

Integrating Terrestrial LiDAR and Stereo Photogrammetry to Map the Tolay Lakebed in Northern San Francisco Bay

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Abstract

The Tolay Creek Watershed drains approximately 3,520 ha along the northern edge of San Francisco Bay.

Surrounded by a mosaic of open space conservation easements and public wildlife areas, it is one of the only watersheds in this urbanized estuary that is protected from its headwaters to the bay. Tolay Lake is a seasonal, spring-fed lake found in the upper watershed that historically extended over 120 ha. Although the lakebed was farmed since the early 1860s, the majority of the lakebed was recently acquired by the Sonoma County Regional Parks Department to restore its natural habitat values. As part of the restoration planning process, we produced a digital elevation model (DEM) of the historic extent of Tolay Lake by integrating terrestrial LiDAR (light detection and ranging) and stereo photogrammetry datasets, and real-time kinematic (RTK) global positioning system (GPS) surveys. We integrated the data, generated a DEM of the lakebed and upland areas, and analyzed errors. The accuracy of the composite DEM was verified using spot elevations obtained from the RTK GPS. Thus, we found that by combining photogrammetry, terrestrial LiDAR, and RTK GPS, we created an accurate baseline elevation map to use in watershed restoration planning and design.

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Introduction

The San Francisco Bay area is a highly urbanized region with approximately 80 percent of remnant wetlands lost to development and agriculture. One of the more uncommon wetland types in the bay is seasonal wetlands, which have declined by nearly 75 percent in the past 150 years (Olofson 2000). Seasonal wetlands are shallowly inundated after winter rains and dry up in the summer depending on seasonal water availability, site hydrology, substrate permeability, and topography. Accurate topographic data with appropriate spatial coverage is used for the design and engineering of seasonal wetland restoration or enhancements. Shallow, intermittently flooded lakes pose unique challenges for elevation surveys. Seasonal wetlands are often densely vegetated with submerged aquatic and tall emergent vegetation.

When inundated, echosounding systems modified for mapping shallow water bathymetry (Woo et al. 2007b; Athearn et al., in press; Takekawa et al., in press) would be suitable for measuring water depths; however, bottom elevations can be obscured by dense aquatic vegetation. Terrestrial or ground LiDAR is a recent alternative method for acquiring topographic data from areas where mobility and accessibility prohibit conventional surveying. Terrestrial LiDAR can be collected rapidly, is feasible for relatively small areas, and may be more accurate because of a greater point density than aerial LiDAR. Terrestrial LiDAR is ideal for unvegetated areas, but errors can increase with the amount of vegetation. Airborne LiDAR may be more appropriate in larger areas or areas with tall vegetative canopies, where vegetation signals may be

identified and filtered from bare ground by analyzing multiple laser returns (Heritage and Hethington 2006).

The restoration of Tolay Lake, a shallow seasonal lake that inundates private properties in addition to the park property, called for an accurate and detailed baseline topographic survey. We used a preexisting stereo photogrammetric dataset and filled data gaps using terrestrial LiDAR (light detection and ranging) and RTK GPS (real-time kinematic global positioning system). In addition, we created a digital elevation model (DEM) from the combined datasets and tested the accuracy of the DEM with spot checks from an RTK GPS receiver.

Site

The Tolay Creek watershed lies in the northern reaches of the San Francisco Bay Estuary and drains approximately 3,520 ha into the San Pablo Bay. This watershed is surrounded by a mosaic of open space, agriculture, conservation easements, public wildlife areas, and public lands that have been acquired for preservation and restoration. The Tolay Lake Regional Park, owned and managed by the Sonoma County Regional Parks, is located at the headwaters of the Tolay watershed in Sonoma County (lat: 38.205°, long: -122.520°). It encompasses 703 ha and composes 20 percent of the watershed.

The most significant feature of the park property is Tolay Lake. With a surface area of 80 ha, Tolay Lake is the largest natural freshwater lake in the San Pablo Bay watershed and ranges between 1.2 and 2.4 m deep (Kamman Hydrology and Engineering, Inc. 2003). Historically, Tolay Lake once had approximately twice the surface area (Kamman Hydrology and Engineering, Inc. 2003). In the mid-to-late 1800s a natural dam that created the lake was removed to facilitate farming of the lakebed, which supported various crops including pumpkins, squash, corn, potatoes, and tomatoes (Kamman Hydrology and Engineering, Inc. 2003). Tolay Lake drains into Tolay Creek, an ephemeral creek that is hydrologically disconnected from lower Tolay Creek, a 5-km reach that was restored to tidal flow from the bay in 1998. Managed by the San Pablo Bay National Wildlife Refuge and California Department of Fish and Game, the lower Tolay Creek wetland restoration project is highlighted as a successful restoration with long-term monitoring that shows recovery of tidal marsh inhabitants and wildlife species (Bias et al. 2006, Woo et al. 2007a). In 2004,

Sonoma County Regional Parks Department acquired the Tolay Lake Ranch in the upper watershed, and in 2007, the Sonoma Land Trust purchased 668 ha of the adjacent Roche Ranch that included a riparian easement along a 4-km stretch of Tolay Creek in the middle portions of the watershed. The connectivity of these landmark acquisitions resulted in the preservation of a majority of the Tolay watershed. Sonoma County identified a gap in their photogrammetric coverage located in the northwest section of the lakebed. We used terrestrial LiDAR and RTK GPS to fill data gaps and integrate the data into a combined DEM for the Tolay lakebed.

Methods

We initially planned to survey the lakebed with an echosounding system designed for shallow water applications (Woo et al. 2007b) combined with ground LiDAR surveys; however, because of dense vegetation growth and because relatively dry winter conditions precluded use of the echosounder, terrestrial LiDAR surveys were restricted. Therefore, we decided to integrate a preexisting photogrammetric dataset collected in 2005 for the Sonoma County Regional Parks (Delta Geomatics Corporation 2005). The dataset contained approximately 22,000 elevation points throughout the project area. The County identified a gap in the coverage for the northwest section of the lake that overlaid private property. We augmented and validated the photogrammetry dataset with RTK GPS spot elevations and terrestrial LiDAR (Figure 1).

Data are reported in the horizontal datum California State Plane NAD 83 Zone II (for comparisons with existing imagery) and orthometric heights were referenced to the vertical datum NAVD88 (U.S. survey feet) using the Geoid03 model (Leica GeoOffice v6.0). Data points were exported as shape files into ArcGIS (ESRI, Redlands, CA).

RTK MAX surveys

We used an RTK MAX GPS system to conduct the RTK surveys. The RTK MAX GPS surveys were primarily used to obtain validation elevation 'spot' checks. We conducted our surveys using a Leica RTK GPS (Smart Rover GPS 1200, Leica Geosystems Inc., Atlanta, GA) within the MAX network where RTK corrections were based on the Master Auxiliary Concept (Leica Geosystems 2008; Haselbach Surveying

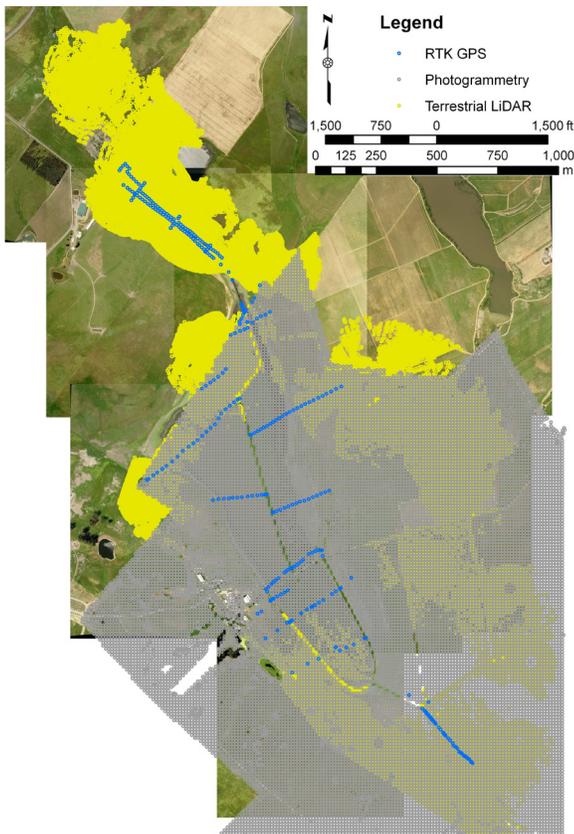


Figure 1. Locations of photogrammetry, terrestrial LiDAR, and RTK GPS elevation points throughout the Tolay Lake project area.

Instruments Inc., Burlingame, CA). Within the MAX network, the rover communicates with the reference station through cellular lines and monitors and changes its calculation of published algorithms in real time to optimize the RTK solution (Leica Geosystems 2008), yielding a real-time accuracy on the order of 2 cm (Brown et al. 2006, Ghilani and Wolf 2008). We used the reference station maintained by the City of Santa Rosa (2008) and collected 446 RTK GPS locations, of which 316 were used as spot validations in the channel, Tolay lakebed within the property, and the upper lakebed on private lands (for which we obtained written access permission).

Terrestrial LiDAR

We conducted 27 terrestrial LiDAR scans, 500 m apart, with an ISITE 4400CR laser unit on 22–23 March 2007. We used an RTK GPS to survey the LiDAR unit setup and back sight locations. These setup locations were used to georeference the LiDAR point clouds during data processing. The laser scanner used a time-

of-flight pulsed range finder with a 905-nm laser and a beam divergence of 1.4 mrad. The unit has a built-in tilt compensator that ensures each scan is level prior to initiation of the scan. It has a measurement rate of 4,400 points per second and a scan range of <3 m to >250 m. Point clouds produced from each scan were aligned, visualized, and processed using ISITE Studio software v 3.0 beta, (I-Site Pty Ltd, Glenside, South Australia). We filtered out vegetation height by applying a 1.5-m topographic filter in which only the lowest point within 1.5 m² was retained for analyses, yielding 395,000 filtered data points. We examined differences between the LiDAR scans and RTK GPS ground elevations that were within 2 m of each other. The LiDAR elevations were 0.58 ± 0.03 m higher than the RTK ground elevations. We further adjusted for vegetation interference by subtracting 0.58 m from the LiDAR datasets because of the small standard error and the uniformity of the grassy vegetation understory in the upper lakebed.

Digital elevation model and validation

We integrated the photogrammetry and terrestrial LiDAR datasets. Values between data points were interpolated using inverse distance weighting (IDW) in ArcGIS (Spatial Analyst, Geostatistical Analyst, ESRI). IDW is an exact interpolator in that the maximum and minimum values in the interpolated surface can only occur at sample points. This method assumes that the surface is being driven by local variation and is appropriate for points that are evenly distributed (Johnston et al. 2001). The DEM was generated with grid cell size of 10 m because of the high point density (Spatial Analyst, ArcGIS; Figure 2).

[Continued on next page]

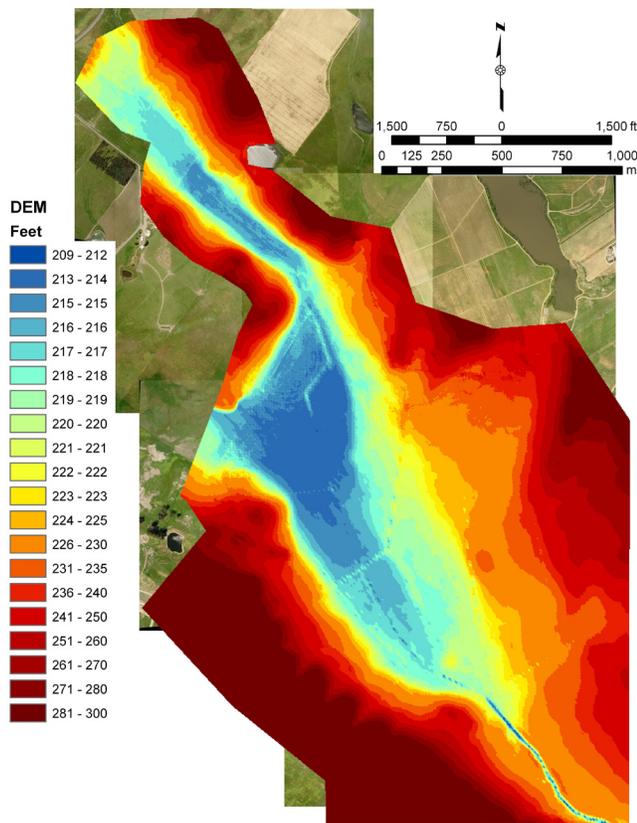


Figure 2. Composite digital elevation model using photogrammetric and terrestrial LiDAR datasets.

We analyzed model errors with the surface spot tool (3D Analyst, ArcGIS, ESRI), where we compared actual RTK GPS point values to the respective locations on the predicted elevation model. We calculated the errors (standard error, standard deviation, root mean square error ($RMSE_z$)) and the vertical accuracy within a 95-percent confidence interval for the entire dataset and by habitat type (channel, Tolay lakebed, upper lakebed; Flood 2004, Aguilar and Mills 2008).

Root mean squared error ($RMSE_z$) is calculated by:

$$RMSE_z = \frac{\sqrt{\sum_{i=1}^n (z_{1i} - z_{2i})^2}}{n} \quad (1)$$

Vertical accuracy within 95-percent confidence interval is calculated by:

$$Vertical\ accuracy\ at\ 95\% \ CI = RMSE_z \times 1.96 \quad (2)$$

Where

Z_{1i} is the vertical coordinate of the i^{th} check point in the dataset,

Z_{2i} is the vertical coordinate of the i^{th} check point in the independent data source of higher accuracy,

n is the number of points being checked,

and

i is an integer from 1 to n .

Results and Discussion

We gathered 446 elevation points with the RTK GPS, of which 316 points were used for validation with the surface spot tool. The RTK GPS locations in the Tolay lakebed and upper lakebed had little topographic variation (Tolay lakebed: mean + se; 216.39 + 0.21 ft; upper lakebed: 215.98 + 0.06 ft. Channel areas had greater variation (212.17 + 0.39 ft) due to tall vegetation near the channel edge.

Digital elevation models consist of errors from field accuracy and errors from data interpolation in elevation models. We found that the interpolated points on the DEM matched the RTK GPS validation points well with a mean difference of 0.06 ± 0.07 ft (Table 1). The $RMSE_z$ was 0.07 ft and the consolidated vertical accuracy (at a 95-percent confidence interval) was 0.13 ft, much more than other reported values for low vegetation such as crops (range 1.15–1.51 ft; Veneziano et al. 2003).

When examined by habitat type, channels had the greatest error (1.84 ± 0.30 ft), compared to the Tolay lakebed (0.10 ± 0.05 ft) and upper lakebed (0.63 ± 0.05 ft; Table 1). The DEM predicted channel elevations nearly 2 ft higher than actually measured, likely a result of the narrow and linear feature of the channel and because the channel ridges and bottoms were obscured by tall vegetation or water, respectively.

Although the Tolay lakebed and surrounding hillsides had grassland and weedy vegetative cover that were not ideal conditions for terrestrial LiDAR, the survey produced accurate elevations with a high density of point coverage. Combined with existing data, the resulting DEM met accuracy standards for the

restoration design. The DEM needs to be ground truthed and validation results reported for each major habitat classification. These values give the user an idea of accuracy of the field data and in the interpolation between points within the selected DEM.

Table 1. Mean error differences and 95-percent confidence interval between the predicted digital elevation model and actual RTK GPS ground points (by overall area, channel, Tolay lakebed, and upper lakebed areas) using surface spot tool (3D Analyst, ArcGIS, ESRI).

[SE, standard error; SD, standard deviation; CI, confidence interval]

Area	Mean	Error (ft)			95% CI
		SE	SD	RMSE _z	
Overall	0.06	0.07	1.16	0.07	0.13
Channel	-1.84	0.30	1.92	0.41	0.81
Lakebed	0.10	0.05	0.61	0.05	0.10
Upper lakebed	0.63	0.05	0.53	0.07	0.14

Conclusions

We found that merging terrestrial LiDAR surveys with available topographic information was effective in filling topographic data gaps, especially in areas with limited physical access. The overall composite DEM had a mean error of about 2 cm, with a consolidated vertical accuracy of 4 cm. We also found that “ground truthing” with the RTK MAX GPS provided an excellent means by which to validate the DEM.

Terrestrial LiDAR methods to determine ground elevations are ideal in bare areas because vegetation signals may not be entirely filtered out; however, this method may also be well-suited for examining vegetation structure and characterizing habitat (Vierling et al. 2008), similar to the use of airborne LiDAR to examine canopy structure and heterogeneity for wildlife (Bradbury et al. 2005, Goetz et al. 2007). Tidal marsh inhabitants face numerous threats (Takekawa et al. 2006) including sea level rise. High marsh to upland transition zones often exist as narrow, linear bands along levees, such that during extreme

floods, animals are forced to travel upland or up tall vegetation for cover, where they may become exposed to predation (Evens and Page 1986). Long-term monitoring at lower Tolay Creek showed a precipitous decline in small mammal captures, including the endangered salt marsh harvest mouse (*Reithrodontomys raviventris*), following extreme winter tides and floods (Woo et al. 2007a; Woo, unpub. data). Terrestrial LiDAR may be particularly useful in characterizing the vegetative canopy of upland transition zones as extreme high tide refugia habitat (Woo et al. 2007a).

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