IMPROVEMENTS IN SPACEBORNE LASER ALTIMETER DATA GEOLOCATION

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Abstract. For many science applications of laser altimetry, the precise location of the point on the Earth's surface from which the laser energy reflects is required. The laser surface return geolocation is computed from the laser altimeter's range observation in combination with precise knowledge of spacecraft position, instrument tracking points referenced to the spacecraft center of mass, spacecraft attitude, laser orientation, observation and attitude data time tags. An approach that simultaneously estimates the geometric and dynamic parameters of the orbit and laser range measurement model by a combined reduction of both spacecraft tracking and laser altimeter surface range residuals is applied to produce improved pointing, orbit and range bias solutions and therefore improved geolocation. The data acquired by the Shuttle Laser Altimeter (SLA)-01 and 02 missions constitute a valuable pathfinder data set to test algorithms in preparation for the upcoming VCL (Vegetation Canopy Lidar) and ICESat (Ice, Cloud and Elevation Satellite) missions. Results from a preliminary SLA-01 data analysis are presented along with a brief description of the methodology and its application to future spaceborne missions.

Keywords: Altimetry, geolocation, instrument biases, laser altimetry, laser remote sensing, on-orbit calibration techniques, orbit determination.

1. Introduction

With two successful Shuttle Laser Altimeter (SLA) Missions (SLA-01 and SLA-02) (Garvin et al., 1998; Carabajal et al., 1999), the Mars Orbiting Laser Altimeter (MOLA) (Smith et al., 1998) and a host of aircraft experiments (Vaughn et al., 1996; Hofton et al., 2000), laser altimetry is revolutionizing the ability of remote sensing to determine the characteristics of complex surfaces including vegetation, slope, surface roughness, topography and time variations. The laser altimeter system measures the time of flight of the laser pulse and provides a digital time series of the returned laser pulse energy or the waveform. The time of flight determines the range to the surface "bounce point", which in conjunction with the knowledge of the position and pointing of the laser altimeter, enables the precise positioning or geolocation of the surface return. The waveform provides a detailed observation of the vertical distribution of intercepted surfaces within the laser footprint (Garvin et al., 1998). To exploit the unique observing capabilities of this technology, two NASA dedicated laser altimeter missions are scheduled for launch in

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2001: the Vegetation Canopy Lidar (VCL) and the Ice and Cloud Elevation Satellite (ICESat).

The ground spot size of a spaceborne laser altimeter can be as small as the VCL footprint of 25 m and can be on the order of 20–80 times smaller than the footprint of a spaceborne radar altimeter now in use (TOPEX, GFO, ERS-2). The returned waveform provides detailed information about the surface characteristics within each footprint. The small laser footprints and the wealth of information they provide, over sometimes highly varying surface characteristics, require precise geolocation, typically on the order of the size of a footprint or less. Since identifying the spot that is illuminated is critical when utilizing laser altimetry, laser bounce point geolocation is a driving issue.

The classic approach to laser altimeter geolocation is to independently obtain laser pointing, body attitude, spacecraft orbit, range and time tag corrections and to simply combine these elements along with the range observation to obtain the geolocated surface return. Our enhanced geolocation approach allows for the simultaneous estimation of orbit, laser pointing, range and time tag parameters from a combined processing of laser altimeter range, spacecraft tracking and body orientation data. The following paper briefly describes the implementation of this approach and presents preliminary analysis of its application to SLA-01 data geolocation improvement. Additionally, the application of these capabilities to future missions is discussed.

2. Laser Altimeter Range Processing – GEODYN Implementation

To facilitate the processing of the laser altimeter range data for the recovery of the model parameters, the laser altimeter range measurement model algorithm has been implemented into NASA/GSFC's GEODYN precise orbit and geodetic parameter estimation system (Paulis et al., 1999). Therefore, the laser altimeter range processing can take advantage of GEODYN's high fidelity reference frame modeling, detailed geophysical modeling and its partitioned Bayesian least squares estimation Process (Paulis et al., 1999). The GEODYN implementation allows for the simultaneous estimation of the geometric and dynamic parameters of the orbit and laser range measurement modeling through the reduction of a combination of spacecraft tracking and laser altimeter range data residuals.

Three laser altimeter measurement models have been implemented within the GEODYN system. The first is a rigorous implementation of the classic geolocation measurement model that takes into account the motion of the laser tracking points over the round trip light time of the laser pulse. The model computes both the transmit and receive leg ranges to precisely geolocate the surface return. This geolocation measurement model is used in constructing the "dynamic crossover" measurement model discussed below and allows GEODYN to provide a standardized geolocation file for any particular solution. The geolocation file includes the location of the surface return in geodetic and Earth Centered Fixed (ECF) cartesian coordinates along with a host of media and geophysical corrections. The geolocation file also contains information about the laser orientation and range and time tag biases.

The second measurement model implemented is an altimeter “crossover” capability, which we term “dynamic crossovers”. This crossover measurement model has been implemented to take into account the small footprint of the laser altimeter along with the observed sloping terrain, and therefore, the horizontal sensitivity of these data. The dynamic crossover measurement model is discussed in detail along with its application to orbit and attitude determination for Mars Global Surveyor (MGS) in Rowlands et al. (1999). The altimeter observations from both the ascending and descending passes surrounding a crossover point trace out two curves in space. These curves contain the signal from topography, orbit, laser pointing, range and timing parameters. Three-dimensional polynomials are used to represent the ascending and descending curves. The crossover pair of observations, and their times, are found at the minimum distance between the curves. The crossover distance is minimized through the estimation of orbit, laser pointing, range and timing parameters. As the solution changes from iteration to iteration, it is possible for the crossover pair of observations to change and hence the name “dynamic crossovers”. This capability has been used to significantly improve MGS orbit and attitude solutions as discussed in Rowlands et al. (1999).

The third measurement model implemented is the “direct altimetry” measurement model. The round trip range is computed using knowledge of the spacecraft position, laser pointing, timing and ranging parameters along with surface height. GEODYN has the capability to ingest multiple surface height grids representing various land areas and the ocean surface. The observed ranges are compared to those computed from the measurement model. The discrepancies between the observed and computed observations (i.e., the residuals) are minimized through the estimation of orbit, pointing, timing and ranging parameters. A detailed discussion of the direct altimetry measurement model and the laser pointing and body attitude parameterization is presented in Luthcke et al. (2000).

The implementation of the above laser altimeter measurement models within a single system that also supports the precision orbit determination process facilitates a truly combined calibration approach for current and future spaceborne laser altimeter missions. Orbit, pointing, ranging and timing corrections can be simultaneously estimated from a combination of calibration data including direct altimetry from ocean surface and detailed calibration land sites, and dynamic crossovers. These data can be accumulated over the course of the mission to strengthen parameter solutions and to observe environmental and system related variations in the parameters.

3. Preliminary SLA Analysis Results

SLA-01 was launched aboard the Space Shuttle Endeavor, mission STS-72, on January 11, 1996. The SLA is capable of measuring land and ocean topography with 75 cm precision or range noise (Bufton et al., 1995). The instrument fired approximately three million 10 Hz pulses during 81 hours of operation. Nearly one million altimeter observations of the Earth's land and ocean topography were acquired with a 740 m horizontal sampling and a 100 m footprint (Garvin et al., 1998). SLA observations were taken from a 300 km near circular orbit with an inclination of 28 degrees. The GEODYN laser altimeter processing capabilities are currently being applied to improve SLA data geolocation accuracy. Results from a preliminary analysis of SLA-01 observation period seven (OBS-7) are presented here. Observation period seven is a 10-hour arc spanning the second half of January 16th.

Precise Shuttle orbits are computed from Tracking and Data Relay Satellite System (TDRSS) 2-way range-rate observations (Rowlands et al., 1997). Through rigorous force and measurement modeling and the inclusion of TDRSS tracking of TOPEX/Poseidon (T/P), the TDRS orbits have been determined to the meter level and thereby significantly reduce their contribution to Shuttle orbit error (Luthcke et al., 1997). During OBS-7 the Shuttle was in a −ZLV (−Z axis along Local Vertical), −XVV (−X axis along the Velocity Vector) Local Vertical Local Horizontal attitude mode. In this attitude mode the shuttle is flying backwards with the Z-axis vector normal to the shuttle bay pointing towards nadir within a specified tolerance. The orientation of the spacecraft remained constant within a 1° attitude 'dead-band' where roll, pitch and yaw maximum deviation from the nominal attitude was ±1° (Rowlands et al., 1997). The 1° attitude dead-band loosely mimics an attitude calibration 'ocean sweep' maneuver as discussed in Luthcke et al. (2000). Therefore, the simultaneous estimation of roll and pitch laser pointing corrections along with range bias were possible.

The description of each solution studied is provided in Table I. It should be stressed again that this is a preliminary analysis. To date, we have not performed an exhaustive analysis to determine the optimal weighting of the TDRSS range-rate tracking and the SLA direct altimetry. However, we have made some preliminary determination that conservatively 'down weights' the altimetry with respect to the TDRSS range-rate tracking. For the purposes of this analysis, the TDRSS 2-way range-rate tracking was weighted at 0.2 cm/s while the direct altimetry was weighted at 15 m. The solutions contained 1764 TDRSS range-rate observations and 12647 SLA deep ocean (depths greater than 1 km) observations where the 10 Hz SLA data were decimated to 1 Hz. In this preliminary analysis only constant and linear rate roll and pitch laser pointing corrections are estimated where indicated. The constant term accounts for systematic misalignment of the laser while the linear rate accounts for the drift of the Shuttle Inertial Measurement Unit (IMU)

TABLE I
Solution description

Solution name	Solution description
orbT_apriori_p+m	Orbit parameters[a] estimated from TDRSS tracking only, direct altimetry processed using apriori pointing (laser aligned with shuttle Z) and apriori range bias (5.6 m).
orbT_est_p+m	Orbit parameters[a] estimated from TDRSS tracking only, Pointing[b] and range bias parameters estimated from direct altimetry only
orbT+DA_est_p+m	Orbit,[a] pointing[b] and range bias parameters simultaneously estimated from TDRSS tracking and direct altimetry

[a] Orbit Parameters (reduced dynamic solution): initial state, drag coefficient per arc, along and cross track periodic empirical accelerations every 22.5 minutes.
[b] Pointing Parameters: constant and linear rate roll and pitch laser pointing corrections per arc.

over the observation period (Carabajal et al., 1999). A detailed description of the 'reduced dynamic' orbit parameterization is provided in Rowlands et al. (1997).

The results of the analysis are presented in Tables II through IV. Table II presents a direct altimetry range residual summary for deep ocean surface returns where the Root Mean Square (RMS) of the residuals for each data and solution type are shown. The Ohio State University Mean Sea Surface 95 (OSU MSS 95) and the Goddard Ocean Tide 99 model (GOT99) were used to model the ocean surface (Yi, 1995; Ray, 1999). The ocean surface residuals are a good indicator of geolocation accuracy since they represent the vertical error of the measurement, and coupled with the varying attitude about nadir (1° dead-band), provide insight into the extent of probable pointing errors and therefore horizontal errors. Significant improvement in the range residuals is gained from estimating the pointing parameters and range bias (from 8.05 to 2.17 m). The recovered laser pointing correction magnitude is on the order of 0.12°, which represents 628 m of horizontal geolocation error. Preliminary comparisons to 90 m spatial resolution digital elevation models (DEMs) show over 600 m horizontal differences with the SLA-01 OBS-7 data when no pointing corrections are estimated. After pointing corrections are estimated the differences are on the order of the spatial resolution of the DEM.10 The recovered range bias is 52 cm greater than the 5.6 m measured in the laboratory. At this point it is unclear how much of this discrepancy is true system delay and how much is simply accounting for height modeling systematic errors and aliasing due to surface wave structure. Nonetheless, this systematic range bias discrepancy must be accounted for as to not alias into the pointing bias recovery (Luthcke et al., 2000).

Still further significant improvement is gained through a simultaneous estimation of the orbit, pointing and range bias parameters from a combination of the tracking and direct altimetry data. Nearly 22% improvement in the direct altimetry range residuals is observed while the TDRSS tracking data residuals are not

TABLE II
SLA-01, OBS-7 residual summary

Solution	TDRSS 2-way range-rate RMS (cm/s)	Direct altimetry RMS (m)
orbT_apriori_p+m	0.195	8.05
orbT_est_p+m	0.195	2.17
orbT+DA_est_p+m	0.199	1.70

TABLE III
SLA-01, OBS-7 orbit overlap summary

Solution	Radial RMS (m)	Total RMS (m)
orbT_est_p+m	0.64	3.44
orbT+DA_est_p+m	0.53	1.94

significantly degraded. Table III presents the results of orbit overlap tests, which clearly show a significant improvement in orbit precision when the direct altimetry is allowed to contribute to the orbit solution. Two 6.5-hour arcs constructed from the 10-hour OBS-7 arc with 3 hours of common data were used to compute the overlap experiment results. A near 45% improvement in orbit precision is obtained with the full combination solution.

In addition to the orbit overlaps, geolocation overlap differences were computed to gauge the precision of the radial orbit, pointing and range bias solutions. Using the precise geolocation measurement model and the converged orbit, pointing and range bias solution, the position of the surface return bounce point is computed in latitude, longitude and ellipsoid height. Similar to orbit overlap tests each arc's overlapping geolocated surface return positions are then differenced. Table IV presents a summary of the geolocation overlap differences in height and horizontal positioning and also as pointing in roll and pitch. Simultaneously estimating orbit, pointing and range parameters from a combination of the tracking and altimeter range data significantly improves the pointing solution precision. A 36% reduction in pointing and horizontal position overlap differences is observed along with a 23% improvement in height consistency.

While a detailed error analysis is out of the scope of this preliminary study, several aspects of the VCL and ICESat detailed consider covariance analysis described in Luthcke et al. (2000) can be applied here to further our understanding of the SLA performance. First, the ocean sweep maneuver, or in the case of SLA, the 1° attitude dead-band provides the necessary surface incidence angle to separate roll, pitch, range and orbit parameters. In the case of SLA OBS 7A, the non-optimal

TABLE IV
SLA-01, OBS-7 geolocation overlap summary

Solution	Ht. RMS (m)	Horiz. RMS (m)	Roll RMS (arcsec)	Pitch RMS (arcsec)
orbT_est_p+m	0.80	140.36	86.42	33.35
orbT+DA_est_p+m	0.62	89.48	53.02	24.99

attitude dead-band results in parameter correlations of: 0.28 range bias-roll or pitch bias, and 0.21 pitch-roll bias. Second, a rough estimate of the impact of height modeling error on pointing bias recovery can be simply computed using equation 1 of Luthcke et al. (2000),and an estimate of height modeling error. We consider a conservative Sea Surface Height (SSH) modeling error of 20 cm in the open ocean basins where the variation in Inverted Barometer (IB) correction has been ignored. We then rss this with a radial orbit error estimate for SLA of 75 cm to get a conservative height modeling error of 78 cm. If we consider all of this height modeling error to be exactly in phase and at the frequency of the attitude dead-band then we will get the worst case pointing error of 31 arcseconds from the SSH and radial orbit error only. This is a simple analysis, but the result is on the order of that which has been found from the geolocation overlaps (see Table IV) and shows the results obtained here are unlikely to be biased significantly. The propagated rss roll and pitch formal uncertainty is 35 arcseconds for OBS 7A.

Due to the low altitude and low amplitude non-optimal (roll and pitch not 100% uncorrelated) pointing variation about nadir (1° attitude dead-band), the Shuttle orbit errors can alias themselves into the pointing parameter recovery. Therefore, it is essential to perform a combination solution where orbit, pointing and range bias parameters are simultaneously estimated from tracking and altimeter range data. These preliminary results show significant improvements in altimeter range residuals, orbit precision and geolocation/pointing consistency have been achieved through the application of this full combination solution. SLA data geolocation can only be properly computed when the orbit, pointing and range bias corrections are calibrated from a simultaneous combined solution. Additional SLA-01 and SLA-02 observation periods are currently being analyzed to improve the resulting geolocation. Enhanced DEM comparisons are being constructed to independently quantify the geolocation improvement. While there is indeed much additional work to be done, these preliminary results are quite encouraging. The enhanced geolocation processing of SLA-01 OBS-7 has provided a valuable real Earth observing data test of the new GEODYN laser altimeter capabilities, and has quantified the SLA geolocation improvements to be expected with further enhanced processing.

4. Application to Future Missions

Currently the full GEODYN laser altimeter range residual processing capabilities are being tested and refined on both MOLA and SLA data. These capabilities are improving the final geolocation accuracy of the surface returns through improved orbit, pointing, range and timing parameter recovery. While we will continue to apply these tools to further improve the data from these missions, soon these capabilities will be used to support NASA's dedicated Earth observing laser altimeters VCL and ICESat. The VCL mission, scheduled for launch in the later part of 2002, will carry a unique Multi-Beam Laser Altimeter (MBLA) instrument designed to observe vegetative canopy structure for a nominal mission duration of 1.5 years (Dubayah et al., 1997). The VCL MBLA is a five-beam instrument where each laser is capable of producing returns with 30 m along-track spacing and 25 m diameter footprints when operating at 242 Hz. Each beam is identical except in its pointing orientation. The orientation of the beams produces an 8 km wide swath on the ground with each beam separated by 4 km. VCL will orbit at an altitude of 400 km and an inclination of 67°. The Geoscience Laser Altimeter System (GLAS) will be launched aboard the ICESat in December of 2001. The primary goals of ICESat are the measurement of ice sheet topography and temporal variations in addition to the characterization of cloud and atmospheric properties. The GLAS instrument possesses three lasers, each with an expected lifetime of 1.5 years, but will operate one laser at a time to provide an expected mission duration of 4.5 years. The GLAS laser footprint at the Earth's surface will be approximately 70 m in diameter with an along track sampling distance of 175 m when operating at 40 Hz. ICESat will orbit at an altitude of approximately 610 km at an inclination of 94°.

Both VCL and ICESat pointing misalignments will be calibrated from the processing of ocean altimeter range residuals from an "ocean sweep" calibration maneuver. The calibration method uses specific commanded spacecraft attitude maneuvers and ocean range residuals for the recovery of pointing and range biases. The design of the calibration maneuver, its implementation and an exhaustive set of simulations and prelaunch error analyses are described in Luthcke et al. (2000). A single calibration maneuver will be capable of recovering pointing misalignment to 1.9 and 0.8 arcseconds 1σ for VCL and ICESat respectively. This is a significant performance improvement over that seen in the preliminary SLA data analysis. However, both VCL and ICESat will have significantly better ranging, pointing jitter and orbit accuracy performance over that of SLA. Additionally, the VCL and ICESat optimized ocean sweep calibration maneuvers will have 5 times the amplitude of the SLA attitude 'dead-band'. Furthermore, the VCL and ICESat maneuvers will ensure both roll and pitch will be out of phase unlike the somewhat random wobbling of the SLA attitude 'dead- band'. The VCL and ICESat calibration maneuvers will be performed regularly to provide additional data, and to support long period monitoring of mission pointing changes due to aging of systems and long period environmental influences.

The GEODYN capabilities allow for a truly combined calibration solution in support of VCL and ICESat. Direct altimetry from "ocean sweeps" and detailed land calibration sites will be processed in conjunction with dynamic crossover and spacecraft tracking data to recover pointing, ranging, timing and orbit parameters from the contribution of all these data. The orbits for both VCL and ICESat will be precisely determined from dual frequency GPS data and will likely not benefit from the addition of direct altimetry to the orbit solution. However, in the event of a GPS receiver failure, or periods of data loss, it will be important to have the capability to combine the altimeter range data with satellite laser ranging (SLR) for the orbit solution. VCL pre-launch orbit error analysis shows significant orbit accuracy improvement can be made if the altimeter ocean range data is included with SLR in the event of a GPS failure. In fact, we can begin to approach the VCL minimum science mission orbit accuracy requirement if the altimeter data is combined with the SLR. With the inclusion of TDRSS data, we can then meet the minimum orbit accuracy requirement with a combined solution as is evidenced by the SLA data results presented above.

5. Summary

The implementation of the laser altimeter measurement models within GEODYN provides the ability to simultaneously estimate orbit, pointing, ranging and timing corrections based on a combination of altimeter range and spacecraft tracking data. These algorithms have been successfully applied to existing spaceborne laser altimeter data to improve the geolocation of the surface returns. The preliminary analysis of SLA-01 OBS-7 shows an improvement in horizontal geolocation precision from 140 m to 89 m and for the vertical from 80 cm to 62 cm. Further analyses, which seek to optimize both the parameterization and data weighting, should yield additional improvements and are currently underway. Several more SLA-01 and SLA-02 observation periods are being analyzed using both direct altimetry and dynamic crossover range observations. The ranging precision, orbit accuracy and non-optimal ocean sweep maneuver (attitude dead-band) limit the performance of the SLA data geolocation as compared to the expected VCL and ICESat performance.

The GEODYN altimeter range residual analysis capabilities will soon support VCL and ICESat surface return geolocation and instrument and orbit parameter calibration and validation. VCL and ICESat pre-launch error analyses show the power of "ocean sweep" direct altimetry range residual calibration in the recovery of pointing misalignments to the arcsecond and sub- arcsecond level, respectively. In support of these missions, a combined calibration solution can be performed where direct altimetry from optimally designed "ocean sweeps" and land calibration sites along with dynamic crossovers and spacecraft tracking data can be used to contribute to instrument and orbit parameter recovery.

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