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Texas Coastal Wetland Surface Elevation Static Survey Campaign Report

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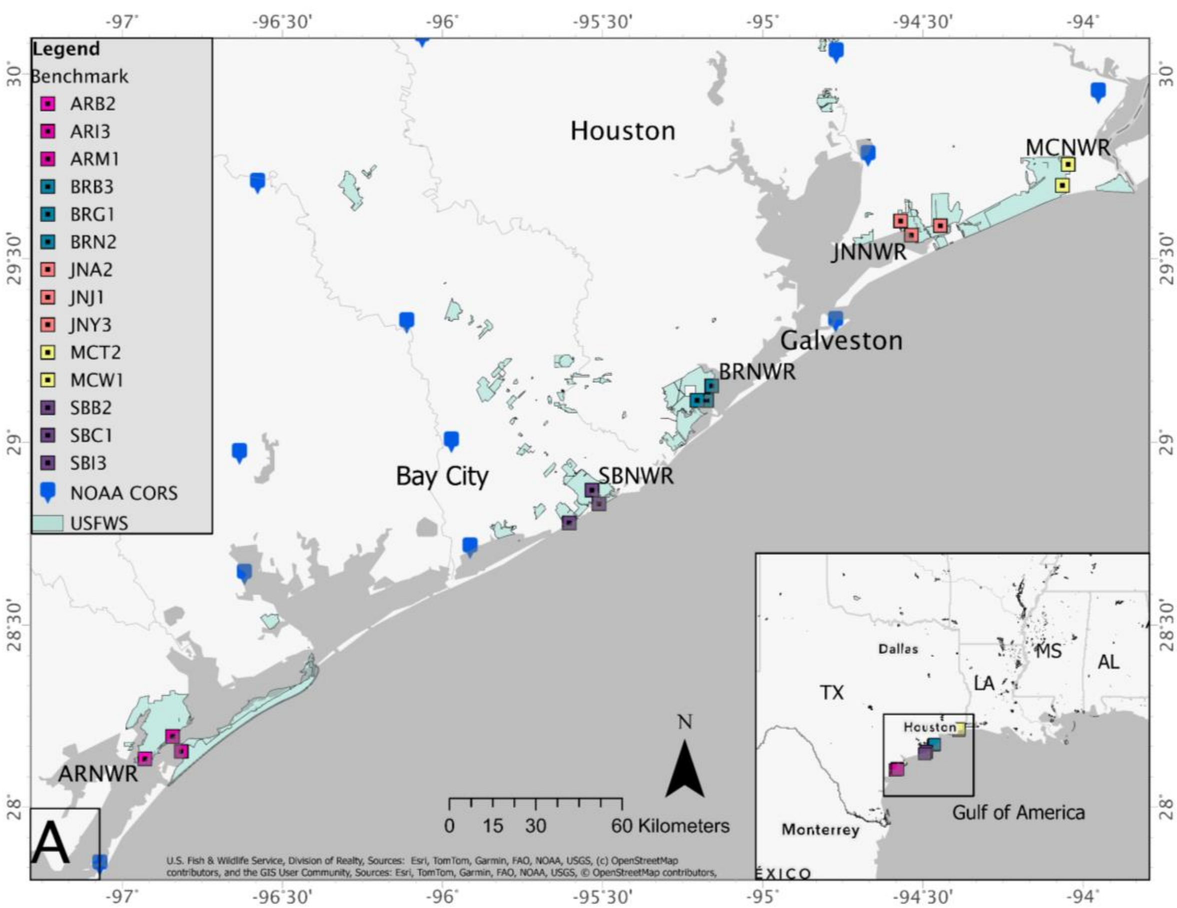
Introduction

Surface elevation data along the Texas Coast is limited, despite having some of the highest rates of relative sea-level rise in the country (Sweet et al., 2022). To narrow these knowledge and data gaps, the U.S. Fish and Wildlife Service (USFWS) established the first landscape-scale rod surface elevation table (RSET) monitoring project aimed at examining surface elevation dynamics of coastal marshes in Texas (Moon et al., 2022). The project, conducted cooperatively between the USFWS and the U.S. Geological Survey (USGS), has focused on 14 coastal marsh sites located within five National Wildlife Refuges (Figure 1). The main objective of this project's RSET data collection is to quantify the impacts of sea-level rise on coastal properties owned by the USFWS and similar surrounding areas. Data from RSETs will be used to determine areas that are at the greatest risk for potential habitat loss and degradation by examining subsidence and accretion rates. However, for the RSET data to be tied into the national vertical datum of 1988 (NAVD88) and, therefore, linked to the relative sea-level change calculations, it is necessary to establish primary vertical control at each study site through highly accurate and precise global navigation satellite systems (GNSS) surveys. Having a clear methodology for standardization is important for quality data. This report focuses on the methods, with particular emphasis on post-processing, used to survey benchmarks for the RSET data collection along the Texas Coast for the USFWS. Furthermore, this report serves as a general reference guide on the technical aspects of performing and processing GNSS surveys within the Texas coastal refuges to maintain quality and consistency.



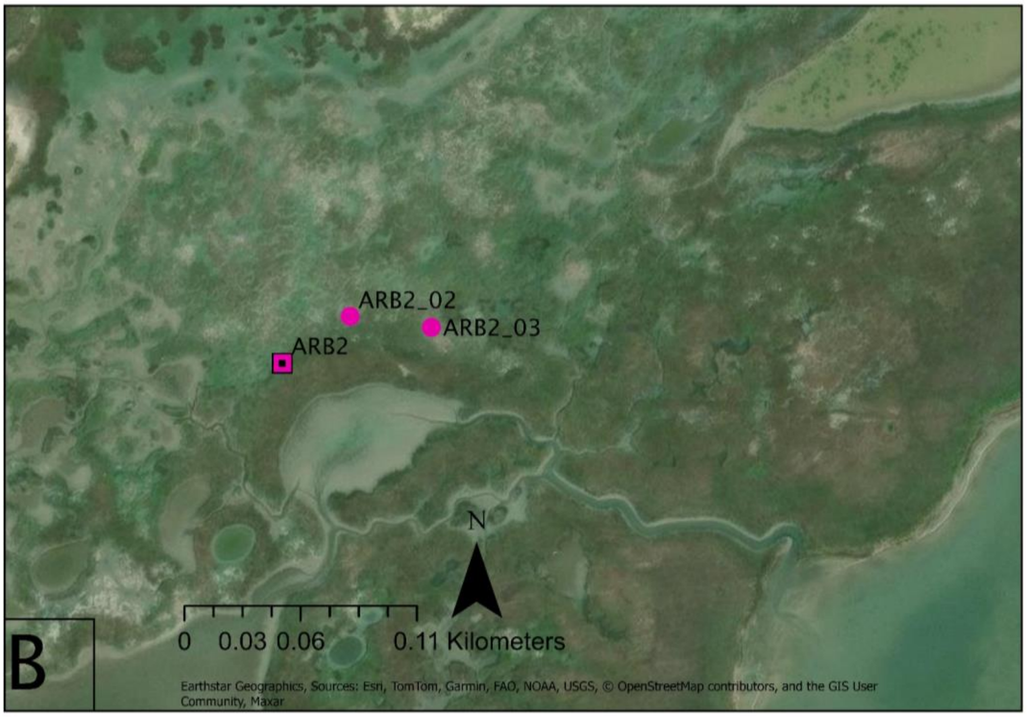


Figure 1. Study area map (A) and site level map (B). Square symbols are benchmarks surveyed with global navigation satellite systems (GNSS); circle symbols are benchmarks surveyed by digital leveling relative to GNSS surveyed benchmarks. NWR=National Wildlife Refuge, AR=Aransas, SB= San Bernard, BR= Brazoria, JN= Jocelyn Nungaray, MC=McFaddin

Methodology

Field Logistics and Preplanning

The equipment used for the surveys consisted of three Trimble dual-frequency R8, R10, and/or R12i GNSS receivers with an integrated antenna and external battery. Under best practices and conditions during a static survey, each Trimble GNSS Global Positioning System (GPS) receiver has vertical positioning performance of ± 5 mm + 0.5 parts per million (ppm) root mean square (RMS) (Trimble). The ppm calculation is an additional error proportional to the distance traveled to resolve baselines (e.g., 5 mm of error for every 1 km traveled). This translates to 5 mm of error plus an additional 0.5 mm of error for every 1 km that is traveled from the Continuously Operating Reference Station (CORS) (baseline). A Trimble DiNi Digital Level with digital bar code staff was also used in the survey campaign for differential leveling. The Trimble DiNi has an accuracy of 0.7 mm per km, though all distances were kept to under 50 m. Prior to the survey campaign, all equipment was tested to ensure operability, accuracy, and precision. Antennas, levelers, and internal components were calibrated as needed before the start of the survey campaign.

A fabricated leveler was used to attach and level the receiver on the primary benchmark (Figure 2). The term benchmark for purposes of this report refers to the deep-set rod (Class B;

Hailegeberel et al., 2018) that was installed at each RSET station (Figure 2). This benchmark is a passive mark for purposes of Online Positioning User Service (OPUS) processing since it is not continuously measured like CORS, and previous elevation measurements were not vertically constrained to the network. The primary benchmark at each site is referred to as station one, which was surveyed by a GNSS static campaign (Figure 1; square symbol). The secondary benchmarks are stations two and three at the site and were surveyed with differential leveling off the primary benchmark (Figure 1B; circle symbol) (Table 1).

Table 1. Texas Coast refuge static survey campaign information. Primary benchmark collected with global navigation satellite systems (GNSS) survey in bold.

Refuge	Site	Station	Survey Date(s)	BENCHMARK ID
Aransas National Wildlife Refuge (ARNWR)	ICWW	1	3/4/2024, 3/5/2024	**ARI3**
		2	3/5/2024	ARI3_02
		3	3/5/2024	ARI3_03
	Matagorda Island	1	3/4/2024, 3/5/2024	**ARM1**
		2	3/5/2024	ARM1_02
		3	3/5/2024	ARM1_03
	Blackjack	1	3/4/2024, 3/5/2024	**ARB2**
		2	3/5/2024	ARB2_02
		3	3/5/2024	ARB2_03
San Bernard National Wildlife Refuge (SBNWR)	Barrier Island	1	3/6/2024, 3/7/2024	**SBB2**
		2	3/6/2024	SBB2_02
		3	3/6/2024	SBB2_03
	ICWW	1	3/6/2024, 3/7/2024	**SBI3**
		2	3/6/2024	SBI3_02
		3	3/6/2024	SBI3_03
	Cow Trap	1	3/6/2024, 3/7/2024	**SBC1**
		2	3/6/2024	SBC1_02
		3	3/6/2024	SBC1_03
Brazoria National Wildlife Refuge (BRNWR)	Barrier Island	1	8/19/2024, 8/20/2024	**BRB3**
		2	8/20/2024	BRB3_02
		3	8/20/2024	BRB3_03
	Alligator Lake	1	8/19/2024, 8/20/2024	**BRG1**
		2	8/20/2024	BRG1_02
		3	8/20/2024	BRG1_03

	North Peninsula	1	8/19/2024, 8/20/2024	**BRN2**
		2	8/20/2024	BRN2_02
		3	8/20/2024	BRN2_03
Jocelyn Nungaray National Wildlife Refuge (JNNWR) (previously Anahuac NWR)	Alice Jackson White	1	8/21/2024, 8/22/2024	**JNA2**
		2	8/21/2024	JNA2_02
		3	8/21/2024	ANA2_03
	Yellow Rail	1	8/21/2024, 8/22/2024	**JNY3**
		2	8/21/2024	JNY3_02
		3	8/21/2024	JNY3_03
	Jackson Ditch	1	8/21/2024, 8/22/2024	**JNJ1**
		2	8/21/2024	JNJ1_02
		3	8/21/2024	JNJ1_03
McFaddin National Wildlife Refuge (MCNWR)	Willow-Barnet	1	7/31/2024, 8/1/2024	**MCW1**
		2	8/1/2024	MCW1_02
		3	8/1/2024	MCW1_03
	10 Mile Cut	1	7/31/2024, 8/1/2024	**MCT2**
		2	8/1/2024	MCT2_02
		3	8/1/2024	MCT2_03

The antenna height is one of the most common errors when conducting a survey. Due to the complexity of the leveler used on the benchmarks (Figure 2), extra caution and steps were made to ensure that the antenna reference point (ARP) was correct for each leveler. Fixed height attachments are the standard for static surveys and are preferable to adjustable attachments (Ryland and Densmore 2012). For our surveys, a 1-m (0.96 m without the point attachment) or 0.25-m fixed height rod was attached to the machine-fabricated leveler, which was then attached to the benchmark (Figure 2B). The fixed-height rod used was dependent on the height of vegetation on site, with the 0.96 m extension used to get above the vegetation. There is a trade-off in using taller (0.96 m) extensions to give more height to the receiver versus the shorter (0.25 m) extensions. While the taller extension results in greater height above vegetation and less satellite signal noise, it may lead to reduced precision due to increased likelihood of movement with wind. Therefore, extension height should be determined based on individual site conditions. Each component of the leveler was measured with calipers prior to field deployment and in the field to crosscheck and ensure accurate values for post-processing. Additionally, to reduce the possibility of measurement error, each leveler apparatus was measured with a Trimble DiNi digital level in a controlled setting prior to field data collection such that at least three measurements agreed to within 0.5 mm (Hailegeberel et al., 2018). Cross-checking and redundant measuring steps ensured that the ARP height was correct for the static survey collection and processing.

Figure 2. (A) Fabricated leveler with global navigation satellite systems (GNSS) receiver attached for pre-field calibration and measurements (Picture credit: Brett A. Patton [USGS]). (B) Fabricated leveler apparatus with rod surface elevation table (RSET) arm on a benchmark in vegetated wetland habitat (Picture credit: Ches Vervaeke [NPS]). (C) Fabricated leveler with 0.25-m extension, GNSS receiver, and benchmark for pre-field calibration and measurements (Picture credit: Ches Vervaeke [NPS]).

Field Data Collection

Between March 5 and August 22, 2024, the 14 primary benchmarks were surveyed to establish vertical control and relate the benchmarks to the National Spatial Reference System (NSRS) at each site for the Texas Coast Project (Table 1). A static, campaign-style GNSS survey was conducted at each refuge with a minimum of two, four-hour sessions on different days and times to ensure different atmospheric conditions (different days) and different satellite geometry (different times) over the occupation periods. Each receiver was set to a static survey style with a 15-second logging interval, 10-degree elevation mask, and all satellite constellations selected for tracking (ASPRS, 2015). Only one mark was surveyed for less than four hours due to a battery cable connectivity issue. It was determined that since this file overlapped with the day two file (6+ hours), two other static receivers collected concurrently, and all other quality checks were optimal, that this mark met acceptable data for the accuracy needed for our survey campaign (Level II survey; Rydlund and Densmore, 2012).

The Trimble DiNi digital level with bar code staff was used to tie the primary benchmarks to the other two benchmarks on site. The DiNi digital level was positioned on a leveled tripod in a stable area of marsh or the bow of the airboat, where there was minimal movement, the view of all benchmarks was unobstructed, and the distance to each benchmark was less than 50 m. The bar code staff was first held on the surveyed (known) benchmark and measured with the DiNi and then carried over to the other two benchmarks and measured with the DiNi. The second and third benchmarks were determined through differential leveling relative to the known benchmark (i.e., the difference between the known mark and the other marks was calculated). For each benchmark measured by digital leveling, multiple measurements (minimum of 5) were made with the DiNi until the cumulative closure tolerance was met with consistent measurements within 1.3 mm (Hailegeberel et al., 2018). All measurements for the DiNi were written down in the field as measured and logged in the DiNi device. The DiNi cable did not work for transferring measurements straight from the DiNi to the computer, so the measurements on the DiNi were checked against the measurements logged in the fieldbook. These measurements were entered into a spreadsheet and then checked by a second person against both the fieldbook and the DiNi device.

Post-processing with OPUS projects

After completion of each static GNSS survey session, the raw data was backed up on a USB drive. Each evening the raw data file (T02 or T04 extension) was sent to the National Geodetic Survey (NGS) Online Positioning User Service static (OPUS-s) processor for quality checks. Final ephemerides are not available until 18 days post survey; however, the ultra-rapid ephemeris provides an estimate of the quality of the data collected. The OPUS-s uses an NGS baseline processing software (Program for Adjustment of GPS Ephemerides-PAGES) with NGS's CORS network to find the unweighted means of three baseline solutions. Each solution for the raw data file that is output from OPUS-s includes geodetic coordinates and elevation for an observed mark. The quality checks of the OPUS-s solution included verifying that the horizontal coordinates and vertical elevation were logical for the given survey location. Additionally, the ultra-rapid ephemeris solutions were checked for additional parameters to ensure acceptable data. Acceptable data for the preliminary (ultra-rapid ephemeris) data included a GNSS data file of ≥ 4 hours; ≥ 70% of observations were used and fixed; ≤ 3 cm of root-mean squared (RMS) error for solution (overall 3D accuracy) ; ≤ 4 cm of peak-to-peak error ranges for the horizontal positioning (latitude and longitude) and vertical positioning (ellipsoid height); and ≤ 8 cm of peak-to-peak error range for elevation (orthometric height) (OPUS, 2023). For post-processing, we also set a stricter 20-degree elevation mask due to the lower height of the benchmarks and presence of marsh vegetation that was near the height of the GNSS receiver at sites.

The OPUS-projects is a free web-based software provided by the NGS that is used to process baselines and calculate network adjustments for static survey campaigns. OPUS-projects allow the user to manage all the survey data files for multiple sessions then use NGS software ADJUST and GPSCOM to produce final geodetic coordinates and elevations for each mark in a project (OPUS, 2023).

OPUS Project Workflow

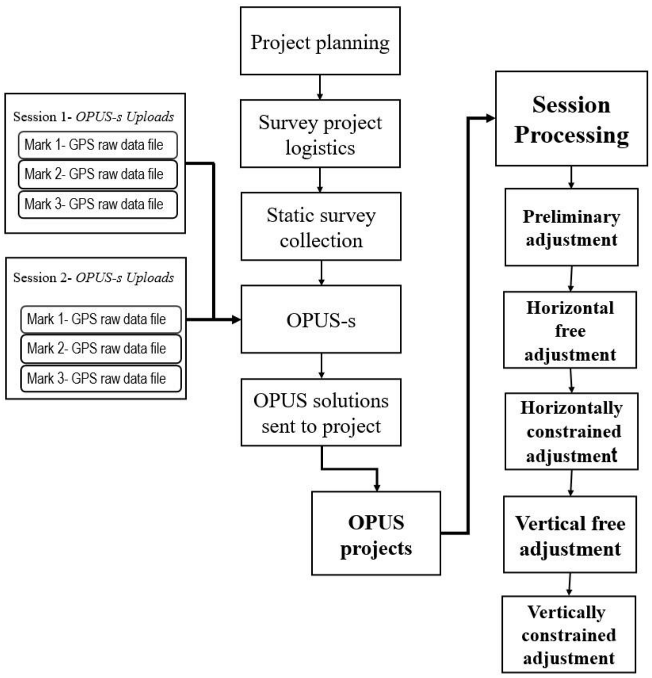


Figure 3. Static survey with online positioning user service (OPUS) projects post-processing workflow. Modified from OPUS, 2023 conceptual diagram.

Session Processing

Data from each refuge was processed individually in OPUS projects. Typically, most of the ionospheric delays that cause errors in positioning can be resolved by using OPUS-s to view the data file. However, for the most accurate positioning it is necessary to further post-process the data to resolve additional errors due to ionospheric and tropospheric delays and constrain to the horizontal and vertical controls within the network. First, all raw data files (T02 and T04 extension) were converted to receiver independent exchange (RINEX) files. The RINEX files were then uploaded to OPUS-s with the appropriate OPUS-project (refuge) name specified. The session processing step calculated baselines between Continuously Operating Reference Stations (CORS) (hub) and the primary control points (benchmarks, user marks). A minimum of four CORS should be used for session processing (Gillins et al., 2019; OPUS, 2023). For session processing we used at least four CORS within 250 km of user marks to resolve ionospheric delays and one distant CORS located greater than 375 km but less than 800 km for tropospheric decorrelation (Figure 4). One CORS within 250 km was constrained in 3D (i.e., latitude, longitude, and vertical) and served as the hub for baselines (Figure 4). All error estimates connected with the baselines, and their correlations were produced through a variance-covariance matrix.

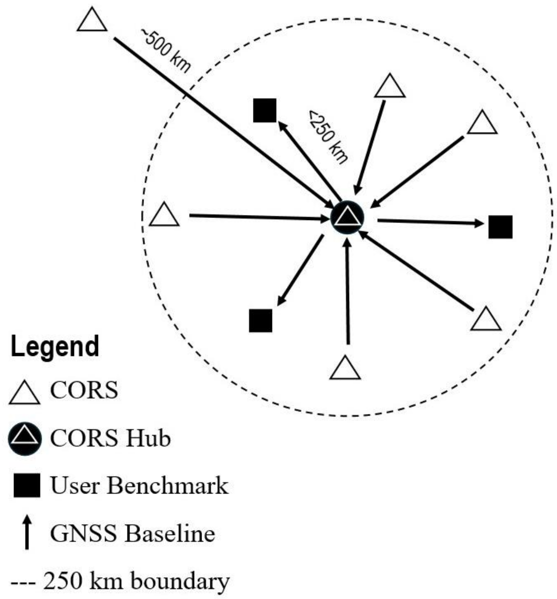


Figure 4. Session processing figure modified from Gillins et al., 2019. CORS = continuously operating reference station. GNSS=global navigation satellite systems

Network Adjustments

The network adjustment process is an iterative process with a sequence of five network adjustment steps that align the project with the National Spatial Reference System (NSRS) in both the horizontal and vertical space (OPUS, 2023). The network adjustment process begins with the preliminary minimally constrained network adjustment and ends with the vertically constrained network adjustment (Figure 3). Through each step of the network adjustment, it is important to scrutinize many inputs including which CORS is used based on distance to surveyed marks, which CORS is used due to availability of quality CORS data during the survey sessions, and which CORS is used as the constraints due to the accuracy and stability of the orthometric heights. Analyzing and revising at each process step ensures the adjustments are not biased by spurious vertical positioning data or incomplete CORS data during the survey sessions. Furthermore, following this process ensures that the benchmarks surveyed during the campaign are aligned and constrained with the NSRS for monitoring velocities over the long-term.

Step 1: Preliminary Network Adjustment

The first step is a preliminary network adjustment in which a minimum-constrained least-squares adjustment was completed on the project. During the first step one CORS station was constrained in 3D (i.e., latitude, longitude, and an orthometric height value) to identify errors or outliers.

Step 2: Horizontal (Geometric) Free Adjustment

The second step uses the adjustment from the first step to detect and remove all data outliers. This is a minimally constrained (e.g.,' free') adjustment where only one CORS was constrained in 3D (latitude, longitude, and ellipsoid height). In Step 2, any CORS used was examined to ensure the computed values matched the published CORS 3D coordinates. Steps 1 and 2 were repeated until all data outliers in the project were removed.

Step 3: Horizontally Constrained Adjustment

The third step is a constrained adjustment based on the results of the minimally constrained adjustments (Steps 1 and 2) with the goal of producing final horizontal coordinates. During this step all CORS except for the distant CORS were constrained in 3D. Through an iterative process, the CORS was adjusted to get to the desired network accuracy, resulting in final adjusted geometric coordinates (latitude, longitude, and ellipsoid height). Additionally, an F-test was performed to determine if the variance (of unit weight) between the observed and adjusted coordinates were within one sigma standard deviation.

Step 4: Vertical Free Adjustment

Step four is a minimally constrained (e.g.,'free') adjustment. During this step a single CORS station was constrained in 2D (latitude and longitude) while a different single CORS was constrained in 1D (vertical only, orthometric height). During Step 4 all orthometric heights used to constrain the benchmarks were scrutinized to ensure that the computed values matched the published orthometric heights.

Step 5: Vertically Constrained Adjustment

Step five is a constrained adjustment based on the results of the minimally constrained adjustment (Step 4) using an iterative process with the goal of final vertical coordinates. During this step a single CORS was constrained in 2D (latitude and longitude), and all CORS (except the distant CORS) with NAVD88 orthometric heights that meet 2 cm/5 cm standards (Zilkoski et al. 2005) were constrained in 1D (orthometric height). During Step 5, all marks and computed orthometric heights were scrutinized to ensure no large coordinate shifts (> 4 cm) or constraint ratios (> 3.00) that could indicate an error in the CORS design exist. If large shifts were observed for a single CORS, then the step was rerun without the CORS that was outside the parameters. Additionally, an F-test was performed to determine if the variance (of unit weight) between the observed and adjusted elevation were within one sigma standard deviation.

Results

All final vertically constrained solutions had a root mean square error (RMSE) less than 2.5 cm. All final vertically constrained elevations met the data quality metrics that were set (Table 2).

Table 2. Vertically constrained solutions and network adjustment parameters. RMSE=root mean square error, SD=standard deviation.

BENCHMARK ID	Observations Used (> 80%)	Ambiguities Fixed (> 90%)	Solution RMSE (cm) (< 2.5cm)	Ellipsoid Height SD (cm) (< 3cm)
ARI3	99.6	100	1.7	1.5
ARM1	99.6	98.5	1.4	1.4
ARB2	99.5	96.8	1.5	1.3
SBB2	98.4	100	1.4	1.5
SBI3	99.6	100	1.4	1.5
SBC1	99.2	100	1.4	1.2
BRB3	99.1	98.0	1.8	1.2
BRG1	98.5	94.3	1.8	1.2
BRN2	98.4	99.0	1.8	1.2
ANA2	98.9	100	1.6	1.3
ANY3	99.9	100	1.6	1.0
ANJ1	99.5	96.2	1.6	1.1
MCW1	99.3	100	2.0	1.7
MCT2	99.7	100	2.0	1.4

All final vertically constrained network adjustments passed the F-test performed to determine if the variance (of unit weight) between the observed and adjusted elevation were within one sigma standard deviation. Note: For future processing efforts, acceptable standard error values should be close to one (i.e., 0.75 or 1.25 is okay, but 7.50 or 0.25 would be unacceptable) (Table 3).

Table 3. F-statistic test results for online positioning user service (OPUS) vertically constrained network adjustments. NWR=National Wildlife Refuge, AR=Aransas, SB= San Bernard, BR= Brazoria, JN= Jocelyn Nungaray, MC=McFaddin

Refuge	Standard Error of Unit Weight	F-Statistic Test
ARNWR	0.993	PASS (1.01 < 2.59)
SBNWR	0.980	PASS (1.04 < 2.50)
BRNWR	0.987	PASS (1.03 < 1.97)
JNNWR	0.993	PASS (1.01 < 1.97)
MCNWR	0.961	PASS (1.09 < 3.09)

Horizontal network accuracies computed using a posteriori standard deviation of unit weight (95 % confidence level) were less than 1.50 cm and averaged 0.95 cm (Patton et al., 2025). Horizontal points deviated (standard deviation) less than 7 mm with a mean standard deviation of 4 mm. All points measured with the Trimble DiNi (digital leveling) had a standard deviation of less than 1 mm. Vertical network accuracies computed using a posteriori standard deviation of unit weight (95 % confidence level) were less than 3.0 cm and averaged 2.22 cm (Patton et al., 2025). Ellipsoid height deviated (standard deviation) less than 1.8 cm and with a mean standard deviation of 1.1 cm (Patton et al., 2025). Orthometric height deviated (standard deviation) less than or equal to 4 cm and with a mean of 3.2 cm (Table 4).

Table 4. Elevations of benchmarks (BM) for the rod surface elevation table (RSET) stations at each site measured with global navigation satellite systems (GNSS) static surveys and digital leveling (DL). RSET elevations were calculated by adding 0.3137 m to the BM elevations (Moon et al. 2022). All Northing and Easting are in UTM 15 except for Aransas sites which were in UTM 14. All elevations are in NAVD88, derived from GEOID18. NWR=National Wildlife Refuge

Refuge	BM ID	Northing (UTM, m)	Easting (UTM, m)	BM Elevation	BM Elevation SD	RSET Arm Elevation	Method
Aransas (ARNWR)	ARB2	3113645	703411	0.471	0.028	0.785	GNSS
	ARB2_02	3113669	703440	0.490	0.028	0.804	DL
	ARB2_03	3113665	703474	0.464	0.028	0.778	DL
	ARI3	3120597	711759	0.510	0.032	0.824	GNSS
	ARI3_02	3120583	711782	0.597	0.028	0.911	DL
	ARI3_03	3120561	711752	0.520	0.028	0.834	DL
	ARM1	3116107	714490	0.442	0.032	0.756	GNSS
	ARM1_02	3116082	714475	0.459	0.032	0.773	DL
	ARM1_03	3116042	714453	0.481	0.032	0.795	DL
Brazoria (BRNWR)	BRB3	3222521	288334	0.538	0.030	0.852	GNSS
	BRB3_02	3222547	288298	0.496	0.030	0.810	DL
	BRB3_03	3222523	288352	0.516	0.030	0.830	DL
	BRG1	3222637	285423	0.589	0.031	0.903	GNSS
	BRG1_02	3222668	285408	0.521	0.031	0.835	DL
	BRG1_03	3222656	285396	0.542	0.031	0.856	DL
	BRN2	3226926	289985	0.576	0.029	0.890	GNSS
	BRN2_02	3226900	289986	0.566	0.029	0.880	DL
	BRN2_03	3226913	290023	0.517	0.029	0.831	DL
Jocelyn Nungaray (JNNWR) (previously Anahuac NWR)	JNA2	3275714	348009	0.357	0.030	0.671	GNSS
	JNA2_02	3275732	347991	0.323	0.030	0.637	DL
	JNA2_03	3275705	347988	0.338	0.030	0.652	DL
	JNJ1	3274130	359973	0.406	0.031	0.720	GNSS
	JNJ1_02	3274128	359956	0.441	0.031	0.755	DL
	JNJ1_03	3274112	359950	0.441	0.031	0.755	DL
	JNY3	3271388	351177	0.802	0.030	1.116	GNSS
	JNY3_02	3271371	351159	0.833	0.030	1.147	DL

	JNY3_03	3271341	351175	0.818	0.030	1.132	DL
McFaddin (MCNWR)	MCT2	3285832	397007	0.433	0.034	0.747	GNSS
	MCT2_02	3285822	396991	0.467	0.034	0.781	DL
	MCT2_03	3285797	396996	0.439	0.034	0.753	DL
	MCW1	3292101	398783	0.338	0.033	0.652	GNSS
	MCW1_02	3292122	398770	0.299	0.033	0.613	DL
	MCW1_03	3292084	398763	0.317	0.033	0.631	DL
San Bernard (SBNWR)	SBB2	3191961	254962	0.483	0.036	0.797	GNSS
	SBB2_02	3191786	255042	0.455	0.040	0.769	DL
	SBB2_03	3191806	255053	0.437	0.040	0.751	DL
	SBC1	3196161	252895	0.575	0.036	0.889	GNSS
	SBC1_02	3196135	252863	0.619	0.036	0.933	DL
	SBC1_03	3196164	252931	0.600	0.036	0.914	DL
	SBI3	3186362	245787	0.444	0.040	0.758	GNSS
	SBI3_02	3186347	245781	0.500	0.040	0.814	DL
	SBI3_03	3186363	245803	0.537	0.040	0.851	DL

Future Improvements

This summary of methodology gives a working document for future data collection. GNSS surveying technology improves and changes with time, and therefore it is important that the methodology is continuously updated. The Trimble R10 and R12i receivers are an improvement over the R8 due to the additional satellite constellation geometries that the R10 and R12i can track. In January 2024, OPUS released a beta version that, in addition to GPS data, can process multiple constellation data from CORS (OPUS-s 5.0 Beta). Once the 2024 beta version is integrated with OPUS-projects, it will likely improve vertical accuracies in the future. Since the R10 and R12i receivers always track at least four satellite constellations at a time, these receivers have the potential to improve accuracies for a survey campaign. McFaddin National Wildlife Refuge (MCNWR) only has two sites, and, therefore, only two primary benchmarks. Accuracy will likely improve with the addition of a third static survey receiver on a second benchmark within a site, allowing for data collection at three static receivers simultaneously (ASPRS, 2024). Since three receivers were used for all other sites, a third receiver at MCNWR would not add much time or expense to the survey campaign. Ideally, a third static survey would be set over a known benchmark (ASPRS, 2024), however, finding a known benchmark with good vertical control and reliability in this area is very difficult or impossible (NGS, 2024). All national geodetic survey (NGS, 2024) benchmarks with vertical control within 15 km of the MCNWR benchmarks were noted to be in areas of vertical motion (NGS). Improved future planning for these surveys could include added reconnaissance for shared benchmark surveys near the refuge with vertical stability and reliability to add to the campaign and/or for additional quality control checks. However, this would require extra personnel and time to monitor equipment over a benchmark in an area with unrestricted public access.

In September 2023, OPUS-projects started accepting Real-Time GNSS Network (RTN) on benchmarks (OPUS, 2023). Through best practices RTN can now reach vertical accuracies of 1.5 cm. This is an innovation that could drastically reduce the amount of equipment and time that is necessary to resurvey in the Texas Coast benchmarks. In theory, one GNSS receiver could be used to survey in all the Texas Coast benchmarks covering one refuge per day. The RTN survey works by creating a virtual reference station (VRS) on site, therefore the ppm error is removed due to very short baseline distances. However, network uncertainty will remain a factor, therefore the vertical stability of CORS and benchmarks must be scrutinized for network adjustments. The RTN survey requires a minimum of three independent occupations at least 180 seconds each until all measurements agree within 2 cm horizontal and 5 cm vertical (orthometric height) (ASPRS, 2024). This is significantly less than multiple-day surveys at four hours each with additional post-processing that traditional static surveys require. Additionally, the VRS can mitigate the errors due to long baselines distances that are common in remote coastal zones. The use of a cellular network and booster could allow for short single baselines that are comparable or more accurate than the multiple baselines required of static processing (ASPRS, 2024).

To modernize the National Spatial Reference System (NSRS), the National Geodetic Survey (NGS) is set to release a new horizontal and vertical datum by the end of 2026 (NGS, 2017). The North American Datum of 1983 (NAD83) and the North American Vertical Datum of 1988 (NAVD88) are projected to be replaced by the North American Terrestrial Reference Frame (NATRF2022) and North American-Pacific Geopotential Datum of 2022 (NAPGD2022). The new vertical datum NAPGD2022 is based off a gravimetric geoid model (GEOID22) as opposed to traditional terrestrial survey techniques on passive survey marks used for NAVD88. It is expected that the modernized NSRS will improve confidence in floodplain and subsidence measurements in relation to sea-level change (Youngman, 2011) due to the more stable and continuous nature of the new datums. In some areas orthometric heights could be adjusted up to 2 m (NGS, 2017). Therefore, it will likely be necessary to resurvey the Texas Coast RSETs for vertical control once the new datums are released. A traditional static survey campaign with an RTN survey at this time could be beneficial to determine if the RTN surveys are an acceptable and reliable replacement to the cumbersome static survey campaigns at these sites.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

American Society for Photogrammetry and Remote Sensing (ASPRS). (2015). ASPRS positional accuracy standards for digital geospatial data. *Photogrammetric Engineering & Remote Sensing*, 81(3), A1-A26.

American Society for Photogrammetry and Remote Sensing (ASPRS). (2024). Positional Accuracy Standards for Digital Geospatial Data, Edition 2, Version 2, 2024. *Photogrammetric Engineering & Remote Sensing,* 91.5 (2025), 247-255.

Gillins, D. T., Kerr, D., and Weaver, B. (2019). Evaluation of the online positioning user service for processing static GPS surveys: OPUS-Projects, OPUS-S, OPUS-Net, and OPUS-RS. *Journal of Surveying Engineering*, *145*(3), 05019002.

Hailegeberel, M., Glassmire, K., Johnson, A., Samant M., and Dusek G. (2018). User's Guide to Vertical Control and Geodetic Leveling for CO-OPS Observing Systems. *NOAA Tides and Currents*.

Moon, J. A., Feher, L. C., Lane, T. C., Vervaeke, W. C., Osland, M. J., Head, D. M., ...and Rankin, N. M. (2022). Surface elevation change dynamics in coastal marshes along the Northwestern Gulf of Mexico: Anticipating effects of rising sea-level and intensifying hurricanes. *Wetlands*, 42(5), 49.

National Geodetic Survey (2024). National Geodetic Survey Web Map. Accessed March 1, 2024 at URL https://geodesy.noaa.gov/datasheets/ngs_map/.

National Geodetic Survey (2017): Blueprint for 2022, Part 2: Geopotential Coordinates, National Oceanic and Atmospheric Association Technical Report NOS NGS 64, 41 p.

OPUS (2023). Online Position User Service Baseline Processing and Adjustment Software User Guide, 2023. https://geodesy.noaa.gov/OPUS-Projects/user_guide/user_guide.

Osland, M. J., Griffith, K. T., Larriviere, J. C., Feher, L. C., Cahoon, D. R., Enwright, N. M., ... and Wilson, K. V. (2017). Assessing coastal wetland vulnerability to sea-level rise along the northern Gulf of Mexico coast: Gaps and opportunities for developing a coordinated regional sampling network. *PloS one*, *12*(9), e0183431.

Patton, B. A., Moran, S.R., Sanspree, C., and Moon, J. (2025). Vertical Control GNSS and leveling data collected across five Texas coastal National Wildlife Refuges, 2024: U.S. Geological Survey data release, https://doi.org/10.5066/P14UUUG8.

Rydlund, P. H., Jr., and Densmore, B. K. (2012). Methods of practice and guideline for using survey-grade global navigation satellite systems (GNSS) to establish vertical datum in the United States Geological Survey: U.S. Geological Survey Techniques and Methods, Book 11, Chapter. D1, 102 pp with appendices.

Sweet, W. V., Kopp, R. E., Weaver, C. P., Obeysekera, J., Horton, R. M., Thieler, E. R., and Zervas, C. (2017). Global and regional sea level rise scenarios for the United States (No. CO-OPS 083).

Youngman, M., Smith D., Lokken S., and Langan, T. (2011): The Effect of Modernizing the National Datums on Floodplain Mapping, 41 pp.

Zilkoski, D., Carlson, E., and Smith, C. (2005). Draft Guidelines for Establishing GPS-Derived Orthometric Heights (Standards: 2 cm and 5 cm) Version 1.4. webpage: http://www. ngs. noaa. gov/PUBS_LIB. *NGS592008069FINAL2. pdf*.