APPLICATION OF AN EXPERIMENTAL AIRBORNE LASER SCANNER FOR SURVEYING A BRAIDED RIVER CHANNEL

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Abstract The National Aeronautics and Space Administration (NASA) has recently developed the Experimental Advanced Airborne Research LiDAR (EAARL). The EAARL is a hybrid topographic and bathymetric airborne laser scanner or light detection and ranging (LiDAR) platform specifically designed for surveying shallow coastal environments. We evaluated the vertical accuracy of the EAARL in mapping the topography and bathymetry of a shallow, braided, sand-bedded river by comparing measurements made by the EAARL to coincident ground-truth measurements collected with conventional ground-based survey-grade real-time kinematic global positioning system (RTK-GPS) technology. The surveys were conducted in the spring of 2002 and the summer of 2005 along the Platte River in central Nebraska. In this paper, preliminary results are presented from the 2005 EAARL flight. The vertical accuracy of the EAARL system was evaluated by first examining the laser pulses or waveforms returned from the exposed bare sandbars in the river. These returns were relatively simple in the sense that they were symmetric and single-peaked. We calculated the range from the aircraft to these sandbars with an algorithm that assumes the centroid of the waveform corresponds to the location of the first surface encountered. Using this 'first-surface' algorithm, the root mean square error of the EAARL ellipsoid heights on the bare sand compared to the ground truth GPS heights were 0.17 m after applying a uniform block correction to account for a small systematic bias. We then approximated the range to all the submerged areas with the first-surface algorithm. The root mean square error of the EAARL derived elevations in the submerged sand areas compared to the ground truth GPS measurements was 0.23 m, also after applying the block correction. Despite the fact that the first-surface algorithm did not account for the speed of light in water, it performed reasonably well for depths to about 0.4 m. In deeper depths, the algorithm computed a range shallower than the riverbed. However, these areas returned more complex waveforms, which are a result of backscatter from the water column, from entrained material, and potentially backscatter from the sand bed. We then approximated the range to the river bed using a specialized bathymetric algorithm on these waveforms. As compared with heights computed with the first-surface algorithm in these deeper areas, the bathymetric algorithm yielded heights with a lower root mean square error.

INTRODUCTION

Background Understanding the morphodynamics of braided river channels is important for a variety of river management issues including flood control, in-channel habitat assessment, and constituent transport. Scientific studies undertaken to address these issues require quantitative representation of the form of these channels. While conventional ground-based surveying technology can be used to collect transect and longitudinal profile data, it is at best inefficient for constructing large-scale, detailed topographic maps of these rivers. Furthermore, conventional technology is incapable of collecting data at the scales needed to characterize the complex spatial and rapid temporal variation in the topography of braided channels.

The Platte River in central Nebraska is a braided sand-bedded river that is the focus of endangered and threatened species recovery efforts by federal and state governments and conservation organizations. Of critical interest to these groups is how flow influences the morphology of the river and in-channel avian habitats. The Platte River presents diverse technological and logistical challenges with regard to collecting topographic and bathymetric measurements. The shallow depth prohibits the use of boats and hydroacoustics. Relatively accurate point measurements can be gathered by wading the river with real-time kinematic global positioning system technology (RTK-GPS). This technique has been used on the Platte River to collect survey data used as input to a multidimensional hydrodynamic model (Kinzel and others, 2001). However, mapping braided rivers by wading with RTK-GPS is a laborious process requiring a large field crew with multiple roving GPS receivers, multiple days, and unfettered access to monitoring sites.

There have been some efforts in applying remote sensing techniques to survey rivers. Westaway and others (2000) describe a digital photogrammetry technique used on a braided river in New Zealand. Others have developed correlations between depth and the grayscale of submerged areas in an aerial photograph, which are a function of the reflectance of light from the riverbed (Gilvear and others, 1995). Multi-spectral imagery also has been used with field calibration data to derive relations between water depth and passive spectral reflectance (Winterbottom and Gilvear, 1997). Gilvear and Bryant (2003) point out that spectral reflectance is spatially variable due to depth of water, the presence of suspended material which complicates the reflectance, and variation in color of the riverbed. Additional drawbacks in using reflectance techniques are the need for field calibration data and the fact that information is only gathered in submerged areas, while the elevation of islands, exposed river bars, and the floodplain are excluded.

Due to the coverage and efficiency of acquisition, LiDAR is an attractive technology for mapping large areas and is readily available from commercial vendors. This technology has been applied for a myriad of mapping investigations and accuracy assessments have been made as a means to judge its appropriateness (Bowen and Waltermire, 2002; Huising and Pereira, 1998; Mietz and others, 2002). Most commercial LiDARs are used for terrestrial mapping and typically make use of a laser that outputs energy in the near-infrared wavelength (1064 nm). When any laser strikes a water target, the laser energy may be absorbed, scattered, or reflected. Generally speaking, near-infrared lasers will not penetrate water to a significant depth, so blue-green lasers are commonly used for this purpose. In addition to this potential limitation, processing algorithms used by commercial vendors are typically proprietary. LiDAR vendors usually deliver a first return and/or last return (bare earth) product. While a commercial LiDAR system could provide useful information on some types of targets in the river, we were not sure of what information we would get, if any, on the submerged areas. Furthermore, the data product would not provide any insight into the character or shape of these submerged laser returns. Because of these limitations, we investigated bathymetric LiDARs. Bathymetric LiDARs are relatively rare compared to terrestrial systems. The Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system is perhaps the most recognized of these instruments (Irish and others, 2000). SHOALS has been operated by the Joint Airborne Lidar Bathymetry Technical Center of

Expertise, a collection of agencies from the U.S. Army Corps of Engineers and the Navy. Bathymetric LiDARs are usually used in clear coastal waters, not rivers. Rivers can have significant turbidity in the water column which could mask the bottom return entirely or provide a return that could be misinterpreted as the bottom. Given the complexity and the potential suite of complications associated with targets in a sandy braided river, we sought to evaluate the performance of the National Aeronautics and Space Administration's Experimental Advanced Airborne Research LiDAR (EAARL).

The EAARL System The EAARL was initially designed to survey coral reefs in relatively clear water (Wright and Brock, 2002). The system is operated from a Cessna 310 aircraft and consists of a Continuum EPO-5000 doubled YAG laser that produces up to 5000, 1.3 nanosecond duration, 70-micro-joule, 532-nm (blue/green) pulses each second. A scanning mirror directs the spacing of individual laser samples along each swath. When the EAARL is operated at a 300-m altitude at 50 m per second, the spacing of individual laser samples in a 240-m swath is 2 m x 2 m in the center and extends to 2 m x 4 m on the edges. To ensure eye safety, the footprint of a bathymetric laser must be spread to reduce the spot energy transmitted. Because the EAARL laser has 1/50th the power of other bathymetric LiDARs, the diameter of this footprint also is much smaller, about 0.15 m as opposed to 2.0 m for the SHOALS system. The EAARL laser pulses transmitted and returned to the aircraft are completely digitized and stored for post-processing. The trajectory of the aircraft is computed using differential GPS. The attitude (pitch, yaw and roll) of the aircraft is recorded with a gyroscopic inertial measurement unit or IMU. Two digital cameras (a 1600x1200 pixel color infrared (CIR) and a lower resolution red, green, and blue (RGB)) acquire imagery at one frame per second of the area below the aircraft and are synchronized with the laser data.

METHODS

EAARL Surveys The EAARL was first used to survey study sites along the Platte River in late March 2002 (Kinzel and Wright, 2002). This time period was selected to take advantage of the fact that water levels were relatively low and vegetation was not present in significant quantities on sandbars. As such, a rather high proportion of the channel area consisted of bare sand. In contrast to these conditions, we purposely selected a time of year in June of 2005 when flow and depths in the river were greater. We knew that this time of year would result in increased complexity of the backscatter but it also provided a better opportunity to evaluate, and possibly help to improve upon, the bathymetric-processing algorithm.

On June 15, 2005 NASA flew 24 flight lines over a 10-km reach of the Platte River at an altitude of 300 m. This area contains the Lillian Annette Rowe Bird Sanctuary; a reach of the Platte River owned and managed by the National Audubon Society. This property provides habitat for migratory birds and is an area where endangered and threatened species are occasionally observed. The total flow of the Platte River 16 km upstream at the USGS streamflow-gaging station at Kearney, Nebraska was approximately 40 cubic meters per second. Only a portion of the total streamflow (approximately 65%) passes through the Rowe Sanctuary channel. A stationary GPS receiver was placed at the airport in Kearney, the base for the EAARL surveys. The trajectory of the aircraft was computed relative to this GPS base station.

EAARL Processing The EAARL waveforms were processed with an open-source software package called ALPS (Airborne LiDAR Processing Software). The ALPS software has been jointly developed by NASA and the USGS Coastal and Marine Geology Program in St. Petersburg, Florida and runs on a Linux operating system. The ALPS software enables researchers to interrogate rasters and individual waveforms, view RGB and CIR imagery, and process waveforms using specialized algorithms to create surface maps. NASA and USGS have developed processing algorithms tailored for various EAARL applications. Researchers collect verification data to evaluate system accuracy and also with the aim of improving the performance of the processing algorithms, especially in complex environments.

Two processing techniques, herein referred to as first surface and bathymetry, were used within ALPS. The first-surface algorithm bases the ranging measurement on the time of flight from the aircraft to the centroid or center of mass of the return laser backscatter or waveform. The bathymetry algorithm requires various input parameters that the user must set. The values of these parameters are chosen by examining waveforms from submerged areas and interactively adjusting them to fit an exponential decay curve to the trailing edge of the waveform. In deep water, waveforms can show an asymmetry and broadening of the base that is the result of backscatter from the water column, entrained material, and potentially the river bottom. The bathymetric algorithm approximates the location of the bottom in a convolved waveform by using an exponential decay function to model the bottom return signal and by working backwards, approximates its location within the waveform. After the first-surface algorithm was used, the data set was filtered using a random consensus filter (RCF) to identify and remove outliers by comparing points in a 0.5-m^2 buffer area. We set the RCF filter to remove points from the dataset that exceeded a 0.2-m tolerance for the consensus elevation in the buffer area.

Ground Surveys While the EAARL aerial surveys were conducted, detailed ground-based surveys of the river were carried out using real-time kinematic global positioning system technology (RTK-GPS). The position of the RTK-GPS base station was determined by post-processing static satellite observations over a benchmark. Coincident with the EAARL flights, we used two roving GPS receivers in RTK mode to compute positions relative to the benchmark. The RTK-GPS survey was projected in the Universal Transverse Mercator coordinate system using the 1983 North American Datum transformation. The GPS heights measured were relative to the same datum. Because it was not necessary for the comparison, we did not convert these ellipsoid heights to orthometric heights with a geoid model. Topographic and bathymetric points were collected along transect lines perpendicular to the center of the main channel and from upstream to downstream in areas where the water depth was greatest. The depth of the water at each surveyed point was measured with aluminum yard sticks affixed to the GPS survey poles. Water clarity at the time of the surveys was spatially variable and a function of water velocity which was positively correlated with depth. In most submerged areas, the water clarity was sufficient so that the ground surveyors could resolve the river bed. In some locations, however, high velocities suspended high concentrations of sand and resolving the bed was more difficult. It should be pointed out that accurate wading GPS measurements were not easy to obtain in these areas. This was due to the uncertainty in the position of the moving sand bed as well as the difficulty in holding the GPS survey pole steady enough in these faster velocities to acquire an accurate measurement.

Comparison of Surveys The first-surface algorithm was initially used to process the EAARL waveforms and create a surface map of ellipsoid height (Figure 1). The horizontal and vertical coordinates of the ground-truth GPS and EAARL surveys were then exported to a geographical information system (GIS) database. The GIS was used to select and pair an EAARL data point that was in close proximity to a ground-truth point. Due to the high density of EAARL points collected over the ground-truth site, approximately 373,000 after using the RCF filter, the average distances between the point pairs was about 0.5 m. The sub-aerial bare sand areas in the river channel provided the best location to evaluate the accuracy of the first-surface algorithm and also a means to identify any systematic vertical bias between the surveys. The vertical bias could be a function of many variables including but not limited to: the precision of the solution for the base station locations, possible measurement error in the setup of the base stations, and precision in the EAARL and ground-truth GPS measurements.

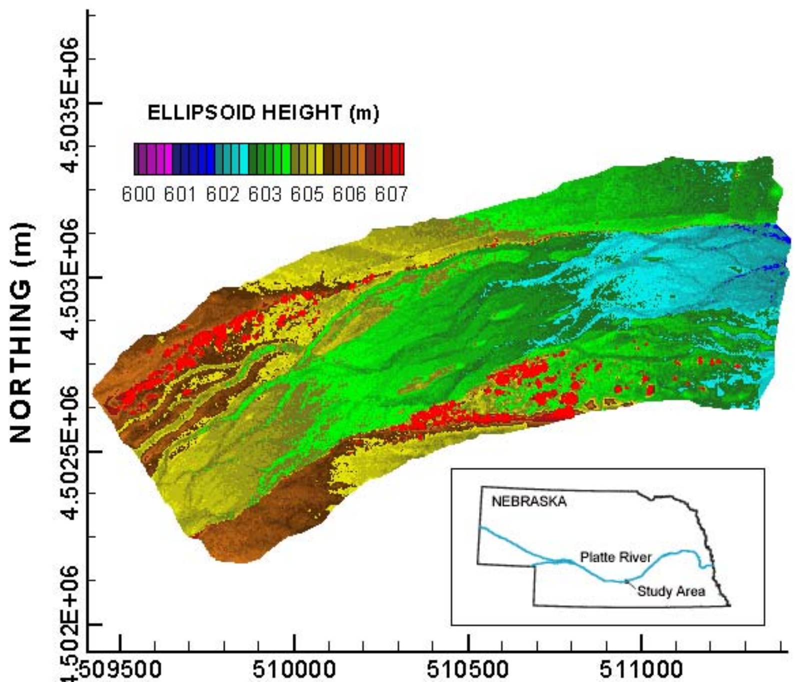

Figure 1 Ellipsoid height map of a reach of the Platte River, Nebraska computed with the EAARL first-surface processing algorithm.

RESULTS

Vertical Accuracy Assessment Examination of 165 point pairs collected on bare sand showed the ellipsoid heights measured with the EAARL first-surface algorithm were generally lower than the corresponding ground-truth point with a mean error of approximately 0.09 m. We assumed that this bias was systematic throughout the survey and a function of the external factors mentioned above rather than the processing technique, but further investigation is needed. Following this assumption, we added 0.09 m to all EAARL computed ellipsoid heights. After correcting for the bias, the root mean square error of the 165 bare sand points was 0.17 m. When the correction was applied to 802 point pairs collected in submerged areas with heights computed using the first-surface algorithm, the root mean square error (RMSE) was 0.23 m. Figure 2 shows the relation between the height of the ground-truth point and the corresponding EAARL first-surface point for a range of water depths overlying the ground-truth point. From this figure we can see that as the water depth increases, the algorithm generally measures the first surface to a point in the water column above the height of the river bed. If the first-surface ranging measurement was made up of a reflection from the river bed only, the ranging measurement would be below the corresponding ground-truth value, and the bed would be measured deeper. This is because the first-surface algorithm assumes that the ranging measurement is through air only and light travels faster through a distance in air as opposed to the same distance made up of air and a small depth of water. We noticed that the RMSE and the bias associated with using the first-surface algorithm increased as the depth of water increased. For depths less than 0.4 m, the RSME was comparable to the magnitude of the errors found on bare sand targets. In depths over 0.4 m, the errors were much larger. We then processed the dataset using the bathymetric algorithm. As compared with the first-surface algorithm, fewer returns satisfied the bathymetric parameters we set and were available for comparison with the ground-truth points. Because the density of points returned was lower, the distance between point pairs was greater. We then plotted the point pairs in the depth range greater than 0.4 m that were also less than 1.0 m apart for each processing algorithm (Figure 3). While the bathymetric algorithm generally tended to approximate the elevation of the river bed deeper than it actually was, the RSME for the bathymetric algorithm was 0.22 m as compared to 0.37 m for the first-surface algorithm.

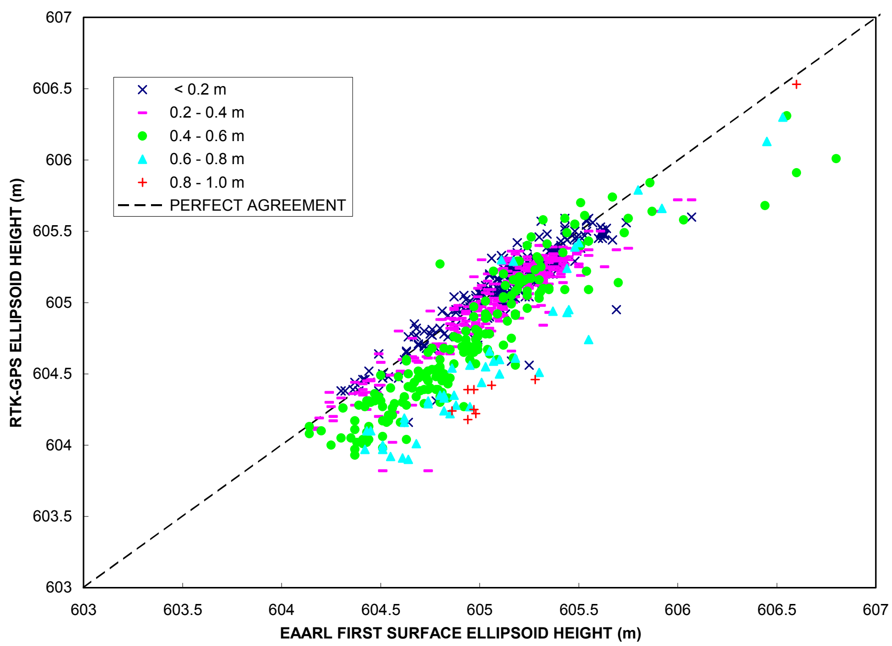

Figure 2 Comparison of ellipsoid heights measured with RTK-GPS to those computed with the EAARL first-surface processing algorithm in various depth ranges.

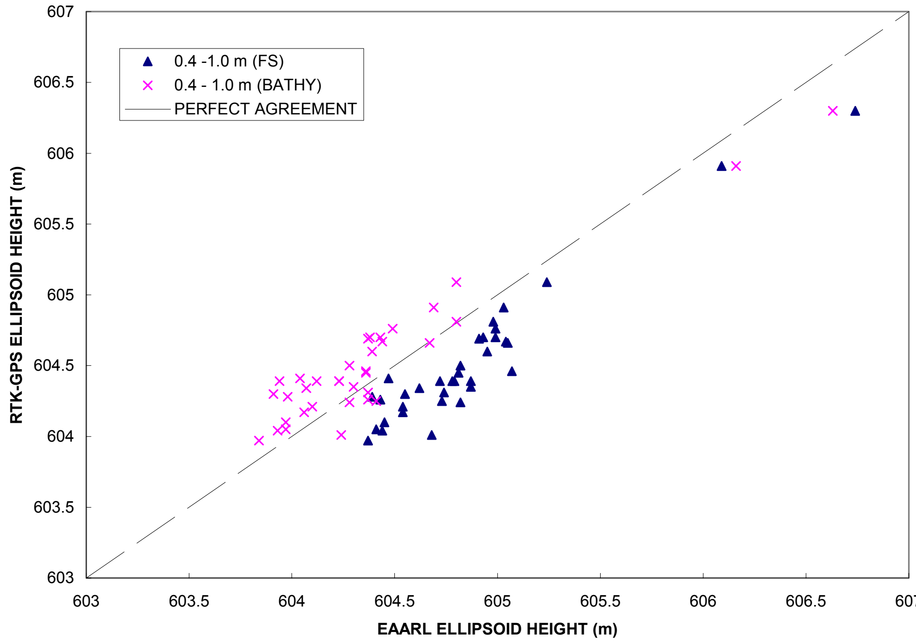

Figure 3 Comparison of ellipsoid heights measured with RTK-GPS to those computed with the EAARL first-surface algorithm (FS) and bathymetry algorithm (BATHY) for depths greater than 0.4 meters and for distances less than 1.0 meter between point pairs.

CONCLUSIONS

The EAARL is an innovative technology for collecting rapid and synoptic measurements of braided channel morphology. A vertical accuracy assessment conducted along the Platte River in Nebraska demonstrated that the EAARL first-surface algorithm computes the position of the river bed reasonably well for depths to about 0.4 m. In deeper depths, the EAARL first-surface algorithm generally underestimated the height of the river bed; however the EAARL bathymetric algorithm may be used in these areas to improve this approximation. Future work involves using the Fresnel reflections generated at the air-water interface to model the water-surface elevation through the reach. This technique could provide a more reliable means to detect and compute the range to the river bed.

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