (Krabill et al., 1995). Problems can arise however if the laser return pulse is complex in shape or noisy, resulting in misinterpretation of the return pulse (either in real-time or post-processing) and a decrease in accuracy of the laser altimeter elevation measurement.

An alternative approach involves the return pulse correlation method (Hofton and Blair, 2000) which uses the shape similarity of near-coincident, vertically-geolocated laser return waveforms from two observation epochs to detect vertical change. A similar method was used previously by Blair and Hofton (1999) to assess laser footprint geolocation accuracy. The shape similarity of two coincident waveforms from different measurement epochs is assessed using the Pearson correlation, a ratio between the shared variance of the two waveforms and their individual variances (Figure 1). If no change in the vertical structure within the footprint area occurred between measurement epochs within the vertical and horizontal extent of the waveforms, then two coincident, temporally distinct, geolocated waveforms will have a high level of correlation. Poorly correlating waveforms indicate that either vertical ground deformation or some kind of vertical structure change (for example, vegetation growth or loss) has occurred. The benefit of the pulse correlation method is that it eliminates subjective interpretation of individual waveforms and the errors resulting from any misinterpretation, especially in circumstances where the waveform is extremely complex.

For this initial study to estimate the capability to detect centimeter-level ground deformation, we assume that the ground deformation is the dominant source of vertical change within the area of the laser footprint (otherwise we risk confusing the ground elevation change with surface structural change such as tree growth). Consequently, we assume that changes in surface elevation result in corresponding changes in the elevations of all reflecting surfaces within the laser footprint between measurement epochs. That is, that all the modes within the waveform are moved up or down relative to the reference surface by an amount corresponding to the ground deformation that occurred. The amount of ground deformation is determined by calculating the correlation of the geographically coincident waveforms from different measurement epochs as the waveforms are vertically shifted relative to each other. The vertical shift at which the maximum correlation occurred indicates the amount of vertical change that occurred between the two epochs at that location. This forms the basis of the pulse correlation method.

Notice that we perform no interpretation of the laser waveform itself, even if the elevation of the desired reflecting surface has previously been misinterpreted (e.g. during real-time processing on the instrument). Thus, we are using an unbiased representation of the surface from which to extract elevation change. A constant bias or offset between the data sets is likely an indication of a systematic error or measurement bias that is easily removed, whereas variations in the vertical offset within or across an area may indicate actual vertical ground deformation signal.

3 RESULTS OF COMPUTER SIMULATIONS

To assess the sensitivity of the pulse correlation technique across an image of return waveforms, we generated a simulated set of laser altimeter waveforms from a series of surfaces with varying roughness and slope characteristics using the method of Blair and Hofton (1999). The surfaces were then deformed using the equation for a Mogi point source to simulate the effect of volcanic intrusion beneath the surface. A second set of waveforms, corresponding to the deformed surface, were then generated. We compared the two sets of waveforms using the pulse correlation method in order to recover the applied deformation signal. Waveforms correspond to 25m-wide footprints, with a laser pulse width of 0.6893m, and digitizer bin width of 0.2997m. Centimeter-level deformation is clearly visible in the results (Figure 2). To assess the potential for this technique under what may be more realistic data collection circumstances, the co-location between the two sets of waveforms (corresponding to the original and the deformed surfaces) was varied to evaluate the degradation of vertical sensitivity resulting from any misalignment between data sets. The results show that moderate horizontal offsets (i.e., several meters) between footprints from the two epochs do not degrade the vertical precision of change detection significantly. Although some horizontal averaging is required to improve the vertical resolution, we can clearly see centimeter-level deformation in the simulated data.

4 BEACH EROSION RESULTS

Assateague Island, MD, is an area that has been extensively surveyed on an almost annual basis using the small-footprint Airborne Topographic Mapper (ATM) system (Krabill et al., 1999). The island is a highly dynamic barrier island of the Atlantic coast, and is characterized by high levels of coastal change in which tens of meters of land can be lost or gained in a matter of months. Return waveforms were synthesized from the 1996 and 1997 ATM data sets using the method of Blair and Hofton (1999) to assess the feasibility of using the laser pulse correlation method to detect vertical change using large footprint laser data in an actively deforming region. The deformation results obtained using the pulse correlation method

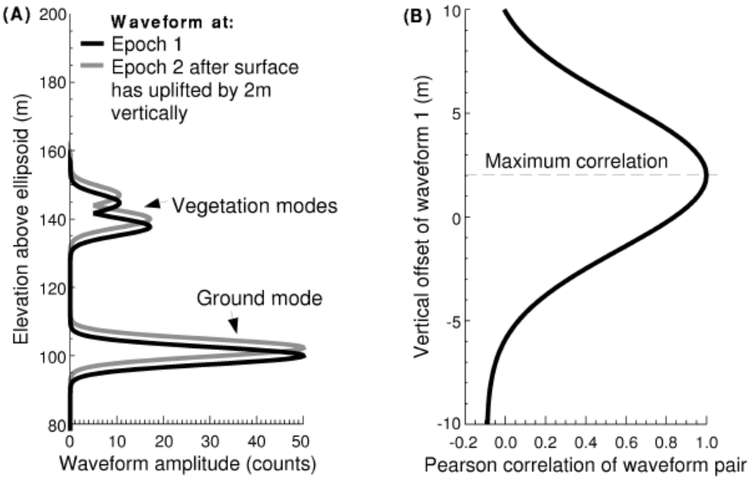

Figure 1. Overview of the pulse correlation method. (a) Two example, geolocated return laser waveforms from the same location but at different measurement epochs showing the effect on the individual waveform modes of 2m of surface uplift occurring between the two measurement epochs. The waveforms contain ground and vegetation modes. The modes within the return waveform collected at the later epoch are higher relative to the reference ellipsoid than at the first measurement epoch. (b) The Pearson correlation of the waveform pair versus their vertical offset. The maximum correlation occurs when the earlier-collected waveform is shifted up by 2m relative to the ellipsoid, i.e., this is the amount of uplift that occurred between the observation epochs.

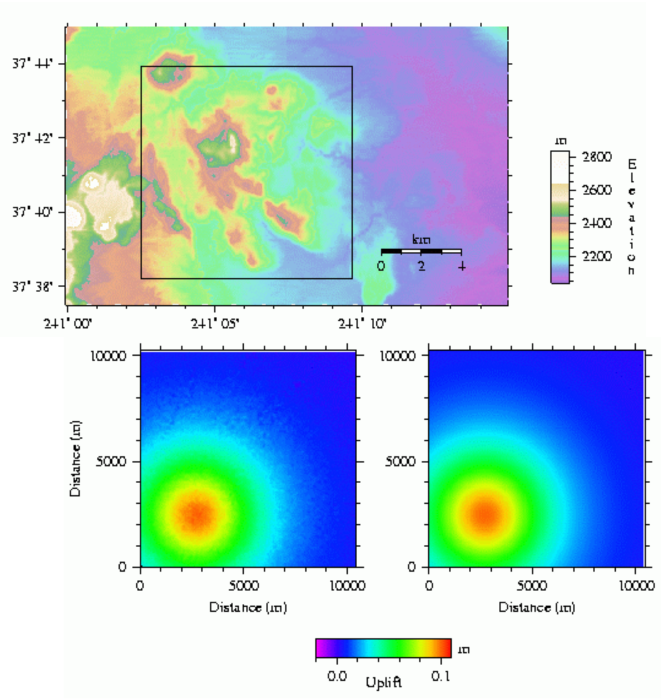

Figure 2. DEM of Long valley, CA. Topographic elevation is colored using the scale on the right. The box indicates the area whose surface elevations were deformed using a Mogi point source. Waveforms corresponding to both the undeformed and deformed elevation surface were synthesized, and compared using the pulse correlation method. The recovered and applied deformation fields are shown in the lower left and right of the figure respectively. The images are shaded according to the amount of uplift. The root mean square (RMS) difference is 0.014 cm.

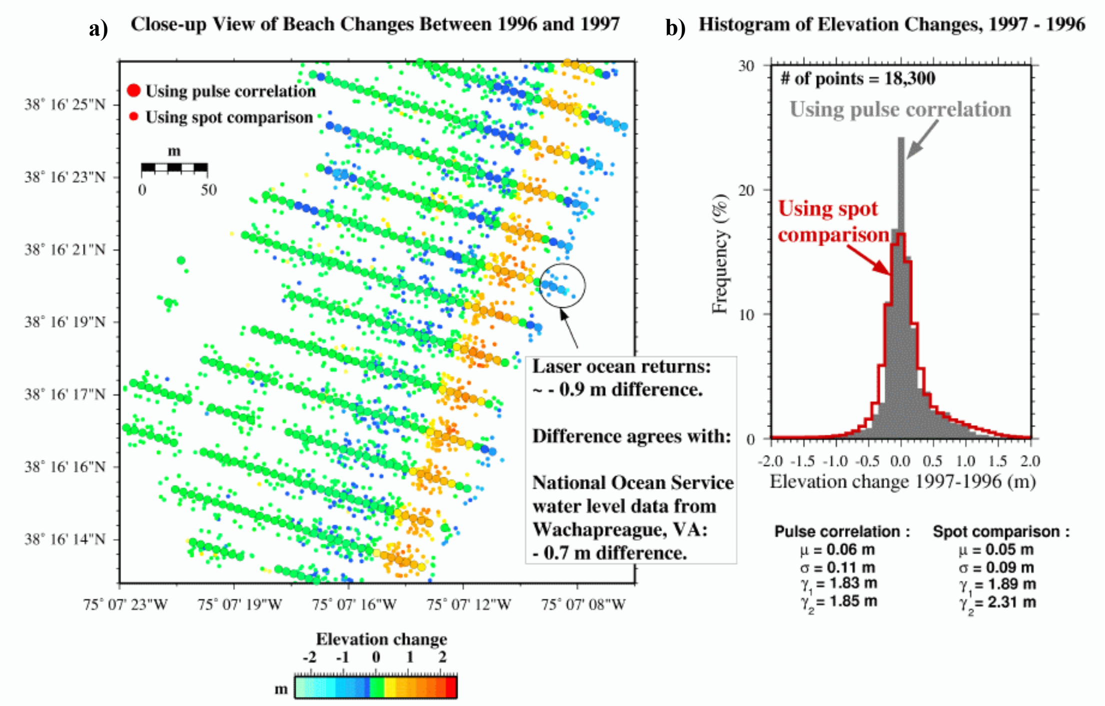

Figure 3. (a) Vertical elevation change detected along part of the Assateague Island beach, 1997-1996. The footprints within which waveforms were synthesized are outlined in black and colored using the amount of change detected using the pulse correlation method. The smaller footprints are those of the ATM, colored using the amount of change detected using the spot comparison method. Neither footprint set is drawn to scale. The elevation change scale bar is shown bottom right. (b) Distribution of vertical elevation change estimates along Assateague Island from 1996 to 1997 determined using the spot comparison (open histogram) and pulse correlation (shaded histogram) methods. The mean, standard deviation, skewness and kurtosis are denoted by ì , ó, ã$_1$, and ã$_2$ respectively.

are also compared to deformation results obtained from the comparison of spot elevation measurements on a footprint-by-footprint basis to establish the accuracy of the laser pulse correlation method relative to a more traditional technique.

Along the ~18 km-long stretch of coastline studied, up to 1.5 m of accretion occurred along the beach front from 1996 to 1997, with the widest zone of accretion occurring to the north. The majority of the area west of the beachfront underwent little or no change, except in the southern part of the surveyed region, where erosion of up to 0.5 m occurred immediately behind the beachfront. A small area (400m by 200m) of the beach front is shown in Figure 3. The amount of vertical elevation change detected using pulse correlation within each laser footprint is shown. For comparison, the elevation change from 1996 to 1997, derived by subtracting the elevation of the 1996 ATM spot closest (within a 1 m search radius) to each 1997 ATM spot are also shown. Similar patterns of deformation to that detected using the pulse correlation method are observed. Areas of deposition and erosion correspond and are of similar magnitude. Some ocean returns remained in the data. These show approximately -0.9 m of vertical change (Figure 3) because of the difference in tides at the times of the 1996 and 1997 surveys. This difference is consistent with that obtained from the differencing of water level data collected by the National Ocean Service (NOS) station at Wachapreague Island, VA, (~60km south west of Assateague Island), a difference of about -0.7m in elevation between the times of the ATM surveys in 1996 and 1997 (NOS, 2001). The difference between these predictions likely results from the proximity of the ocean returns to the shore and the distance of the water level station from the laser measurements. The distributions of elevation changes from 1996 to 1997 using the pulse correlation and spot differencing methods are similar in shape and have similar mean changes, standard deviations, and skewness values (Figure 3). The use of the pulse correlation method gives nearly identical vertical ground deformation estimates to those derived using a spot comparison method in this actively deforming region (Hofton and Blair, 2001).

5 SUMMARY

We show that by treating large-footprint laser altimeter return waveforms as “raw observations” we can potentially detect centimeter-level vertical change in topography and greatly reduce the potential for misinterpretation of the return waveforms. It is hoped that this technique will allow precise vertical topographic change detection from large-footprint, spaceborne laser altimeter data. Since this method is not restricted to use only under “bare Earth” conditions, it could potentially be used to complement change detection data collected by Interferometric Synthetic Aperture Radar, the current baseline measurement in natural hazards and surface change detection. The use of laser pulse correlation with medium-large (i.e., 10-100 m diameter) footprint laser altimeter waveforms cuold enable some altimeter system requirements such as footprint diameter and laser pulse-width to be relaxed to allow faster and easier change detection data collection over wider areas.

ACKNOWLEDGEMENTS

The authors would like to thank W. Krabill, E. Frederick, and the ATM group; and the members of the VCL team, in particular S. Luthcke, R. Dubayah, R. Knox, N. Casey-McCabe and D. Rabine. This work was funded as part of the calibration/validation activities of the Vegetation Canopy Lidar Science Team.

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