Title: Datum Conversion Issues with LIDAR Spot Elevation Data

Description: Three techniques are described for ground truthing, identifying systematic offsets, and adjusting LIDAR spot elevation data to maximize compatibility with local geodetic vertical control networks.

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Abstract

Light Detection and Ranging (LIDAR) elevation data are generally referenced to the World Geodetic System of 1984 datum. To utilize this data in a local or regional setting it is often necessary to convert the elevation data to a traditional vertical datum such as the North American Vertical Datum of 1988. This datum conversion is done utilizing a local geoid model developed through a detailed GPS survey covering the area of interest or a model developed by the National Geodetic Survey. Three techniques are described here for identifying systematic errors that may be introduced into LIDAR elevation data during this conversion process.

Introduction

Light Detection and Ranging (LIDAR) systems have proven to be an efficient, timely, and cost effective method for obtaining elevation data over large areas (Watkins and Conner, 2000). However, as the precision and availability of LIDAR elevation data has improved the need to tie the LIDAR elevations to a local geodetic control network and to identify and correct systematic errors within the data has increased. This paper presents three methods for ground-truthing LIDAR elevation data to insure it has been correctly converted into the desired datum and that any systematic offsets that may exist in the data are identified and removed.

LIDAR systems use a laser with a known wavelength that emits a pulse of light at a surface. The time elapsed between the emission of the pulse and the return from the surface is measured. The distance, or range, over which the pulse traveled is calculated based on the elapsed time and the speed of light. When combined with GPS and inertial navigation data the ranges stored by the onboard computer may be converted to a 3-dimensional spot position –in this case expressed in International Terrestrial Reference Frame (ITRF) coordinates based on the World Geodetic System of 1984 (WGS 84) datum.

To utilize this data in a local or regional setting it is often necessary to convert the WGS 84 ellipsoid heights to a vertical datum such as the North American Vertical Datum of 1988 (NAVD 88). This conversion requires the use of a geoid model, where the geoid is the equipotential surface of the gravity field of the Earth which best fits, in a least squares sense, mean sea level. The geoid model used may be developed by conducting a GPS survey within the region of interest or by using models available in the United States from the National Geodetic Survey (e.g., GEOID96 or GEOID99).

Project Background

The Southwest Washington Coastal Erosion Study is investigating coastal erosion processes within the Columbia River littoral cell (Figure 1), which extends 165-km in length from Tillamook Head, Oregon to Point Grenville, Washington. The study is funded and coordinated by the Washington Department of Ecology (Ecology) and the U.S. Geological Survey (USGS) Coastal and Marine Geology Program (Kaminsky et al. 1998). The study is currently utilizing LIDAR spot elevation data collected by the Airborne LIDAR Assessment of Coastal Erosion (ALACE) Project in 1997 and 1998 to develop digital elevation models (DEM) of the region. The DEMs have been used to calculate sediment volumes, identify morphologic changes, derive shorelines, and aid in the production of digital orthophotos within the littoral cell (Gelfenbaum and Kaminsky, 2000).

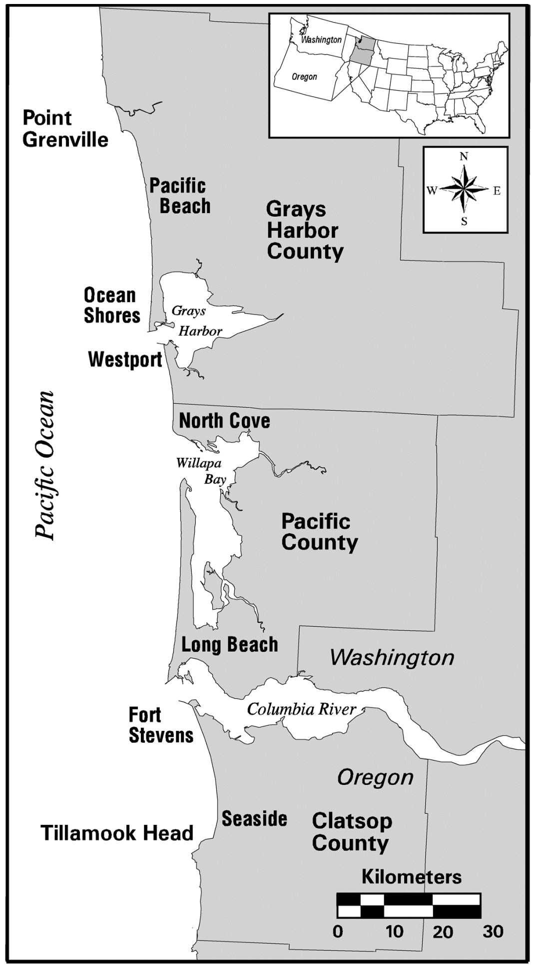

Figure 1. The Columbia River littoral cell extends 165 km from Tillamook Head, Oregon, to Point Grenville, Washington and includes portions of Grays Harbor, Pacific, and Clatsop counties.

The ALACE Project is a collaborative effort between the NOAA Coastal Services Center, NASA Wallops Flight Facility, NOAA Aircraft Operations Center, and the USGS Coastal and Marine Geology Program (Krabill et al. 1997). The project is designed to demonstrate the capability of aircraft LIDAR mapping to provide accurate information on coastal processes (e.g., Sallenger et al. 1999).

The ALACE Project currently uses the Airborne Topographic Mapper 2 (ATM-2) LIDAR system developed by NASA's Wallops Flight Facility, Wallops Island, Virginia (Krabill et al. 1995). During beach surveys the ATM-2 laser transmitter was operated at a frequency-doubled wavelength of 523 nm in the blue-green spectral region with a pulse rate of 5,000 Hz. The system was flown at an elevation of about 700 m and had a LIDAR swath width of 350 m. During the flights the ATM-2 collected 3,000 to 5,000 spot elevations per second at a ground speed of approximately 60 meters per second (135 miles per hour). Each individual spot elevation was derived from a laser footprint 0.5 to 1 m in diameter (Meredith et al. 1998, Krabill et al. 1999).

Working in cooperation with the NOAA Coastal Services Center, Ecology has conducted extensive quality assurance tests on the LIDAR data gathered for southwest Washington and northwest Oregon by the ALACE Project. This paper describes three tests that users of LIDAR data may conduct to quantify the accuracy of their vertical height data and to identify systematic offsets in the data that may have been introduced during the datum conversion process.

Datum Conversion

The height data derived from a LIDAR system is a product of the measured ranges (from the laser) and the computed aircraft trajectory (from the GPS). The information collected by the laser, inertial navigation system, and onboard GPS are stored on-board during the mission. The data are post-processed using information from a GPS base station and the horizontal and vertical position of each data point calculated. When calibrated, LIDAR data collected by the ATM-2 system has been shown to produce point coordinates with horizontal and vertical accuracy better than ±1.50 m and ±0.15 m, respectively (Krabill et al. 1995, Krabill et al. 1999).

The X, Y, Z coordinates derived for the ALACE Project were stored in International Terrestrial Reference Frame (ITRF) of 1994 longitudes and latitudes and WGS 84 ellipsoid heights in meters. Unfortunately, this coordinate system was not compatible with many existing data sets that have been collected by surveyors or coastal managers. As such, the ITRF coordinates collected by the ALACE Project for each spot height was converted to a format suitable for use by state and local governments. The conversion of the horizontal component of the ITRF spot height coordinate triplet to NAD 83 State Plane is supported by several computer programs currently available from the National Geodetic Survey (NGS). Conversion of the vertical component of this triplet was more problematic however.

Elevation Conversion

WGS 84 is a solid Earth model in which the shape of the Earth is approximated by a geometric construct called an ellipsoid. The first step of converting a WGS 84 height to a value comparable to leveled orthometric height in NAVD 88 is the transformation of the WGS 84 ellipsoid elevation to a value based on the Geodetic Reference System of 1980 (GRS 80). The GRS 80 ellipsoid is the same as used by the NAD 83 horizontal datum, the most common horizontal datum in use in the United States. Conversion to the GRS 80 ellipsoid from WGS 84 produces an NAD 83 ellipsoid height, h, on the order of –15 m for the coast of Washington.

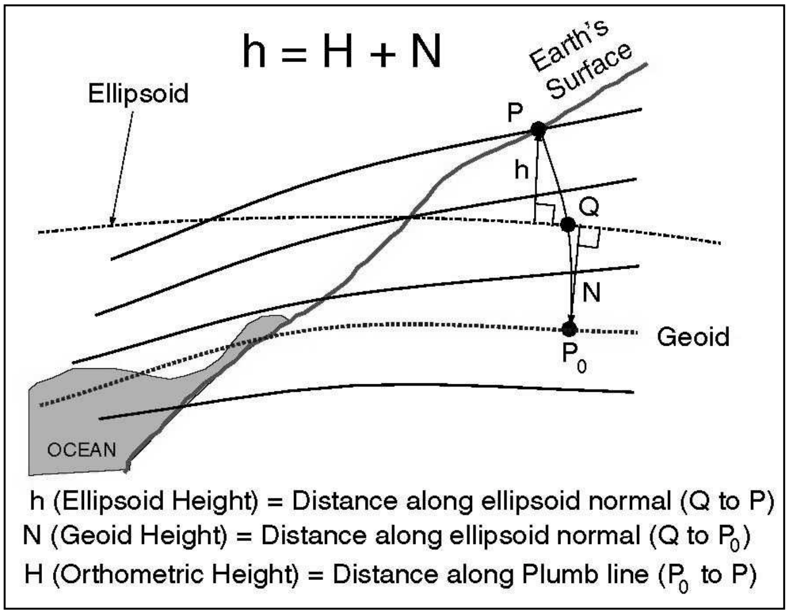

Figure 2. Graphical relationship between the Earth's surface (orthometric height), ellipsoid, and geoid height. Note that the ellipsoid is *above* the geoid. This is the actual case for all points in the conterminous United States (Source: Smith and Roman, 2000).

The height relationship between the NAD 83 ellipsoid height, *h*, and a NAVD 88 orthometric height, *H*, is as portrayed in Figure 2. The difference of height *h* and *H* for the same horizontal position is the geoid height (*N*). For example, if one is on the coast of Washington at an elevation (*H*) of 8.69 m NAVD 88 and an NAD 83 ellipsoid height (*h*) of –15.63 m, then the ellipsoid surface would be overhead. The approximate geoid height for this location would be –24.3 m. This height relationship can be expressed by the following equation

$$h_{83} = H_{88} + N \qquad (1).$$

Thus, conversion of an NAD 83 ellipsoid height to an elevation comparable to published orthometric heights found in a geodetic leveling network requires the use of a geoid model. The geoid model used here was developed by the National Geodetic Survey and is known as GEOID96. GEOID96 is a model of the Earth's gravitational field and supports direct conversion between NAD 83 ellipsoid heights and the NAVD 88 height system (Milbert and Smith, 1996a).

Note an updated geoid model was released by the National Geodetic Survey on September 30, 1999. This new model, GEOID99, was not available at the time this work was conducted. The new geoid model improves on GEOID96 by including over 400,000 additional gravity measurements, using an updated 1 arc second digital terrain model for the U.S. Pacific Northwest, and by fitting the model to 6,169 NAD 83 GPS heights on NAVD 88 leveled benchmarks. By utilizing additional NAVD 88 benchmarks the new model is able to more precisely support the direct conversion between GPS derived NAD 83 ellipsoid heights and NAVD 88 orthometric heights. The additional benchmarks have improved the fit of the geoid model. GEOID96 had an absolute agreement of ±0.055 m (1 sigma) relative to 2,951 benchmarks while GEOID99 has an absolute agreement of ±0.046 m (1 sigma) relative to 6,169 benchmarks (Reilly, 2000, Fei and Sideris, 2000).

The development of the GEOID96 model (and now GEOID99) has allowed GPS users to interpolate a geoid height for any horizontal position in the United States and to subtract this value from their GPS derived NAD 83 ellipsoid height, h_{83}, to obtain an estimated NAVD 88 orthometric height, H_{88}. When utilizing Equation 1 to derive an estimated NAVD 88 orthometric height "do not expect the difference of a GPS ellipsoidal height at a point and the associated GEOID96 height to exactly match the vertical datum you need" (Milbert and Smith, 1996b). The difference between the leveled and estimated orthometric height for a station is partially a result of error in the geoid model and other problems with datum definition.

The GPS derived height, H_{88}, for a previously surveyed benchmark may be subtracted from the published or leveled orthometric height for the same point to obtain a "local orthometric height correction factor". After the local orthometric height correction factor is calculated for a given area it may be applied to other nearby stations to obtain sub-decimeter accuracy (Milbert and Smith, 1996b). If many points over an extensive area (>100 km) are used to estimate the correction factor, trends in the correction factor may be detected (this point illustrates why the ALACE Project stored its data in ITRF/WGS 84 coordinates rather than in one of the traditional datums -such as NAVD 88). Once the correction factor has been determined for a given region, Equation 1 may be rewritten as follows:

$$H_{88} = h_{83} - N_{96} + L \qquad (2),$$

where L is the local orthometric height correction factor. In the case of southwest Washington and northwest Oregon, L was estimated independently in three ways (via base station correction, local orthometric height correction, and regional offset correction).

Base Station Correction

The calculation of point elevations for most LIDAR systems utilize the kinematic GPS survey technique (Trimble, 1996) with a base station at a known location and a roving receiver co-located with the LIDAR instrument on the aircraft. Since the LIDAR data analyzed here were referenced to ITRF/WGS 84, one can not make the assumption that the base station was tied into the national geodetic leveling network. Even if the base station were located on a surveyed benchmark, where the orthometric height correction factor would be built into the elevation correction process (i.e., H_{88} would be known), this correction would apply only to the immediate area surrounding the base station.

The base station used during the LIDAR survey of southwest Washington and northwest Oregon was not located on a leveled benchmark. The X, Y, Z coordinates of the base station were calculated independently of the local network by averaging over 48 hours of data collected by the GPS base station. The resulting station coordinates are assumed to be accurate within their own reference frame (i.e., ITRF 94, WGS 84). If the base station had been located at a surveyed benchmark the local orthometric height correction factor would have been absorbed into Equation 2. However, since the base station was not tied into the local geodetic network, the local correction factor was unknown and L assumed to be zero.

In order to tie the LIDAR data to the local vertical control network, a description of the base station (station ASTO) was obtained from Mr. Earl Fredrick at the NASA Wallops Flight Facility and a geodetic survey was conducted that followed current National Geodetic Survey guidelines (Zilkoski et al. 1997). The goal of the survey was to derive vertical and horizontal coordinates for station ASTO, the mark used by NASA during the 1997 and 1998 LIDAR flights over the Columbia River littoral cell, that would be tied to the local geodetic control network.

A two-day GPS survey was carried out that obtained baselines between station ASTO (Figure 3) and three first order benchmarks (UU 282, SMUR, and 944 0574 A TIDAL) that were located 1.5, 8.2, and 19.7 kilometers from the station. The survey consisted of six forty-five minute sessions carried out over two days. The geodetic survey produced six independent baselines to station ASTO. All redundant baselines in the survey agreed to better than 2 cm and were used to derive adjusted horizontal and vertical coordinates for ASTO (Daniels et al. 1999).

Figure 3. Trimble 4400 GPS survey system setup over station ASTO at the Astoria Airport, Oregon during the geodetic survey that was conducted to derive first order horizontal coordinates and a ±0.02 m NAVD 88 elevation for the station.

The NAVD 88 elevation corresponding to the ITRF/WGS 84 coordinate used by NASA for station ASTO was 2.90 m. The elevation obtained by the geodetic survey was 3.03 m ±0.02 m NAVD 88. Thus, a +0.13 m offset from the local NAVD 88 vertical control network in the spot elevation data was identified and corrected.

Local Orthometric Height Correction

In this case a description for the base station was available from NASA and the physical point used for their base station was recoverable in the field. This may not always be the case. In situations where a station description is not available, or the station is not recoverable, one may estimate the local orthometric height correction factor based on surveyed benchmarks within the area of interest. This option is based on the assumption that it is “known” that the base station was not tied to the local vertical network.

In southwest Washington and northwest Oregon, a National Geodetic Survey approved geodetic control network had been installed and surveyed throughout the region (Daniels et al. 1999). Several of the stations observed were benchmarks with both leveled NAVD

88 elevations and GPS-derived NAD 83 ellipsoid heights. The GEOID96 elevation for each station was calculated based on the station's horizontal coordinates. By rearranging Equation 2 the local orthometric height correction factor for each second order or higher benchmark within the survey network was calculated (Table 1).

Table 1. Calculation of the local orthometric height correction factor based on National Geodetic Survey benchmarks with published NAVD 88, NAD 83 ellipsoid, and GEOID96 heights within southwest Washington and northwest Oregon. Stations ordered from north to south, values in meters.

Benchmark Name	NGS PID	Northing	NAD 83 Ellipsoid	NAVD 88 Elevation	GEOID96 Separation	Correction Factor
SOUTH	SD0132	225290	-19.65	4.643	-24.09	0.20
L 443	SD0129	223556	-17.46	6.857	-24.11	0.21
R 443	SD0117	212765	8.72	32.988	-24.07	0.20
944 1102 TIDAL 2	SD0042	181306	-19.92	4.652	-24.39	0.18
GUNVILLE	SD0020	176953	-19.41	4.934	-24.19	0.15
FLAG	SC0916	158294	-19.67	4.095	-23.64	0.13
SOUTH BEND	SC2806	153108	2.42	25.193	-22.66	0.11
MESS	SD0358	144910	-19.90	4.210	-23.96	0.15
X 537	SD0323	137587	-18.54	5.763	-24.15	0.15
M 536	SC1020	127434	-15.61	7.788	-23.29	0.11
TURN RM 4	SD0287	116240	-18.91	5.358	-24.11	0.16
944 0574 A TIDAL	SD0299	110670	-19.50	4.872	-24.24	0.13
X 711	SC1033	88256	-13.71	9.742	-23.30	0.15
					Mean	0.16

Note: Projection is Washington State Plane, NAD 83, meters.

The average of the correction factors shown in Table 1 is +0.16 m. Note that the mean correction factor is within 0.03 m of the elevation offset calculated by the geodetic survey for the base station. This value (+0.16 m) provides an estimate of the average offset that is contained in the ALACE spot elevation data for the entire 165-km long Columbia River littoral cell.

The large linear extent of the littoral cell has made it possible to detect a trend in the correction factor. In the study area the correction factor ranges from 0.13 m at station 944 0574 A TIDAL, next to the Columbia River (about 3.8 km north of station ASTO), to 0.20 m at station SOUTH near Point Grenville, Washington, located 110 km north of the Columbia River.

Regional Offset Correction

When information is not available as to the location of the base station and it is unknown if the local orthometric height correction factor has been taken into account, a third option for detecting and correcting offsets in LIDAR data sets exists. This option is based on the collection of sample survey points on the ground using real-time-kinematic (RTK) or kinematic GPS methods. Survey points would be collected within the area covered by the LIDAR system at locations whose elevations have remained unchanged over the time that had elapsed since the flight. Examples of such sites include roads, parking lots, and sidewalks.

A large number of these ground based sample points are needed, as LIDAR systems collect individual data points (spot elevations), not a continuous topographic surface. In many cases these points are processed to derive a continuous raster DEM. However, it is the original spot elevation data that needs to be compared to the sample survey data. As such, pairs of ground sample and LIDAR points need to be obtained that have horizontal coordinates within 2.5 m of each other (the horizontal accuracy of the ATM-2 system used in Washington and Oregon was ±1.50 m with a laser footprint of 0.5 to 1.0 m). Note that we assume here that common data points within this footprint are on a level surface.

The sampling scheme used in our region included eight hundred random samples surveyed within five areas distributed throughout the length of the littoral cell. The sample data points were entered into a GIS and a proximity analysis conducted to obtain a listing of LIDAR spot elevations that were within 0.50 m and 2.50 m of the GPS sample points. Of the eight hundred points sampled, 75 were found to be within 0.5 m of a LIDAR point and 524 were found to be within 2.5 m of a LIDAR point. The difference in elevation between each GPS sample point and the height obtained by the LIDAR system was calculated. When plotted, these differences were found to be normally distributed around the mean.

Table 2. Difference of RTK-GPS sample points and LIDAR spot elevations obtained by the ATM-2 LIDAR system for points that are within 0.5 m and 2.5 m of each other, values in meters.

Land Cover Type	Search Radius	Minimum Elevation Difference	Mean Elevation Difference	Maximum Elevation Difference	Number of Samples
Road or Sidewalk	0.5 m	-0.02	0.21	0.51	75
Road or Sidewalk	2.5 m	-0.63	0.20	0.89	524

Table 2 shows the mean elevation difference between the LIDAR and the GPS samples for each of the two sample groups. Of the 75 (524) samples in the 0.5 m (2.5 m) radius group, only 26% (30%) fell within ±0.15 m of zero, the reported accuracy of the LIDAR system. Based on the assumption of a normal error distribution, the mean error should have been near zero. The fairly large size of the sample indicated that a positive offset or datum shift was present in the data. Based on this information, we used the mean as an estimate of the local orthometric height correction factor and subtract the mean (taken to be +0.20 m) from the ATM-2 data. When the mean was subtracted from the spot elevations in Table 2 the percentage of samples that fell within ±0.15 m of zero increased to 83% (84%) for the 0.5 m (2.5 m) radius group.

To test if the sampling method could identify regional trends in the mean elevation difference (a.k.a. correction factors), Figure 4 was constructed with the sample pairs obtained using the 2.5 m radius group. Note that the accuracy of the RTK-GPS method used was ±0.02 m. In Figure 4 the sample points have been divided based on latitude (northings) into five groups and the mean offset calculated for each. The groupings are based on the sampling sites used in the analysis and, from south to north, are: Seaside, Oregon, Fort Stevens, Oregon, Long Beach, Washington, Westport, Washington, and Pacific Beach, Washington (see Figure 1).

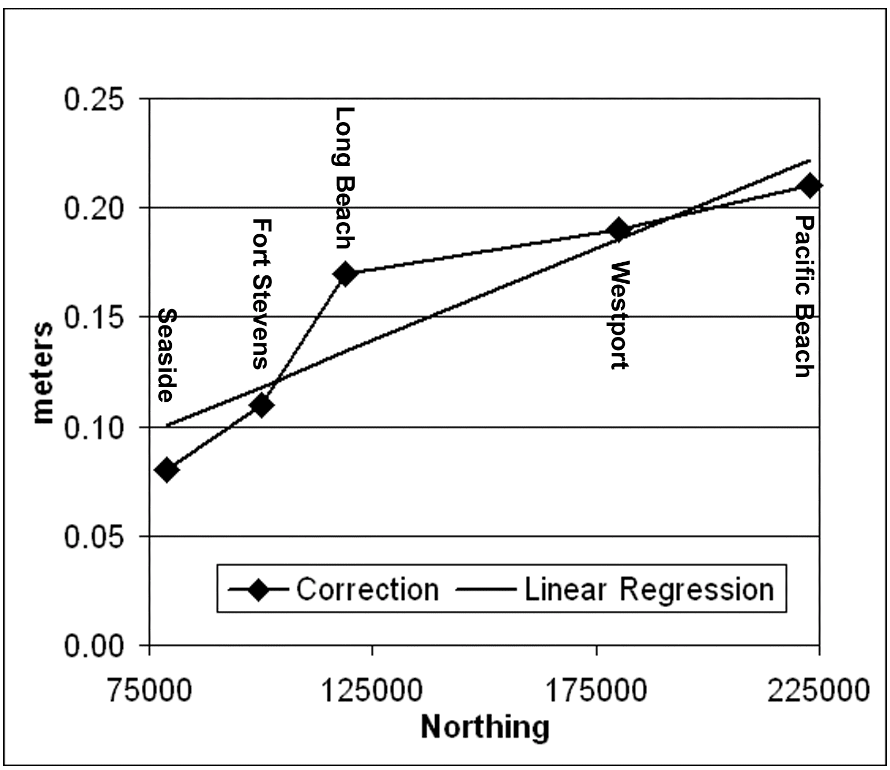

Figure 4. Bin-averaged difference of RTK-GPS sample points and ATM-2 LIDAR spot elevations for five regions within the Columbia River littoral cell, values in meters.

The average offset for the five regions is +0.15 m, with the minimum value located at Seaside, Oregon and the maximum value being located near Pacific Beach, Washington. These samples have a near linear trend, with the mean offset increasing as one travels north from the Columbia River toward Point Grenville, Washington. It is interesting to note that these mean values closely approximate the trend identified in Table 1, where local orthometric height correction factors were calculated using National Geodetic Survey benchmarks.

Results

The ALACE Project has been successful in providing internally accurate digital elevation data that may be used for beach morphology mapping and beach erosion modeling over large areas (> 100 km in length). These point data were originally collected using ITRF 94 horizontal coordinates and WGS 84 ellipsoid heights. Transformation of these coordinate triplets to the more familiar NAD 83 and NAVD 88 reference frames without the inclusion of local orthometric corrections may have introduced identifiable datum offsets in the derived products.

Within the Southwest Washington Coastal Erosion Study area three different correction factors were obtained. The correction factors ranged from a low of +0.13 m at the NASA base station near the Columbia River in Oregon to a high of +0.20 m, the sample mean in Table 2. A regional trend in the local orthometric height correction factor was identified in Table 1 and Figure 4. When this trend is approximated by a linear regression line it is possible to explain the range of values obtained by the three methods tested here. This regional trend implies that the use of an orthometric height correction factor calculated for the base station alone will not correct all offsets in the data, and that the correction factor required may vary based on the location of the LIDAR instrument in relation to the base station.

Conclusions

The use of LIDAR data to derive topographic data and to generate digital elevation models has moved from the basic research phase into production in just the last few years. LIDAR is now seen as a viable alternative to photogrammetric methods when highly accurate digital elevation data needs to be collected quickly (e.g., after a Hurricane). LIDAR derived elevation models may be used with traditional air photography or satellite data to produce orthorectified images, thus avoiding the time consuming stereo-compilation process.

This paper has demonstrated three tests (i.e., base station correction, local orthometric height correction, and regional offset correction) that may be used to isolate potential datum offsets in LIDAR data. Users of LIDAR data who require sub-decimeter accuracy and who plan to compare LIDAR data to elevation data derived from conventional topographic surveys should conduct similar quality assurance tests. These surveys will insure that the LIDAR data has been corrected for the local orthometric height correction factor and that any potential offsets in the data are identified and removed.

The importance of conducting some level of quality assurance tests on the very large data sets produced by a LIDAR survey can not be over-stated. This need has grown as the precision of available LIDAR instrumentation has increased. This point is made by the following simple example. If a 2.0 m contour line were derived from LIDAR data for a beach with a slope of 2%, and the data contained an –0.20 m offset, the resulting contour line would be displaced landward from its true location by 10 m (30 ft). Such a large horizontal error could mitigate one of the primary motivations for using LIDAR data for morphologic mapping of dynamic surfaces, such as beaches.

Acknowledgments

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