Laser
Review

Satellite Laser Altimetry:
On-Orbit Calibration Techniques for Precise Geolocation

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In the thirty years since the launch of the Skylab radar altimeter, satellite-based altimetry has proven to be a powerful tool to map the Earth and other planets. In order to fully exploit an orbiting altimeter, it is necessary to calibrate certain parameters not only before launch, but also after the altimeter is in orbit. Over the years, techniques have been worked out for on-orbit calibration of radar altimeters. Our use of Earth-orbiting satellite laser altimetry began in 1996 with the Shuttle Laser Altimeter. Although laser altimetry presents unique opportunities, it also requires new on-orbit calibration techniques. These techniques are still evolving and include the integration of multiple tracking data types with planned pointing maneuvers over oceans and waveform analysis. This paper describes on-orbit calibration techniques for the several missions that have flown laser altimeters to date and for laser altimeter missions which will launch in the near future.

Key Words: Laser altimetry, Orbit determination, On-orbit calibration techniques, Instrument biases, Altimetry geolocation

1. Introduction

The opportunity to develop laser altimeter instruments for routine operations in space originated with the Mars Observer Laser Altimeter (MOLA) investigation in 1988. The laser altimeter measurement technique and MOLA-1 instrumentation are described by Zuber *et al.*[1] The Mars Observer spacecraft that carried MOLA-1 failed at the point of insertion into Mars orbit and MOLA-2 was built and launched in November 1996 as one instrument of a replacement mission called the Mars Global Surveyor (MGS). While MOLA-2 was under construction, test, and launch preparations, a spare set of MOLA-1 laser, detector, and altimetry electronics were used successfully in Earth orbit on the Space Shuttle as the Shuttle Laser Altimeter (SLA). The SLA-01 payload operated in January 1996 in a 28 degree inclination orbit on Shuttle Mission 72 and then SLA-02 operated in a 57 degree inclination orbit on Shuttle Mission 85 in August 1997. Each SLA flight acquired over 1 million laser altimeter pulse returns of the Earth's surface. The SLA data have been used extensively, as described by Garvin *et al.*,[2] as pathfinders for the present generation of operational laser altimeters that starts with MOLA-2. The MOLA-2 instrument and MGS reached Mars in 1998 and began successful range measurements. At the present time MOLA-2 is well into its second year of operational mapping of Mars topography from the 400 km circular orbit of MGS. Smith *et al.*[3] describe the initial mapping data products of MOLA-2. As of November 2000 over 475 million laser altimeter measurements of Mars have been acquired. The MGS Mission is planned to extend into the year 2001.

The laser altimeter instrumentation common to SLA and MOLA are illustrated in Fig.1. The transmitter is a diode-pumped neodymium yttrium aluminum garnet (Nd:YAG) laser oscillator operated to produce 15-to-20 nsec wide, 20-to-50 milliJoule pulses (dependent on temperature) at a fixed rate of ten pulses per sec. The detector is a single-element silicon avalanche photodiode which is enhanced to work at the 1064 nm wavelength of Nd:YAG with greater than 30 % quantum efficiency. The altimetry electronics process the transmitted and received pulse waveforms to determine pulse-time-of-flight and thus range (*i.e.* distance) to the planetary surface. An instrument computer sends the altimetry data to the spacecraft and receives commands that are sent to the instrument to alter its data acquisition parameters. Separate spacecraft subsystems such as a star tracker, gyroscope, and range/range-rate electronics provide the pointing and tracking data that must be combined with SLA and MOLA altimetry data in order to locate the 3-axis coordinates of individual laser pulse measurements on the Earth or planetary surface.

A primary goal of any altimetry mission is the accurate deter-

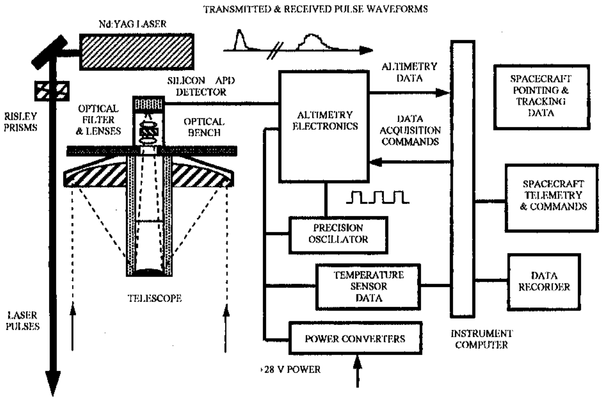

Fig.1 MOLA and SLA instrument configuration.

mination of the planet fixed coordinates of the spots (bounce points) on the planet illuminated by the altimetric ranges. The accuracy of this geolocation depends on accurate determination (calibration) of many different parameters. Some of these parameters can only be accurately calibrated while the altimeter is orbiting. All altimeters require an on-orbit calibration of range bias and instrument timing bias. With their small foot print and their ability to point off nadir, laser altimeters also need a thorough on-orbit calibration of the parameters which determine their pointing. The thermal behavior of the lasers as they are turned on or off or have their firing rate changed adds a level of complication to the calibration of pointing parameters.

Luthcke *et al.*[4] show the degradation in geolocation of laser bounce points which can arise from pointing misalignments and Luthcke *et al.*[5] show the benefit to shuttle laser altimeter geolocation from calibrating parameters which take into account not only pointing misalignments but also time variation in pointing misalignments. Rowlands *et al.*[6] found it necessary to calibrate a parameter which takes into account a bias in the time tagging of the Mars Global Surveyor spacecraft body attitude for the Mars Orbiting Laser Altimeter (MOLA).

In order to properly geolocate laser altimetry, it is quite likely that the following list of parameters need to be calibrated after launch:

Instrument timing bias
Instrument range bias
Instrument range scale bias
Timing Offset (time tag bias) for precision attitude solution

For Roll and Pitch:
Constant Bias
Linear Rate
Quadratic Rate
Periodic Variation (Amplitude and Phase) at near orbital period

Geolocation also depends heavily on the computation of orbits. Orbits for altimeter missions are usually computed from fundamental tracking types. These types include ground based tracking of the altimeter satellite like Satellite Laser Ranging (SLR), tracking received at the altimeter satellite from Global Positioning System (GPS) satellites and ground based tracking of the altimeter satellite through Tracking and Data Relay System Satellites (TDRSS). Laser altimetry (which is a tracking data type itself) can be withheld from orbit solutions that were based on more fundamental tracking data types. In that role, it is used to check (validate) these orbits. On the other hand, it can be combined with those other data types to provide potentially stronger orbital solutions.

We will discuss techniques to calibrate the above parameters and also to check (validate) the calibrations. We will focus our discussions on techniques which exploit three unique aspects of laser altimetry: the waveforms, the small footprint, and the ability to observe at off-nadir angles. The techniques will fall into two categories: satellite tracking data analysis (orbit determination) and matching observed elevation profiles and return waveforms to those predicted from Digital Elevation Models (DEMs). We will explore the integration of these two technologies and for tracking data analysis, we will explore the integration of laser altimetry with the other tracking data types which are commonly available.

2. Tracking Data Analysis

2.1 Radar Versus Laser Altimetry

Orbit determination solutions often use tracking data types which are measurements of range (distance) between a satellite and some other object. Often, the "other" object is a tracking station whose position is well known. However, there are other possibilities. For example, the "other" object can be the surface of the planet that the satellite is orbiting. This is exactly the case when altimetric ranges are used as a tracking data type. Radar altimetry has often been used in solutions for orbit and geophysical parameters. In addition to being used directly as range observations, altimetry has often been used to form constraint equations called crossovers at locations where altimeter ground tracks intersect (*i.e.* cross over). Crossover constraint equations exploit consistency conditions that should be met at these intersections.

When used directly as ranges, the a priori model distance (height) of the altimeter above the planet's surface is compared to the observed altimeter range. Differences (residuals) between the computed and observed ranges are attributed to errors in geophysical and orbital parameters and used to get improved estimates of these. Of course, in order to model the height of the altimeter above the planet surface, a detailed knowledge of the surface (distance from the center of mass of the planet to the surface) is required. Fortunately, the mean sea surface has been modeled quite well. The global root mean square error of that surface is probably well under 10 centimeters and the errors over open oceans are much better than that.[7] There are also high fidelity models available for tides and for other time dependent effects on surface heights.[8]

Crossovers exploit the fact that an altimeter will have illuminated nearly the same location at two different times as ground tracks intersect. Of course, the altimeter fires ranges at a finite rate, so there will be no bounce point from the ascending track which matches perfectly with any bounce point from the descending track. However, there will be a pair of bounce points from the ascending track whose planet fixed coordinates match closely with the coordinates of a pair of bounce points from the descending track. The latitude and longitude of the intersection of the ground tracks can be determined from these four points (more points can be used to exploit nonlinearities). Matching bounce points from the ascending and descending tracks can be inferred by interpolating so that the interpolated pair (one from each track) have identical horizontal positions (latitude and longitude). These matching bounce points will not necessarily have the same height (vertical component), even after correcting for time variations of the planet surface (like tides). After correcting for time variations in the surface, the vertical discrepancies are attributed to errors in orbital or geophysical parameters and are used to get refined estimates of these.[9] One advantage of using crossovers is that no a priori knowledge of the planet's surface elevations is required.

Radar altimeters have large footprints and they point nearly directly nadir (actually geodetically) so that the incidence angle over the ocean surface will be very nearly 90 degrees. At such angles any pointing misalignments would cause mainly horizontal errors in geolocation. As long as the pointing is maintained close to nadir, these horizontal errors will be very small relative to the size of the footprint. However, as the altimeter tilts off nadir the sea state bias is affected and this effect of attitude is calibrated with waveform analysis.[10] The geolocation of radar altimeter bounce points can assume perfectly geodetic pointing and this greatly simplifies the modeling of altimeter range observations and crossover constraint equations in tracking data residual analysis (orbit determination) software. Radar altimetry used either as ranges or as crossover constraints directly corrects only the radial components of a satellite orbit. However, it should be noted that correction of the radial component will affect the horizontal components of the orbit, especially the along track component. It should also be noted that crossovers have always been an excellent way to calibrate altimeter timing (time tag) biases.

Laser altimeters are often pointed at off-nadir angles and have small footprints. At nearly nadir angles, the horizontal errors in geolocation caused by pointing misalignments can be significant compared to laser footprint size.[1] At off-nadir angles, pointing misalignments contribute significantly to vertical error in geolocation. Furthermore, laser altimetry returns valid observations over rough and sloping land surfaces. Luthcke *et al.*[4] show the changes that need to be made to orbit software so that range modeling can account for the complications caused by the off-nadir pointing of an altimeter at a complex surface. Figure 2 illustrates the geometry involved. Rowlands *et al.*[6] advocate modifying traditional crossover constraints to exploit the small footprint and greater horizontal resolution of laser altimetry. That formulation exploits the fact that the altimeter observations from the ascending and descending passes surrounding the crossover location trace out two curves in space. Those curves contain signals from topography, orbit, pointing biases and instrument biases. The crossover discrepancy is considered to be the minimum distance between those two curves and the discrepancy is minimized through the estimation of orbit, pointing and instrument bias parameters. The constraint equation takes into account that the horizontal location of the crossover can be changed to exploit slope. Sloping terrain adds strength to parameter recovery.

$\hat{n}$ = nadir unit vector in LVLH
h = height above surface, m
S = surface slope, rad
θ = off-nadir angle, rad
ρ = range, m
σ_ρ = standard deviation of range, m
σ_θ = standard deviation of the pointing angles, rad

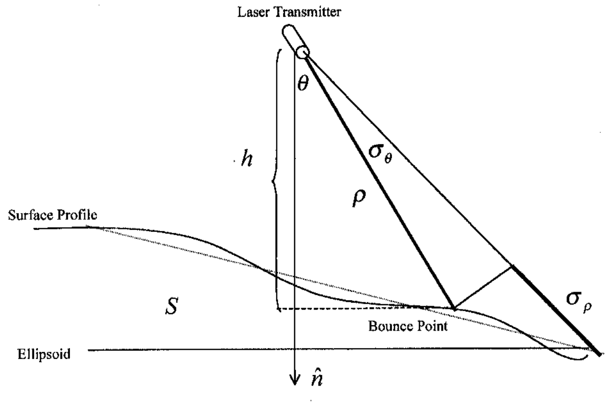

Fig.2 Simple laser range geometry (Luthcke *et al.*[4]).

When range and crossover constraint modeling take into account the attributes of laser altimetry, it is possible to get an accurate calibration of pointing misalignments. Luthcke *et al.*[5] demonstrate that direct laser altimeter ranges from the SLA-01 and SLA-02 can be used together with TDRSS Doppler tracking to simultaneously estimate the orbit of the Shuttle and pointing biases of the altimeters. They were able to demonstrate that the use of laser altimetry in the combined solution contributed to improved geolocation in two ways, the calibration of pointing parameters and through improved orbits. It is also possible to exploit the good horizontal resolution of laser altimetry over sloping terrain to directly correct the horizontal components of a satellite's orbit. Rowlands *et al.*[6] were able to use laser altimetry crossovers from MOLA to recover pointing biases on Mars Global Surveyor (MGS) and also strengthen the horizontal components of the MGS orbit as well as the radial.

2.2 Direct Laser Altimetry Ranges Over Oceans

A good bit of the Earth's surface is oceans, which have already been mapped extremely well by radar altimeters. The primary goal of laser altimeter missions like the Vegetation Canopy Lidar (VCL) and ICESat (Ice, Cloud and Land Elevation Satellite) is to measure the Earth's topography, land cover, and surface change. Furthermore, during nadir pointing ocean passes, altimetric ranges residuals are relatively insensitive to pointing misalignments. That is because the ocean surface has very small slopes so that a small change in horizontal location of a bounce point coming from pointing misalignments does not cause a change in range. Considering the above points, it can be advantageous to have a laser altimeter swing off nadir during ocean passes. At off-nadir angles of only a few degrees, the range residuals are quite sensitive to pointing misalignments. Luthcke *et al.*[4] give a detailed discussion of these ocean sweep maneuvers. The discussion shows how to design a maneuver so that the pointing parameters for roll and pitch will be orthogonal and so that the effect of unmodeled ocean phenomena like swells will be minimized. Expected accuracies of recovered parameters are presented taking data dropouts into consideration. Practical design considerations are also discussed. It should be noted that in the SLA-01 and SLA-02 analysis of Luthcke *et al.*,[5] direct altimetry ranges over oceans were used to resolve pointing biases. They did not have the advantage of a planned maneuver, but fortunately the shuttle was not pointing perfectly nadir. Many observations were taken at as much as a half of a degree off nadir.

For missions like ICESat it is hoped that direct altimetry over the oceans will help to calibrate range bias parameters at the several centimeter level. If this is possible, it will be in part due to the high fidelity of current mean sea surface models. TOPEX

(Ocean Topography Experiment) launched in 1992 is the radar altimeter mission which is probably the most responsible for the quality of these mean sea surface models. So, in part, the calibration of ICESat's range bias parameters will exploit the calibration of the TOPEX range biases by researchers like Hayne *et al.*[10] and Christensen *et al.*[11] Luthcke *et al.*[4] point out some issues involved with using direct laser altimetry over oceans to recover range biases. They point out that random aspects of surface waves will average, but over large ocean basins the shape of waves and the likely sampling of the waves may make a laser range appear to be biased with respect to the mean sea surface. They also point out that the planned maneuver mitigates this problem for the pointing biases, but not for the range bias. This potential problem needs to be further investigated. The solution may lie in waveform analysis.

2.3 Laser Crossovers Over Oceans

For precise measurement modeling over oceans, radar altimeters do have an advantage. With their large footprint, radar altimeters can average out waves and other surface effects which are almost impossible to model. Laser altimeter ranges are much more affected by these phenomena. When laser altimetry is used as direct ranges, that problem is largely overcome with the high rate of the data (SLA was 10 Hz, ICESat will be 40 Hz and VCL will be 242 Hz). The unmodeled ocean phenomena are likely averaged out over a long enough series of contiguous shots. The least squares estimation process should be able to filter the noise coming from ocean surface effects when long passes of high rate data are used, especially for pointing biases. At any rate, Luthcke *et al.*[5] were able to use direct altimetric ranges over oceans to obtain a very good calibration of orbit, instrument and pointing parameters for SLA-01 and SLA-02.

Ocean crossovers from laser altimetry may be less able to exploit this averaging to mitigate surface effects. There simply are not as many crossovers as direct altimeter ranges and they do not form continuous passes. However, at some level, laser crossovers can exploit averaging. The laser crossover formulation uses three-dimensional polynomials to represent the geolocated bounce points surrounding the crossover. Typically for 10 Hz data, five points on each track are used (in each dimension) to solve for the polynomials. After the polynomials are fit, the individual ranges are not used in the modeling. The polynomials are usually overdetermined (as in a quadratic from five points) and so they may act as smoothers and as such might benefit from the higher rate data coming from ICESat and VCL. Furthermore, when the polynomials are overdetermined, the discrepancies between the bounce points and their polynomial representation can be used to judge if the crossover should be edited. The usefulness of laser altimetry crossovers over oceans is something which needs to be further investigated.

At present, SLA-01 and SLA-02 are the only orbiting laser altimeters available to us that have flown over oceans and they have not produced many crossovers. However, as part of the continuation of the investigation of Luthcke *et al.*,[5] we have looked at SLA-01 crossovers over oceans. Table 1 shows how well the current SLA-01 orbit and pointing solutions fit the direct altimetry ranges which were used in the combined orbit pointing solution (89 centimeters). The crossovers in Table 1 were not used in the orbit solution and fit at just a little bit more than the square root of two times the fit of the direct altimetry. This is near the level of fit which would be predicted if the crossovers are averaging out ocean effects as well as the direct altimetry. We have also tested the ability of SLA-01 ocean crossovers to solve for pointing parameters. Since we have only a limited number of crossovers, we solved for only a simple pointing model (constant bias, linear and quadratic terms). We repeated the solution using only direct altimetry ranges with the same (reduced) parameterization. The parameter values obtained from each data type are presented in Table 2 and compare quite well considering only 140 crossovers were used versus 9919 direct altimetry ranges.

Off-nadir pointing increases the ability of ocean crossovers to resolve pointing parameters just as in the case of direct altimetry. However, crossovers can not fully exploit the maneuver described by Luthcke *et al.*[4] That maneuver is designed so that when there is a nearly continuous stream of direct altimetry ranges, roll and pitch parameters will have very little correlation.

We plan to investigate the use of radar-laser (inter-mission) crossovers by looking at SLA-01/TOPEX crossovers. This will have at least one advantage, a greater number of crossovers to consider. Also, radar-laser crossovers will have diminished unmodeled ocean effects on at least one side of the crossover. Furthermore, the orbit of TOPEX is known very well, *i.e.* better than 3 cm root mean square (RMS) radially.[12] It should be noted that high quality TOPEX class radar altimetry should be available for some time to come with the launch of JASON (TOPEX follow-on). Hopefully this will help make laser ocean crossovers a valuable contributor to the calibration of orbit parameters and pointing parameters for some time to come.

2.4 Direct Laser Altimeter Ranges Over Land

The modeling of direct altimeter ranges over land is in principle almost exactly the same as the modeling done over oceans. Both require good models of mean surface elevations. The effect of solid earth tides is easy to model in each case. Ocean tides do have a small effect over land, *i.e.* ocean loading. This effect is usually neglected, especially inland. However, high

Table 1 SLA-01 processing tracking data fits.

Data type	Number of observations	Fit (RMS) (m)
Altimeter range	33211	0.89
Crossovers	140	1.32

Table 2 SLA-01 pointing parameters test solutions.

Parameter	Altimeter range (9919 observations)	Crossover (140 contraints)
Roll (°)	4.37E-02	5.81E-02
Roll rate (°/s)	2.40E-06	2.60E-06
Roll rate rate (°/s/s)	- 4.54E-11	- 5.40E-11
Pitch (°)	1.35E-01	1.25E-01
Pitch rate (°/s)	- 6.72E-06	- 5.06E-06
Pitch rate rate (°/s/s)	2.00E-10	1.66E-10

fidelity mean surface elevation models (DEMs) are not readily available over most land areas, although that may change after missions like SRTM (Shuttle Radar Topography Mission), ICEsat and VCL. The ICESat mission will conduct high fidelity GPS and high resolution airborne laser altimetry surveys of certain land areas for use in calibration and validation of ICEsat altimetry.

Laser altimetry ranges taken over areas where there are high fidelity DEMs can in principle contribute to the calibration of orbit, instrument bias and pointing bias parameters, just as over oceans. Data over land has advantages for the calibration of pointing and orbit parameters. Slopes which are often present over land make range residuals very sensitive to horizontal errors in geolocation. This means that laser altimetry over undulating topography should be useful in resolving pointing biases even when the altimeter is pointing nadir. Laser altimetry over undulating topography has the capacity to directly contribute to the resolution of all components of the satellite's orbit. Even so, the use of direct altimetry over land has yet to be fully explored and exploited.

2.5 Laser Crossovers Over Land

Laser crossovers benefit from undulating topography in the same way that direct altimetry does, but without the need for DEMs. That is what has made crossovers from MOLA so valuable for the Mars Global Surveyor mission where high fidelity DEMs were not available a priori.[6,13] However, laser crossovers over land can suffer from some of the same problems as laser ocean crossovers. In particular, laser altimetry with its small footprint will not average out the short wavelength effects which come from rough or vegetated topography. Still, there is every reason to believe that most crossovers over arid or sparsely vegetated regions of the Earth will be useful. Neumann *et al.*[13] were able to use over 24 million crossovers from MOLA in the Mars Global Surveyor (MGS) mission.

This paper is focused on the calibration of non-empirical parameters, in other words, on the calibration of parameters which can be used to give a detailed physical description of the trip that a pulse makes from the time it is fired from the laser to the time it is received back at the laser's detector. These non-empirical parameters are then used in detailed geolocation of the bounce points. It should be mentioned, however, that there are other ways to use laser crossovers to improve geolocation of bounce points. Neumann *et al.*[13] describe a technique to use laser crossovers to estimate three dimensional empirical parameters. These parameters are used to re-geolocate bounce points that may still have errors even after a calibration of non-empirical parameters. The technique exploits the fact that most errors in geolocation are likely to be periodic with a frequency of the orbital period. This technique is potentially very valuable because it is designed to use millions of crossovers simultaneously. It simultaneously estimates empirical parameters from time periods which span a mission and it can tie geolocation of bounce points which were determined from separate standard short arc orbit solutions. In standard tracking data residual analysis there is a practical limit to the number of crossovers which can be used.

2.6 Integration of Tracking Data Types

The above sections have discussed two basic forms of altimetry, direct ranges and crossover constraints. Each of these two forms of altimetry has its own strengths, weaknesses and precision. Within each form there are differences between land and ocean returns. This means that there are at least four types of altimetry which need to be integrated. Furthermore, as will be explained further below, it is advantageous to integrate these four types of altimetry together with the other available tracking data types (like SLR, GPS or TDRSS). Simultaneous solutions for orbit and bias parameters (instrument and pointing) have advantages.

All four forms of altimetry can be used to calibrate instrument and pointing biases. It is possible to use the altimetry to calibrate only these bias parameters. In that case it is necessary to hold orbit parameters fixed to values obtained from other solutions. Those solutions may or may not have used altimetry as a tracking data type. If not, then the orbit parameters will have not benefited from the altimetry and they will contain some errors that the altimetry would have removed. Those errors would be forced into the bias parameters. If altimetry was used in the separate orbit solution, then errors from the (as yet) uncalibrated biases would cause orbit errors in that solution. Furthermore, altimetry (even laser altimetry) does not have enough geometric strength to solve well for orbit parameters on its own. It is best to use all available tracking data in a simultaneous solution for orbit and bias parameters.

The key to integration of data types in combination solutions is data weighting. When one data type is inappropriately weighted relative to the other data types, the resulting solution can suffer. In orbit determination, there are several ways to check on the health of a solution, especially in a relative sense. These are residual analysis, orbit overlap tests and subset solution tests. The time span over which the orbit can be determined is broken into two overlapping pieces (each greater than one half). Solutions are performed for the whole time span, and each of the two subsets (giving three solutions). The resulting three trajectories are compared wherever they share a common time. These tests can be used to compare the performance of two solutions which differ only in the way the data types were weighted. They can therefore be used as a guide to arrive at an optimal weighting scheme. Rowlands *et al.*[14] describe how this technique was used to decide on a weighting scheme for the information used in the preliminary orbit solutions of STS-72 for SLA-01. In essence, only one data type at a time is added to a solution. The weight of that data type relative to the data types already in the solution is determined by varying only the weight of the new data type until the best test results are achieved.

The final product of a solution for orbit, instrument and pointing biases is improved geolocation. The geolocation is sensitive to all of the parameters. So, the concept of orbit overlap and subset tests can be extended to geolocation overlap and subset tests. Geolocation tests in combination with orbit tests are used for the weighting schemes involving laser altimetry when pointing and instrument biases are being calibrated.

Although the final geolocation will result from a combined solution using all data types, it is probably best to start with separate solutions for orbit and attitude. The best weighting scheme for all non-altimetric data types can be determined in orbit only solutions. The resulting orbits can be used as input to solutions using altimetry for bias parameters (only). In these solutions an optimal weighting scheme for the altimetric data types can be determined by using geolocation tests. At this point, the relative weights of non altimetric data types among themselves and the relative weights of altimetric data types among themselves will have been determined. What remains to be determined is a single scale factor to multiply all of the previously determined altimetric weights when they are used together in one large combined solution. Again, geolocation and orbit tests are used in the determination.

2.7 Integration of Tracking Data Analysis with Waveform and Profile to DEM Matching

Tracking data analysis calibrates the parameters that are needed to produce accurate geolocation. Other forms of analysis require this accurate geolocation as input. Profile and waveform to DEM matching, which will be described in the next section, are two such forms of analysis. They are forms of residual analysis (computed quantities are compared to observed quantities) and their residuals will be sensitive to the geolocation produced by tracking data analysis. That fact can and should be exploited to discriminate between two candidate geolocation solutions. The candidate solutions may have different data weighting schemes but similar orbit and geolocation overlap tests. In this case the geolocation solutions should be used as inputs to the DEM matching analyses (profile to DEM and waveform to DEM). This is a way to validate one solution or the other.

3. Profile and Waveform Matching to DEMs

A strength of the combined solution based on processing direct altimetry and cross-over data simultaneously with spacecraft tracking data is the highly accurate determination of instrument calibration parameters, and temporal trends in those parameters. The associated analysis of residuals and segment subsets and overlaps for geolocated laser footprint ground tracks can assess the relative accuracy and reproducibility of the resulting geolocation. However, there is still a need to further develop tools that can assess the absolute accuracy of geolocation solutions in horizontal and vertical position, at the same time discriminating between different geolocation solutions. Also, these tools can be used to validate beam quality parameters such as pulse width, footprint diameter and circularity, and validate footprint derived properties, like mean elevation, slope, roughness and vegetation height. Profile and waveform matching are suitable techniques for this task.

3.1 Profile Matching

The comparison of geolocation results to accurate DEMs provides a means to assess the absolute accuracy and systematic errors of the laser footprint position, and to evaluate alternative geolocation results. The comparison can be done based on differencing elevation profiles or waveforms with respect to the DEM. In the former, the elevation for each footprint along a profile is differenced with respect to the corresponding DEM elevation. The standard deviation of the differences establishes a residual for the profile as a whole. By computing the profile residual for positions systematically shifted with respect to the DEM in X, Y, and Z, the position of the residual minima establishes the proper geolocation of the profile. This approach has been developed to assess the geolocation accuracy of SLA profiles.2)

Profile matching requires that a geolocation solution is available to initiate the search for the residual minima, as would be provided by the techniques described above. The approach also requires that the DEM accurately represents surface elevations, that it is of sufficient spatial extent and resolution, and that it represents a sufficiently complex surface so that there is sensitivity to tested changes in profile location. There are trade-offs between each of these DEM attributes. For example, a DEM covering a small area with very high resolution and accuracy may in fact provide a less sensitive test than a DEM covering a much larger area with less resolution and accuracy. The latter would include many more laser footprints and a greater diversity of terrain relief, increasing the statistical power of the technique. The potential of this technique is illustrated in Fig.3. Two different geolocation solutions for SLA-01 first-return (ranging to the highest surface within the footprint) data have been used to test their accuracy against a 90-meter resolution DEM. The first shuttle orbit solution was obtained using TDRSS tracking data only. The orbit was held fixed while using the altimetry as another data type in solving for a full attitude model. This solution was then compared against a solution where tracking TDRSS and altimetry data were combined to simultaneously solve for orbit and pointing parameters. The RMS contours for the corresponding differences between shifted sub-orbital tracks in the X and Y directions (latitude and longitude) and a 90-meter DEM, show an improvement in the match for the combined solution when shifting at the pixel size level. In this particular case, indicating that no shift was necessary to minimize the differences. The elevation profile is also shown, together with the differences between the comparisons between the simultaneous solution and the DEM (with zero shift for this case), and statistics of the comparison. It is important to note that the mean of the differences is associated with the accuracy of the DEM for the particular region. The laser waveforms represent the interaction of the laser energy with the different surfaces encountered within the footprint. If waveform information is available, comparisons to DEMs can be made when ranging to the lowest surface encountered (last-return). It is anticipated that sub-sampling of the DEM at sub-pixel increments will increase the strength of this technique in discriminating between solutions while giving a more precise estimate of the optimal shift in the horizontal direction. The implementation of shifting in the Z-direction will be useful in assessing any possible vertical biases. The potential use of DEMs of regional to continental scales (*e.g.* USGS 30 m DEMs, NIMA 90 m DTED, SRTM 30 m DEM) and more accurate and higher resolution local DEMs needs to be further investigated, establishing the sensitivity of the technique as a function of DEM properties.

3.2 Waveform Matching

With the ability of laser altimeters to digitize the backscattered energy (waveform), the waveform matching approach potentially has greater sensitivity in assessing footprint geolocation than the profile matching approach. Many more observables are involved in the analysis (the waveform amplitude in many height increments as compared to a single elevation or first return). Rather than differencing a footprint elevation to a DEM elevation, waveform matching is accomplished by minimizing the residual between within-footprint surface height distributions as recorded by the observed waveform and a simulated waveform derived from the DEM. The residual can be computed for an individual footprint or a group of footprints. The DEM must be of very high accuracy and spatial resolution. Again, by shifting the position of the laser footprints with respect to the DEM in X, Y, and Z in order to minimize the observed-to-simulated waveform residual, the geolocation of the laser waveforms can be assessed. The DEM measure of within-footprint slope and roughness can then be used to validate these geophysical parameters

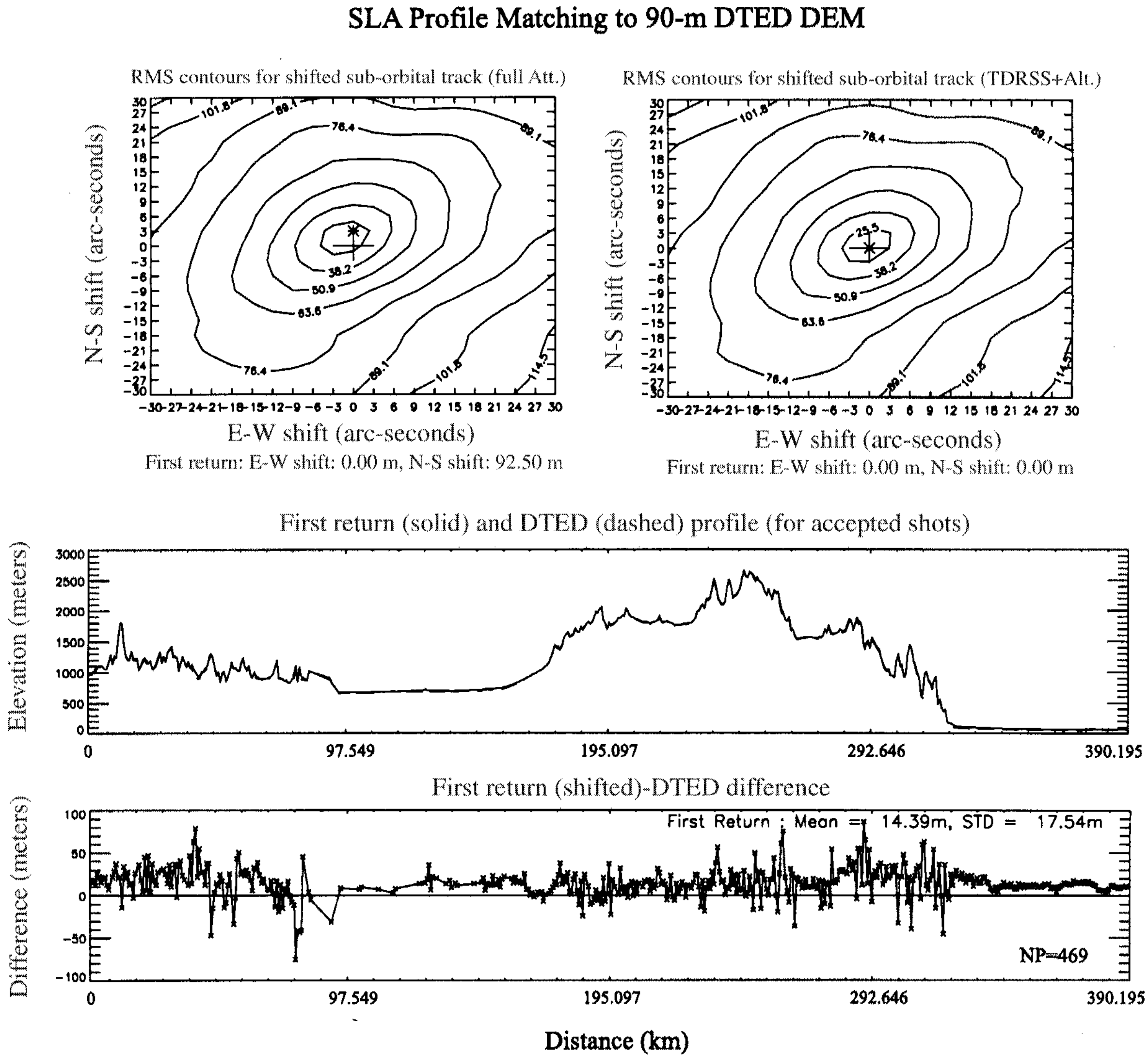

Fig.3 SLA Profile Matching to 90-m DTED DEM: Profile segments corresponding to two different geolocation solutions for SLA-01 data have been compared against a 90-meter resolution DEM. The upper left and right figures show RMS contours for differences between sub-orbital tracks shifted in the X-Y direction (longitude and latitude) and the corresponding DEM values obtained using a pixel size (3 arcsec) increment. The solution to the left (full Att.) was obtained holding TDRSS-tracking data only orbit solutions fixed, using the altimetry as a tracking data type to recover pointing parameters for a full attitude model. The contours to the right correspond to differences in geolocation against DEM for a combined orbit and pointing solution using TDRSS tracking and altimetry simultaneously in solving for a full attitude model (TDRSS + Alt.). The elevation profile which corresponds to the selected approximately 400 km profile segment across the DEM (469 points) is also shown, exhibiting a large range of elevations. The differences for the optimal shift that minimizes discrepancies between the first-return profile and the DEM profile are also shown for the combined solution (as symbolized by the location of the star in the RMS contour plots), along with the statistics of the comparison. This Figure shows the strength of Profile Matching in helping differentiate between different geolocation solutions.

inferred from the observed waveform. In addition to validating footprint geolocation, slope, and roughness, attributes of the laser beam quality such as the beam diameter, circularity, and pulse width can also be assessed. This is accomplished by incrementally varying these parameters in turn and searching for a waveform residual minima. It is likely that iteration between position and beam quality searches will be necessary to identify the residual minima in the multi-parameter search space.

The waveform matching approach was first described by Blair and Hofton,[15] in which they compare laser altimeter waveforms for 25 m diameter footprints acquired by the airborne Laser Vegetation Imaging Sensor (LVIS) to simulated waveforms, derived from a DEM constructed from very-high resolution elevation data acquired by a helicopter-borne scanning laser altimeter (FLI-MAP). The altimeter data consisted of first-return ranges to 10 cm diameter footprints spaced approximately every 30 cm across a 2 × 4 km area of dense, tropical rain forest in Costa Rica. These data were gridded, creating a DEM of 33 cm horizontal spacing and approximately 10 cm vertical accuracy. The waveform simulation first summed each DEM grid elevation within a circular footprint after convolution with functions that represented the LVIS along-beam (*i.e.*, pulse width) and across-beam (*i.e.*, footprint diameter) Gaussian energy distributions. The sum was then convolved with the impulse response of the LVIS receiver, yielding the simulated waveform. The simulation did not determine absolute magnitude of the waveforms (*i.e.*, number of photoelectrons received), no optical or electronic noise functions were added, and the reflectance across the footprint was held constant, assuming the dense canopy reflectance was everywhere uniform. Once a simulated waveform was obtained, the similarity between each observed and simulated waveform pair was assessed using the Pearson correlation. Maximizing the mean correlation for all waveforms (equivalent to a residual minima) was used to search for the spatial correspondence between the LVIS waveforms and DEM, as well as for beam quality parameters. Shifts of the observed waveforms with respect to the DEM in west, north and vertical directions all yielded well defined correlation maxima, as did variation of pulse width and footprint diameter. Departure from footprint circularity was not tested for. The precision in determining the maximum correlation was 0.01 m for the vertical shift and pulse width variation, and 0.1 m for the east, west, and diameter parameters.

The high precision in determining spatial correlation and beam quality achieved by Blair and Hofton[15)] was due to the great diversity of vertical structure present in the rain forest canopy, the relatively small LVIS footprints and their spatial density, and the extremely high resolution of the FLI-MAP scanning laser altimeter data. Unvegetated surfaces, presenting much less vertical structure at short length-scales, will be less sensitive to geolocation shifts or variation in beam quality parameters. Larger footprints will typically include a more complete distribution of surface elevations, yielding smoother waveforms less suitable for unique matching of distinctive waveform features. In addition, non-contiguous footprints will require a much larger DEM extent as compared to the dense LVIS waveform image in order to include the same number of waveforms in a residual analysis. To use the waveform matching approach, the spatial variation of reflectance at the laser wavelength (1064 nm) within the footprint must be minimal or independently known, because the simulated return intensity depends on the reflectance of the surface elements. In addition, the surface elevation must be sufficiently complex at the footprint-scale, rather than profile-scale, to yield sensitivity during matching. Moreover, the method of simulating waveforms from the DEM must be validated in order to ensure that residual minima are not corrupted by simulator errors.

During post-launch calibration and validation, ICESat profile and waveform matching tests will be conducted across those DEMs having appropriate characteristics for the matching techniques. This will be done with the intention of assessing the quality of the geolocated data sets and perhaps contribute to the validation of derived geophysical parameters (elevation, slope, roughness) by comparing to the same quantities calculated from the high-resolution DEMs.

4. Summary

Tracking data analysis using laser altimetry is a powerful tool for calibrating the parameters which are required for the geolocation of the altimetric bounce points. We have shown that laser altimetry can and should be used in different forms within the tracking data residual analysis. Profile and waveform to DEM matching are two valuable tools for validating geolocation solutions (produced from tracking data residual analysis) and validating geophysical parameters derived from laser pulse waveform records. They can and should be used as complementary tools to tracking data residual analysis.

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