APPLICATION OF THE SHUTTLE LASER ALTIMETER IN AN ACCURACY ASSESSMENT OF GTOPO30, A GLOBAL 1-KILOMETER DIGITAL ELEVATION MODEL

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ABSTRACT

Continental-scale topographic profiles between 28.45° N and S latitudes acquired by the first flight of the Shuttle Laser Altimeter (SLA) experiment are used to evaluate the vertical accuracy of GTOPO30, a global digital elevation model with a grid spacing of approximately 1 km. GTOPO30 is a compilation of eight sources of elevation information, including raster and vector data sets. The mean and standard deviation of SLA to GTOPO30 elevation differences are computed for Africa, southern Asia, central South America, and Australia. Variations in mean differences between continental regions and GTOPO30 sources indicate that there are vertical datum discrepancies incorporated in GTOPO30 on the order of 10 m. Variation in the standard deviation of the differences confirms that raster sources in GTOPO30 are more accurate than vector sources.

1. INTRODUCTION

Digital Elevation Model (DEM) compilations of the Earth’s land topography at a grid spacing of approximately 1 km have recently become available publicly. These include two products distributed by United States federal agencies, GTOPO30 from the Geological Survey (USGS) and GLOBE from the National Atmospheric and Oceanic Administration. These data have great utility in regional and continental scale studies requiring topographic data and are a significant advance upon previously available global topographic data sets. However, the vertical accuracy of these compilations is variable and poorly quantified because the elevation measurements have been assembled from numerous topographic sources of varying, and uncertain, quality. Significantly, the compilations include sources using disparate and poorly documented reference ellipsoids and datums; thus, the DEM’s are not internally-consistent, geodetic representation of the Earth's surface.

Profiling laser altimeter observations from orbital platforms provide the opportunity to obtain elevation data of very high vertical accuracy in a consistent, Earth-centered reference frame (Harding et al., 1994). Laser altimeters are particularly well suited to measuring land topography, as comparing to radar altimeters, because of the ability to use smaller footprints that have no difficulty ranging to complex, high-relief terrain. Also, the optical backscatter return can be used to establish the surface height distribution within the laser footprint and differentiate features at multiple heights such as vegetation canopy layers and the underlying ground. Orbital profiling altimeter data lack the sampling density necessary to construct DEM's with spatial resolutions comparable to those derived utilising orbital stereoscopic or interferometric capabilities. However, they do provide data very well suited to evaluating the accuracy and error characteristics of global DEM’s constructed by other means. Here we us data from the first flight of Shuttle Laser Altimeter (SLA-01) to evaluate one of the global 1 km DEM's, GTOPO30, providing an independent assessment of that product’s quality.

1.1. GTOPO30

GTOPO30 is a global DEM resulting from a collaborative effort led by the staff at the USGS's EROS Data Center (EDC). GTOPO30 was developed over a three-year period and completed in 1996. Elevations are regularly spaced at 30 arc seconds (approximately 1 kilometre). GTOPO30 was developed to meet the needs of the geospatial data user community for regional and continental scale topographic data. The horizontal co-ordinate system is latitude and longitude referenced to WGS84. The vertical units represent elevation in meters above mean sea level. GTOPO30 is based on data derived from eight sources of elevation information, including raster and vector data sets.

The raster data sets include Digital Terrain Elevation Data (DTED) and USGS 1-degree DEM’s, both gridded at 3 arc seconds (approximately 90 m), and a New Zealand DEM gridded at 500 m. DTED is produced by the U.S. National Imaging and Mapping Agency (NIMA) and the USGS DEM’s are primarily reformatted versions of DTED. In areas lacking raster data, the primary data source was the Digital Chart of the World (DCW), a vector cartographic data set based on the 1:1,000,000-scale Operational Navigation Chart (ONC) series. Some areas are based on digitised versions of 1:1,000,000 scale paper maps from the Army Map Service (AMS), the International Map of the World (IMW), and the Peruvian government. Coverage for Antarctica was included using the Antarctic Digital Database (ADD). The GTOPO30 data sources and the processing methods used to assemble them are detailed in documentation provided, along with the data set, at http://edcwww.cr.usgs.gov/landdaac/dataproducts.htm.

The manner in which a GTOPO30 elevation value in a 30 arc second grid cell represents the topography for that portion of the Earth's surface varies depending on the data source and on processing methods which varied between continents. Processing of the raster source data involved generalising the higher resolution data to the 30 arc second horizontal grid spacing. As the GTOPO30 project progressed, several methods of generalisation were used. Selection of the representative 30-arc second value was accomplished by systematic subsampling for North and South America, by calculation of the median value for Eurasia, and by the breakline emphasis approach (Gesch and Larson, 1996) for Africa (essentially selecting either the maximum or minimum value from the higher resolution grid). The 500-meter New Zealand DEM was generalised to 30-arc seconds by reprojecting it from the New Zealand National Grid projection to geographic co-ordinates using bilinear resampling. The topographic information from the vector cartographic sources was converted into elevation grids through a vector-to-raster gridding approach. Contours, spot heights, stream lines, lake shorelines, and ocean coastlines were input to the ANUDEM surface gridding program developed at the Australian National University (Hutchinson, 1989). ANUDEM employs an approach known as drainage enforcement to produce raster elevation models that represent more closely the actual terrain surface and contain fewer artefacts than those produced with more general purpose surface interpolation routines.

The absolute vertical accuracy of GTOPO30 varies by location according to the source data. Generally, the areas derived from the raster source data have higher accuracy than those derived from the vector source data. The vertical accuracy associated with each source type is provided in Table 1, either from product specifications, calculation or estimation. For DTED, and the derived USGS DEM's, vertical accuracy specifications are provided by NIMA. However, these are generalised specifications and the method for establishing DTED accuracy is not documented. DTED accuracy is known to vary geographically and with method of production. The DCW accuracy reported in Table 1 was obtained by calculating differences with respect to DTED in areas of overlap. The accuracies of the other sources were estimated from their contour interval. The assumptions used in deriving the accuracies in Table 1 are detailed in the online documentation provided with the data set.

Source	90% LE	RMSE
DTED	30	18
USGS DEM	30	18
N.Z. DEM	15	9
DCW	160	97
AMS maps	250	152
IMW maps	50	30
Peru map	500	304
ADD	variable	variable

Table 1. GTOPO30 absolute vertical accuracy by source, as linear error at the 90% confidence level (90% LE) and as root mean square error (RMSE).

1.2. Shuttle Laser Altimeter

SLA, developed at NASA's Goddard Space Flight Center, was designed as a pathfinder experiment to evaluate engineering and algorithm techniques for obtaining high-resolution, orbital laser altimeter observations of terrestrial surfaces. The first flight of the SLA instrument was in January 1996 aboard the space shuttle Endeavour on the STS-72 mission. Of the approximately 3 million laser shots transmitted during the course of the 10 day mission, approximately 475,000 yielded geolocated laser returns from land surfaces. Due to the shuttle orbit inclination, the SLA observations are distributed between 28.45° N and S latitudes. Details on the SLA-01 instrumentation and results are provided in Bufton et al. (1995, 1999) and Garvin et al. (1998). The geolocation processing of the SLA-01 laser footprints used essentially the same methods as those for SLA-02, described elsewhere in this volume by Carabajal et al. (2000). SLA data sets and documentation are available at http://denali.gsfc.nasa.gov/lapf.

SLA utilises a first-return ranging scheme yielding geolocated elevations that correspond to the highest detected surface within the 100 m diameter footprint. Detection of a surface requires reception of sufficient backscatter energy exceeding the instrument detection threshold. The backscatter return depends on the nadir-projected area of the laser-illuminated surface, its reflectance at the 1064 nm laser wavelength, and atmospheric transmissivity. The detection threshold is varied as the background optical noise level changes. The background noise is dependent on the amount of solar illumination (e.g., day versus night) and the reflectance of the surface observed by the receiver field-of-view. For cloud-free locations where vegetation is present, the geolocated elevation will depend on the density and spatial organisation of the vegetation. For areas with sufficiently dense vegetation cover the reported elevation will correspond to the top of the vegetation canopy. Similarly, in urbanised areas the geolocated elevation will depend on the spatial organisation of buildings, corresponding to the building top with sufficient area and reflectance to cause the detection threshold to be exceeded. In cloud-free areas lacking vegetation or buildings, the elevation corresponds to the highest ground surface of sufficient area and reflectance. Where optically dense clouds are present, SLA-01 yields a cloud-top elevation.

The vertical accuracy of the SLA elevation data has been assessed for flat surfaces by comparison to Mean Sea Surface ocean topography, derived from TOPEX/Poseidon radar altimeter data, with a correction applied for ocean tides but not for sea state (Carabajal et al., 2000). For nearly 728,000 SLA-01 ocean surface returns the resulting residuals show a near Gaussian distribution with a mean difference of 0.26 m and a standard deviation of 2.78 m (Garvin et al., 1998). The observed deviations from the ocean surface are thought to be primarily due to long-wavelength orbit errors (e.g., once or twice per revolution). A procedure was developed to correct these errors using smoothed ocean residuals and to extrapolate the correction over land, as described in Carabajal et al. (2000). The horizontal accuracy has not been as well quantified but the reported SLA footprint locations are thought to be within several hundred meters of their actual location based on inferred instrument pointing uncertainty and by matching SLA topography profiles to 90 m resolution DTED.

2. SLA VERSUS GTOPO30 DIFFERENCES

SLA-01 elevations correspond to the highest detected surface within a 100 meter diameter footprint whereas GTOPO30 elevations are 'representative' of elevations in 30 arc second grid cells (approximately a 1 km x 1 km area). Therefore, elevations in the two data sets are not equivalent; SLA elevations refer to a specific location covering only approximately 0.8% of the area represented by a GTOPO30 grid cell. Also, the manner in which GTOPO30 is representative of the topography varies as a function of source and continent, as described above. Because of these differences in the way topography is sampled, differences between SLA and GTOPO30 elevations may be large for an individual footprint, particularly in areas of high relief. However, because of the high absolute vertical accuracy of the SLA data and the large number of observations, the GTOPO30 elevation accuracy can be assessed in a statistical sense using the SLA data.

GTOPO30 elevations are referenced to a mean sea level vertical datum, an approximation of the geoid, whereas SLA-01 elevations refer to the TOPEX/Poseidon ellipsoid reference frame. SLA elevations were therefore converted to orthometric heights with respect to the geoid by subtracting the geoid height at the footprint as defined by the Earth Geoid Model 96 (EGM96) (Lemoine et al., 1998). SLA to GTOPO30 differences were then computed by subtracting an interpolated GTOPO30 elevation from the SLA orthometric elevation. The interpolated GTOPO30 elevation was computed for the SLA footprint location by bilinear interpolation using the four nearest GTOPO30 grid cells. Elevation differences were computed for the four regions having the greatest density of SLA-01 ground tracks. The regions are Africa including Saudi Arabia, southern Asia between 60° and 120° E longitude, South America south of 10° S latitude, and Australia. Refer to Carabajal et al. (2000) for a global map of SLA-01 ground tracks.

The elevation differences (SLA orthometric minus interpolated GTOP30) are summarised in Table 2 as a function of region and in Table 3 as a function of region and GTOPO30 data source. Only elevation differences less than or equal to 200 m are included in an effort to exclude SLA returns from clouds above the land surface. Histograms of differences for each region show distributions that decrease to near zero at elevation differences well less than 200 m, indicating no significant number of land surface returns are excluded.

Region	Number of Differences	Mean (m)	St. Dev. (m)
Africa	244,640	-1.40	44.75
Southern Asia	109,286	14.22	49.03
South America	50,602	6.78	53.32
Australia	29,139	-21.72	48.92

Table 2. Mean and standard deviation of elevation differences (SLA-01 orthometric minus interpolated GTOPO30) as a function of geographic region.

Region and Source	Number of Differences	Mean (m)	St. Dev. (m)
Africa DTED	134,062	2.00	28.88
Africa DCW	109,240	-5.64	58.46
S. Asia DTED	97,804	15.30	45.73
S. Asia DCW	10,654	4.98	72.64
S. Am. DTED	27,583	16.22	32.12
S. Am. DCW	21,112	-4.31	69.09
S. Am. AMS	498	-39.88	86.71
S. Am. IMW	1147	3.39	55.75
Australia DCW	29,139	-21.72	48.92

Table 3. Mean and standard deviation of elevation differences (SLA-01 orthometric minus interpolated GTOPO30) as a function of region and source.

3. DISCUSSION

The mean differences in Table 2 are indicative of systematic biases between the two data sets on continental scales, with the southern Asia and South America regions being systematically higher in the SLA data, Africa showing little systematic difference, and Australia being systematically lower. For flat surfaces SLA elevations show little bias, based on the near-zero mean difference with respect to the ocean surface. However, one might expect SLA land elevations to be systematically biased high in the presence of vegetation cover, buildings or high local relief at the footprint scale due to the first return ranging. This might account for the mean SLA to GTOPO30 differences observed in southern Asia and South America. However, if that were the case one would also expect the extensive forested landscapes of Africa to yield a positive mean difference that is not observed. The large negative mean for Australia is also contrary to an expected high SLA bias.

A bias could also be introduced in converting SLA from ellipsoid to orthometric elevations. However, the formal root mean square error at long wavelengths for EGM96 is less than 50 cm (Lemoine et al., 1998), and the ellipsoid references used for SLA and EGM96 agree at the centimetre level. Therefore, the continental variations in mean differences must at least in part be due to systematic errors in the GTOPO30 data set. These systematic errors may well be due to deviations from mean sea level of the vertical datums in the GTOPO30 source materials. The variations in mean differences between data sources for individual regions (Table 3) indicate that there are datum discrepancies incorporated in GTOPO30 on the order of 10 m.

With the incorporation of improved and fully analysed backscatter waveforms in the SLA-02 data set (Carabajal et al., 2000), a more rigorous assessment of regional biases can be performed. The waveforms record the within-footprint height distribution of backscattered laser energy, characterising surface relief caused by vegetation, buildings and ground slope and roughness. Comparison of highest, mean and lowest detected elevations within SLA-02 footprints to DEM's will reduce bias effects due to first-return ranging.

The standard deviations in Table 2 and 3 are likely a consequence of four sources of difference. One is the sampling issue whereby the SLA point observation is not equivalent to the representative GTOPO30 grid cell value; as local relief increases, the sampling difference will cause larger standard deviations. A second source is the spatially heterogeneous nature of vegetation and urban cover causing a 'random' SLA error; in some places SLA is measuring canopy or building tops whereas in other locations bare ground is measured. A third source is actual random error in the SLA elevation results. For flat surfaces this error is small, as indicated by the narrow distribution of residuals with respect to the ocean surface (Garvin et al., 1998), but as surface slope increases random error due to pointing uncertainty increases (Harding et al., 1994). The final source is any random error in the GTOPO30 product.

It is not possible from this analysis to separate these four contributions to the observed standard deviations of elevation differences. However, the analysis does show that the raster based source material (DTED in the regions studied) does have less error as compared to the sources based on 1:1,000,000 scale contour maps, as expected (Table 1). Separation of the four sources of elevation difference could be achieved by examining SLA elevation repeatability in the vicinity of ground-track cross-overs as a function of local relief, land cover, and distance between laser footprints and comparing that to SLA to GTOPO30 differences as a function of local relief and land cover.

4. CONCLUSION

The flight of SLA has provided the first opportunity to utilise orbital laser altimeter data in an accuracy assessment of global DEM's of the Earth. The consistent reference frame, high absolute accuracy, and ability to range to all types of land surfaces, regardless of cover or relief conditions, makes orbital laser altimeter observations well suited for characterisation of systematic biases in global DEM's. However, sampling differences between the laser altimeter data and 1 km gridded DEM's lead to differences in the manner in which topography is represented and thus contribute to the variation observed in altimeter to DEM elevation differences.

Through this study methodologies have been developed which will be applied using Vegetation Canopy Lidar (VCL) and Ice, Cloud and land Elevation Satellite (ICESat) laser altimeter profiles to validate the accuracy of a 30 m resolution global DEM to be produced by the Shuttle Radar Topography Mission (SRTM). SRTM, scheduled for launch in January 2000, is a joint project between NIMA, the National Aeronautics and Space Administration (NASA), the California Institute of Technology's Jet Propulsion Laboratory and DLR. VCL, the first in NASA's Earth System Science Pathfinder spacecraft series, is led by the University of Maryland and is scheduled for launch in September 2000. ICESat, a part of NASA's EOS flight program, is scheduled for launch in 2001. Integration of VCL, ICESat and SRTM topographic data will lead to a global representation of Earth topography with unprecedented resolution and documented accuracy that will greatly contribute to Earth science studies.

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