Spaceborne Laser Altimeter Instrument Parameter Calibration From Integrated Residual Analysis – A Brief Overview

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ABSTRACT

To take advantage of the unique observing capabilities of lidar technology, two NASA dedicated Earth observing laser altimeter missions are scheduled for launch in the near future: the Vegetation Canopy Lidar (VCL) and the Ice, Cloud and land Elevation Satellite (ICESat). To properly geolocate the surface returns it will be necessary to verify and calibrate pointing, ranging, timing and orbit parameters once the instrument is in orbit. In preparation for these spacborne lidar missions, detailed algorithms and methodologies have been developed and tested to precisely geolocate the surface returns. Rigorous laser direct altimetry, dynamic crossover and geolocation measurement models have been implemented within NASA's state of the art Precision Orbit Determination (POD) and geodetic parameter estimation software, GEODYN. The algorithms and their implementation provide an integrated range residual analysis capability to simultaneously estimate orbit, pointing, ranging and timing parameters from a combined reduction of direct altimetry, dynamic crossover and spacecraft tracking data. The following is a brief overview of the integrated residual analysis methodology and implementation. In addition, results of simulations and error analyses along with the application of the technique to the processing of Shuttle Laser Altimeter (SLA) data will be briefly discussed. The topics discussed are detailed within several papers currently in print and in review. The following is meant simply as an overview and to provide the reader with the necessary background and references to pursue the work in more detail.

1 INTRODUCTION

Two NASA dedicated Earth observing laser altimeter missions are scheduled for launch in the near future: the Vegetation Canopy Lidar (VCL) and the Ice, Cloud and land Elevation Satellite (ICESat). The ground spot size of these spaceborne laser altimeters is as small as the VCL footprint of 25m, and is on the order of 20-80 times smaller than the footprint of spaceborne radar altimeters now in use (TOPEX, GFO, ERS-2). The small laser footprints and the small spatial scale over which the surface characteristics of interest vary require precise geolocation, typically significantly smaller than the footprint itself.

One approach to spaceborne laser altimeter data geolocation is to independently obtain laser pointing, spacecraft body attitude, spacecraft orbit, range bias and time tag corrections and to simply combine these elements along with the range observation to obtain the geolocated surface return. However, these data have errors and their pre-launch parameter values and models must either be verified or more likely corrections must be estimated once the instrument is on orbit. Towards this end, the laser range observations can be fully exploited in an integrated residual analysis to accurately calibrate these corrections or geolocation/instrument parameters (Luthcke et al., 2000 and Rowlands et al., 2000). Our "integrated residual analysis" approach allows for the simultaneous estimation of orbit and geolocation parameters from a combined reduction of laser range and spacecraft tracking data.

While this technique is not entirely new for spaceborne radar altimetry, what is new is the implementation and application of the laser altimeter measurement models that take into account the additional complexities of the spaceborne laser altimeter observation. Laser altimeter measurement models must precisely consider the pointing of the instrument, the small lidar footprint and the highly varying surface characteristics from which the data are collected. The laser altimeter range measurement model algorithms have been implemented within NASA/GSFC's GEODYN precise orbit and geodetic parameter estimation system (Pavlis et al., 1999). Therefore, the laser altimeter range processing can take advantage of GEODYN's high fidelity reference frame modeling, detailed geophysical modeling and estimation process. The GEODYN implementation allows for the simultaneous estimation of the geometric and dynamic parameters of the orbit and laser range measurement model through the reduction of a combination of spacecraft tracking and laser altimeter range data residuals.

2 IMPLEMENTATION and METHOD OVERVIEW

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. While the geolocation measurement model cannot be used to directly estimate parameters, it is used to construct the "dynamic crossover" measurement model (discussed below) and provides the geolocation data for any particular solution.

The second measurement model implemented is an altimeter "crossover" capability, termed "dynamic crossover". 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). 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 formulation can exploit change in horizontal crossover location as well as change in radial position of the satellite.

The third measurement model implemented is the "direct altimetry" measurement model. A detailed discussion and mathematical description of the direct altimetry measurement model is presented in Luthcke et al. (2000). The round trip range is computed using knowledge of the spacecraft position, laser pointing, timing and ranging parameters along with the surface height. Multiple surface height grids representing the ocean surface and various land areas can be used.

The GEODYN implementation of these measurement models supports Multi-Beam-Laser-Altimeters (MBLA), like that to be flown on VCL, as well as single beam instruments like ICESat's Geosciences Laser Altimeter System (GLAS). Laser range observation time tag bias, spacecraft attitude time tag bias, range observation bias and scale, and laser pointing parameters can be estimated. These parameters can be recovered on a time period basis where different parameter sets can be estimated for each distinct time period within a data reduction arc. Multiple time periods of user-defined length can be employed. The pointing parameterization is sufficiently complex to allow for the estimation of both laser and spacecraft body pointing bias, drift, quadratic and periodic terms. This level of detail facilitates the calibration of pointing effects due to thermal and environmental drivers and not simply constant pointing bias misalignments. The pointing parameterization is discussed in detailed in Luthcke et al. (2000).

3 ANALYSIS and RESULTS OVERVIEW

Several pre-launch simulations and error analyses have been conducted to gauge the performance of the integrated residual analysis algorithms and methodology. Luthcke et al. (2000) detail an extensive pre-launch error analysis and set of simulations to quantify the performance of "ocean sweep" maneuvers in calibrating VCL and ICESat pointing and range corrections. Practical design considerations, the impact of various error sources and performance results are discussed. The paper shows how the recovery of pointing corrections can be made to the sub-arcsecond level for a single maneuver under the worst expected conditions taking into account a detailed error model. The paper also shows how complex variations in pointing misalignment (e.g. orbital period and laser "warm-up" temporal variations) can be recovered using the calibration maneuver and the resultant direct altimeter ranges.

Additional simulations have been conducted to gauge the performance of land direct altimetry and dynamic crossovers. While these simulations were not performed to the same rigor as the ocean sweep error analysis described in Luthcke et al. (2000), they do provide important insight. An ICESat 8-day repeat crossover simulation was performed to quantify the ability of the dynamic crossovers to recover a simple pointing misalignment bias. Both land and ocean crossovers were simulated (6,797 land and 8,106 ocean). Only nadir pointing direct altimeter ranges were considered in the crossover simulation, and no errors other than ranging noise were simulated. The GTOPO-30 DEM was used to simulate the land ranges, while an ellipsoid was used to simulate the ocean ranges. The simulation showed that the dynamic crossovers were capable of recovering a simple pointing misalignment to 0.34 arcsecond (noise only) as compared to 0.06 arcseconds (noise only) for a single ocean sweep maneuver. Although, it should be noted again, that this is a nadir pointing only case, and it is expected that the results would be further improved if there were some variation in pointing during the 8-day repeat. Additionally, another simple (noise only) simulation was performed to look at the ability to recover ICESat pointing misalignment using direct altimetry from highly accurate 50km to 1600 km land Digital Elevation Model "patches". This land DEM direct altimetry technique is capable of recovering a simple pointing misalignment to the 0.15 arcsecond (noise only) level.

Although, these simulations and detailed error analyses show the power of each separate technique, the real strength in the integrated residual analysis approach is the ability to simultaneously estimate the instrument/geolocation parameters from a combination of calibration data including direct altimetry from ocean surface and detailed land calibration site DEMs, and dynamic crossovers. While data from a few, small (~100 km pass length) detailed calibration sites provides an opportunity to estimate simple geolocation parameter biases for that particular time and location, by combining these data with global crossovers and long duration ocean sweeps we can further the accuracy and observe complex environmental and system related variations in the calibrated geolocation parameters.

While it is important to perform the various pre-launch error analyses and simulations, these studies do not fully test the laser altimeter measurement model algorithms and processing software. Systematic errors in the software and algorithms can cancel and may not be detected in pre-launch simulations. In preparation for VCL and ICESat, it is imperative that these algorithms are rigorously tested. Complete testing includes the processing of actual Earth observing spaceborne laser altimetry to fully test the algorithms, reference frames and geophysical models. While the dynamic crossover capability was exercised on MGS data, still further testing is needed to verify the algorithms for the processing of an Earth orbiting laser altimeter's data in conjunction with the direct altimetry algorithms. In addition, the application of intra-mission crossovers must also be tested and verified. Towards this end, the data from two Shuttle Laser Altimeter missions (SLA-01 and 02) have been reprocessed and analyzed in detail. Applying the new integrated residual analysis measurement model algorithms and capabilities has resulted in an

Enhanced Data Product (EDP) geolocation, which represents a significant improvement over the current SLA Standard Data Products (SDP). The details of this SLA/EDP analysis, and the results obtained are discussed in Luthcke et al. (2001). A brief overview of the analysis and results found in Luthcke et al. (2001) are provided below.

Data from several SLA-01 and SLA-02 observation periods, representing a good sampling of the mission data, have been reprocessed using the integrated residual analysis algorithms, software and analysis methodologies. Residual and overlap performance have been used as metrics to determine the optimal data weighting (between tracking and altimeter data) and orbit, pointing, ranging and timing parameterization. Significant improvements in geolocation have been achieved from a combined reduction of laser altimeter range observations and spacecraft tracking data simultaneously estimating pointing, ranging and orbit parameters. Intra-mission dynamic crossovers with TOPEX/Poseidon (T/P) (constructed from SLA laser and T/P radar direct altimeter ranges) have been used to contribute to the orbit and geolocation parameter recovery, and both inter- (constructed from SLA only direct altimeter ranges) and intra-mission crossovers have been used to assess the solution performance. Resultant SLA-01 enhanced geolocation precision is on the order of 40 m RMS horizontal and 26 cm RMS in elevation. Independent DEM profile accuracy assessments show similar performance at 60 m horizontal positioning. Ocean range residuals show the SLA ranging performance is now at the 1m level. Overall improvement over the SLA-01 SDP geolocation is nearly a factor of two. Orbit precision and accuracy have also been improved by more than a factor of 2 over the SDP orbits and are at the 30cm radial RMS level. Detailed analyses of SLA-02 enhanced data geolocation, also obtained from a combined solution, show significant improvement in resultant overlap, residual and DEM profile comparison performance. Finally, the analysis presented in Luthcke et al. (2001) shows that complex temporal variations in pointing, and not just simple biases, can and must be recovered for accurate geolocation.

4 CONCLUDING REMARKS

While the shuttle is not a geodetic satellite and the SLA does not possess the ranging performance that both VCL and ICESat will achieve, the data has been invaluable in developing, validating and assessing our processing algorithms, software and methodologies. Furthermore, when taking into account the SLA data limitations and the various simulations and error analyses performed, the results achieved show that the integrated residual analysis algorithms, software and methodologies can, and will meet VCL and ICESat geolocation performance requirements. A truly combined calibration solution for VCL and ICESat instrument and geolocation parameters will be made processing direct altimetry from "ocean sweeps" and detailed land calibration sites along with land and ocean dynamic crossover (both inter- and intra-mission) and spacecraft tracking data.

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