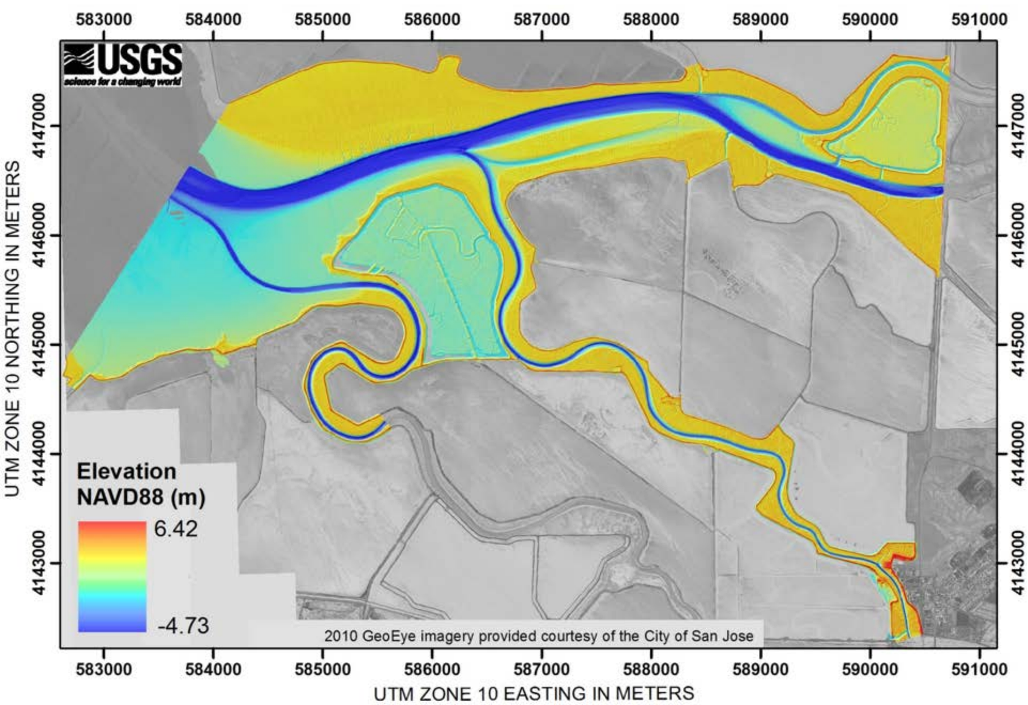
Bathymetry and Digital Elevation Models of Coyote Creek and Alviso Slough, South San Francisco Bay, California

By Amy C. Foxgrover, David P. Finlayson, Bruce E. Jaffe, and Theresa A. Fregoso



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Cover: Seamless bathymetric/topographic DEM of Coyote Creek and Alviso Slough, south San Francisco Bay, California; from figure 9.

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Abstract

In 2010 the U.S. Geological Survey (USGS), Pacific Coastal and Marine Science Center completed three cruises to map the bathymetry of the main channel and shallow intertidal mudflats in the southernmost part of south San Francisco Bay. The three surveys were merged to generate comprehensive maps of Coyote Creek (from Calaveras Point east to the railroad bridge) and Alviso Slough (from the bay to the town of Alviso) to establish baseline bathymetry prior to the breaching of levees adjacent to Alviso and Guadalupe Sloughs as part of the South Bay Salt Pond Restoration Project (http://www.southbayrestoration.org). Since 2010 the USGS has conducted twelve additional surveys to monitor bathymetric change in this region as restoration progresses.

The bathymetry surveys were conducted using the state-of-the-art research vessel R/V Parke Snavely outfitted with an interferometric sidescan sonar for swath mapping in extremely shallow water. This publication provides high-resolution bathymetric data collected by the USGS. For the 2010 baseline survey we have merged the bathymetry with aerial lidar data that were collected for the USGS during the same time period to create a seamless, high-resolution digital elevation model (DEM) of the study area. The series of bathymetry datasets are provided at 1 m resolution and the 2010 bathymetric/topographic DEM at 2 m resolution. The data are formatted as both X, Y, Z text files and ESRI Arc ASCII files that are accompanied by Federal Geographic Data Committee (FGDC) compliant metadata.

Data Collection

Fifteen high-resolution bathymetric surveys were collected in the southernmost reaches of south San Francisco Bay between January 2010 and March 2017 (table 1). The three surveys collected in 2010 were combined into a single composite surface of pre-breach baseline bathymetry covering the main channel, shallow intertidal mudflats, and Alviso and Guadalupe Sloughs. Since 2010 twelve additional surveys have been performed to monitor bathymetric change in this region as restoration progresses. The surveys extend east from Calaveras Point along Coyote Creek to the railroad bridge, along Alviso Slough to the town of Alviso (slightly more than 7 km), and along the 3.7 km of Guadalupe Slough closest to the bay (fig. 1). The spatial coverage of the surrounding intertidal flats varies by survey, as accessibility by boat is highly dependent upon the tides.

Table 1. Bathymetric cruise IDs and survey dates.

USGS Field Activity ID	Cruise Dates
S-2-10-SF[1]	1/13/2010 – 1/15/2010
S-18-10-SF[1]	9/11/2010 – 9/13/2010
S-24-10-SF[1]	12/3/2010
S-10-11-SF	10/24/2011 – 10/30/2011
S-02-12-SF	2/3/2012 – 2/9/2012
S-03-12-SF	4/2/2012 – 4/6/2012
S-06-12-SF	10/12/2012 – 10/19/2012
S-05-13-SF	4/2/2013 – 4/3/2013, 4/23/2013 – 4/25/2013
S-08-13-SF	11/1/2013 – 11/7/2013
2014-670-FA	10/23/2014 – 10/24/2014
2015-633-FA	4/26/2015 – 4/27/2015
2015-669-FA	10/13/2015 – 10/16/2015
2016-628-FA	4/5/2016 – 4/6/2016
2016-678-FA	10/12/2016 – 10/13/2016, 10/15/2016 – 10/19/2016
2017-628-FA	3/28/2017 – 3/29/2017

[1]Surveys combined into a single 2010 bathymetric surface.

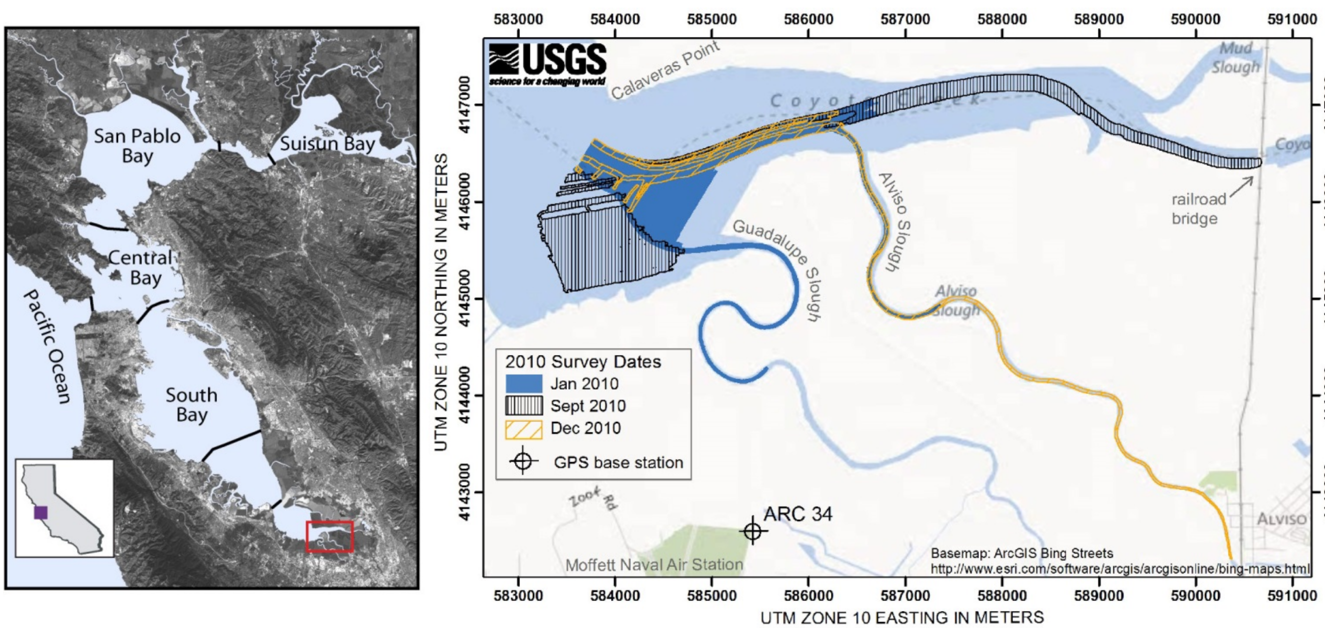

Figure 1. Map of study area and location of GPS base station, south San Francisco Bay, California.

All of the surveys were done aboard the R/V *Parke Snavely* outfitted with a 234.5 kHz SEA (Systems Engineering & Assessment, Ltd.) SWATHplus-M phase-differencing sidescan sonar (figs. 2 and 3). Global positioning system (GPS) data were passed through either a CodaOctopus F180 inertial measurement unit (IMU) or an Applanix Position and Orientation System for Marine Vessels (POS MV) to the sonar hardware and data collection software. Sonar heads, GPS antennae, and the IMU were surveyed in place to a common reference frame with a Geodimeter 640 Total Station. The R/V *Parke Snavely* was outfitted with three networked workstations and a navigation computer for use by the captain and survey crew for data collection and initial processing. See table 2 for the sonar system specifications.

Figure 2. The U.S. Geological Survey, Pacific Coastal and Marine Science Center R/V *Parke Snavely*. Photo courtesy of Thomas E. Reiss.

Figure 3. Fore and aft views of the SWATHplus sonar pole mount on the U.S. Geological Survey Pacific Coastal and Marine Science Center R/V *Parke Snavely*.

Table 2. SWATHplus-M sonar specifications (Systems Engineering and Assessment, Ltd., 2004).

Sonar frequency	234.5 kHz
Maximum water depth	120 m
Maximum swath width	300 m (typically 7 to 12 times water depth)
Resolution across track (best case)	5 cm
Transmit pulse length	34 to 500 ms
Ping repetition rate	
150 m swath width	10 pings per second
300 m swath width	5 pings per second
Vertical accuracy (range dependent)	
57 m	0.1 m
114 m	0.2 m
171 m	0.3 m

Geodetic Control

Geodetic control for the 2010-2012 surveys was established using a shore based GPS base station broadcasting real-time kinematic (RTK) corrections to the survey vessel by UHF radio link. The base station was at Moffett Naval Air Station, on a pre-existing benchmark identified as ARC 34 (fig. 1; table 3). The National Geodetic Survey (NGS) lists this monument as PID DG6881 (see appendix A for NGS datasheet).

Table 3. Global positioning system base-station benchmark.

Reference frame	NAD83 (NSRS2007)
Latitude	N 37° 25’ 34.57880"
Longitude	W 122° 02’ 05.53373"
Orthometric height	1.28 m (NAVD88 height modernization project elevation)
Epoch date	2007.00

Prior to 2013 the R/V *Parke Snavely* was equipped with a CodaOctopus F180 attitude and positioning system. The F180 runs F190 firmware, and receives RTK positioning corrections directly. The RTK GPS data (2 cm error ellipse) are combined with the inertial motion measurements directly within the F190 hardware so that high-precision position and attitude corrections are fed in real time to the sonar acquisition equipment. The NAD83 (NSRS2007) Epoch 2007.00 3-dimensional reference frame was used for horizontal positioning, with elevations referenced to NAVD88. All data are projected in UTM coordinate space in meters, zone 10 north.

In 2013, the F180 IMU was replaced by an Applanix Position and Orientation System for Marine Vessels (POS MV) which eliminated the need to set up an RTK base station. The POS MV utilizes global navigation satellite system (GNSS) data in combination with angular rate and acceleration data from the IMU, and heading data from the GPS Azimuth Measurement Systems (GAMS) to produce accurate position and orientation information through a virtual network of base stations. As opposed to receiving high-accuracy RTK corrections in real time, the POS records raw inertial and GNSS data while surveying that is later refined through post processing to incorporate publicly available GPS data from nearby base stations. During post processing the POS MV data is run through POSPac software to produce a smoothed best estimate of trajectory (SBET) file, which is then imported back into Swath Processor to produce high-accuracy positions relative to the WGS84 ellipsoid. The root mean square error (RMSE) results from our POS MV surveys show positional errors of less than 5 cm in the X, Y, and Z directions.

We conducted a series of tests to assess any potential biases that may have been introduced by switching from the F180 to POS MV. In April and November of 2013 we conducted repeat bathymetric surveys of intertidal flats using both systems. On April 23, 2013, we surveyed 66,000 m^2 of the Alviso intertidal flats with the POS MV and we returned to the same location two days later and surveyed with the F180. On November 1, 2013, we surveyed nearly 170,000 m^2 of tidal flats just south of the Dumbarton Bridge, which is approximately 8 km northwest of the Alviso study site, with the F180. The following day we surveyed the same location using the POS MV. All survey instrumentation and settings were identical with the exception of the IMUs. To assess differences between the repeat surveys, the bathymetric tracklines were aggressively trimmed in CARIS's HIPS and SIPS software to retain only the soundings greater than 1 m and less than 2 m from nadir (the soundings across each swath with the highest precision). For the April 2013 survey of the Alviso tidal flats, the POS-derived bathymetry was, on average, 15 cm (SD = 3) deeper than the F180-derived bathymetry. There was a similar offset in the November 2013 surveys of the Dumbarton tidal flats, where the POS-derived bathymetry was an average of 11 cm (SD = 3) deeper than the F180-derived bathymetry. The source of the offset is unknown, but the similarity in magnitude and direction on the two separate surveys suggests that it is a real bias. Data from the POS surveys were shoaled by the average offset of 13 cm to keep the vertical reference frame consistent with the 2010 baseline bathymetric survey.

Sound Velocity Measurements

Sound velocity measurements were collected continuously with an Applied Micro Systems Micro SV (accurate to ±0.03 m/s) deployed on the transducer frame for real-time sound velocity adjustments at the transducer/water interface. Additionally, sound-velocity profile measurements of the water column were collected at least once per day. Sound-velocity profile measurements were collected using an Applied Micro Systems SvPlus 3472 which provides time-of-flight sound-velocity measurements using invar rods with a sound-velocity accuracy of ±0.06 m/s, pressure measured by a semiconductor bridge strain gauge to an accuracy to 0.15 percent (full scale), and temperature measured by thermistor to an accuracy of 0.05 degrees Celsius (Applied Microsystems, Ltd., 2005).

Processing Procedures

The general processing workflow for converting raw bathymetric soundings to a DEM is shown in figure 4. Critical aspects of the processing procedure are discussed in more detail below.

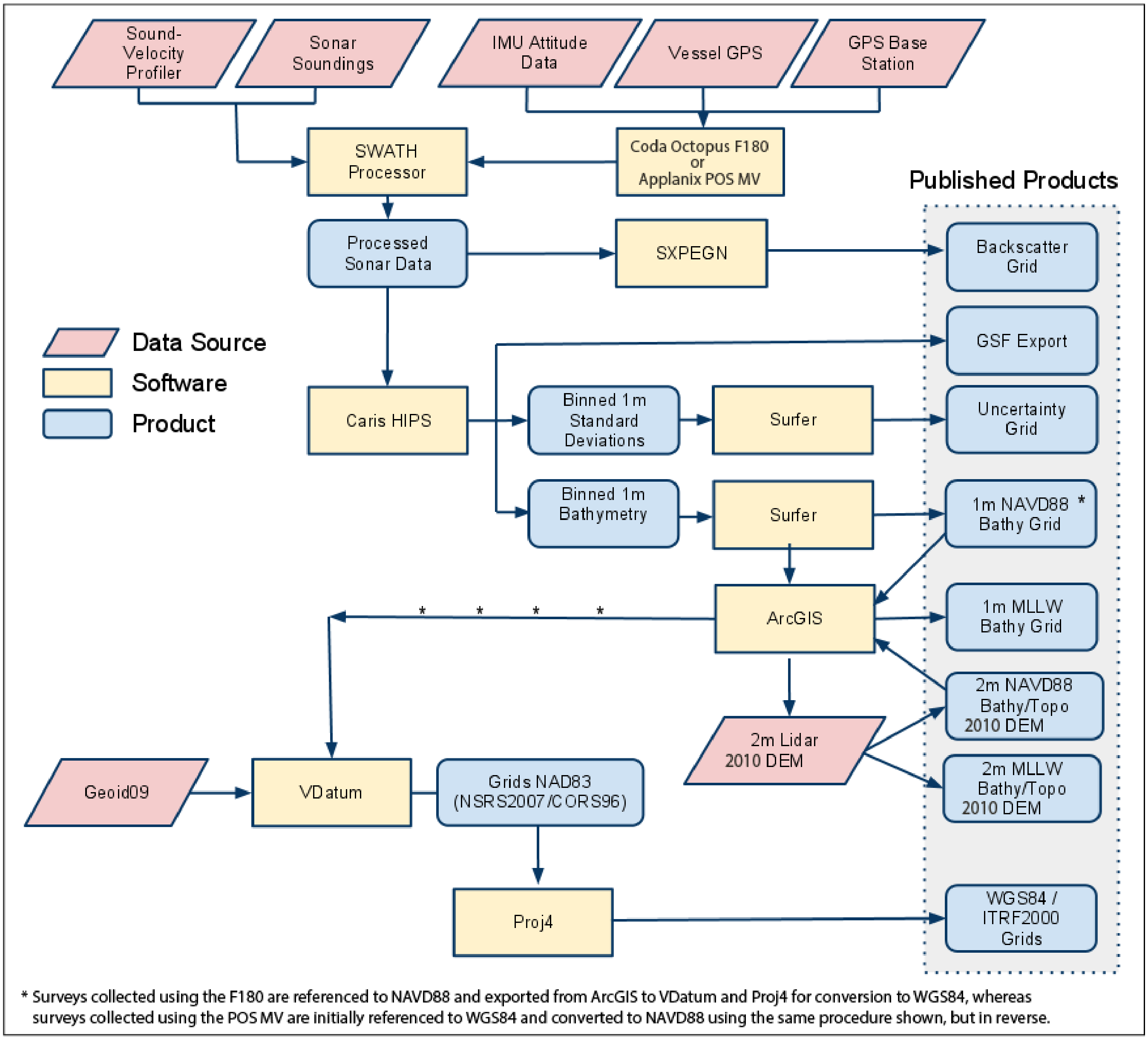

Figure 4. Processing workflow diagram for converting soundings to a digital elevation model.

Real-Time Sonar Sounding Processing

GPS data and measurements of vessel motion are combined in the F180 or POS MV hardware to produce a high-precision vessel attitude packet. This packet is transmitted to the Swath Processor acquisition software and combined with instantaneous sound velocity measurements at the transducer head before each ping. As many as 20 pings per second are transmitted, with each ping consisting of 2,048 samples per side (port and starboard). The returned samples are projected to the seafloor using a ray-tracing algorithm working with the previously measured sound velocity profiles in SEA Swath Processor. A series of statistical filters are applied to the raw samples that isolate the seafloor returns from other uninteresting targets in the water column. Finally, the processed data are stored line-by-line in both raw (.sxr) and processed (.sxp) trackline files. When using the POS MV, temporary sxp files are generated using attitude derived from tide predictions in real time, and final sxp files are generated during post processing when the POS SBET files are incorporated back into Swath Processor. For all of the Alviso surveys, processed files were filtered across-track with a mean filter at 0.2 m resolution.

Backscatter Image Production

The relative differences in bay-floor backscatter strength (that is, the amplitude of the acoustic signal that is reflected back to the sonar head) can be a valuable tool for identifying changes in texture or composition of bay floor sediments. The raw 16-bit backscatter that is recorded simultaneously with the bathymetry by the SWATHplus was georeferenced and gain-normalized by the program SXPEGN (build 151) by David Finlayson (USGS) to enhance the backscatter of the SWATHplus system. The program normalizes for time-varying signal loss and beam directivity differences. The resulting normalized amplitude values are rescaled to 16-bit and gridded in Surfer (version 10) as shown in figure 5.

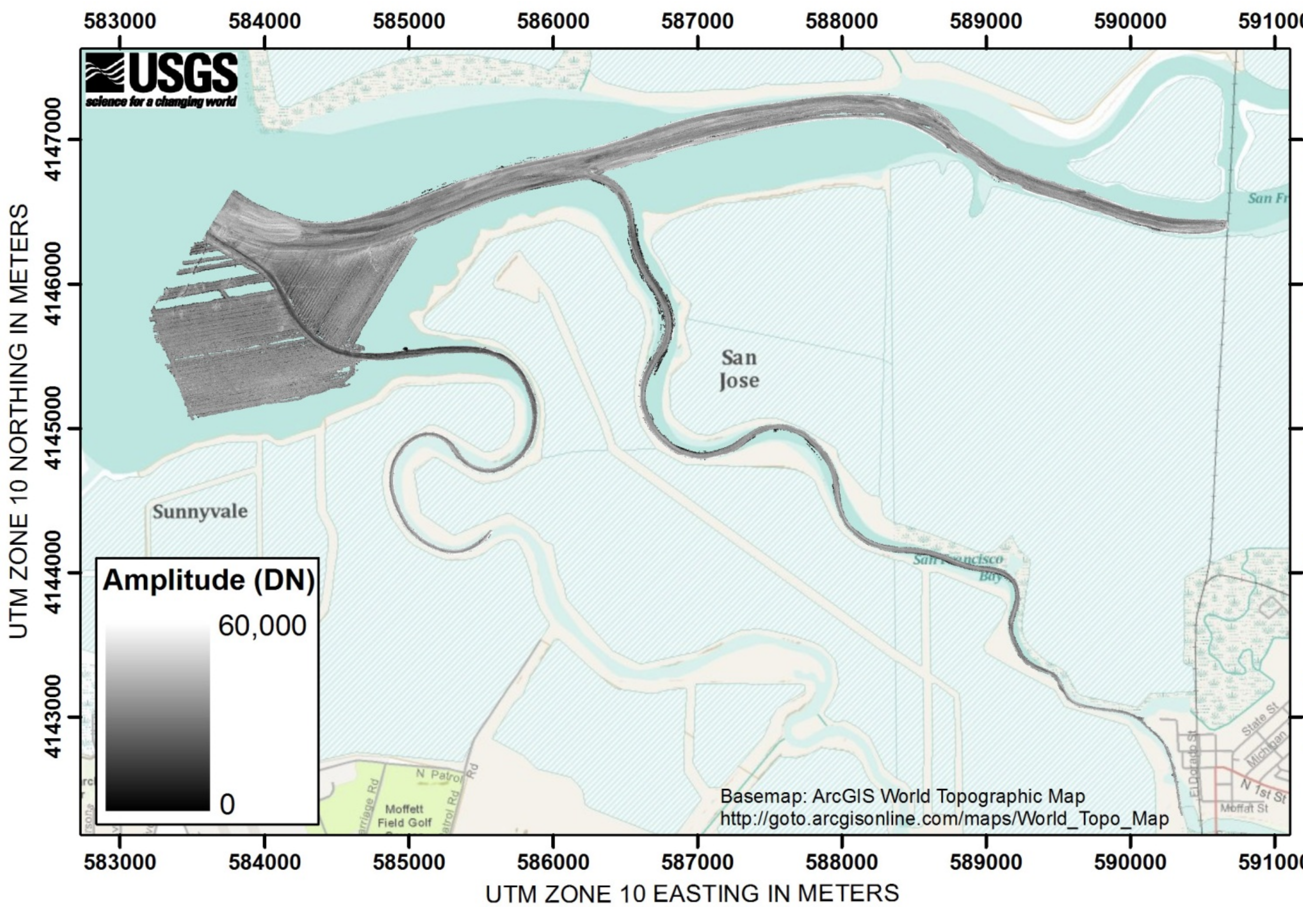

Figure 5. Map of backscatter amplitude (raw 16-bit digital number, DN), south San Francisco Bay, California.

Swath Cleaning and Filtering

Prior to creating the bathymetry grids, the processed .sxp files were imported to CARIS's HIPS and SIPS software for additional cleaning and filtering. Swath filters were applied to clean the data based upon characteristics such as depth, across track angle, and across track distance. A CARIS Swath

Angle BASE (Bathymetric with Associated Statistical Error) surface was created at 1 m resolution and the subset editor was used to eliminate any remaining outliers or artifacts manually. The average depth within each 1 × 1 m cell was exported as an ASCII text file along with calculations of the binned (of all soundings within the 1 × 1 m cell spacing), standard deviation, and sounding density. These ASCII files were used for statistical analyses and imported into Surfer (version 10) for gridding.

Digital Elevation Model Production

Bathymetric Grids

The 1 m resolution ASCII data were imported to Surfer (version 10) for statistical analysis and DEM generation. The binned ASCII data were interpolated in Surfer using a linear kriging algorithm with a 1-sigma nugget of 0.05 m (the mean standard deviation of all 1 × 1 m cells in the dataset) and a 2 × 2 m search radius. This process filled small gaps in the surface and provided some minor smoothing through the statistical noise inherent to interferometric bathymetry. The 1 m resolution bathymetry grid was exported to ESRI ArcMap software for display purposes (fig. 6) and converted from NAVD88 to the tidal datum of mean lower low water (MLLW) using the conversions generated by the National Oceanic and Atmospheric Administration (NOAA) and provided in Foxgrover and others (2007). Changes in the elevation of the bay floor over time can be determined by simply differencing surveys (fig. 7).

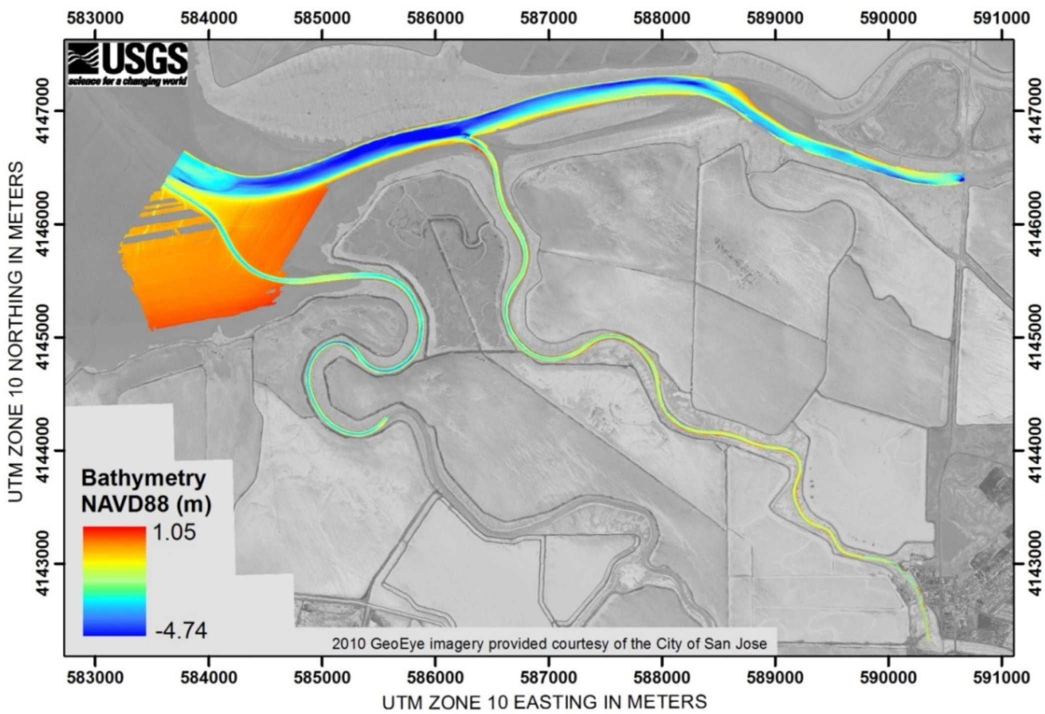

Figure 6. The 1 m resolution 2010 bathymetry grid generated by merging surveys S-2-10-SF, S-18-10-SF and S-24-10-SF. Elevation in meters relative to NAVD88.

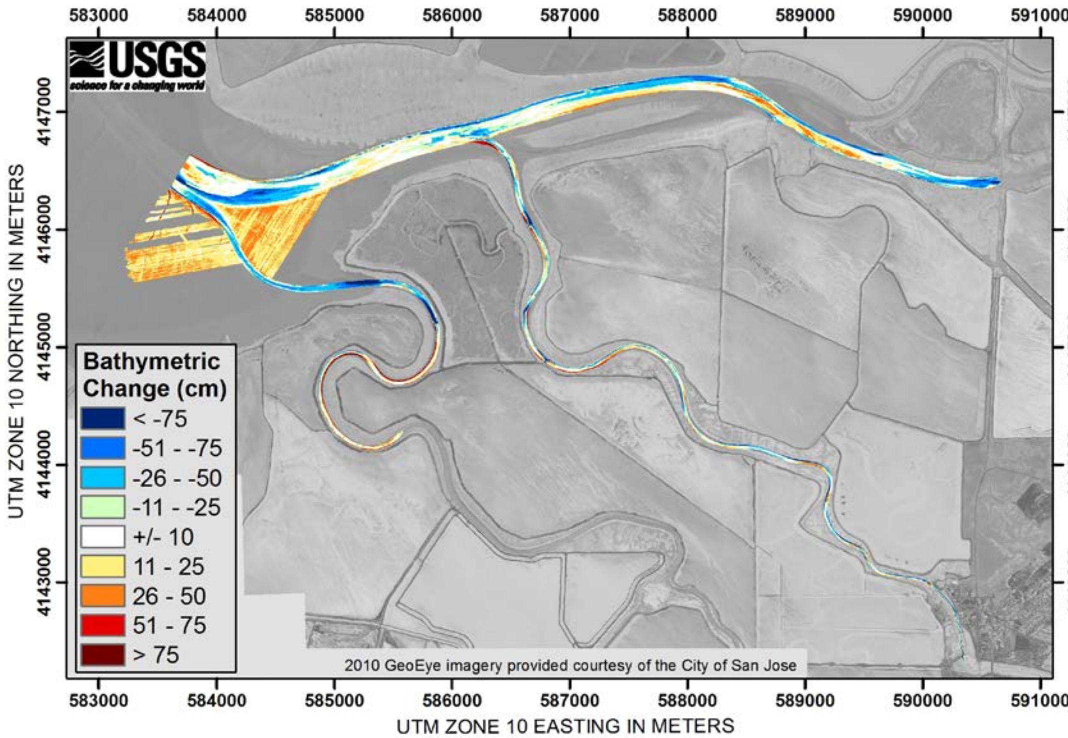

Figure 7. Bathymetric change from 2010 to October 2016.

2010 Lidar Data

In 2010 the USGS, with funding provided by the American Recovery and Reinvestment Act (ARRA), contracted the acquisition of aerial topographic lidar in the San Francisco Estuary that included our study area. Data for the USGS San Francisco Coastal Lidar project were collected by Terrapoint USA, and Dewberry served as the primary contractor for the project and was responsible for all final data post-processing and classification necessary to develop project deliverables. The USGS aerial lidar was collected between June 11 and November 7, 2010, using a Piper Navajo twin engine aircraft equipped with a 100 kHz Optech ALTM 3100EA lidar system. Acquisition was designed to support a nominal point spacing of 1 m and was collected at low tide to optimize coverage of the intertidal flats. Lidar data was processed by Dewberry to achieve a bare earth ground surface and provided as 2 m resolution hydro-flattened DEMs. When Dewberry compared the lidar to survey-grade GPS points in generally flat, nonvegetated areas, the vertical accuracy of 95 percent of the positions had errors less than or equal to 18 cm (equivalent to a 9 cm RMSE if evenly distributed). The lidar is projected in UTM coordinate space, zone 10 north. The vertical datum is NAVD88 and the horizontal datum NAD83(NSRS2007). Within our study area NAD83(NSRS2007) closely approximates the horizontal datum of the bathymetric data, NAD83(CORS96), and is within the accuracy of the data. For our purposes, the two versions of NAD83 are considered equivalent. For additional information on USGS's ARRA San Francisco Coastal Lidar project or to download the data directly, visit https://earthexplorer.usgs.gov/ or http://www.coast.noaa.gov/dataviewer.

2010 Bathymetric / Topographic DEM

Prior to merging the 2010 bathymetry data with the topographic lidar data, a comparison was made between elevations of the two independent datasets where they overlap in the intertidal flats. There is approximately 1.5 km^2 of overlap between lidar and bathymetry data within the study area (fig. 8). For all areas of overlap, the lidar is a maximum of 3.3 m higher than or 1.2 m lower than the bathymetry in the region of overlap. The average difference is 0.05 m (SD=0.30). Upon close examination, it became apparent that large differences between the two surfaces (greater than 1 m) occurred along very narrow strips of channel margins or at two specific sites: (1) along Coyote Creek (fig. 8*B*), and (2) along Alviso Slough south of UTM northing 4144000 (fig. 8*C*). At these two locations the lidar elevations are more than 1 m higher than the bathymetry elevations and are an artifact of the lidar reflecting off the water surface, not the bay floor. These areas were removed from the lidar DEM and excluded from further analyses. When the difference analyses were restricted to the intertidal flat areas adjacent to the confluence of Guadalupe Slough and Coyote Creek (fig. 8*A*) the statistics greatly improved. In the intertidal flats the lidar is a maximum of 1.2 m higher than or 0.8 m lower than the bathymetry. The mean offset on the tidal flats is 0 m (SD=0.07), which suggests that there is not a consistent offset or bias between the two and serves as an independent check on the quality of the two datasets.

Prior to merging the surfaces, the bathymetry was resampled to 2 m resolution to match the lidar DEM by using a bilinear interpolation. The bathymetry was then merged with the topographic lidar by using the blend algorithm in the “Mosaic to New Raster” tool in Arc Toolbox. The resultant DEM is provided at 2 m resolution with elevations relative to NAVD88 (fig. 9). To provide intertidal elevations relative to the tidal datum of MLLW, the DEM was clipped to the approximate extent of the shoreline (modified from the San Francisco Estuary Institute EcoAtlas [1998] modern baylands shoreline) and converted to MLLW by using the NAVD88 to MLLW conversions calculated by NOAA and provided by Foxgrover and others (2007; fig. 10).

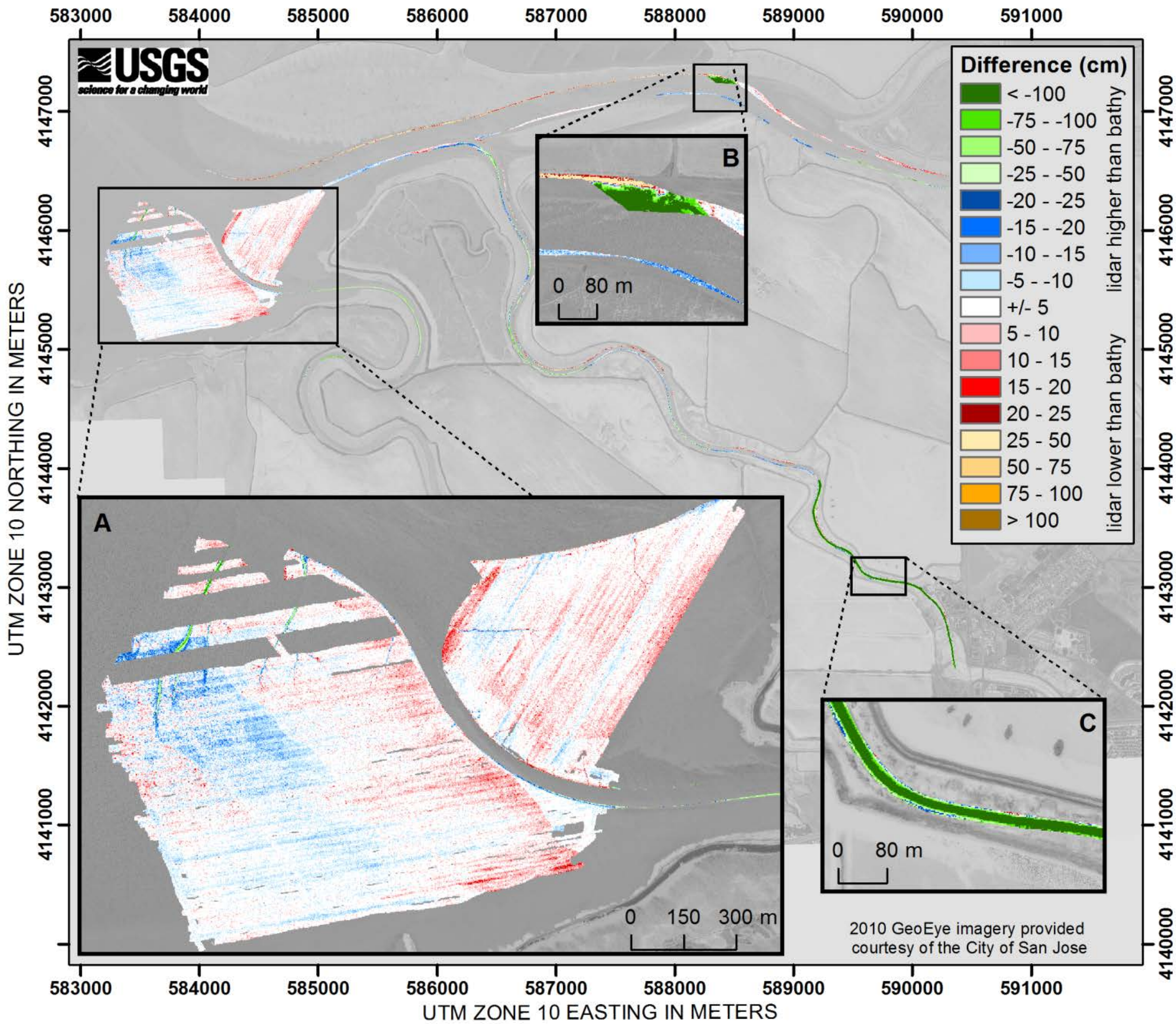

Figure 8. Difference between tidal flat elevations calculated from 2010 aerial lidar data versus bathymetry data, south San Francisco Bay, California.

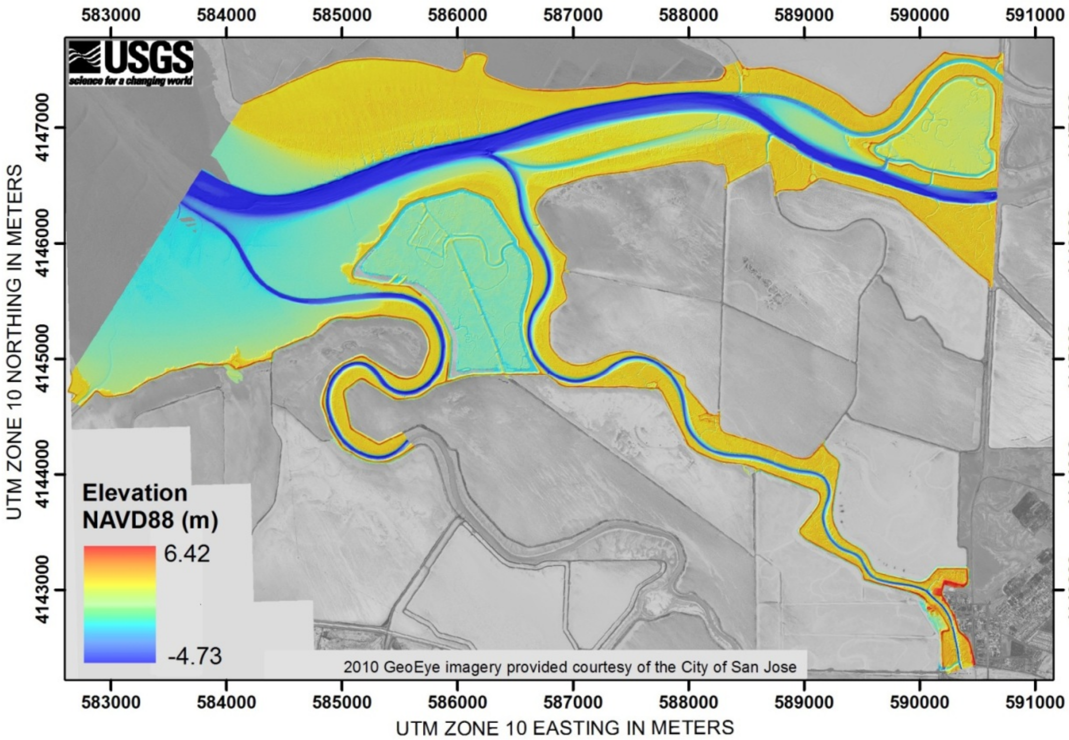

Figure 9. The 2010 seamless bathymetric/topographic DEM of the region surrounding Coyote Creek and Alviso Slough, south San Francisco Bay, California. Elevations relative to NAVD88.

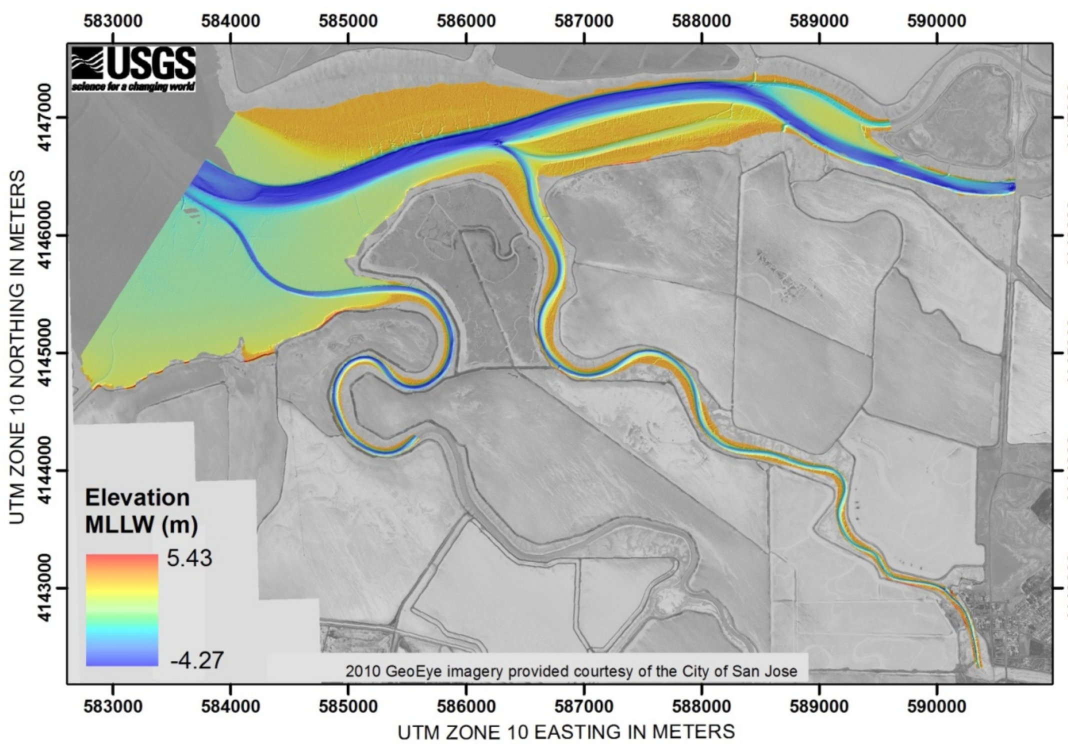

Figure 10. The 2010 seamless bathymetric/topographic DEM of Coyote Creek and Alviso Slough clipped to the approximate extent of the shoreline, south San Francisco Bay, California. Elevations relative to MLLW.

Horizontal and Vertical Datum Conversions

To meet the varying needs of the end users of these data products the surfaces are provided relative to orthometric heights NAD83(CORS96)/NAVD88, the ellipsoid WGS84(G1150), and relative to the tidal datum of MLLW. V-Datum (version 2.3.3) does a poor job of converting between geodetic and tidal datums in far south San Francisco Bay. Some investigations have revealed that benchmark information for the Dumbarton Bridge Station (station 9414509) was not used in development of the VDatum model. Due to the lack of model constraint in this region, VDatum consistently underestimates the offset between NAVD88 and MLLW for regions south of the Dumbarton Bridge. A comparison of conversions from NAVD88 to MLLW generated by VDatum to those provided by the CO-OPS division of NOAA for a 2005 bathymetric survey of south San Francisco Bay (Foxgrover and others, 2007) reveals a difference between the two of approximately 17 cm near Dumbarton Bridge, approximately 20 cm where Guadalupe Slough meets Coyote Creek, and greater than 30 cm near the island ponds. The conversion to MLLW used for this report is based upon the CO-OPS data provided by Foxgrover and others (2007), and we caution that using VDatum for converting between geodetic and tidal datums south of Dumbarton Bridge could introduce errors on the order of tens of centimeters.

To convert the data from orthometric heights NAD83(CORS96)/NAVD88 to ellipsoid heights on ITRF2000 (also known as WGS84 G1150), the Surfer grids were exported as ASCII tables. NOAA's VDatum version 2.3.0 (http://vdatum.noaa.gov) was used to apply Geoid09 (National Geodetic Survey, 2009) and convert the orthometric height data into ellipsoid heights on the NAD83(CORS96) ellipsoid. The data were next transformed from the NAD83 (CORS96) ellipsoid to the ITRF2000 ellipsoid by using a 14-point Helmert transformation described by Soler and Snay (2004) using the command line tool CS2CS in the Proj4 library (http://trac.osgeo.org/proj/). The parameters were calculated for an Epoch date of 2007.0000 as shown in table 4. The conversion from NAD83(CORS96) to ITRF2000 shifts the Easting coordinates of the survey by approximately –1.3 m, the Northing coordinate by approximately +0.40, and the z coordinate by about –0.54 m. To convert the POS-derived bathymetry from ellipsoid heights on WGS84 to orthometric heights NAD83(CORS96)/NAVD88, the same CS2CS transformation was applied but in reverse, and rather than using VDatum, a fixed Geoid09 offset of –32.63 m from our base station detailed in table 3 was applied.

Table 4. Parameters adopted for transformation between NAD83(CORS96) and ITRF2000

Parameter	Definition	Units	Value at t_0 = 1997.0	Value at t_F = 2007.0
T_x	x-shift	meters	0.9956	1.0026
T_y	y-shift	meters	-1.9013	-1.9083
T_z	z-shift	meters	-0.5215	-0.5165
ω_x	x-rotation[1]	arc seconds	-0.025915	-0.026585
ω_y	y-rotation[1]	arc seconds	-0.009426	-0.001856
ω_z	z-rotation[1]	arc seconds	-0.011599	-0.011089
s	scale	parts-per-million	0.00062	-0.00118

[1]Note that the Proj4 program cs2cs reverses the sign of the rotation parameters from the Soler and Snay (2004) algorithm. Because the transformation here is from NAD83 to ITRF2000, the program is run in reverse-mode (-I).

Estimates of Bathymetric Uncertainty

There are multiple techniques for assessing the uncertainty of bathymetric surveys. For relatively flat portions of the seafloor, the standard deviation of sounding elevations within a small area is a good measure of the precision of the sonar instrumentation; this is not true in areas where the seafloor is naturally variable or steep. In these areas, the standard deviation reflects the combination of natural variation of the surface in addition to sonar measurement uncertainty.

A plan-view map of typical spatial variability in standard deviations throughout the study area is shown in figure 11. The overall spatial pattern of standard deviation reveals low standard deviation in the low-relief intertidal flats and increases with increasing depth and slope (that is, in and along channel banks). The mean standard deviation of the 2010 soundings within each 1 × 1 m cell (containing 19 soundings on average) for the entire study area is 0.05 m, and 97 percent of the cells have a standard deviation less than 0.15 m (fig. 12). The mean standard deviation over the intertidal flats for each of the thirteen surveys collected between 2010 and 2017 varies from 2–5 cm, with the exception of the April 2013 survey, which has a mean standard deviation of 7 cm. In general, the coverage of the intertidal flats during our spring surveys is severely limited due to unfavorable tidal conditions. The fall surveys, when favorable tidal conditions allow greater intertidal flat coverage, provide a more robust statistical measure of survey precision. However, since a large portion of our study area is comprised of channels, the overall mean standard deviation alone does not provide an adequate approximation of survey precision.

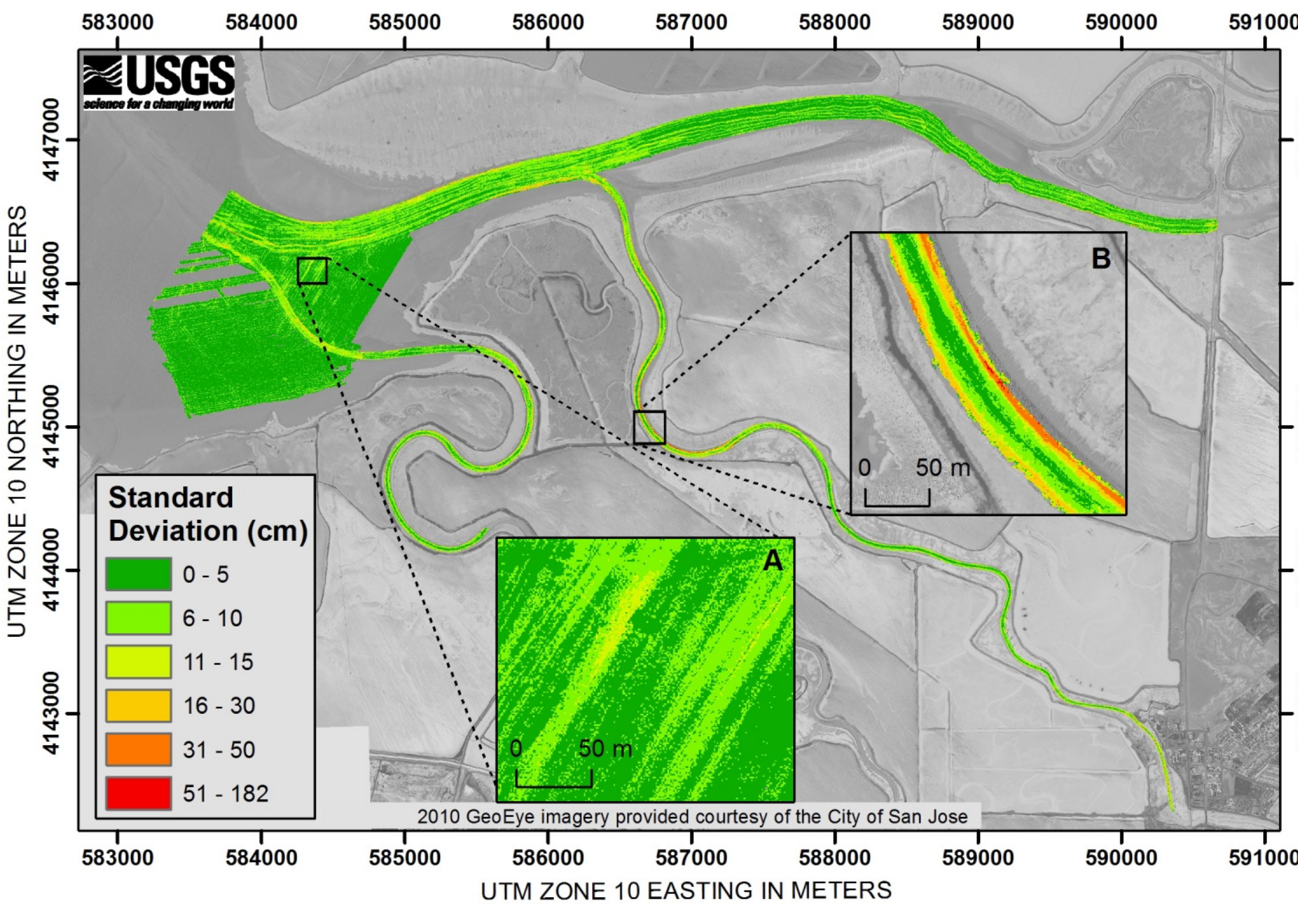

Figure 11. Plan-view map of bathymetric soundings standard deviation within each 1 × 1 m cell, south San Francisco Bay, California.

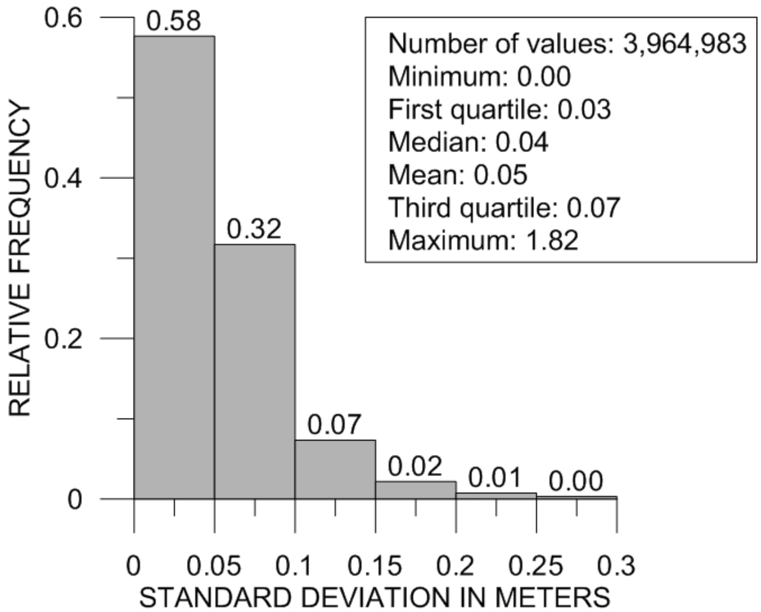

Figure 12. Histogram of sounding elevation standard deviations within each 1 × 1 m cell.

A second technique for assessing the precision of bathymetric data is to compare the elevation at a given location as calculated from data collected on independent tracklines that intersect. For this analysis a number of survey tracklines were collected on the intertidal flats running in an approximate northwest/southeast direction that is nearly perpendicular to the primary trackline orientation for this region. For the 2010 survey, these intersecting tracklines (also known as tie lines) result in approximately 100 intersections which are used for statistical analyses. For the purposes of error assessment, the tie lines were aggressively trimmed in CARIS's HIPS and SIPS software to retain only the soundings greater than 1 m and less than 2 m from nadir (the soundings across each swath with the highest precision). The surface generated from these tie lines was differenced from the bathymetric surface generated from the northeast/southwest oriented primary survey tracklines to see how the two compared. For the 2010, February 2012, and April 2012 surveys the mean difference between the tie line intersections was 1 cm and the standard deviation 3 cm, which suggests a vertical uncertainty of approximately ±5 cm in the intertidal flats. Tie line analyses for POS-derived bathymetric surveys collected in 2013, 2014, April 2015, and April 2016 revealed comparable mean differences of 2 cm or less with standard deviations of 3–5 cm.

The mean difference from tie line analyses of the fall surveys of 2011, 2012, 2015, and 2016 were slightly elevated and warranted further examination. It was determined during the October 2011 survey that the configuration offset between the IMU and the primary GPS antenna was accidentally inverted during the first four days of surveying. As a result, the IMU was unable to properly calibrate its position. Fortunately, eight tie lines were collected throughout the western and eastern tidal flats during the last three days of this survey when the IMU was functioning properly. The extensive coverage of the tie lines enabled us to evaluate offsets due to the IMU problems and shoal the survey lines by the appropriate amount (varying from 8 to 33 cm) to minimize offsets. After performing these corrections the mean difference between tie line intersections dropped to 2 cm (SD=3).

During post-processing of the October 2012 survey tie line analyses revealed a depth-bias in lines collected on the western intertidal flats on October 19th. The cause of this bias is uncertain; however it may be the result of an imprecise IMU position calibration on that day. These intertidal flat survey lines collected on October 19th were shoaled by 8 cm to minimize offsets between tie lines. After the shift was applied the mean difference of tie line intersections for this survey was 2 cm (SD=4). Note that Guadalupe Slough was also surveyed on October 19th, but data within the slough did not appear to show the same offset as soundings within the flats, and as a result, were not adjusted. The spatial extent of survey lines that were manually adjusted for both the October 2011 and October 2012 surveys are delineated in a polygon shapefile that is provided with the bathymetric grids. The accuracy of elevations within these polygons is less reliable than for the remainder of these datasets.

The October 2015 and October 2016 surveys have mean tie-line differences of 7 cm (SD=4) and 6 cm (SD=6), respectively. There was no discernable bias by survey day and we are uncertain of the cause of the decline in survey precision. The SWATHplus system was modified prior to the October 2015 survey to incorporate a third, forward-looking transducer to fill the nadir gap beneath the survey vessel in an attempt to decrease surveying time. Although data from the additional transducer was not included in our post-processing due to software limitations, it is possible that modifications made when the third transducer was added, either within the system itself, or within processing software, could be introducing additional noise in the data. The third transducer was also collecting data during the spring 2016 and 2017 surveys, which show mean differences of 1–2 cm (SD=3), values consistent with earlier surveys collected using only two transducers. However, intertidal flat coverage during these spring surveys was extremely limited, making it difficult to perform a robust assessment of survey precision.

Vertical Adjustments to Post-2010 Surveys

Over the years various improvements have been made to our bathymetric mapping system. For the purposes of bathymetric change detection, it is important to keep all of our surveys as consistent with the 2010 baseline survey as possible. Every effort has been made to ensure that difference maps between any of the Alviso surveys reflect actual changes of the bay floor and are not simply a reflection of changes to our survey system. The following uniform vertical shifts have been applied to post-2010 surveys to adjust them to the vertical reference plane of the 2010 baseline survey. All of the post-2010 surveys have been deepened by 6 cm to account for a recalculation of the transducer lever-arm offsets that was performed in 2011. All of the surveys collected since April 2013 using the POS MV IMU, were also shoaled by 13 cm to account for the measured F180/POS MV bias. All surveys collected since October 2015, when the forward-looking transducer was added, have been deepened by 3 cm to account for transducer mounting plate modifications and more precise lever arm to IMU measurements. Surveys collected in March 2017 using the upgraded POS MV V5 have been shoaled by an additional 7 cm to account for an IMU reference-point offset that had inadvertently shoal biased all of the surveys collected with the POS MV V4. The cumulative effects of changes due to either modifications to the survey platform, or changes within software settings have resulted in the net vertical adjustments listed in table 5.

Table 5. Cruise dates, type of Inertial Measurement Unit (IMU) used, number of SWATHplus transducers collecting data, and net vertical adjustment applied to align surveys with the same vertical reference plane as the 2010 baseline survey.

Cruise Dates	IMU used	Number of Transducers	Net Vertical Adjustment to 2010 Baseline
Jan 2010	F180	2	0
Sept 2010	F180	2	0
Dec 2010	F180	2	0
Oct 2011	F180	2	−6 cm
Feb 2012	F180	2	−6 cm
Apr 2012	F180	2	−6 cm
Oct 2012	F180	2	−6 cm
Apr 2013	POS MV V4 Model 320	2	+7cm
Nov 2013	POS MV V4 Model 320	2	+7cm
Oct 2014	POS MV V4 Model 320	2	+7cm
Apr 2015	POS MV V4 Model 320	2	+7cm
Oct 2015	POS MV V4 Model 320	3	+4cm
Apr 2016	POS MV V4 Model 320	3	+4cm
Oct 2016	POS MV V4 Model 320	3	+4cm
Mar 2017	POS MV V5 Model 320	3	+11cm

Data Tables

Bathymetry

Bathymetry data are provided as elevation in meters relative to both the ellipsoid WGS84(G1150) and as orthometric heights NAD83(CORS96)/NAVD88, as well as relative to the tidal datum of MLLW (table 5). All data are projected in UTM, zone 10 north, and all values (eastings, northings, and elevation) are in meters. Each zip file contains the data formatted as both ASCII X, Y, Z text files (*.xyz) and ESRI ASCII files (*.asc; see appendix A), as well as FGDC compliant metadata in both text and .xml format.

Table 6. Bathymetric data files provided.

File name	Horizontal resolution, in meters	Reference frame	Vertical datum
2010_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
2010_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
2010_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Oct11_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Oct11_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Oct11_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Feb12_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Feb12_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Feb12_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Apr12_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Apr12_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Apr12_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Oct12_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Oct12_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Oct12_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW

File name	Horizontal resolution, in meters	Reference frame	Vertical datum
Apr13_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Apr13_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Apr13_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Nov13_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Nov13_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Nov13_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Oct14_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Oct14_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Oct14_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Apr15_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Apr15_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Apr15_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Oct15_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Oct15_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Oct15_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Apr16_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Apr16_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Apr16_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Oct16_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Oct16_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Oct16_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW
Mar17_bathy_NAVD88.zip	1	NAD83(CORS96)	NAVD88
Mar17_bathy_WGS84.zip	1	WGS84(G1150)	WGS84(G1150)
Mar17_bathy_MLLW.zip	1	NAD83(CORS96)	MLLW

2010 Bathymetric / Topographic DEM

Seamless bathymetric/topographic DEMs generated from merging the 2010 bathymetry (above) with aerial lidar are provided as elevations in meters relative to both the ellipsoid WGS84(G1150) and as orthometric heights NAD83(CORS96)/NAVD88 (table 6). The merged DEM was clipped to extent of the shoreline and converted from the geodetic vertical datum of NAVD88 to the tidal datum of MLLW based upon the conversions calculated by NOAA and provided in Foxgrover and others (2007). All data are projected in UTM, zone 10 north and all values (eastings, northings, and elevation) are in meters. Each zip file contains the data formatted as both ASCII X, Y, Z text files (*.xyz) and ESRI ASCII files (*.asc; see appendix A) as well as FGDC compliant metadata in both text and .xml format.

Table 7. Bathymetric/topographic DEM files provided.

File name	Horizontal resolution, in meters	Reference frame	Vertical datum
2010_DEM_NAVD88.zip	2	NAD83(CORS96)	NAVD88
2010_DEM_WGS84.zip	2	WGS84(G1150)	WGS84(G1150)

File name	Horizontal resolution, in meters	Reference frame	Vertical datum
2010_DEM_bay_NAVD88.zip	2	NAD83(CORS96)	NAVD88
2010_DEM_bay_WGS84.zip	2	WGS84(G1150)	WGS84(G1150)
2010_DEM_bay_MLLW.zip	2	NAD83(CORS96)	MLLW

A Note on Coordinate Systems and Datums

WGS84 and NAD83 have been revised several times resulting in coordinate shifts of as much as several meters in the X, Y, and Z directions. The revision is indicated by the designator following the name (G1150 following WGS84, for example). Software that does not distinguish between the different versions of these datums likely does not support 3D datums properly. Users should pay particular attention to the accompanying metadata files to ensure that the data are properly georeferenced. In particular, note that most current GIS software (including ArcGIS 10) cannot properly transform high-resolution elevation data from one 3D datum to another (such as WGS84 G1150 to NAD83 CORS96) without introducing errors on the order of 1–2 m in X, Y, and Z directions. For this reason, data are provided in both WGS84(G1150), which is equivalent to ITRF2000, and NAD83(CORS96), which is equivalent to NSRS2007.

Acknowledgments

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Appendix A

National Geodetic Survey Datasheet for Monument ARC 34 (PID DG6881) Used as geodetic control for the Alviso Survey

```
DATABASE = ,PROGRAM = datasheet, VERSION = 7.85

1 National Geodetic Survey, Retrieval Date = JUNE 8, 2010
DG6881
*********************************************************************
**
DG6881 HT_MOD - This is a Height Modernization Survey Station.
DG6881 DESIGNATION - ARC 34
DG6881 PID - DG6881
DG6881 STATE/COUNTY- CA/SANTA CLARA
DG6881 USGS QUAD - MOUNTAIN VIEW (1997)
DG6881
DG6881 *CURRENT SURVEY CONTROL
DG6881
___________________________________________________________________
DG6881* NAD 83(2007)- 37 25 34.57880(N) 122 02 05.53373(W) ADJUSTED
DG6881* NAVD 88 - 1.28 (meters) 4.2 (feet) GPS OBS
DG6881
___________________________________________________________________
DG6881 EPOCH DATE - 2007.00
DG6881 X - -2,690,026.780 (meters) COMP
DG6881 Y - -4,299,118.359 (meters) COMP
DG6881 Z - 3,855,050.006 (meters) COMP
DG6881 LAPLACE CORR- 0.35 (seconds) DEFLEC09
DG6881 ELLIP HEIGHT- -31.308 (meters) (02/10/07) ADJUSTED
DG6881 GEOID HEIGHT- -32.62 (meters) GEOID09
DG6881
DG6881 ------- Accuracy Estimates (at 95 percent Confidence Level in
cm) --------
DG6881 Type PID Designation North East Ellip
DG6881 --------------------------------------------------------------
-----
DG6881 NETWORK DG6881 ARC 34 0.39 0.35 1.02
DG6881 --------------------------------------------------------------
-----
DG6881
DG6881.The horizontal coordinates were established by GPS
observations
DG6881.and adjusted by the National Geodetic Survey in February 2007.
DG6881
DG6881.The datum tag of NAD 83(2007) is equivalent to NAD
83(NSRS2007).
```

DG6881.See National Readjustment for more information.
DG6881.The horizontal coordinates are valid at the epoch date displayed above.
DG6881.The epoch date for horizontal control is a decimal equivalence
DG6881.of Year/Month/Day.
DG6881
DG6881.The orthometric height was determined by GPS observations and a
DG6881.high-resolution geoid model using precise GPS observation and
DG6881.processing techniques.
DG6881
DG6881.The X, Y, and Z were computed from the position and the ellipsoidal ht.
DG6881
DG6881.The Laplace correction was computed from DEFLEC09 derived deflections.
DG6881
DG6881.The ellipsoidal height was determined by GPS observations
DG6881.and is referenced to NAD 83.
DG6881
DG6881.The geoid height was determined by GEOID09.
DG6881
DG6881; North East Units Scale Factor Converg.
DG6881;SPC CA 3 - 603,912.284 1,864,158.605 MT 0.99994515 -0 56 22.9
DG6881;SPC CA 3 - 1,981,335.55 6,115,993.69 sFT 0.99994515 -0 56 22.9
DG6881;UTM 10 - 4,142,598.916 585,392.741 MT 0.99968982 +0 35 11.7
DG6881
DG6881! - Elev Factor x Scale Factor = Combined Factor
DG6881!SPC CA 3 - 1.00000491 x 0.99994515 = 0.99995006
DG6881!UTM 10 - 1.00000491 x 0.99968982 = 0.99969473
DG6881
DG6881 SUPERSEDED SURVEY CONTROL
DG6881
DG6881 NAD 83(1998)- 37 25 34.57542(N) 122 02 05.53012(W) AD(2002.75) B
DG6881 ELLIP H (08/23/04) -31.247 (m) GP( ) 4 1
DG6881
DG6881.Superseded values are not recommended for survey control.
DG6881.NGS no longer adjusts projects to the NAD 27 or NGVD 29 datums.
DG6881.See file dsdata.txt to determine how the superseded data were derived.
DG6881
DG6881_U.S. NATIONAL GRID SPATIAL ADDRESS: 10SEG8539242598(NAD 83)
DG6881_MARKER: DD = SURVEY DISK
DG6881_SETTING: 7 = SET IN TOP OF CONCRETE MONUMENT
DG6881_STAMPING: ARC 34

DG6881_STABILITY: C = MAY HOLD, BUT OF TYPE COMMONLY SUBJECT TO
DG6881+STABILITY: SURFACE MOTION
DG6881_SATELLITE: THE SITE LOCATION WAS REPORTED AS SUITABLE FOR
DG6881+SATELLITE: SATELLITE OBSERVATIONS - September , 2002
DG6881
DG6881 HISTORY - Date Condition Report By
DG6881 HISTORY - UNK MONUMENTED NASA
DG6881 HISTORY - 200209 GOOD JOHFRA
DG6881
DG6881 STATION DESCRIPTION
DG6881
DG6881'DESCRIBED BY JOHNSON-FRANK 2002 (RAF)
DG6881'THE STATION IS ON MOFFETT AIRFIELD, NEAR MOUNTAIN VIEW. FROM THE
DG6881'INTERSECTION OF HWY 101 AND ELLIS ST (SE OF HWY 85), EXIT NORTH TO
DG6881'THE ENTRANCE TO MOFFETT FIELD. AFTER GOING THROUGH THE GUARDPOST,
DG6881'CONTINUE AHEAD TO SIGNAL LIGHT. TURN RIGHT ON PERIMETER RD
DG6881'(LOCALLY-CALLED) AND DRIVE 0.7 MI PARALLELING HWY 101 UNTIL THE SHARP
DG6881'BEND TO THE LEFT. FOLLOW THE ROAD AND DRIVE 1.3 MI TO A SIDE ROAD
DG6881'RIGHT AND A GOLF COURSE. TURN RIGHT AND DRIVE 0.2 MI TO AN
DG6881'INTERSECTION, THEN LEFT FOR 0.5 MI TO THE STATION ON THE RIGHT JUST
DG6881'BEFORE THE ROAD MAKES A NINETY-DEGREE TURN TO THE LEFT AT THE VERY
DG6881'NORTHEAST CORNER OF THE MOFFETT FIELD FACILITY. THE MARK IS ABOUT 23
DG6881'M (75 FT) SOUTH OF A CHAIN LINK GATE.
DG6881'
DG6881'MARK IS AN 8.2 CM (3.25 IN) NATIONAL AERONAUTICS AND SPACE
DG6881'ADMINISTRATION DISK STAMPED 'ARC 34' WITH A PUNCH NEXT TO THE '34'.
DG6881'THE DISK IS SET IN AN IRREGULAR CONCRETE MASS FLUSH WITH THE SOIL,
DG6881'6.7 M (22 FT) EAST OF THE CENTER OF THE PAVED PERIMETER ROAD, 22.8 M
DG6881'(75 FT) SOUTH OF A CHAIN LINK FENCE GATE AT THE END OF THE ROAD, 4.3
DG6881'M (14 FT) SOUTH OF THE CONCRETE BASE FOR A SMALL SQUARE WHITE TANK.
DG6881'
DG6881'THIS STATION WAS OBSERVED AS PART OF THE SOUTH SAN FRANCISCO BAY
DG6881'HEIGHT MODERNIZATION PROJECT.

```
*** retrieval complete.
Elapsed Time = 00:00:00
```

Appendix B

Description of the ESRI ASCII raster format:

To import ASCII files into common GIS packages:
ArcGIS: Use ArcTools's ASCII to Raster function
ArcView: Use the import ASCII Grid function (May need Spatial Analyst)
GRASS: Use the 'r.in.arc' function.

The ASCII file consists of header information containing a set of keywords, followed by cell values in row-major order. The file format is:

<NCOLS xxx>
<NROWS xxx>
<XLLCENTER xxx | XLLCORNER xxx>
<YLLCENTER xxx | YLLCORNER xxx>
<CELLSIZE xxx>
{NODATA_VALUE xxx}
row 1
row 2
.
.
.
row n

where xxx is a number, and the keyword nodata_value is optional and defaults to -9999. Row 1 of the data is at the top of the grid, row 2 is just under row 1 and so on. The nodata_value is the value in the ASCII file to be assigned to those cells whose true value is unknown. In the grid they will be assigned the keyword NODATA. Cell values are delimited by spaces. No carriage returns are necessary at the end of each row in the grid (although they are included in this case). The number of columns in the header is used to determine when a new row begins. The number of cell values is equal to the number of rows times the number of columns.