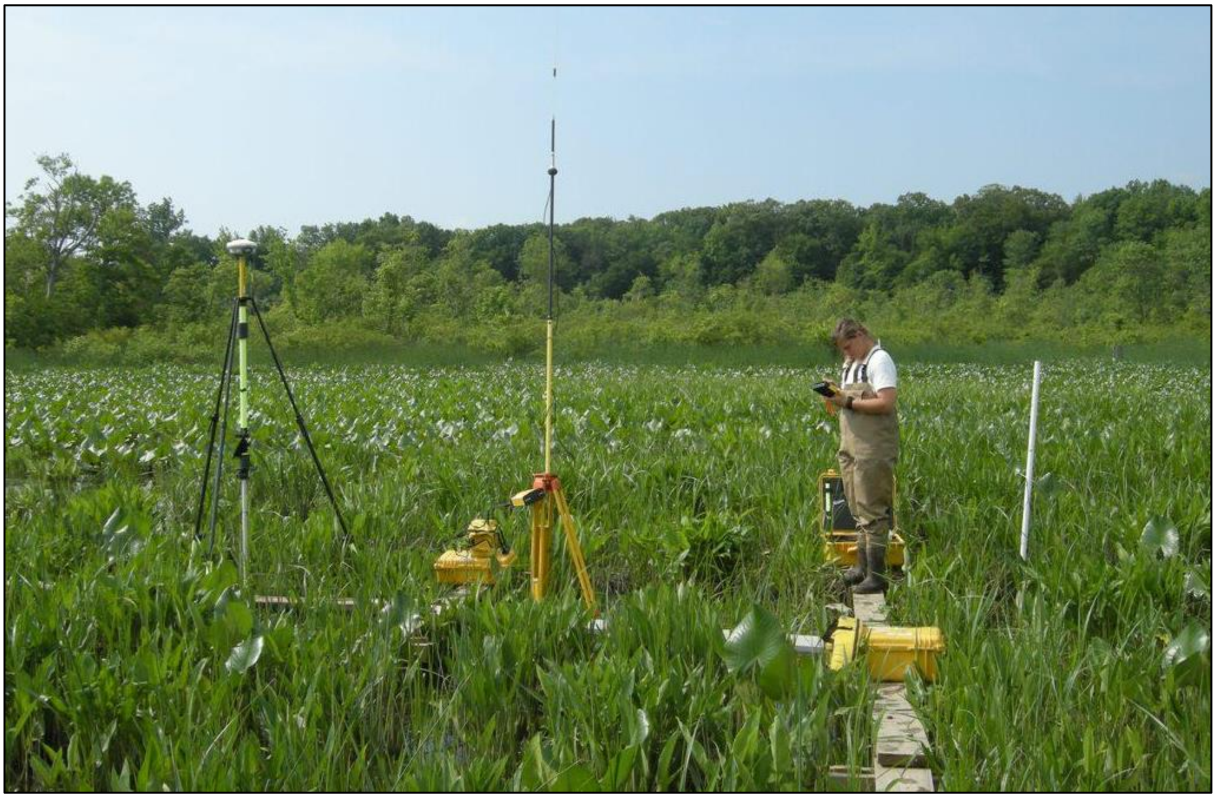
NOAA NOS Manual

ACCURATE ELEVATIONS FOR SEA LEVEL CHANGE SENTINEL SITES



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NOAA National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
National Geodetic Survey
Center for Operational Oceanographic Products and Services
Office for Coastal Management

National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

National Geodetic Survey

The National Geodetic Survey (NGS), a program office of National Oceanic and Atmospheric Administration's (NOAA's) National Ocean Service (NOS), provides the framework for all positioning activities in the United States. NGS defines, maintains, and provides access to the National Spatial Reference System (NSRS), the official coordinate system of the federal civilian government for latitude, longitude, elevation, gravity, and shoreline and how they change over time. Access to the NSRS contributes to informed decision making and impacts a wide range of important activities including mapping and charting, navigation, flood risk determination, transportation, land use, and ecosystem management. NGS' authoritative spatial data, models, and tools are vital for the protection and management of natural and manmade resources and support the economic prosperity and environmental health of the Nation. The NSRS was traditionally determined by survey marks in the ground: access to the NSRS now includes a large network of Global Navigation Satellite System (GNSS) Continuously Operating Reference Stations (CORS). Geopotential data; acceleration due to gravity; deflection of the vertical; GNSS satellite orbits; the orientation, offset, and scale between the national and international reference frames are all elements of the NSRS and are determined by NGS. NGS is responsible for procuring geodetic data, processing these data, and making the data available to users.

Center for Operational Oceanographic Products and Services

The NOS Center for Operational Oceanographic Products and Services (CO-OPS) provides the National infrastructure, science, and technical expertise to collect and distribute observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and tidal current products required to support NOS' Strategic Plan mission requirements, and to assist in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), a national network of Physical Oceanographic Real-Time Systems (PORTS®) in major U.S. harbors, and the National Current Observation Program (NCOP) consisting of current surveys in near shore and coastal areas utilizing bottom mounted platforms, subsurface buoys, horizontal sensors and quick response real time buoys. The Center establishes standards for the collection and processing of water level and current data; collects and documents user requirements which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

Office for Coastal Management

The NOS Office for Coastal Management focuses on coastal management, a broad term that covers many aspects of the built and natural coastal environment. Included are four major programs: the Coral Reef Conservation Program; the National Coastal Zone Management Program; the National Estuarine Research Reserve System; and the Digital Coast. In addition to implementing federal mandates and specific initiatives, the office also provides the data, tools, and training communities need to increase their resilience to the negative impacts associated with coastal hazards (flooding, erosion, storms, sea level rise, etc.). To learn more visit coast.noaa.gov.

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Philippe F. Hensel and Christine M. Gallagher, National Geodetic Survey

Artara Johnson, Center for Operational Oceanographic Products and Services

Scott Lerberg, Chesapeake Bay National Estuarine Research Reserve, Virginia; Office for Coastal Management

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U.S. DEPARTMENT OF COMMERCE
Gina Raimondo, Secretary

National Oceanic and Atmospheric Administration
Dr. Richard Spinrad, Under Secretary of Commerce for Oceans and Atmosphere

National Ocean Service
Nicole LeBoeuf, Assistant Administrator

National Geodetic Survey
Juliana P. Blackwell, Director

Center for Operational Oceanographic Products and Services
Marian Westley, PhD, Acting Director

Office for Coastal Management
Jeffrey L. Payne, Ph.D., Director

NOTICE

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

cm	centimeter
CO-OPS	Center for Operational Oceanographic Products and Services
CORS	Continuously Operating Reference Stations
ft	foot
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellites
IDB	Integrated Data Base
km	kilometer
lb	pound
LCM	Local Control Mark
MHHW	Mean Higher High Water
MHW	Mean High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
mm	millimeter
MN	Mean Range of Tide
MTL	Mean Tide Level
NAD	North American Datum
NAVD	North American Vertical Datum
NERRS	National Estuarine Research Reserve System
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NSRS	National Spatial Reference System
NTDE	National Tidal Datum Epoch
NWLON	National Water Level Observation Network
OCM	Office for Coastal Management
OPUS	Online Positioning User System
PBM	Primary Tidal Bench Mark
PID	Permanent Identifiers
PDOP	Positional Dilution of Precision
RMS	Root Mean Square
RTK	Real-Time Kinematic
sav	submerged aquatic vegetation
SET	Surface Elevation Tables
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VPR	Vertical Point of Reference

FOREWORD

The National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) developed a "coastal habitat response to changing water levels" program to monitor sea level change impacts in coastal areas across the National Estuarine Research Reserve System (NERRS) (NERRS, 2016). Sea level change is becoming an increasingly important concern for coastal managers and stakeholders. NOS, given its unique position as steward of coastal resources and provider of accurate elevations and water levels, is leveraging its capabilities to provide coastal managers and stakeholders with the data necessary to understand and plan for or mitigate the risks associated with changing water levels. The resulting effort has brought together the Office for Coastal Management (OCM), the parent office of the NERRS; the National Geodetic Survey (NGS), the federal authority regarding high accuracy geodetic control; and the Center for Operational Oceanographic Products and Services (CO-OPS), the federal authority regarding tidal observations and tidal datum computation.

As these offices helped define recommended infrastructure, data, and methodologies, it became clear that the success of the program hinged on the ability of local staff within the NERRS to carry out much of the installation, surveying, data processing, as well as maintenance of the infrastructure. Consequently, there arose a need for OCM, NGS, and CO-OPS to support education and training. Informed by field experiences and hands-on training, this document strives to provide the essential information needed to support the establishment and maintenance of sea level change sentinel sites.

Although the genesis of this document arose within NOAA, other agencies and organizations have developed similar initiatives to monitor sea level change impacts along our Nation's coasts. As a result, the scope of this document was broadened to apply to parks, refuges, and other coastal habitats where sea level change impacts will be monitored. The consistent use of similar techniques with known accuracies and uniform connections to both geodetic and tidal datums will create a large, consistent, national network of sea level change monitoring sites.

The NERRS has focused resources on long term monitoring of climate change impacts related to changing water levels. As a result, many examples within this document are drawn from work completed at individual NERRS. These examples illustrate how reserves have developed different approaches to best support long term monitoring. Despite these differences, fundamental questions that remain consistent across the system include:

1. Where do our wetlands and submerged vegetation sit within the tidal frame?
2. What is happening to the tidal range at a given site?
3. What is happening to the marsh surface relative to the water level?
4. Can we detect a vegetation response to changes in these factors?
5. How can accurate positioning help monitor habitat responses to other site specific, relevant factors – e.g., temperature change, invasive species, etc.?

1. INTRODUCTION

1.1. Overview

This document provides guidelines for coastal reserves, parks, refuges, and other coastal habitat management areas to be identified as long-term "sea level change sentinel sites," monitoring both the changes in local water levels as well as the resulting impacts on the adjacent coastal ecosystem. The term "sea level change sentinel site[1]" has been defined differently by various agencies and organizations, but this document assumes any strategy to monitor climate change impacts related to water level changes must include three basic components described below.

1. Local, high accuracy vertical control network connected to a consistent reference frame (i.e., the National Spatial Reference System (NSRS)), with maintained high accuracy connections among all other components of the sentinel site;
2. Long-term high accuracy water level sensor(s) with verified vertical stability and high frequency data capture (e.g., 6-minute data);
3. Long-term coastal habitat monitoring infrastructure (e.g. Surface Elevation Tables (SETs); groundwater wells, permanent vegetation transects or monitoring plots, etc.).

This document provides information to develop a survey plan, install geospatial infrastructure, and establish local vertical control networks with connections to both the National Spatial Reference System (NSRS) and any local monitoring infrastructure. The document also describes how to establish a local water level station and gives general information on what is needed to process water level data. Any specific technical language used to identify the sentinel site components will be defined and discussed throughout the document.

For example, the NERRS defines sentinel sites as areas in coastal and marine environments that have the operational capacity for intensive study and sustained observations to detect and understand changes in the ecosystems they represent. To be an established and operational NERRS Sentinel Site Program, reserves must address all of the following requirements, many of which have associated protocols:

1) Develop Sentinel Sites Program Plan
2) Identify Audiences and Management Issues
3) Establish Programmatic Capacity
4) Monitor Tidal Marsh, Mangrove, or Submerged Aquatic Vegetation (SAV)
5) Measure Wetland Surface Elevation Change
6) Measure Water Level
7) Detect Elevation Changes
8) Collect Water Quality Data
9) Collect Meteorological Data
10) Synthesize and Translate Data

Given the diverse nature of locations, infrastructure, and staff capacity across both the NERRS and other institutions and programs, these guidelines reflect a philosophy of "best achievable accuracy" with regard to which particular methods to use in establishing the sites. This document does not provide specific instructions describing how to use the different components of long-term coastal habitat monitoring infrastructure (e.g., SETs, groundwater wells, etc.). Guidelines and procedures regarding those components may be available, and this text will reference existing resources or other documents known to be in development whenever possible.

[1] "Sea level change sentinel site" is shortened to "sentinel site" in the rest of the guidelines document

The document's intended audience is the site manager, researcher, or Geographic Information System (GIS)/surveying technician who is considering establishing a sentinel site. The document attempts to balance thoroughness with readability for those who are not professional surveyors or oceanographers. The attention to detail should help on-site personnel complete most tasks with minimal additional training, but formal training in surveying techniques such as leveling and Global Navigation Satellite System (GNSS) may still be required. GNSS is the broader term for all satellite-based navigation systems, including the Global Positioning System (GPS). NOAA's NGS provides some training[2] for survey techniques, and manufacturer-specific training can be arranged through the vendor of the survey equipment. In addition, NGS provides online educational materials[3] that the user might find helpful.

To learn more about establishing a sentinel site, please see NERRS Sentinel Site Application Module 1 (2016).[4] After thoroughly reviewing available guidance documents, the reader may decide to contract out some tasks to local survey professionals rather than complete all work with on-site personnel. If that is the case, the document's detailed information will help ensure that correct specifications are written into the contract. Typically, a small percentage of professional surveyors may have the necessary equipment and experience to perform high precision leveling; similarly, it may be difficult to find oceanographers willing and able to assist with the collection and processing of water level data. If any work will be performed by a contractor, it will be important to obtain the services of a company that can clearly demonstrate proficiency in the areas described in this document. Additionally, there may be opportunities to collaborate with other agencies or researchers who are planning similar monitoring systems.

This document is divided into sections that relate to the different phases of sentinel site construction (Figure 1-1). Each section is meant to be as "stand-alone" as possible for each phase of the project. As a result, there may be some repetition of concepts among the different sections described below:

1. **Section 1** defines the scope of the document, discusses the importance of elevation in the coastal zone, and introduces some technical concepts or terms used in the text.
2. **Section 2** introduces national observation networks, and then presents the local infrastructure that will to establish a sentinel site.
3. **Section 3** discusses how to complete an inventory of current sentinel site components, reconnaissance field work, and a preliminary survey plan. **The survey plan will have to be revisited after reading the entire document to incorporate specific information regarding the survey methods employed.**
4. **Section 4** presents methods for establishing a water level station and processing water level data.
5. **Section 5** presents methods for establishing vertical control marks.
6. **Section 6** presents high precision leveling and static GNSS surveying as methods for connecting the local vertical control network to the NSRS.
7. **Section 7** presents methods for connecting water level sensors (water level stations) and ecosystem monitoring infrastructure to the local vertical control network.
8. Appendices are included to provide examples and additional in-depth information on several topics discussed in the text.

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[2] https://geodesy.noaa.gov/corbin/calendar.shtml
[3] https://geodesy.noaa.gov/INFO/training-education.shtml
[4] https://coast.noaa.gov/data/docs/nerrs/Research_SentinelSitesGuidanceDoc.pdf

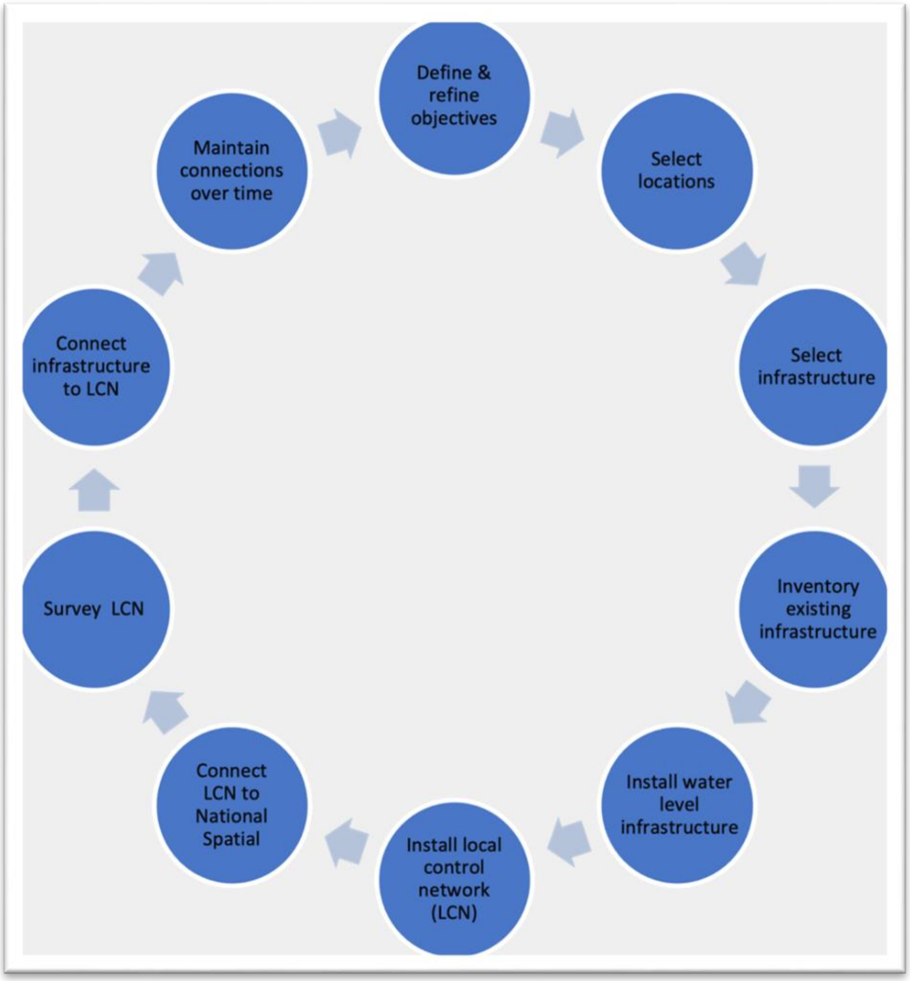

Figure 1-1. Conceptual diagram showing basic workflow associated with a sea level change sentinel site.

"Accurate Elevations for Sea Level Change Sentinel Sites" should be considered a "living document," so that valuable case studies, tips, short cuts, and updated methods can be incorporated in future versions of the document. This strategy will ensure that the document remains relevant as technology improves and as more experience is gained in the establishment and maintenance of sentinel sites. **Please share relevant information by contacting the authoring NOAA Program offices.**

Finally, this document is written in an informal style and attempts to avoid complex and indirect expressions when possible. Plain text is used to provide narrative, lists, or instructions. Additionally, call-out boxes are used to highlight critical information or useful tips, as illustrated below.

Critical information is highlighted with the heading "Important Information" in call-out boxes with solid red lines.

Case studies and/or other useful information are highlighted in call-out boxes with dotted green lines.

1.2 Importance of Elevation in the Coastal Zone

Wetland plants, which structure the coastal intertidal community and are a foundational element of coastal ecosystems' goods and services, have very specific tolerances to flooding frequency and duration, both of which are dependent on the relationship between elevation and water levels. Surface elevation is a critical structural component of low-lying coastal areas, where slight changes in elevation can mean the difference between extensive wetland habitats and open water. Therefore, maintaining elevation with respect to sea level is critical to coastal wetland survival. This is especially critical in areas of rapid local sea level rise, for example, along subsiding coastlines. With the rapid loss of coastal wetlands worldwide and predicted increases in global sea level rise, it is important to carefully monitor the elevations of existing coastlines or critical wetland habitats with respect to sea level, understand the processes leading to elevation change, and predict the outcome of possible mitigation scenarios.

A leading cause driving the reduction of coastal wetlands is the loss of coastal elevation with respect to local water levels. Many factors may contribute to this apparent elevation loss including global sea level rise, restricted hydrology and sedimentation, local geologic subsidence, and human activities (e.g., withdrawing drinking water from aquifers). Given these factors, wetland loss is especially pronounced where upslope migration is constrained by low elevations and hardened structures such as levees, roads, buildings, and other structures. In other words, the wetlands have nowhere to go as they become more inundated. Mitigation actions to strengthen wetland resiliency in the face of rising sea levels may be very challenging, both economically and politically. However, high accuracy, scientifically valid measurements of both surface elevations and water levels, and how they change through time, will help inform decision makers on potential wetland mitigation/adaptation measures to increase wetland resiliency and avoid/delay wetland collapse.

Determining elevations and assigning elevations to permanent reference points, also known as "establishing vertical control," is challenging in coastal wetlands because the methods commonly used are problematic in the inherently unstable intertidal zone. Challenges to establishing vertical control include a lack of nearby survey control marks ("bench marks"), difficulty or inability to level between control marks, and uncertainties in satellite-based (e.g., GNSS) elevations in coastal areas. Table 1-1 summarizes these issues, explains why the problem exists in coastal wetlands, and what steps are being taken to address these challenges.

Important Information
Geodetic control serves as a common reference system for establishing coordinate positions, and vertical control points have established elevations. Traditionally, geodetic control points are established as permanent physical monuments placed in the ground and precisely marked, located, and documented.

Despite these challenges, the ability to establish accurate vertical control in coastal and intertidal zones is improving. One strategy that takes advantage of technological advances is Height

Modernization[5] an initiative focused on establishing accurate, reliable elevations using GNSS technology in conjunction with traditional leveling, gravity, and modern remotely sensed information.

Table 1-1. Challenges to establishing vertical control in the coastal and intertidal zones.

What is the challenge?	Why does this issue occur?	What is being done?
Survey control marks rarely extend into intertidal zone.	Survey control marks are installed in stable locations, and intertidal zones are inherently unstable.	NGS & partners are establishing networks of intertidal bench marks with accurate elevations.
Leveling generally is not conducted in the intertidal zone.	Leveling is typically conducted over stable surfaces, such as roads or paved surfaces.	Innovative field work is extending leveling into the wetland, but sometimes it is not possible.
Geoid models* not well defined in coastal zone.	Shipborne sensors collect offshore data, terrestrial gravity collected on stable uplands, but measurements in wetlands are difficult.	NGS has begun collecting airborne gravity to improve geoid models.
Water level stations are difficult to install and maintain in remote coastal wetland areas.	Tidal datums are local in nature and cannot always be interpolated nor extrapolated accurately from a nearby station.	The sentinel site concept is meant to provide water level information where no vertically referenced water level data currently exist.

*For definition of geoid models, see section 1.3.

[5] www.geodesy.noaa.gov/heightmod

1.3 Terminology Associated with Vertical Control and Water Level Monitoring Networks

When attempting to combine or compare vertically referenced data, it is critical that the elevations be expressed relative to the same zero point (Figure 1-2). For example, if a vegetation plot is measured at an elevation of 0.253 meters (m) and mean sea level is measured at -0.012 m, these measurements are of little importance unless they are expressed with the same zero point. This is the purpose of a vertical datum. A datum is a reference frame or surface from which positions and elevations are referenced. The use of a consistent vertical datum is all the more important when measurements are taken to sub-centimeter levels of accuracy. The diversity of datums in use today, and the technological advancements that have made obtaining highly accurate positions easier require careful datum selection and careful conversion between coordinates in different datums.

Official datums change over time as science and our understanding of geophysical processes evolve. In the coterminous United States and Alaska, the current official geodetic horizontal datum is North American Datum of 1983 (NAD 83), and the official geodetic vertical datum is North American Vertical Datum of 1988 (NAVD 88; Figure 1-3). Note that islands will have their own vertical datum, such as the American Samoa Vertical Datum of 2002 (ASVD 02). The vertical datum that preceded NAVD 88 was the National Geodetic Vertical Datum of 1929 (NGVD 29), but it is generally no longer used. While NGVD 29 elevations can sometimes be transformed into NAVD 88 elevations, it may be more accurate and preferable to establish a new NAVD 88 elevation if possible. In a few years, the United States and its territories will adopt new, modernized datums,[6] both geometric and geopotential. New tools and procedures will be made available to ensure data taken under one datum can be easily converted to the new datums.

[6] https://geodesy.noaa.gov/datums/newdatums/index.shtml

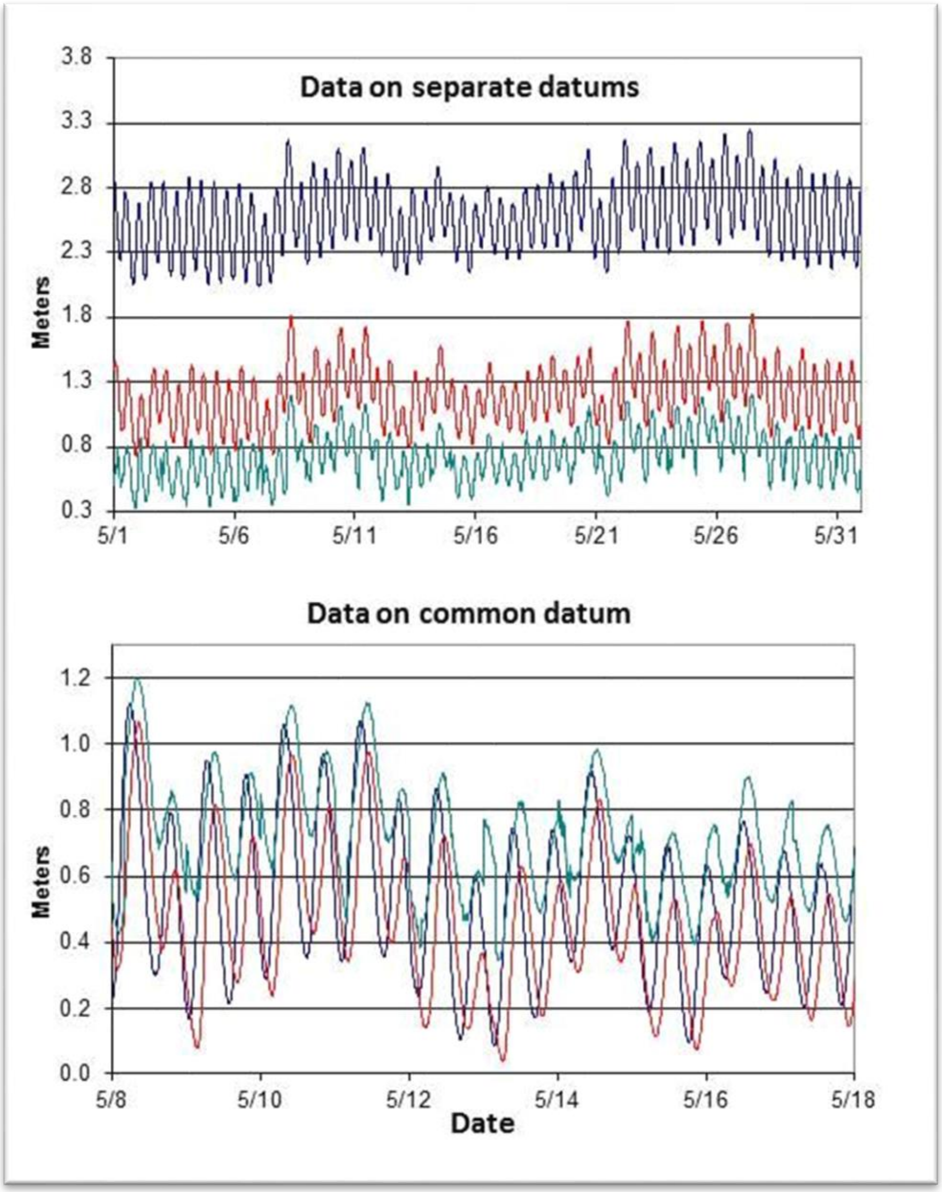

Figure 1-2. Top panel: without a common vertical reference, heights cannot be directly compared. Bottom panel: the comparison of actual heights is enabled by expressing vertical data with reference to the same zero point (i.e., on the same vertical datum).

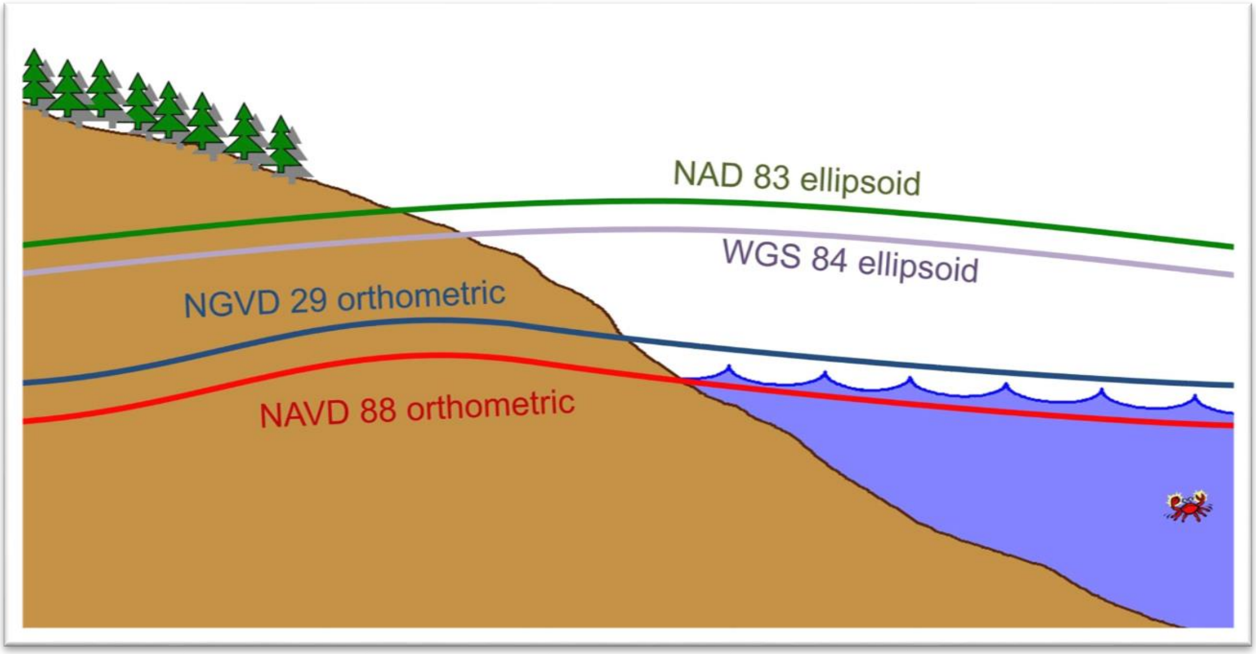

Figure 1-3. Conceptual diagram showing the relationship between ellipsoids and orthometric vertical datums.

Elevations measured relative to the Earth's surface are called **orthometric heights**. Orthometric heights, traditionally established through leveling, are tremendously important when examining impacts of sea level change or inundation because they are elevations that relate to the flow of water in relation to land. NAVD 88 elevations are orthometric heights, and they are **not** equivalent to the elevation of local Mean Sea Level (MSL), a point of common confusion. Although a NAVD 88 height and the elevation of local MSL are sometimes close numerically at some coastal locations, it cannot be assumed that they are equivalent and the magnitude of differences between the two datums varies spatially across North America.

It is important to note that positions measured using GNSS are measured relative to the center of mass of the Earth, which is then related to a mathematical approximation of the Earth's surface, which is an **ellipsoid** (while the earth is often thought of as a sphere, it is geometrically closer to an ellipsoid). Different satellite systems may use different ellipsoid references. GPS uses the World Geodetic System of 1984 (WGS 84), whereas the Russian GLONASS system currently uses the PZ-90 reference frame. In addition, ellipsoid datums may change over time, as either our understanding of the center of the earth's mass improves (e.g., WGS 84) or as the movement of the North American plate is taken into account (e.g., NAD 83). Transformations are possible among the different ellipsoid reference frames, but one has to know exactly which versions of the reference surfaces are being compared. Finally, NAD 83 is part of the NSRS of the United States and is based on the Geodetic Reference System of 1980 (GRS-80) ellipsoid. Figure 1-3 is a conceptual diagram of the relationship between ellipsoid and orthometric vertical datums.

The diversity of datums in use today makes datum selection important, and conversions between coordinate systems must be completed carefully. The datums presented in this section are introduced to provide some familiarity with the different names and concepts; however, only a subset of these datums might be used when establishing a sentinel site. Table 1-2 lists some of the more popular geodetic datums currently in use and ones that may be of particular interest or used most often when establishing a sentinel site.

Unfortunately, an ellipsoid elevation does not have a spatially consistent relationship with an orthometric elevation. The difference between the two is related to gravity, which fluctuates based on how mass is distributed over the earth's surface. The **geoid** is a reference surface based on gravity: NAVD 88 is the vertical datum that best approximates the geoid in the continental United States (see Figure 1-4). The geoid is understood by visualizing a global mean sea level surface if there were no tides, ocean currents or weather affecting it. These assumptions facilitate creating a model but in reality the ocean surface is very dynamic with significant long-term and short-term slopes in surface elevation.

Table 1-2. Geodetic datums[7] and corresponding "type" of elevation.

Datum	Acronym	Significance	"Type" of elevation	Should I use this datum to establish my sentinel site?[8]
North American Vertical Datum of 1988	NAVD 88	Current vertical datum of NSRS	Orthometric	YES – this should be the primary datum for terrestrial elevations in the contiguous United States.
North American Datum of 1983	NAD 83	Current geometric datum of NSRS[9]	Ellipsoid (also the horizontal reference frame)	YES – this is the primary datum for horizontal positions of bench marks in contiguous United States.
National Geodetic Vertical Datum of 1929	NGVD 29	Superseded national vertical datum (preceded NAVD 88)	Orthometric	NO – NAVD 88 elevations should be established, either through re-observations or transformations.
International Terrestrial Reference Frame 2014	IGb14	Current reference frame – International Association of Geodesy	Ellipsoid	NO – used Worldwide within GNSS observations.
World Geodetic System 1984	WGS 84	Current GPS reference frame	Ellipsoid	NO – Primarily used by the US military.
Geodetic Reference System 1980	GRS-80	Often considered equivalent to a particular version of WGS 84 datum	Ellipsoid	NO – used within GNSS-based computations but is opaque to the user.

The orthometric, or actual, elevation (H) is determined by subtracting geoid undulation (N) from the ellipsoidal elevation (h) so $H = h - N$. In other words, an orthometric elevation is the difference between the topographic surface of the Earth and an approximate surface of the Earth based on MSL. See Figure 1-4 for a visual representation. At the time of this writing, the current

[7] This is not an all-inclusive list of geodetic datums.
[8] This column provides general guidance but does not attempt to see all possible datum applications that may arise in establishing sea level change sentinel sites.
[9] There are regular updates to the datum, called "realizations." The current realization in the fall of 2021 is 2011, epoch 2010. The NGS plans to move to new geometric and geopotential datums sometime after 2022.

geoid model for computing an orthometric height from an ellipsoidal elevation in the coterminous United States and Alaska is GEOID18. Independent of an ellipsoid or geoid, elevations can also be referenced to local datums that are measured and derived from tides. A vertical datum is called a **tidal datum** when it is defined by a certain phase of the tide (e.g., Mean Lower Low Water). Due to the effects of morphology and bathymetry and changes in the range and type of tide along the shore, the elevation of tidal datums, such as Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW), are not fixed universal elevations relative to the land, but are local and vary depending on location (Figure 1-5).

Officially defined tidal datums are computed based on observed water levels collected for 19 years, a time period called the Metonic cycle and referred to as a tidal datum epoch. An epoch is generally used for a number of years after the epoch is defined, but it is eventually necessary to update to a new National Tidal Datum Epoch (NTDE) due to changes in relative mean sea level (Figure 1-6). The current NTDE is 1983–2001, but in areas experiencing high rates of relative sea level change [e.g., 5–10 millimeters per year (mm/yr) as observed in coastal Louisiana] tidal datums are computed based on water levels of the most recent five years of data. The Center for Oceanographic Products and Services (CO-OPS) is in the process of updating the NTDE to a new Epoch, which will be the 2002-2020 NTDE. The planned release for the new Epoch is in the 2025 timeframe.

A tidal datum epoch is necessarily defined in the past, as it refers to a completed period of observation. One has to wait at least 19 years for a new NTDE to be published.

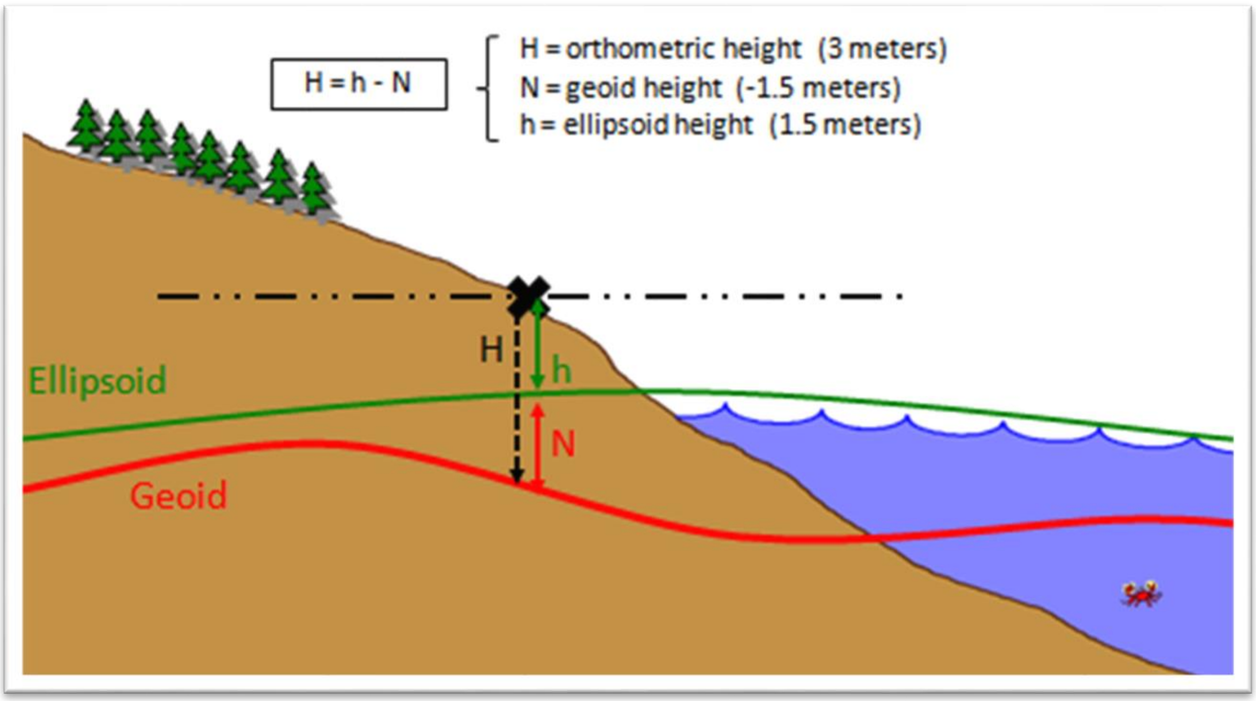

Figure 1-4. Conceptual diagram showing relationship between different geodetic datums. The geoid is typically below the ellipsoid in the conterminous U.S., Puerto Rico and Virgin Islands; the reverse is true in Alaska, Hawaii and the Pacific territories.

For locations with shorter data series (<19 years), a comparison of simultaneous observations is made with a nearby primary control water level station to derive a 19-year equivalent (National Ocean Service, 2000a; Marmer, 1951). The shorter the time series compared to a 19-year period or tidal epoch, the greater the error in the tidal datum determination. Additionally, tidal datums are referenced to fixed points on land known as tidal bench marks, so they may be recovered when needed.

Full definitions of all terms relating to tidal datums can be found in the NOS Tide and Current Glossary (National Ocean Service, 2000b). In practice, the datums listed below are operationally determined relative to the 1983–2001 NTDE (See Table 1-3).

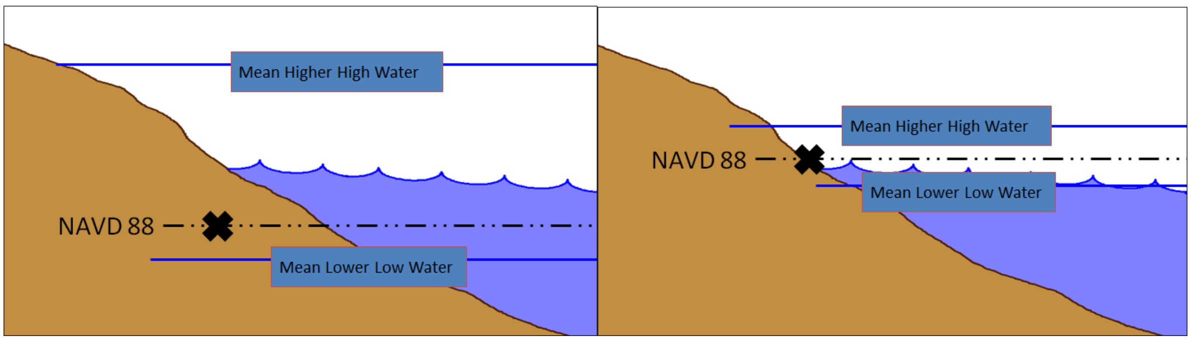

Figure 1-5. Examples of the relationships between tidal datums and NAVD 88 in two hypothetical locations with different tidal signatures.

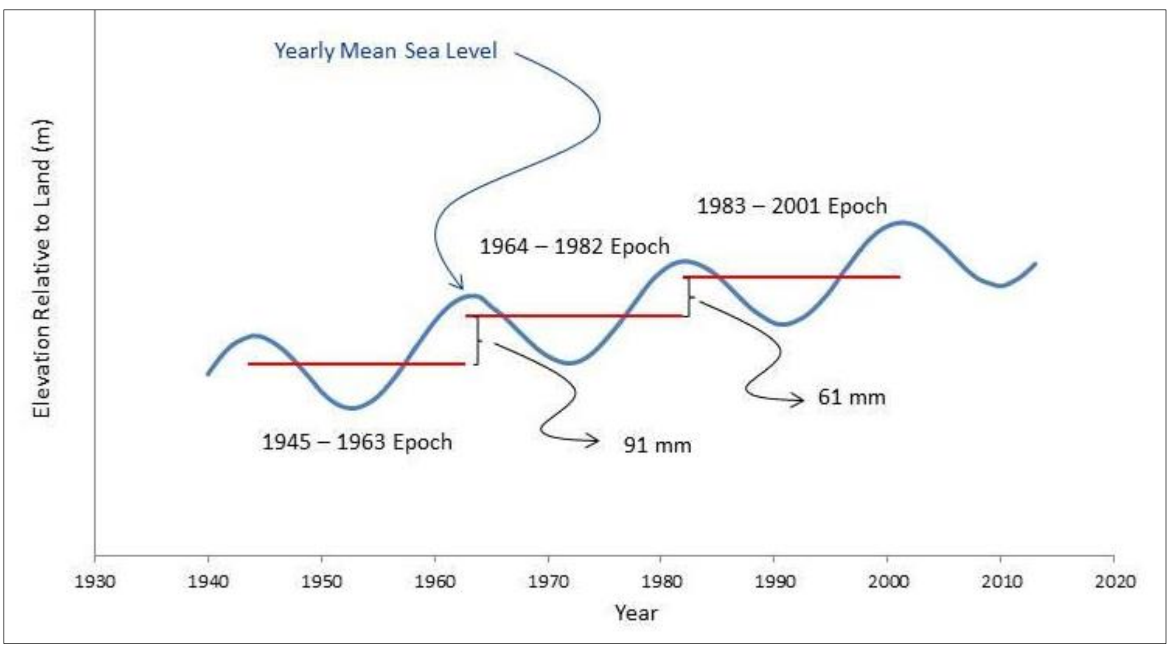

Figure 1-6. Illustration showing concept of a 19-year tidal epoch within a longer sea level rise trend. Note that the variability in tidal datums among epochs is not necessarily constant despite a long-term sea level trend.

Table 1-3. Examples of Tidal Datums and Definitions.

Datum	Datum	Definition
Mean Higher High Water	MHHW	A tidal datum determined from the arithmetic mean of the higher high-water elevations observed each tidal day.
Mean High Water	MHW	A tidal datum determined from the arithmetic mean of the high-water elevations observed each tidal day.
Mean High Water Line	MHWL	This is the intersection of the plane of the MHW tidal datum with shore. The elevation of the MHWL is fixed for given time periods and does not change unless tidal datums are updated. The horizontal location of the MHWL may move landward with seasonal or long-term coastal erosion and may move seaward with shoreline accretion.
Mean Low Water	MLW	A tidal datum, which is determined from the arithmetic mean of the low water elevations observed each tidal day.
Mean Lower Low Water	MLLW	A tidal datum which is determined from the arithmetic mean of the lower low water elevation of each tidal day observed.
Mean Tide Level	MTL	A tidal datum which is determined from the average of the MHW and MLW tidal datum elevations.
Mean Range of Tide	MN	The difference in elevation between the tidal datums of MHW and MLW.
Diurnal Range of Tide	GT	The difference in elevation between tidal datums of MHHW and MLLW.
Mean Sea Level	MSL	A datum defined as the arithmetic mean of observed hourly elevations.
Relative Sea Level Trend	RSL	Long-term (e.g. >40 years) rate of change in elevation of sea level at a particular location relative to the land and a function of three main components: 1) global sea level change due to increased volume of water in the ocean (e.g., thermal expansion and melting of glaciers and ice masses), 2) long-term changes in ocean and estuary circulation patterns and river flow, and 3) local vertical motion of the land due to large scale or regional tectonic movement, local land subsidence, or isostatic rebound (due to melting glaciers) (Zervas, 2001)

2. FUNDAMENTAL SEA LEVEL AND ELEVATION INFRASTRUCTURE

Sentinel sites should leverage existing networks of observing infrastructure that include the National Water Level Observation Network (NWLON) and the National Spatial Reference System (NSRS). These observation systems exist to provide the nation with accurate water level data as well as an accurate geospatial framework that can link all other geospatial observation systems. This section introduces the national observation infrastructure, and then presents the local infrastructure, including habitat monitoring components, that will establish a sea level change sentinel site.[10]

2.1 CO-OPS National Water Level Observation Network (NWLON)

The NWLON, maintained by National Oceanic and Atmospheric Administration (NOAA), Center for Operational Oceanographic Products and Services (CO-OPS), is a network of 210 long-term, continuously operating water level stations throughout the United States, including its island possessions and territories and the Great Lakes (Figure 2-1). NWLON stations serve as the foundation for NOAA's tide prediction products, the control stations in determining tidal datums for all short-term water level stations, and the primary data network for estimating relative trends in sea level.

[10] This document assumes the term "sea level change sentinel site" as any strategy to monitor climate change impacts related to water level changes. See Section 1 of this document for more information.

Figure 2-1. The red and yellow symbols on the map show the distribution of NOAA's NWLON, 210 continuously operating water level stations streaming data online at near real-time. The blue symbols represent current meter stations.

The data continuity, vertical stability, and careful referencing of NWLON stations have enabled the data to be used to estimate relative sea level trends for the Nation, compute local tidal datums, and allow for periodic updates to new National Tidal Datum Epoch (NTDE) periods. Sensors are calibrated and vertically referenced to nearby networks of bench marks to monitor vertical stability. A backup water level sensor is also installed to ensure data continuity. Additionally, NWLON data collection platforms are capable of measuring other oceanographic and meteorological parameters.

Data from NWLON stations become part of the official verified water level and products database used for archiving and dissemination. NWLON stations are equipped with Geostationary Operational Environmental Satellites (GOES) antennas transmitting near real-time preliminary data that is made available to all users through the CO-OPS web page.[11] Verified products, such as verified 6-minute water level data, hourly heights, high and low water, and monthly means, are made available online within one to four weeks after data collection. Preliminary and verified data relative to mean lower low water (MLLW) datum, Station Datum, or special water level datum (such as Columbia River datum) are also available. NWLON data and accepted tidal datums can also be used to provide control for datum determination at

[11] www.tidesandcurrents.noaa.gov

subordinate (i.e., short-term) stations. Other tidal data and data products may be requested through the web page.

NOAA configurations for water level station installation are relatively sophisticated and expensive to permit continuous operation during severe storms or other events (e.g., tsunamis, etc.) and to ensure that the data's accuracy and application can be reliably met and legally defended, thus meeting NOAA's nautical charting and marine boundary missions. Since it is not cost effective to maintain long-term gauges everywhere along the coast, NOAA has traditionally deployed temporary gauges at specific points of interest or need. Water level observations are recorded for a period long enough (preferably at least three months) to effectively allow the computation of an equivalent 19-year tidal datum referenced to the current NTDE from the nearest NWLON to the location of the temporary gauge. Based on the period of observation, NOAA classifies different types of records that include active NWLON stations and historic NWLON stations as well as primary, secondary, and tertiary stations, whose definitions are included in Table 2-1.

2.1.1 NWLON datum coverage

NWLON "coverage" is the geographic area in which a particular water level station can provide accurate control for the determination of local tidal datums using time periods shorter than the required 19-year epoch. NWLON coverage is very helpful when establishing a sentinel site because when a site lies within NWLON coverage, the datum at the NWLON station can be used in the computation of local tidal datums for the sentinel site. Computing a tidal datum at the sentinel site provides a reference for all vertical observations (e.g. water levels, wetland elevation) based on a specific phase of tide such as mean sea level or mean high water. Although the datum itself is a static value (defined by the NTDE), it is very useful in comparing different observations on the same vertical reference.

Important Information

NWLON coverage is the geographic area in which a particular tide station can provide accurate control for the determination of local tidal datums using time periods shorter than the required 19-year epoch.

Table 2-1. Description of Select Tidal Record Types

Water Level Station Type	Period of Operation	Planned Lifetime	Primary Function	Geographic Placement	Derived Data Products
Primary control water level station (NWLON)	19 years or more[12]	Expected to continuously operate in future	Obtain a continuous record of water levels in a locality	Site to provide datum control for multi-purpose national applications	Precise independent determination of tidal datums and sea level trends; provides control for datum determination at shorter-term stations
Secondary water level station	At least one year, but less than 19 years	Planned finite lifetime	Realize localized tidal effects in bays and estuaries; measures annual variability	Provide control where localized tidal effects are not realized at nearest primary control station	Satisfactory determination of tidal datums when reduced by comparison with simultaneous observations of monthly means at a suitable control water level station
Tertiary water level station	More than one month, but less than one year	Planned finite lifetime	Local tidal datum elevations	Either site specific for correlation with other measurements or located for interpolation of large changes in tidal characteristics	Data reduced to equivalent 19-year tidal datums through mathematical comparison of simultaneous observations from a nearby control station or appropriate secondary station
Short-term water level station	Less than one month	Planned finite lifetime	Time and range corrections to longer term water level stations	Located for interpolation of tidal characteristics between other nearby stations in tidally complex areas	Data reduced to equivalent 19-year tidal datums through comparison of simultaneous observations with a nearby primary control or secondary stations

A NWLON datum gap analysis can be obtained from NOAA CO-OPS for the U.S., including Puerto Rico and Virgin Islands (Gill, 2014[13]); example given in Figure 2-2). The gap analysis developed polygons of coverage for each existing NWLON station representing the estimated geographical area in which the uncertainty in tidal datums is less than 0.037 m (0.12 ft) at the 95% confidence interval for a 3-month tertiary water level station. This product will help

[12] If more than 40 years of data have been collected, then a sea level trend may be published. See CO-OPS Sea Levels Online at http://tidesandcurrents.noaa.gov/sltrends/index.shtml.
[13] https://tidesandcurrents.noaa.gov/publications/Technical_Memorandum_NOS_COOPS_0048_Updt.pdf

prospective sea level sentinel sites identify whether and which NWLON station(s) can be used to provide datum control for a given sentinel site. The analysis can also point to areas where new water level data would be useful.

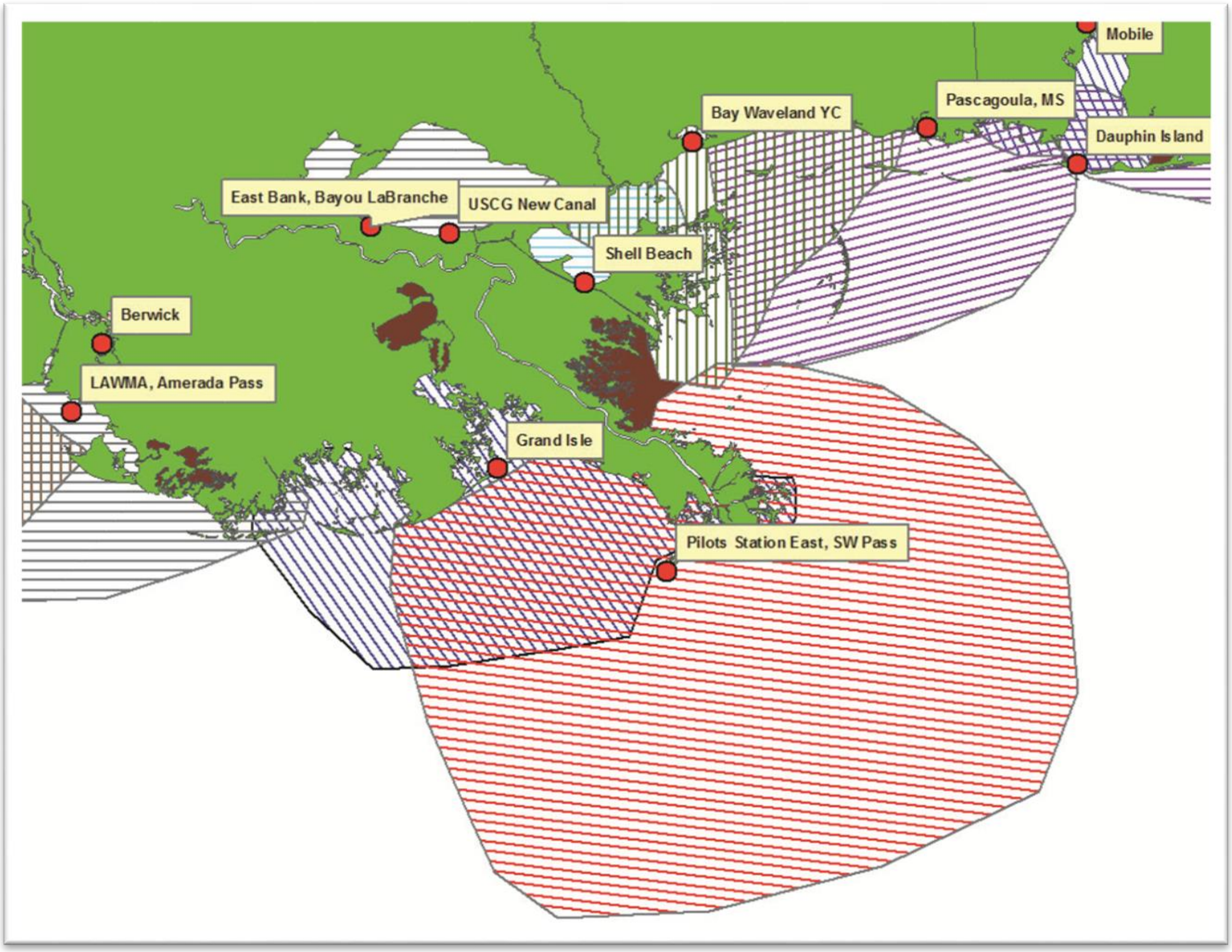

Figure 2-2. Example map of the GIS analysis results for Grand Isle, Louisiana and nearby NWLON stations. (data from Gill, 2014).

2.2 CO-OPS Water Level Station (Water Level Gauge)

Each water level station consists of at least a water level gauge or sensor(s) collecting six-minute water level data, a data collection platform or data logger, and a set of tidal bench marks established in the vicinity of the water level station. Besides providing long-term and near-real-time water level observations, trends, and datums, water level stations can also support a variety of programs including hydrographic and shoreline mapping projects, marine boundary determination, real-time navigation systems, and coastal habitat and vertical datum transformation projects. The data collected and predictions derived can also be used to ensure safe, efficient and environmentally sound maritime commerce. There are other non-navigational, critical applications which can utilize water level and datum information including coastal engineering, dredging, coastal planning and management, wetland restoration projects, long-term sea level assessments, storm-surge monitoring, emergency preparedness, and climate change and HAZMAT response.

Various types of water level sensors and station configurations are possible; and a schematic of a typical water level station is shown in Figure 2-3. For more information on CO-OPS specifications and procedures, refer to this publication.[14]

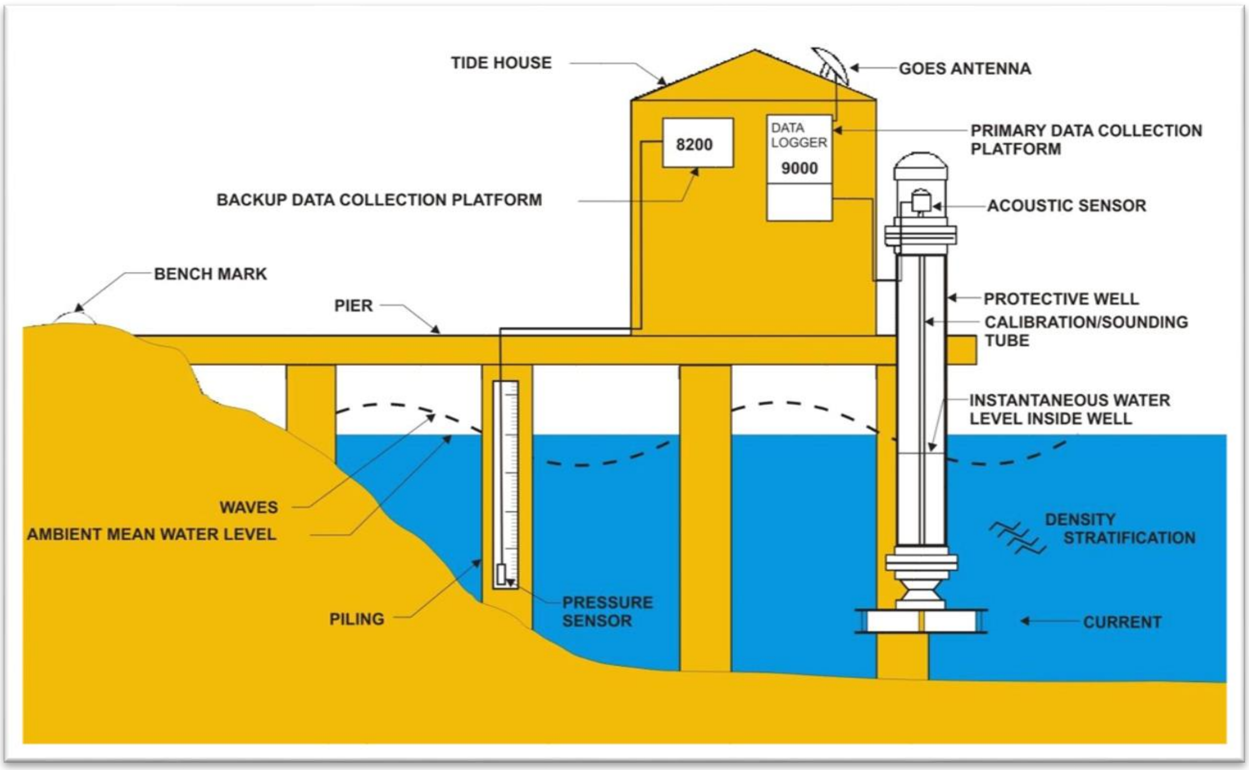

Figure 2-3. Diagram showing typical components of a CO-OPS water level station, including both the primary acoustic sensor as well as a back-up water pressure sensor.

A key component of the CO-OPS water level station is the local bench mark network, which is used to assure the long-term stability of the gauge and the water level data. Up to ten bench marks support a water level station. There is a "primary tidal bench mark" (PBM) which is usually one of the bench marks that is expected to be more stable than the others, is near the gauge, itself and is the main vertical reference point for the gauge. On a periodic basis, leveling is conducted among some or all of the marks (and always includes the PBM) and the vertical point of reference (VPR) of the water level gauge itself. Any significant change in the vertical relationships of the gauge and the bench marks will result in the need to adjust the water level data and/or evaluate local land movement.

2.3 Local Water Level Stations

Unless a NWLON already exists within the sentinel site, a separate local water level station is required to monitor local water level changes and to compute/update local tidal datums. Key to

[14]CO-OPS_Specs_and_Deliverables_for_the_Installation,_Maintenance_and_Removal_of_WL_Stations.pdf https://tidesandcurrents.noaa.gov/fieldlibrary/ViewDoc?d=96 (Dec. 2017) .

the ability to monitor local water level change is the deployment and maintenance of a permanent, dedicated, high accuracy water level sensor with verified stability. Although the ideal situation would be a water level sensor and a water level station that meet all CO-OPS standards, there are other instruments available with various deployment configurations, operation settings and maintenance schedules that can provide very useful water level data for a sentinel site.

2.3.1 Water level sensors

Although CO-OPS water level stations typically use the Aquatrak and ParoScientific pressure sensors as the primary water level gauge, these sensors can be expensive and labor intensive to maintain. To learn more about CO-OPS sensor specifications, please review CO-OPS Environmental Measurement Systems Sensor Specifications and Measurement Algorithm.[15]

Some other cost-effective sensors that do not currently meet CO-OPS requirements but can be considered include Valeport, YSI (600 or 6000 series), and Ohmart/Vega VegaPuls 62 (with horn antenna) unit. Other manufacturers may also supply similar products. Different sensor types and even sensor models have different precision and accuracy capabilities, which may also be a function of the allowable data settings. Information about different sensors, including some typical time interval settings, is shown in Table 2-2. Also, barometric pressure compensation can affect sensor accuracy. For example, an unvented pressure sensor may have the precision of one millimeter (1 mm), but its accuracy may be on the order of two centimeters (2 cm) if it is not corrected for atmospheric pressure. A vented version of the same sensor could have one mm (1 mm) precision and three mm (3 mm) accuracy (but care must be taken to place the vent tube high enough to remain dry under the highest water levels and adverse environmental conditions).

Table 2-2. Examples of water level sensors and some user-determined settings.

	Sensor			
Characteristic	**Aquatrak**	**ParoScientific**	**NOAA Nile**	**YSI 6000 series or similar**
Sensor Type	Acoustic	Pressure	Radar	Pressure
Precision	1 mm	0.1 mm		1 mm
Accuracy		0.8 mm	2 mm	3 mm
Recommended installation method	Protective well	Bottom mounted or open face piling mount	open face; arm extension mount	Anchored below the lowest expected water level
Data averaging interval	181 one second water level samples centered on each tenth of an hour are averaged	36 five second water level samples centered on each tenth of an hour are averaged	359 one second water level samples centered on each tenth of an hour are averaged	4 seconds
Data recording interval	6 minutes	6 minutes	6 minutes	15 minutes

15 https://tidesandcurrents.noaa.gov/publications/CO-OPS_Measurement_Spec.pdf

Other Comments	NWLON standard sensor	NWLON standard sensor		NERR standard sensor. Default setting can be changed, but will affect battery life and memory

2.3.2. Additional challenges for establishing and maintaining local water level stations

In addition to sensor costs, there are a number of additional considerations that affect the cost of establishing and maintaining a local water level station. All in all, the installation, maintenance, and data processing for a water level station could run from $25,000 to as much as $100,000 in the first year.

- ***Data collection and onboard data storage:*** Even if data are transmitted off-site, there is still a need to store data locally as backup. If the data are stored in the sensor itself, then there is a trade-off between data collection and data storage: a short measurement interval will mean more data are collected, resulting in rapid filling of memory. If data retrieval requires removal of the sensor, rapid filling of memory leads to more frequent sensor disturbance.
- ***Data processing****:* Staff will need to be trained and staff time will be spent on running quality assurance and quality control, as well as computing water level derived products (e.g., inundation, datums).
- ***Bench mark installation and stability checks****:* Greater bench mark stability comes at a greater cost: whereas a four-foot deep concrete post mark may cost less than $100, a deep rod mark may run in the range of $400 - $700. Yearly leveling among the bench marks supporting the water level may require hiring professional surveyors; otherwise, equipment needs to be purchased or rented and staff trained. Costs increase if elevations on bench marks are to be published (specific procedures need to be followed).
- ***Stable structure:*** A stable pier structure is essential for a stable water level station installation. If no pier or piling is available, then a new pier/piling must be installed. The distance between the pier and mainland is also an important factor in leveling to the associated network of tidal bench marks.
- ***Maintenance costs:*** Maintenance, including replacement of the water level sensor, may be required due to losses from natural (such as, storm, flood, or ice) or man-made causes (such as vandalism).
- ***Insufficient data storage*****:** A typical, six-minute water level station operating for one year generates 10 gigabytes (GB) of data including all the metadata (e.g., station metadata and elevation, equipment metadata). Any long-term deployment of a water level station must consider data storage for computational purposes as well as archiving.
- ***Data transmission/communication*****:** Some form of communications is useful to receive data on a periodic basis and if possible communicate with the data collection system to perform some remote maintenance functions. Consider phone, IP modem, line-of-sight radio, and/or satellite communications if the system is too remote to periodically inspect it and download data directly from the system.

As can be gathered from this list, a water level station is an expensive investment. The benefit is that local water levels can be reliably monitored and local tidal datums can be derived, both of which are essential to the sea level change sentinel site concept.

2.4 National Spatial Reference System

The National Spatial Reference System, or NSRS, is a consistent coordinate system that defines latitude, longitude, elevation, scale, gravity, and orientation throughout the United States; access to the NSRS allows geographically referenced observations to be accurately compared through the use of a common datum. For example, remotely sensed data including elevations and bathymetry can be accurately mapped when all the data are expressed on the same datum. The National Geodetic Survey (NGS) defines, maintains, and provides access to the NSRS. NGS also monitors how these values change over time and updates coordinates and reference frames when necessary. As discussed earlier, the official datums defining the NSRS include NAD 83 and NAVD 88.

2.4.1 Survey control networks

Historically, the NSRS was defined through a system of permanent survey marks that are set in the ground and whose high accuracy position (latitude and longitude and/or elevation) have been established following geodetic observation and analysis procedures. These procedures can be very laborious, so the positions are not routinely monitored or updated. With recent improvements in Global Navigation Satellite System (GNSS) technology, GNSS surveying is rapidly replacing classical surveying, despite its lower precision for orthometric elevations. NGS supports high accuracy GNSS surveying through its data, models, and tools, which themselves rely in large part on the national (and international) network of Continuously Operating GNSS Reference Stations (CORS).

GNSS CORS have become the modern backbone of the NSRS. As of 2022, the CORS network, consisting of about 1,800 stations distributed across the United States and partner countries, provides continuous GNSS data that are used to ensure the integrity of the foundation of NAD 83. CORSs provide very high accuracy GNSS data due to the volume of data collected at each station. CORS data are an essential component of high accuracy GNSS surveying (see below and Section 6.2).

2.4.2 Accessing geodetic control networks

NGS publishes positions (i.e., latitude, longitude, and elevation) for permanent survey marks (often referred to as bench marks) and CORSs, and these coordinates are available thru online databases and resources.[16] NGS also provides models and tools to help users access the NSRS. For example, NGS publishes a geoid model[17] that allows users to derive orthometric elevations using GNSS observations, effectively converting an ellipsoid elevation to better match the surface of the earth. Other models or tools (e.g., NCAT[18]) help users transform positions among a variety of datums. Figure 2-4 shows the CORS network.

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[16] http://geodesy.noaa.gov/
[17] http://geodesy.noaa.gov/GEOID/
[18] https://geodesy.noaa.gov/NCAT/

Figure 2-4. National CORS Network. The different colored marks refer to the different frequencies at which the GPS data are being collected and processed by NOAA.

Precise geodetic leveling remains an important method to establish a local network of vertical control points connected to the NSRS. While there are three leveling techniques (i.e., differential, trigonometric, and barometric), differential leveling is the most accurate technique to transfer heights within a vertical network. It is also more precise than a GNSS-derived height, especially over shorter distances (e.g., <30 km). Graduated level rods are set up over two fixed points while a level instrument is set up equidistant to them both. The level instrument reads elevation differences between the two points (at millimeter accuracy with modern digital levels). This is repeated in a line extending between survey marks in an area such that accurate elevation differences have been determined for each mark. When an accurate elevation is assigned to any one of the marks in the line – either through a published elevation or through GNSS observations, all connected marks can likewise bear an accurate elevation. While a digital level is preferred, an optical level or laser level may also provide acceptable results over short distances. A synopsis of typical accuracies associated with leveling and GNSS-based surveying techniques is given in Table 2-3.

Table 2-3. Mark accuracies estimated from the survey technique used.

Observation Category	Observation type	Adjusted network accuracy[19]	Accuracy of a measured height difference[20]	Time required
Leveling (optical or digital)	First-Order, class I	0.5 mm	3 mm/√km	Depends on distance of connection
	First-Order, class II	0.7 mm	4 mm/√km	
	Second-Order, class I	1.0 mm	6 mm/√km	
	Second-Order, class II	1.3 mm	8 mm/√km	
	Third-Order	2.0 mm	12 mm/√km	
Observation Category	**Observation type**	**Accuracy relative to local network[21]**	**Accuracy relative to NSRS[8]**	**Time required**
GPS or GNSS	Static		2 - 3 cm	Four to 48 hours or more
	Real-time	1 – 5 cm		1 second to 6 minutes or longer

GNSS is also an important method to connect a local vertical control network to the NSRS. Static GNSS observations (e.g., GNSS antenna fixed atop a mark for hours to days) are used to provide a connection to the ellipsoid datum. Transformation from the ellipsoid to the orthometric datum will add an additional component of error that will vary locally dependent upon the accuracy of the geoid model in that particular region. High accuracy GNSS positioning is typically based on "post-processing" the data. This entails making corrections for atmospheric effects over the duration of the static GNSS observing session. The NGS Online Positioning User Service (OPUS) is a free, publicly available post-processing engine that ensures high accuracy positions by using data from several CORSs from the network. Vertical errors to the ellipsoid datum for any single point solution with OPUS Static are in the range of ±2 cm (1σ) for four hours of observations or longer (Soler et al., 2006). OPUS requires the user to input only a minimal amount of information, and its self-explanatory instructions with additional details can be found on its webpage.[22] If short observing sessions are taken (<2 hrs.), there is a functionality called OPUS Rapid Static, or OPUS-RS. The solution is based on a different mathematical algorithm, and typically has larger errors. For consistency and robustness, these guidelines recommend OPUS static solutions for connection to the NSRS.

NGS' OPUS is also the gateway to another free tool, a web-based geodetic software which enables the processing of simultaneous, static GNSS observations, called OPUS-Projects[23]. This tool results in a least-squares network adjustment of GNSS-derived baselines and provides better network and local accuracies. Although recent developments in OPUS-Projects have made it easier to use, and have also greatly simplified the task of submitting GNSS projects to NGS for inclusion into the national database, the tool is nevertheless recommended for the more advanced

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[19] Referred to as "maximum elevation difference accuracy." Within a least-squares adjusted network; units are mm/√km; if two points located 10 km apart were leveled using Second-Order, Class I leveling, the maximum elevation difference accuracy between them would be about three mm (3 mm).

[20] Referred to as "section misclosure" (see Section 6); units are mm/√km

[21] One standard deviation (ʃ).

[22] http://geodesy.noaa.gov/OPUS/

[23] https://geodesy.noaa.gov/OPUS-Projects/OpusProjects.shtml

user, and is outside the scope of this document. The interested reader is referred to the OPUS-Projects User Guide[24] and the NGS training calendar[25] for more information.

Another common GNSS-based technique for obtaining positions is called Real Time Kinematic (RTK) GNSS. The technique is based on having two simultaneous GNSS observations: one atop a point with known coordinates (the "base"), and one atop a "rover" that can easily be moved from place to place. The base obtains local atmospheric correctors (comparing measured coordinates to known coordinates), and sends them via radio transmission to the rover. The correctors are applied on the fly (real time), and the positional information is stored in a hand-held data collector. Although the vertical connection to the NSRS may be upwards of six (6) cm or more (2σ), relative elevations (elevation differences) can be much better (assuming short-distance baselines, excellent satellite distribution and reception, etc.).

A relatively recent development is the availability of Real Time Networks (RTNs). These networks, either private or state-run, enable users to obtain real-time positional correctors at their rover locations without requiring them to set up a base as in RTK. The continuously operating GNSS reference stations that are part of the network provide the correctors that are continually broadcast and received by the user typically via cell phone/data connection. The relative ease of this real-time technique has resulted in its widespread use among professional surveyors.

2.4.3 Alternate remote sensing and positioning tools

A number of remote sensing and positioning methods can establish accurate elevations, but each has its own procedures, advantages, and levels of accuracy. This document will focus on GNSS observations and leveling because they will provide consistently high accuracy data. Nevertheless, the geo-referenced vertical infrastructure established through these techniques can take advantage of both established and emerging remote sensing technology.

For example, the accuracy of aerial light detection and ranging (lidar) can be improved using local geodetic control points with positions and elevations established using GNSS observations or leveling. A variety of statistical and non-parametric methods have been developed to correct errors and improve the accuracy of lidar-derived digital elevation models using field survey data and ancillary data sources (Buffington et al., 2016). Similarly, the emerging field of Interferometric Synthetic Aperture Radar (InSAR) to detect vertical change requires the deployment of fixed position radar reflectors with known positional coordinates. Therefore, the establishment of a high accuracy local vertical control network can be the foundation of a number of location-based environmental change datasets, which will help document change over time, understand the mechanisms, and predict future outcomes.

2.5 Local Positional Control Network

A local positional control network is an ensemble of permanent, physical reference marks that are stable, natural, or artificial objects bearing a marked point (e.g., survey disk or rod) capable of referencing a precise three-dimensional position (latitude, longitude, and elevation). The positions of all marks within the local positional control network are known with respect to each other, and have been obtained using geodetic surveying techniques (e.g., through leveling or GNSS observations). In addition, the local network needs be consistent with the NSRS, meaning

[24] https://www.ngs.noaa.gov/OPUS-Projects/docs/Documentation.pdf
[25] https://geodesy.noaa.gov/corbin/calendar.shtml

that accurate positions must be referenced to nationally accepted datums (i.e., NAD 83, NAVD 88). This implies that accurate positions (latitude, longitude, and elevation) with respect to the NSRS are obtained for at least one point in the local network. These are the points of "connection" to the NSRS, and will be referred to as "Local Control Marks," or LCM's. All other local positions are obtained relative to them. For the purposes of this document, we will restrict our focus to vertical control networks, as the vertical dimension is of critical importance. A vertical control network is composed of marks that have accurate elevations assigned to them.

2.5.1 Bench mark selection or installation

Local vertical control networks supporting sentinel sites should include stable marks to ensure that the elevations assigned remain accurate over time. Pre-existing or newly installed marks generally fall into one of several classes, each with an implied stability (Table 2-4). The different mark types also have different inherent costs. In addition, if GNSS will be used to provide a high accuracy position, then the mark should have an unobstructed view of the sky. The most stable mark is an outcrop, which is very inexpensive to instrument, but generally very hard to find in a coastal wetland environment. Huge structures (e.g., bridge pilings and large building foundations) are also very stable, but generally hard to find in these areas. The third most stable monument type is the deep rod mark, whose typical installation costs between $600 and $1,200 per mark on average (not including labor). Deep rod Surface Elevation Table (SET) marks can be used as local vertical control points, so these may add to the local control network without incurring additional costs if they were pre-existing or planned components of the sentinel site. A relatively inexpensive alternative is a concrete post mark, but it may not be suitable for areas with shallow groundwater. Make sure to note the stability of any selected or newly installed marks, because the stability will be important when ranking the marks in terms of their roles in defining the local geodetic control network.

Table 2-4. Explanation of the survey mark stability classification.

Mark Type	Stability Rating	Stability Definition	Limitations for Use
Metal survey marker cemented into bedrock, the footings/foundation of a very large structure.	A	Settings of the *most reliable* nature, which are expected to hold well	Outside of New England and Alaska, most coastal areas are low-lying with no rock outcrops
Deeply driven rod marks	B	Settings that *probably hold* well	Hopefully, driven into the underlying bedrock would be the most stable in lieu of outcrops
Survey marker set in concrete post mark that extends 4' deep into the sediments	C	Settings that *may hold* well but are commonly subject to movement	May not be suitable for areas with shallow groundwater
Survey marker set in structure of uncertain stability, such as a sidewalk, curb, or concreted pad	D	Settings considered least stable	Not recommended for sentinel site vertical control network; can be used as temporary marks supporting leveling or ground control points

A sentinel site containing legacy SET marks can definitely use this pre-existing infrastructure as part of the local geodetic control network. In fact, it is highly recommended to routinely survey all SET marks to document vertical stability. An example of what a local geodetic control network can look like is given in Figure 2-5.

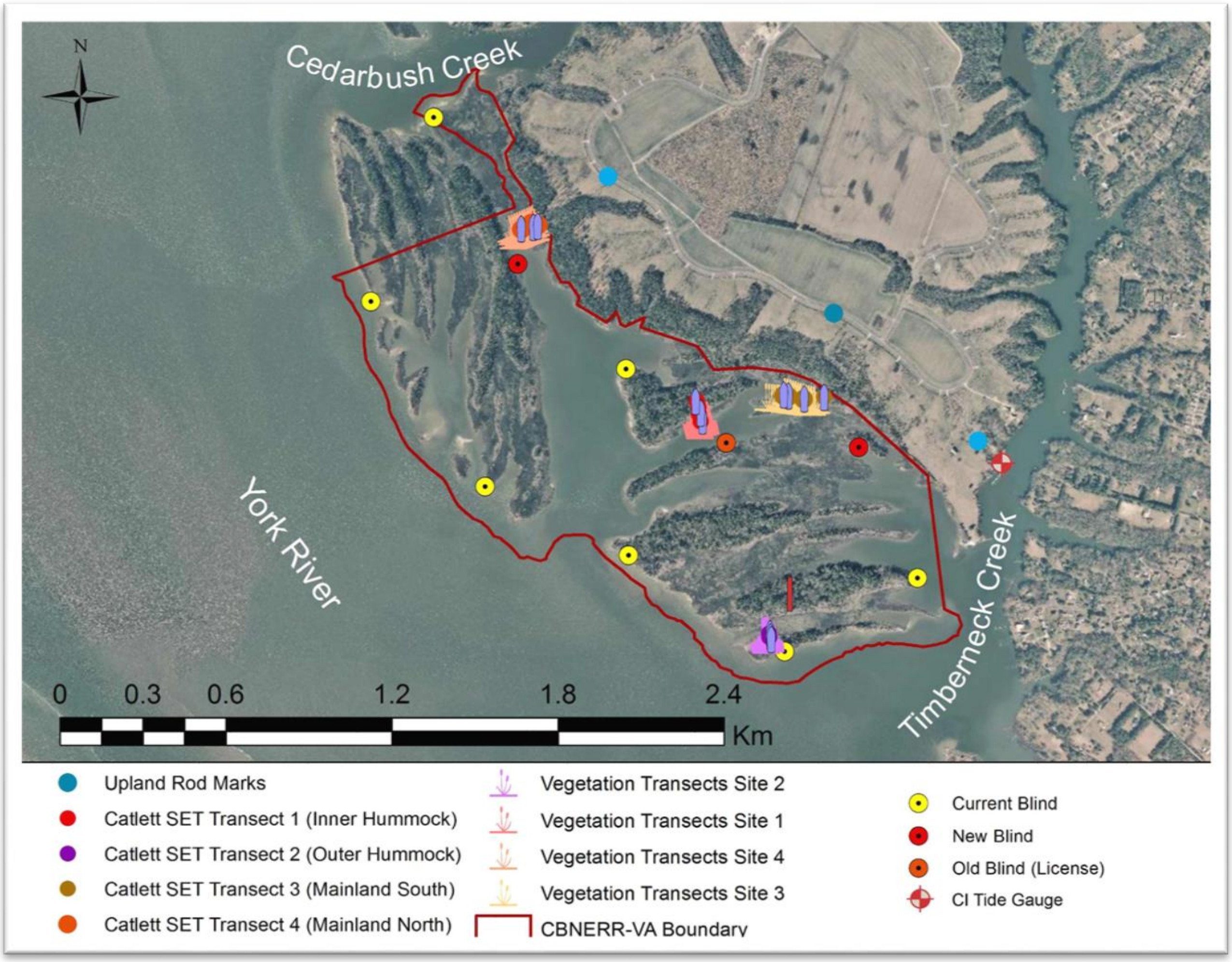


Figure 2-5. Example of the physical infrastructure involved in a local vertical control network (CBNERR-VA). The control network at this example site includes upland bench marks, marsh bench marks (deep ROD SETs), water level station (i.e. tide gauge(s)), and vegetation transects.

2.5.2 Establishing bench mark coordinates

Although a vertical control network should be permanent and stable, marks in the ground move when the ground moves. Therefore, any vertical control network must be maintained over time by conducting repeated surveys among the local marks on a regular basis (e.g., every 5 years). In this manner, any local motion between the marks may be noted. Similarly, the connection to the accepted geodetic datum (e.g., NAD 83) needs to be updated periodically to account for larger scale vertical land motion (e.g., subsidence).

Different types of geodetic observations will yield different levels of confidence or accuracy in the resulting coordinates, as was shown in Table 2-4. The equipment required to establish these coordinates (i.e., geodetic surveying equipment) is expensive, although there is a wide range of price points (Table 2-5). Top of the line, multi-constellation GNSS receivers are not required to obtain high accuracy positions. A less expensive GPS-only receiver may work equally as well. Similarly, for the purposes of a sentinel site, a less expensive digital barcode level can provide excellent results, especially if the user has sufficient training in geodetic leveling techniques.

Table 2-5. Costs associated with different surveying techniques.

Method	Equipment	Equipment cost	Labor
Geodetic leveling	digital barcode levels	\$1,500 - \$15,000	10 people days of labor
	laser levels or auto-compensating optical levels[26]	\$2,000 - \$6,000	10 people days of labor
Static GNSS	Modern, dual-frequency GNSS combined receivers and antennas[27]	\$5,000 - \$20,000 each	Often require operators all day; multiple operators may be needed for multiple days of simultaneous observations
RTK	single base and rover	at least \$25,000	
RTN	Single rover	\$5,000-\$20,000 for the rover, then up to \$2,500 per year subscription fees[28]	Only one operator needed

Establishing accurate coordinates can also include substantial labor costs. A typical local leveling job can require ten people/days of labor because progress can be very slow requiring at least two individuals and often including a third. Static GNSS observations will likely require operators monitoring the equipment over long observation periods (all day). If a project requires a simultaneous deployment of five GNSS units, up to five operators may be needed for multiple days of simultaneous observations depending on the distance between the marks to be surveyed and/or the level of trust in leaving the equipment unsupervised. RTK surveys, however, generally require only one operator, the same with RTN surveys. RTN surveys require the least amount of equipment, but also rely on a subscription service (some free services may also be available locally, depending on the state).

2.5.3 Additional challenges for establishing the geodetic infrastructure include:

- ***Physically intensive:*** There are significant physical demands required for the establishment of stable, deep rod marks (driven to refusal or substantial resistance) or concrete post marks (digging deep holes) while trying to minimize site disturbance.
- ***Geospatial limitations:*** Spatial separation among sites may require separate vertical control networks.
- ***Equipment management:*** Storing, calibrating, and transporting all the required surveying equipment can incur additional costs or logistical challenges.
- ***Technological limitations:*** Existing vegetation canopy or geology may significantly interfere with GNSS signals, rendering GNSS surveying impossible. Leveling across unstable wetland can make leveling challenging to impossible.

[26] including software, survey rods, cases, etc.
[27] not including tripods, software and hand-held data sensors
[28] some areas may have access to free, state-run RTN services

2.6 Coastal Habitat Monitoring Systems

A sentinel site will have a system consisting of at least (1) a local, high accuracy vertical control network; (2) high accuracy local water level sensor(s); and (3) long-term coastal habitat monitoring infrastructure, including but not limited to SETs. It is this third component which otherwise distinguishes a sentinel site from a typical tide station. The key is to relate changes in water levels to observable changes in coastal habitat.

Numerous long-term monitoring infrastructure options exist for the coastal manager or researcher to choose from, depending on needs and interests. Choices also depend on whether the effort focuses on research (hypothesis testing) or monitoring (observation data). Research and monitoring have different needs with regards to the quantity and distribution of sampling stations throughout the sample space. The choice of the monitoring components for the sentinel site is based on the specific questions that one is addressing at the reserve, refuge, park, etc. For example, the NERRS recommend three specific types of monitoring infrastructure as sentinel site elements: SETs, vegetation monitoring transects and groundwater wells. Since SETs, vegetation monitoring transects and groundwater wells may be of general interest, brief descriptions are included below.

- **Surface Elevation Tables** (SETs) are portable measuring instruments deployed atop wetland vertical bench marks, allowing millimeter-level changes in surface elevation to be measured over time. SETs integrate both surface and shallow subsurface processes (e.g., accretion, root production, compaction, etc.) affecting elevation change down to the depth of the bench mark. However, the SETs do not convey information about elevation with respect to sea level. Water level stations have traditionally been used to estimate sea level; however, since these gauges are tied to upland elevations, they do not include elevation change within coastal wetlands. Therefore, NGS has developed guidelines to provide orthometric elevations on SET bench marks, so that wetland surface elevation measurements can be related to local sea level (Figure 2-6). Using these guidelines, the vertical motion of the whole SET bench mark can also be measured, providing estimates of subsidence occurring below the SET mark.

Figure 2-6. SET being operated in the field.

- **Vegetation monitoring plots** along permanent transects will provide valuable data to evaluate the wetland response to a variety of climate change impacts, including water levels. Permanent, geo-referenced plots arranged along a flooding gradient is an example of a long-term biomonitoring strategy used by the NERRS to understand vegetation responses to local sea level change, including changes in productivity, species composition.
- **Groundwater wells** help monitor changes in groundwater level as well as groundwater composition (e.g., salinity, sulfides); both of these characteristics can result from changes in local sea level. They can also be used to evaluate inundation. Figure 2-7 shows a conceptual diagram of groundwater dynamics in response to increased local sea levels.

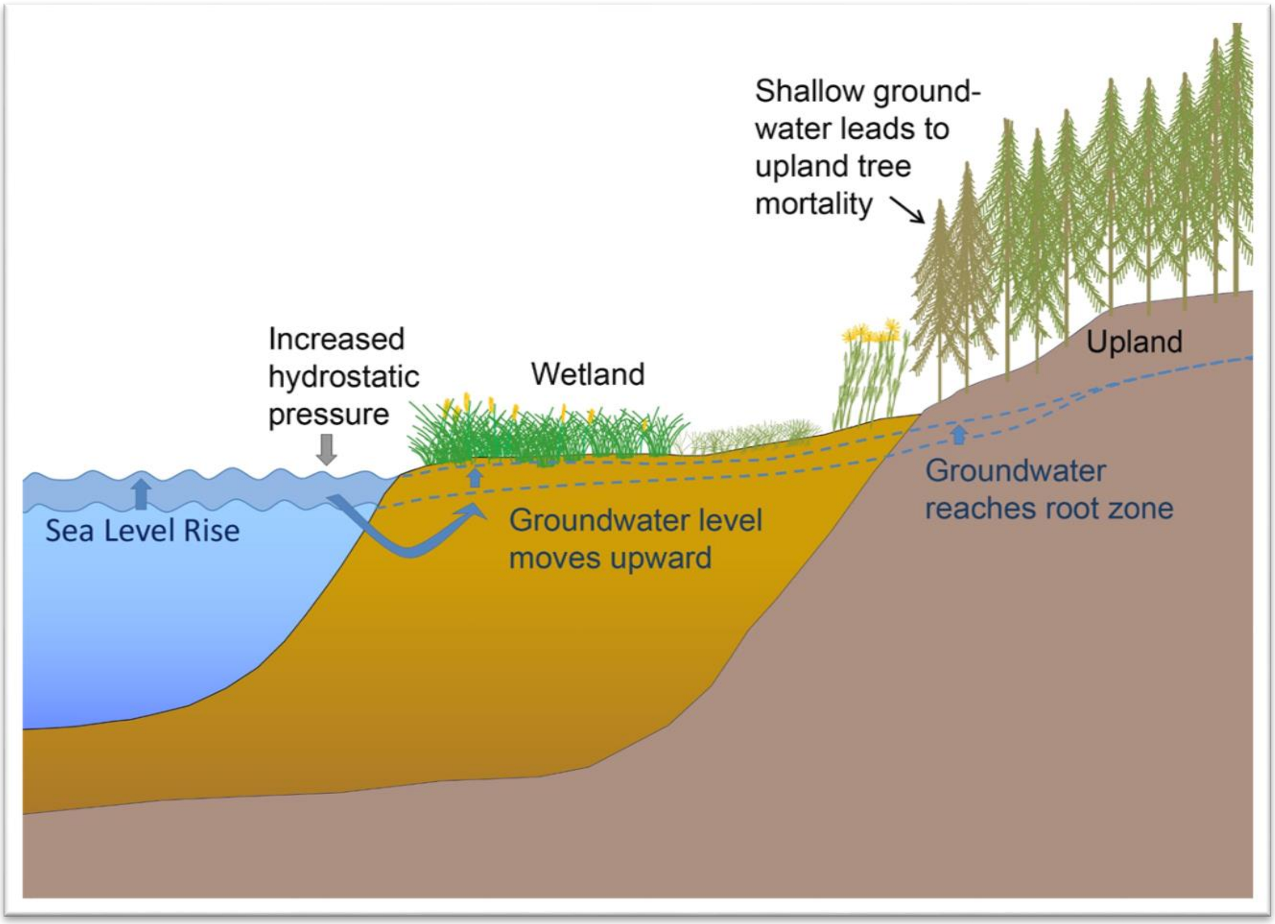


Figure 2-7. Conceptual diagram showing groundwater level increasing as a result of local sea level rise, leading to upland tree mortality.

- Besides these three monitoring systems parks, refuges, and reserves may consider other monitoring infrastructure such digital elevation models (DEMs) to track habitat change through time, permanent georeferenced points for remotely sensed imaging and other types of permanent plots or transects for monitoring responses from beaches, dune communities, and other coastal habitats.

3. GETTING STARTED: RECONNAISSANCE AND PLANNING

Careful planning is key to successful sentinel site implementation. The first step is to define the research or monitoring objectives. The particular objectives will naturally lead to a selection of sentinel site components. Once the general location(s) and components are selected, the next step is to make an inventory of the geodetic and water level infrastructure and data already present and available at or near the location that can be used to advance the sentinel site without significant additional cost or effort.

Regardless of what geodetic or water level infrastructure is already present, the sites and monitoring infrastructure will ideally be chosen based primarily on scientific merits. Still, it may become necessary to redefine the sentinel site boundary or select particular areas within the boundary for component studies (e.g., ecological monitoring, water level station, SET marks, etc.) after evaluating any budget and human resource constraints; personnel skills and abilities; and time and effort to perform specific tasks.

After performing the desktop and field reconnaissance described in this section, it may be necessary to install new bench marks and/or a permanent long-term water level station (detailed in the subsequent sections). The final step in the preparation process is to develop a detailed survey plan which will indicate the scope of field work required to establish the sentinel site.

> Complete the desktop reconnaissance for water level and geodetic infrastructure before you begin field reconnaissance. This may prevent you from making repeat trips to the same locations; bench marks play an important role for both water level and geodetic infrastructure.

3.1 Mapping the Sentinel Site

To begin planning, create a map of the area that will ultimately include all existing and intended sentinel site components (Figure 3-1). Ideally, the map would be created in a Global Information System (GIS) environment that would allow the importing and plotting of geographic coordinates. Identify on the map the site boundary, as well as existing or planned sentinel site components including:

- water level sensors
- permanent vegetation plots, transects, or other biomonitoring infrastructure
- SET marks
- other physical sensors (e.g., groundwater wells)
- existing geodetic infrastructure (e.g., bench marks)

If other monitoring infrastructure or specific geographic features are to be considered in the site boundary for the purposes of answering a particular research or monitoring questions, then the corresponding locations should be indicated as well. Two examples of this initial map are provided from the NERRS, highlighting different kinds of research/monitoring interests.

Example at the North Inlet – Winyah Bay NERR

The researcher wanted to understand vegetation responses to marsh transgression along a marsh age gradient, as it related to changes in local sea level. To address this question, a relatively young marsh complex was chosen. The marsh is actively migrating upslope, and an adjacent pine forest is succumbing to flooding and salt stress. This marsh is situated near a road with existing bench marks as well as an active NOAA water level station, which is very fortuitous. Two study areas were chosen: one near the mouth of Crab Haul Creek (the oldest part of the marsh) and one at the farthest upstream end (near the forest was giving way to marsh). In each area, replicate SET marks, permanent vegetation transects, and ground water wells were established within both fringing marsh and marsh interior (Figure 3-1). The study will provide long-term data on how local sea level rise affects wetland development, vertical change in wetland surfaces, and interspecific plant responses to changing inundation patterns.

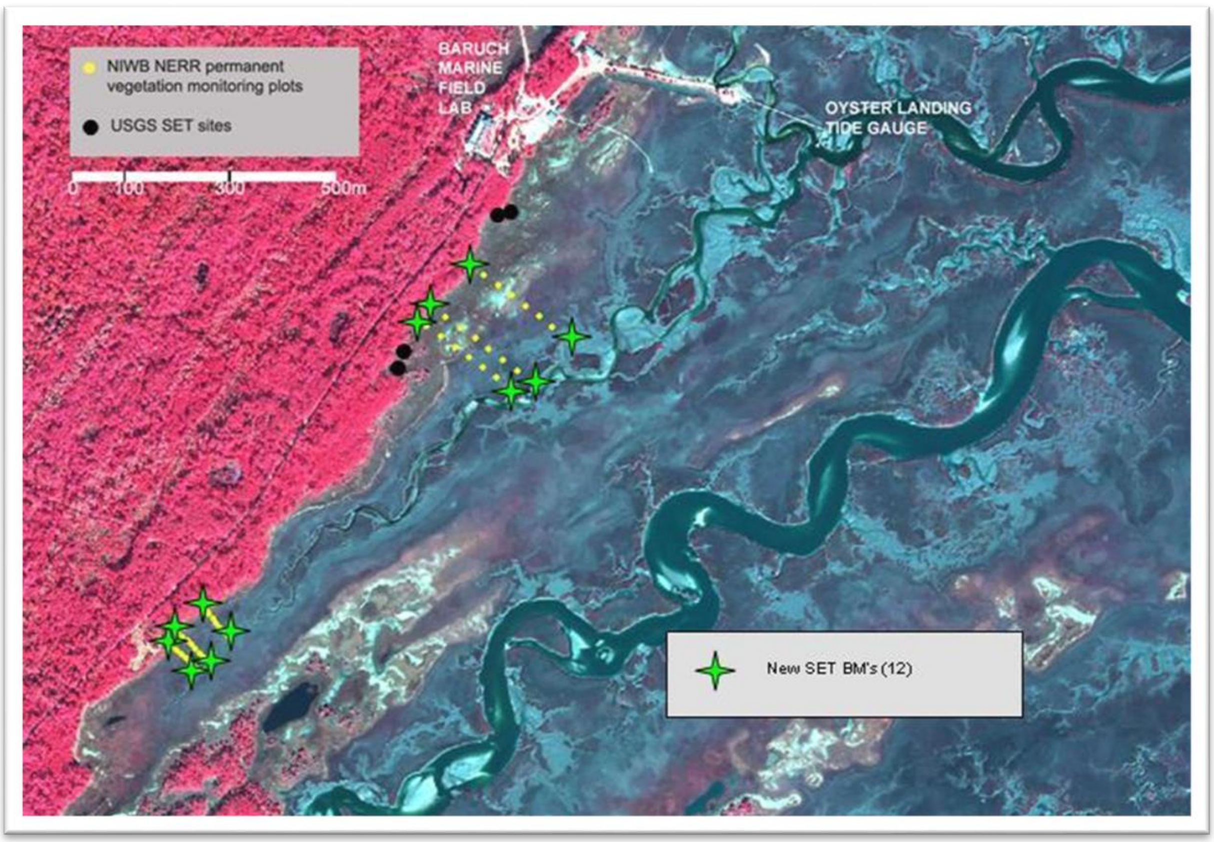


Figure 3-1. Map showing location of permanent vegetation transects, SET bench marks, and water level station at Crab Haul Creek, North Inlet-Winyah Bay NERR (NIWBNERR; image courtesy Eric Smith).

Example at the Chesapeake Bay Maryland NERR
It is important to understand how the marsh response to local changes in water levels was influenced by its position along the tidal freshwater reach of the Patuxent River. Two sites were chosen along channels feeding into the main stem: one upstream (Western Branch) and one downstream (Mataponi Creek); the upstream site was also influenced by the proximity to a sewage treatment plant. A third site (Railroad bed) was along the main stem itself, between the northern and southern sites. All three sites are instrumented with vegetation transects, water level sensors, and SET marks (Figure 3-2).

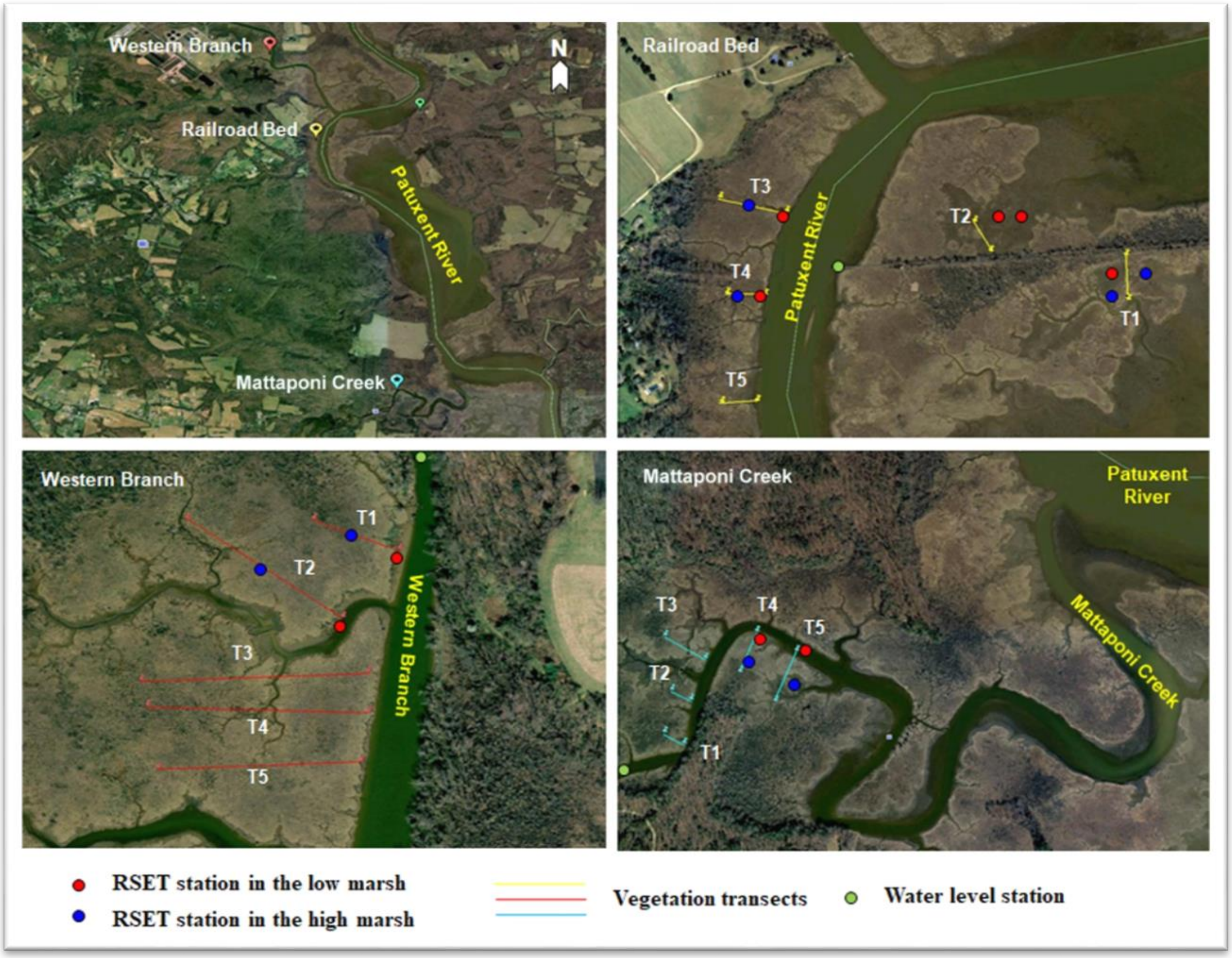


Figure 3-2. This figure shows the location of sentinel site infrastructure at each of the three components of the Jug Bay Sentinel Site. The upper left-hand panel provides a high-altitude view of all three components (Western Branch, Railroad Bed, and Mattaponi). The upper right panel shows a closeup of the Railroad Bed site, including Surface Elevation Tables and vegetation transects. The lower left panel gives a closeup of the Western Branch component, showing the location of the Surface Elevation Tables and vegetation transects. Finally, the lower right panel provides a closeup of the Mattaponi component, showing the location of Surface Elevation Tables and vegetation transects.

3.2. Inventory, Evaluating, and Reconnaissance of Water Level Infrastructure

Once the sentinel site boundaries and monitoring components have been located on the map, identify the existing or historical water level infrastructure. Knowing where the site is in relation to water level infrastructure is important because it may allow you to use existing water level data for monitoring or allow you to compute local tidal datums on an equivalent 19-year NTDE with only several months of data (Section 3.3). It may also provide you with useful pre-existing bench marks.

3.2.1 Inventory of water level infrastructure

A "desktop reconnaissance" will help you identify if active and/or historical water level infrastructure exists within or near the sentinel site boundary. Begin by consulting the list of water level stations[29] (Figure 3-3).

At the top of the water levels page, you can choose either "Active Stations Only" or "Active & Historic Stations" Active & Historic Stations will provide a more robust list. Selecting your state(s) of interest will bring up a list of stations that includes the station ID, name, and dates of operation (Figure 3-4).

Operational or active stations will have the word "present" under the station id and station name (Figure 3-4). However, some stations in the list identified as "present" may be temporary or short-term stations, which have an identified period of operation. Based on the latitude and longitude of the sentinel site, find the nearest active CO-OPS water level station and any historic stations located within or near the site boundary.

[29] https://tidesandcurrents.noaa.gov/stations. html?type=Water+Levels

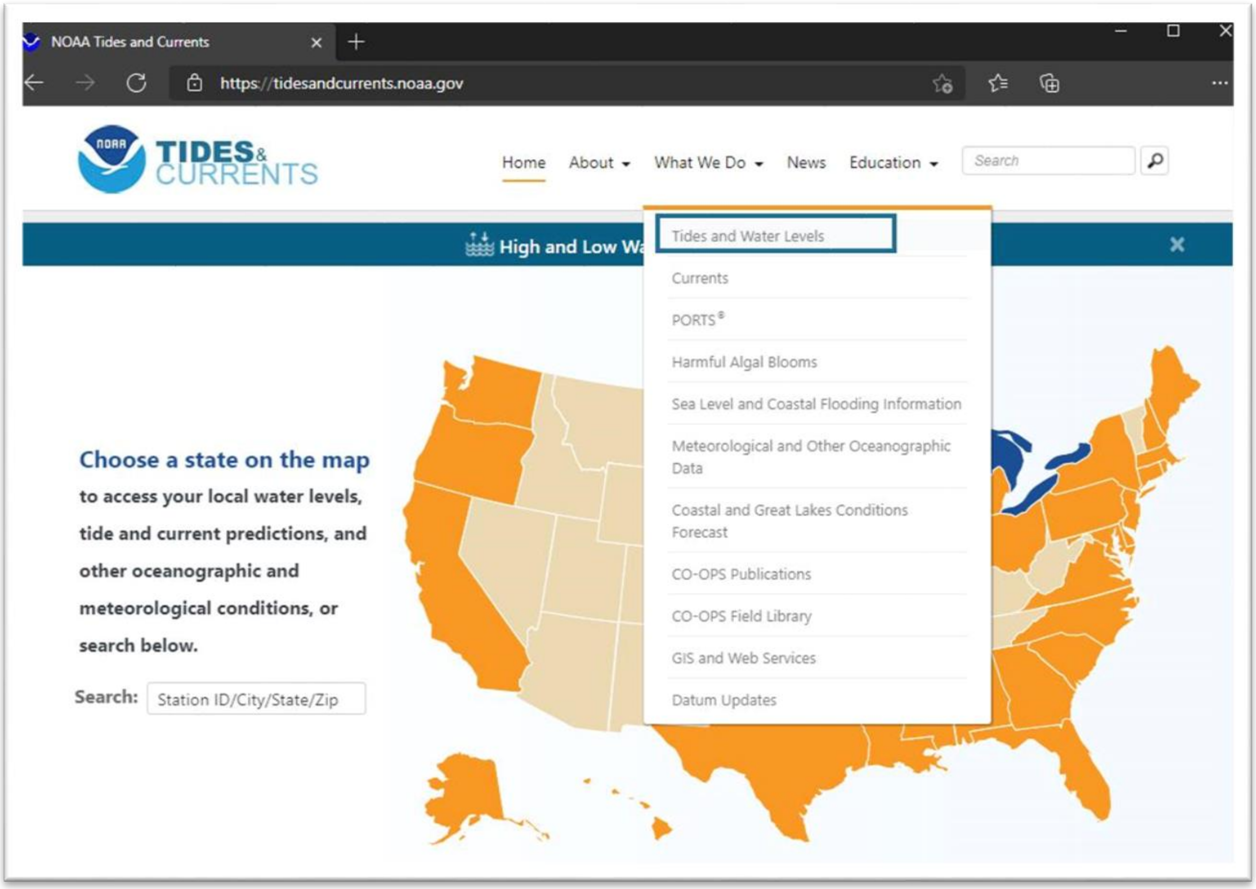


Figure 3-3. Screen capture showing how to access information on active or historic water level stations in a given geographic area of interest.

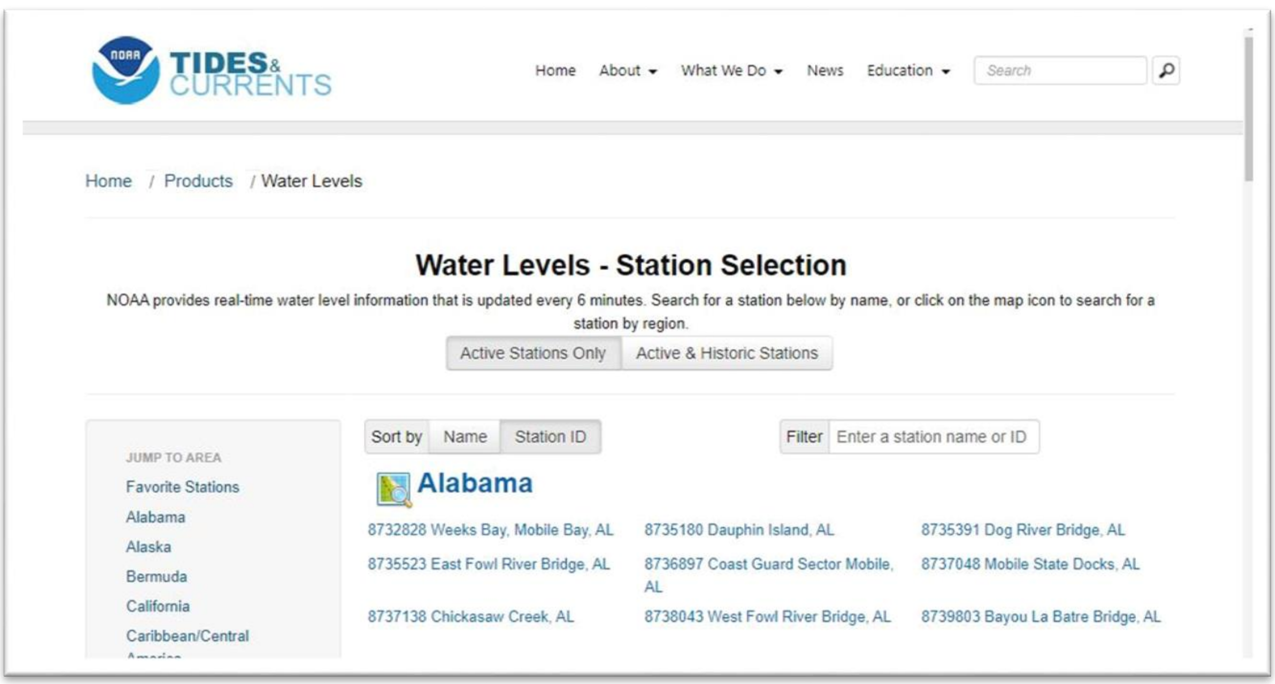


Figure 3-4. Screen capture showing the Water Level - Station Selection webpage. Make sure to document the latitude, longitude, and tidal datum epoch.

Review the available historical station data (e.g., published bench sheets, presently accepted tidal datums) near the sentinel site area. Historical water level stations found near the site may have updated tidal datums, meaning water level observations were collected, tidal datums were computed, and bench mark elevations were computed using the most recent tidal datum epoch (i.e., 1983–2001).

If there are no historical tide stations with updated tidal datums in or near the sentinel site, and the site is within an NWLON gap, then tidal datums will rely exclusively on local (i.e., non-CO-OPS) water level observations.

For historical tide stations note the following information found on the CO-OPS website:

- bench mark descriptions and NGS datasheets, if applicable (Figure 3-5)
- the water level station "To Reach" statement (Figure 3-5)
- tidal datum epoch, preferably on the 1983–2001 NTDE, or a more recent epoch (Figure 3-6)
- published bench mark elevations relative to tidal datums (Figure 3-6)
- available environmental data

Some tidal bench marks may have published coordinates in the NGS database. These have a hyperlink from the CO-OPS published bench mark sheet to the NGS datasheets (Figure 3-5). NGS datasheets can also be retrieved from the NGS Data Explorer[30] (see Section 3.1.2). Including these bench marks in your vertical control network provides a connection to the NAVD 88 datum.

Important Information
Active stations can be removed
Be advised some of the stations identified as "present" on the station list may be temporary or short-term gauges. If you believe an active station may be installed only for a short period of time, you may want to contact CO-OPS Stakeholder Services, at Tide.Predictions@noaa.gov to help you identify the life expectancy of the station.

[30] http://www.geodesy.noaa.gov/NGSDataExplorer/

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Service

Datums Page | Page 1 of 8

Station ID: 8410140 PUBLICATION DATE: 04/21/2003
Name: EASTPORT, PASSAMAQUODDY BAY
ME
NOAA Chart: 13328 Latitude: 44° 54.2' N (44.90330)
USGS Quad: EASTPORT Longitude: 66° 59.1' W (-66.98500)

To reach the tidal bench marks from the intersection of U.S. Highway 1 and State Highway 190 proceed south on State Route 190 to downtown Eastport. From the post office proceed south along Water Street to the Municipal Pier. The bench marks are within 1.6 km (1 mi) radius of the tide station. The tide station is located at the east end of the pier.

T I D A L B E N C H M A R K S

PRIMARY BENCH MARK STAMPING: NO 3 1918
DESIGNATION: 841 0140 TIDAL 3

MONUMENTATION: Tidal Station disk VM#: 143
AGENCY: US Coast and Geodetic Survey (USC&GS) IDB PID#: PD0006
SETTING CLASSIFICATION: Stone steps OPUS PID:
LATITUDE: 44° 54.3' N (44.90425) LONGITUDE: 66° 59.1' W (-66.98503)

The primary bench mark is a disk set in the steps leading to the Peavey Library, located in downtown Eastport at the NW corner of the intersection of Key and Water Streets, 15.54 m (51.0 ft) north of the NE curb of Key Street, 6.85 m (22.5 ft) west of the west curb of Water Street, and 0.76 m (2.5 ft) above the sidewalk.

Figure 3-5. Screen capture showing Bench Mark Sheets for Station at Eastport, Maine. The "to reach" statement is identified in the red box. If an NGS datasheet is available, there will be a PID# as identified in the green box. If the PID# is listed, then using the hyperlink will immediately open the NGS datasheet in your web browser. Also note that a Primary Bench Mark (PBM) is designated, identified in the blue box.

```
                              T I D A L   D A T U M S


Tidal datums at EASTPORT, PASSAMAQUODDY BAY based on:

     LENGTH OF SERIES:       19 Years
     TIME PERIOD:            January 1983 - December 2001
     TIDAL EPOCH:            1983-2001
     CONTROL TIDE STATION:


Elevations of tidal datums referred to Mean Lower Low Water (MLLW), in METERS:

     HIGHEST OBSERVED WATER LEVEL (01/10/1997)          =  7.383
     MEAN HIGHER HIGH WATER                     MHHW    =  5.874
     MEAN HIGH WATER                            MHW     =  5.729
     North American Vertical Datum              NAVD88  =  3.029
     MEAN SEA LEVEL                             MSL     =  2.958
     MEAN TIDE LEVEL                            MTL     =  2.932
     MEAN LOW WATER                             MLW     =  0.136
     MEAN LOWER LOW WATER                       MLLW    =  0.000
     LOWEST  OBSERVED WATER LEVEL (08/09/1972)          = -1.426

North American Vertical Datum (NAVD88)

Bench Mark Elevation Information                In METERS above:

     Stamping or Designation                    MLLW       MHW

     NO 3 1918                                  14.223     8.494
     MAINE 40 1907                              15.199     9.470
     NO 2 1918                                  10.779     5.050
     NO 4 1930                                  15.139     9.409
     NO 8 1975                                  11.791     6.062
     NO 9 1975                                   7.974     2.245
     NO 10 1975                                  9.732     4.003
     0140 K 1976                                12.114     6.385
     0140 L 1990                                 7.975     2.245
     EASTPORT 1989                               7.855     2.126
     8519208                                     7.961     2.231
```

Figure 3-6. Screen capture showing Bench Mark Sheets for Station at Eastport, Maine. Elevations of tidal bench marks relative to tidal datum (i.e., MLLW and MHW) are published, as identified in the box.

Available environmental data

After using the CO-OPS webpages to find existing water level infrastructure, you will also want to find environmental or meteorological data for your sentinel site area. Environmental data is needed to evaluate if and how wave energy, freshwater influence, salinity, and water density may be affecting local water levels. The data is also helpful when deciding the type of water level sensor to be installed. For example, if local barometric pressure data is available, then an unvented pressure sensor may be the preferred option (the barometric pressure is needed to accurately calculate the water height). Environmental and meteorological data (such as barometric pressure, density, etc.) can be found on the NOAA Tides and Currents webpages, which include NOAA PORTS;® however, it may be necessary to visit other NOAA webpages such as the National Weather Service.

Web navigation tips: Visit www.tidesandcurrents.noaa.gov

To find "to reach" info, bench mark elevations, descriptions, and NGS datasheets (if applicable):

1. Hover over "What We Do" tab.
2. Select "Tides and Water Levels".
3. Scroll down and select "Bench Marks Sheets."
4. Select your station of interest from the list or enter the Station ID directly in the dialog box. ***Note:*** *Screenshots identifying where bench mark elevations, descriptions, and NGS datasheets (if applicable) are available online are given in Figures 3-5 and 3-6.*

To find NOAA tide predictions:

1. Hover over "What We Do" tab.
2. Select "Tides and Water Levels".
3. Select "NOAA Tide Predictions" menu item.
4. Choose a station using our Google Map, Google Earth, click on a state below, or search by station name, ID, or latitude/longitude. ***Note:*** *Screen shots showing predicted water levels shown in Figure 3-7.*

To find meteorological observations:

1. Hover over "What We Do" tab.
2. Select "Meteorological & Other Oceanographic Data".
3. Select "Meteorological Observations" menu item.
4. Select your station of interest from the list or enter the Station ID directly. in the dialog box.

Tidal datums and lowest observed (or predicted) water levels

CO-OPS tidal datums for active and historical water level stations calculated relative to the current NTDE as well as superseded epoch (1960 - 1978) are available here.[31] The datums page not only lists the tidal datums, but also identifies the highest and lowest observed water level for those stations with one or more years of data. An example datum page is shown in Figure 3-7. The extreme water level elevations will help determine the maximum range of the tide, which can help inform: 1) how high to install the system components (e.g., electronics) which must not get submerged and 2) the depth of the sensor such that the sensor captures the full range of tide. If published tidal datums are not available near your sentinel site area, the NOAA Tide Predictions[32] can provide information helpful in determining these extreme water level elevations (Figure 3-8). Note, these elevations are derived mathematically and could be significantly different than elevations during an actual storm event.

[31] https://tidesandcurrents.noaa.gov/stations.html?type=Datums
[32] https://tidesandcurrents.noaa.gov/tide_predictions.shtml

Elevations on Station Datum

Station: 8410140, Eastport, ME
Status: Accepted (Apr 17 2003)
Units: Meters

T.M.: 75
Epoch: 1983-2001
Datum: STND

Datum	Value	Description
MHHW	7.336	Mean Higher-High Water
MHW	7.191	Mean High Water
MTL	4.395	Mean Tide Level
MSL	4.420	Mean Sea Level
DTL	4.399	Mean Diurnal Tide Level
MLW	1.598	Mean Low Water
MLLW	1.462	Mean Lower-Low Water
NAVD88	4.491	North American Vertical Datum of 1988
STND	0.000	Station Datum
GT	5.874	Great Diurnal Range
MN	5.593	Mean Range of Tide
DHQ	0.145	Mean Diurnal High Water Inequality
DLQ	0.136	Mean Diurnal Low Water Inequality
HWI	3.300	Greenwich High Water Interval (in hours)
LWI	9.690	Greenwich Low Water Interval (in hours)
Maximum	8.845	Highest Observed Water Level
Max Date & Time	01/10/1997 16:18	Highest Observed Water Level Date and Time
Minimum	0.037	Lowest Observed Water Level
Min Date & Time	08/09/1972 00:00	Lowest Observed Water Level Date and Time
HAT	8.457	Highest Astronomical Tide
HAT Date & Time	11/05/1998 16:06	HAT Date and Time
LAT	0.367	Lowest Astronomical Tide
LAT Date & Time	02/09/1997 23:24	LAT Date and Time

Figure 3-7. Screen capture showing Tidal Datums for Station at Eastport, Maine. Values are relative to the local Station Datum.

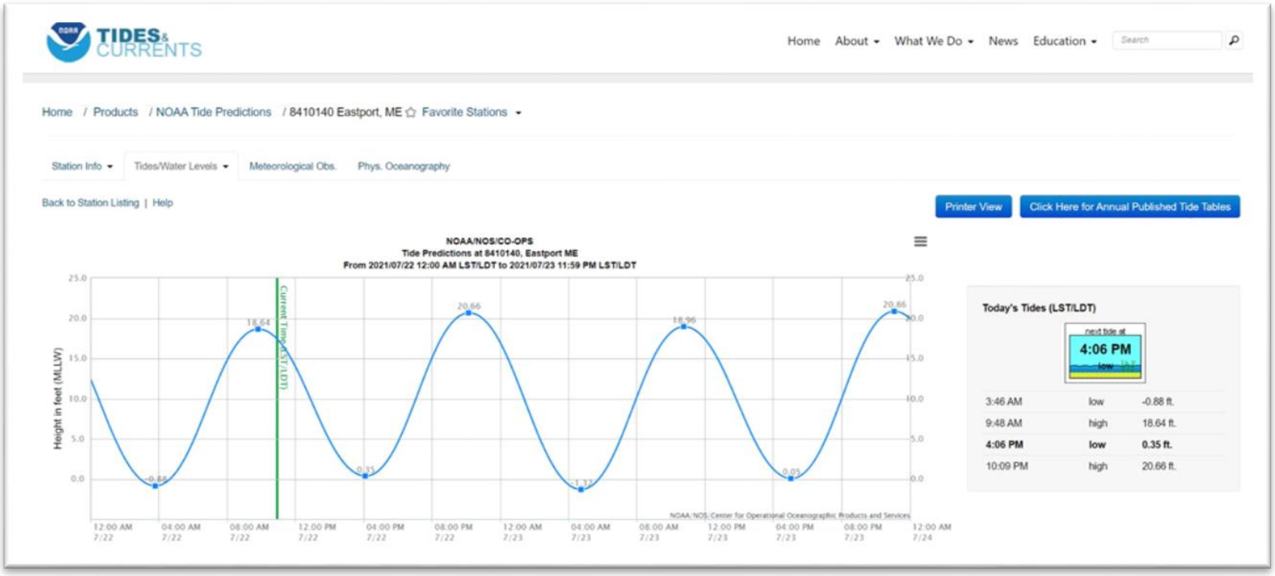


Figure 3-8. Screen capture showing predicted water levels for station at Eastport, Maine.

Tidal Datum Elevations: If you subtract the value of MLLW (Figure 3-7) from all values on the station's "Datum" page, then you will obtain elevations of tidal datums relative to MLLW, which will be the same values as "Elevations of tidal datums..." in Figure 3-6.

3.2.2 Evaluating water level inventory

An evaluation of NWLON coverage for the sentinel site is helpful because it will help prioritize options regarding the use of available water level products. At best, if the nearest active NWLON lies within the sentinel site, it may serve to provide all water level products, from local water levels and water level trends to tidal datums. This assumes that the water level characteristics (e.g., time and range of tides, freshwater flow, currents, etc.) are shared by the NWLON and the other sentinel site components.

If the nearest active NWLON does not share water level characteristics with the other sentinel site components, or if it is located outside the sentinel site but the site is within NWLON coverage (based on NWLON gap report), NTDE equivalent tidal datums may be computed based on local water level observations and a tide-by-tide comparison (Section 4.2) .

Additionally, if the NWLON station bench marks (active or historical) are within or near the site, then the bench marks can be included in the site's local vertical control network, or otherwise be used to transfer elevations into the site. Since most NWLON stations have five to ten bench marks, any or all of the marks can be used to help monitor vertical stability in the area.

If the sentinel site is located in a NWLON gap, then local water level observations are critical for the computation of local water level datums. A minimum of one year's worth of observations is recommended to account for seasonal variations in the datums.

A detailed dichotomous key describing recommended options for using new, existing, or historical water level data and infrastructure is presented in Appendix 1.

To identify whether or not the area of research is covered by an NWLON station refer to the network gaps analysis for the NWLON found at: http://tidesandcurrents.noaa.gov/publications/Technical_Memorandum_NOS_COOPS_0048.pdf.

How do I choose the Primary Bench Mark (PBM) to support a water level station?

For new water level station(s), the Primary Bench Mark (PBM) will need to be selected and assigned an elevation above station datum. Preferably, this mark will be the most stable bench mark in proximity to the water level gauge. If you are deploying a new water level sensor at the same location as a historical tide station, the historical PBM should be recovered if the mark is in good condition and stable. The historical PBM is identified on the CO-OPS published bench mark sheet.[33] Once the historical PBM has been identified and recovered, contact CO-OPS for the PBM elevation above station datum or determine the elevation through a few simple steps described in the Eastport example in the call-out box given below.

If the historical PBM cannot be recovered or is to be found unstable, any other recoverable bench mark in the tidal bench mark network with a published MLLW or MHW elevation can be used as the PBM.

It is important to recover the station datum since all published tidal datums are expressed with respect to the station datum. A historical station datum can be recovered by leveling to two or more bench marks with published elevations above station datum or MLLW or MHW as identified on the published bench mark sheet and accepted datum page. This reoccupation process, called "datum recovery," will allow you to compare new water level observations to the historical record, keeping everything on the same station datum. The PBM's elevation above station datum will be used as the starting elevation for every level run for the water level station.

If all of the bench marks in the tidal bench mark network are newly established and not connected to a tidal datum, then an arbitrary station datum must be established. Station datum should be set such that even the lowest observed water levels are a positive number (usually a starting elevation of 10.000 m or 20.000 m will suffice).

[33] https://tidesandcurrents.noaa.gov/stations.html?type=Bench+Mark+Data+Sheet

Important Information
Station Datum is an arbitrary datum to which all bench mark and sensor elevations in a local tidal network are referenced. This datum is chosen to ensure that all water level observations from the sensor are positive numbers, facilitating tidal datum computations. This datum should not be confused with a tidal datum such as MLLW.

Using a published tidal datum for the sentinel site is an option only if your site and the historical station are within areas of common water level characteristics, if the historical station has an updated tidal datum, and if tidal bench marks can be recovered and are stable. If you wish to pursue this strategy, specific expert recommendations are needed for each site.

Eastport Station Example: The PBM is NO 3 1918 (from Figure 3-5), and its elevation relative to MLLW is 14.223 m (from Figure 3-6). Now add the elevation of MLLW above Station Datum, which is 1.462 m (from Figure 3-7) to obtain 15.685 m for the elevation of the PBM above Station Datum.

3.2.3 Field reconnaissance and recovery of water level infrastructure

Once you have identified what type of existing tidal infrastructure is available, you may visit and recover (when applicable) some or all of the following:

- an active water level station
- existing bench marks
- an existing safe and stable infrastructure to support a new water level sensor (e.g., pier)
- location for new bench marks

If your proposed location for the water level station has existing and stable infrastructure, visit the site (Servary, 2012) taking the measurements listed below. Also, make sure to take photographs of the structure from different angles, noting the measurements below:

- distance between the surface of the structure (e.g., pier) and the bottom of the water body (e.g., harbor bottom, channel bottom, etc.)
- distance of the structure's surface above water surface, noting the time of water surface measurements (to account for relative water height, such as low or high tide)
- piling diameter (if applicable)
- pier width (if applicable)
- evidence of high-water marks relative to the land, based on visual evidence

If there is no safe, secure, stable infrastructure (e.g., pier) to attach the protective well, then infrastructure must be fabricated and installed to mount the water level sensor. In the construction of this infrastructure, consider the measurements described above, the sediment type at the sensor location, and the extreme water level values observed at this location. Photos of the proposed location of the water level sensor and other ancillary sensors needed to quality control the water level data (e.g., barometer for unvented water level sensors) may be attached to the survey plan to support the proposed installation or infrastructure decisions.

Finally, if any published bench marks (from either the CO-OPS published bench mark sheets or any NGS datasheets) will be used, they will need to be recovered (Section 3.3).

Compiling all of the collected information will help you determine if, where, and to what specifications a water level station will need to be installed; what CO-OPS water level station can be used as vertical and/or datum control for the newly established station; and how many bench marks are existing or need to be newly established. All this information should be included in the map and survey plan, which can be submitted to CO-OPS for review.

3.3 Inventory, Evaluating, and Reconnaissance of Geodetic Infrastructure

3.3.1 Inventory of geodetic infrastructure

As with water level infrastructure, pre-existing geodetic infrastructure will need to be inventoried if it includes:

- Physical survey marks that can be used as part of your local vertical control network(s). If they have published high accuracy vertical positions, then it will be easy to transfer elevations to other marks and monitoring infrastructure within your network.
- High accuracy vertical control marks that lie outside your site, but close enough that you may use geodetic leveling techniques to transfer those elevations to your network. Note that if you will be running levels from existing control into your site, you will need at least two existing high accuracy vertical marks (explained in Section 6.1)
- High accuracy vertical control marks that lie several kilometers outside your site, but can still be used to enhance the accuracy of a Global Navigation Satellite System (GNSS) survey to bring elevations within your network as part of a network adjustment.[34]

Identifying tidal bench marks was previously discussed in Section 3.2 (CO-OPS bench mark sheets or NGS database). This section will focus on identifying NGS and other geodetic bench marks using several different tools. Please note that some pre-existing bench marks may not be in the NGS databases. If that is the case, then it is likely that the positional information is out of date.

Web navigation tips for finding and using NGS IDB:

1. Visit geodesy.noaa.gov
2. Select upper right-hand corner button labeled "Looking for Bench Marks?"
   or
   Hover over the "Data & Imagery" tab, select "Survey Mark Datasheets"

   Screen shots illustrating retrieval and search options are shown in Figures 3-10 and 3-11.

[34] Network solutions are not covered in this document; refer to vendor software or contact NGS for more information.

The NGS Integrated Data Base (IDB) is the largest National database of high accuracy bench marks and is available through a new Data Explorer, the new NGS Web Map[35], or through its own datasheets retrieval system.[36]

The Data Explorer and the NGS Web Map are an intuitive map-based interfaces for accessing positions published in the NGS IDB (Figure 3-9). Other mechanisms exist for retrieving bench mark information. For example, shapefiles can be specified from the datasheets webpage (Figure 3-10). Shapefiles allow you to plot bench marks on your own GIS mapping projects, and the associated attribute table also contains important metadata that will help you evaluate your inventory per Section 3.3.2:

- PID – six-character unique identifier of each bench mark
- ELEV_DATUM – make sure it is NAVD 88, the orthometric datum
- ELEV_SRCE – the method used to determine its elevation (e.g., via leveling or GNSS)
- LAST_RECV – date the bench mark was last recovered
- LAST_COND – condition of the bench mark when it was last recovered
- STABILITY – stability of bench mark (see Section 2.4)

(Note: the information is also found, albeit in a different format, on a complete datasheet. Datasheets will be discussed further in Section 3.3.2.).

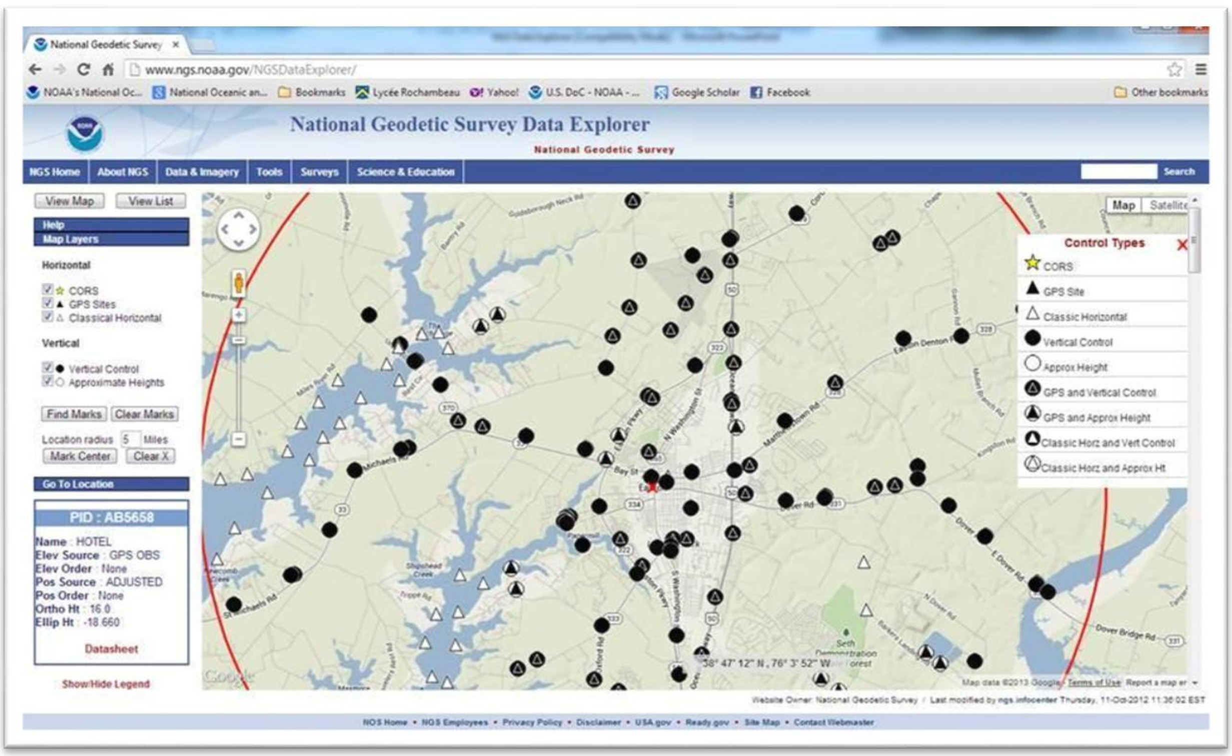


Figure 3-9. NGS Data Explorer, an intuitive, map-based datasheet retrieval portal (example taken from a five-mile radius centered around the city of Easton, on Maryland's Eastern Shore.

[35] https://geodesy.noaa.gov/datasheets/ngs_map/
[36] https://geodesy.noaa.gov/datasheets/index.shtml

There are several avenues for retrieving data as shapefiles. Three of these are described below.

1. ***Radial Search for Shapefiles****:* Select "Shapefiles" under "Retrieval Link" (Figure 3-10). Next, select "Radial Search" as your "Retrieval Method." Input the latitude, longitude, and specify a search radius. Since you are interested in local marks, stay within a couple kilometers of your site (See Figure 3-11R). The retrieval provides a table of the available marks; select them all to download. Subsequently, the shapefiles can then be uploaded to the map.
2. ***Download by County***: First, select the state, then the county within the state, to download the corresponding shapefiles.
3. ***Download State Shapefiles****:* Select "Monthly Archives by State" under "Retrieval Link" (Figure 3-10). Select your state of interest and your preferred compression option [Figure 3-11(L)]. This strategy downloads all the bench marks for a state in a single shapefile. The only drawback to this strategy is the information is archived monthly, so you may miss a recent submission to the database.

The NGS IDB publishes coordinates on marks that have gone through a rigorous quality check and control process, and it does not include positions derived solely through the use of single, post-processed solutions from the NGS Online Positioning User System (OPUS). Users can allow their individual OPUS solutions to be shared, if they become part of a public database referred to as "OPUS Shared Solutions." Note that these positions are not considered official NGS published geodetic control.

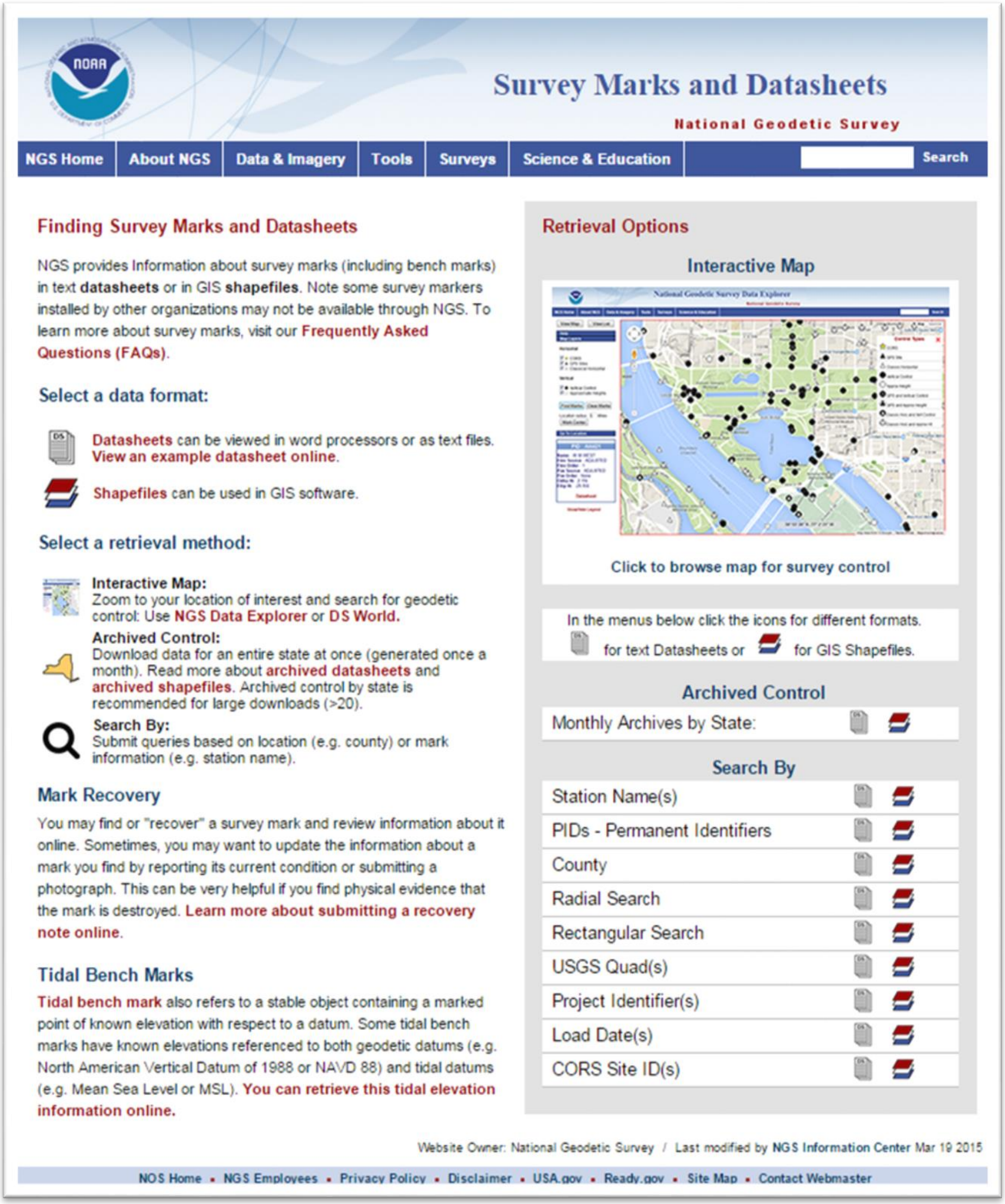


Figure 3-10. Screen capture showing options for retrieving data sheet information. Both HTML text and GIS shapefile output options are available.

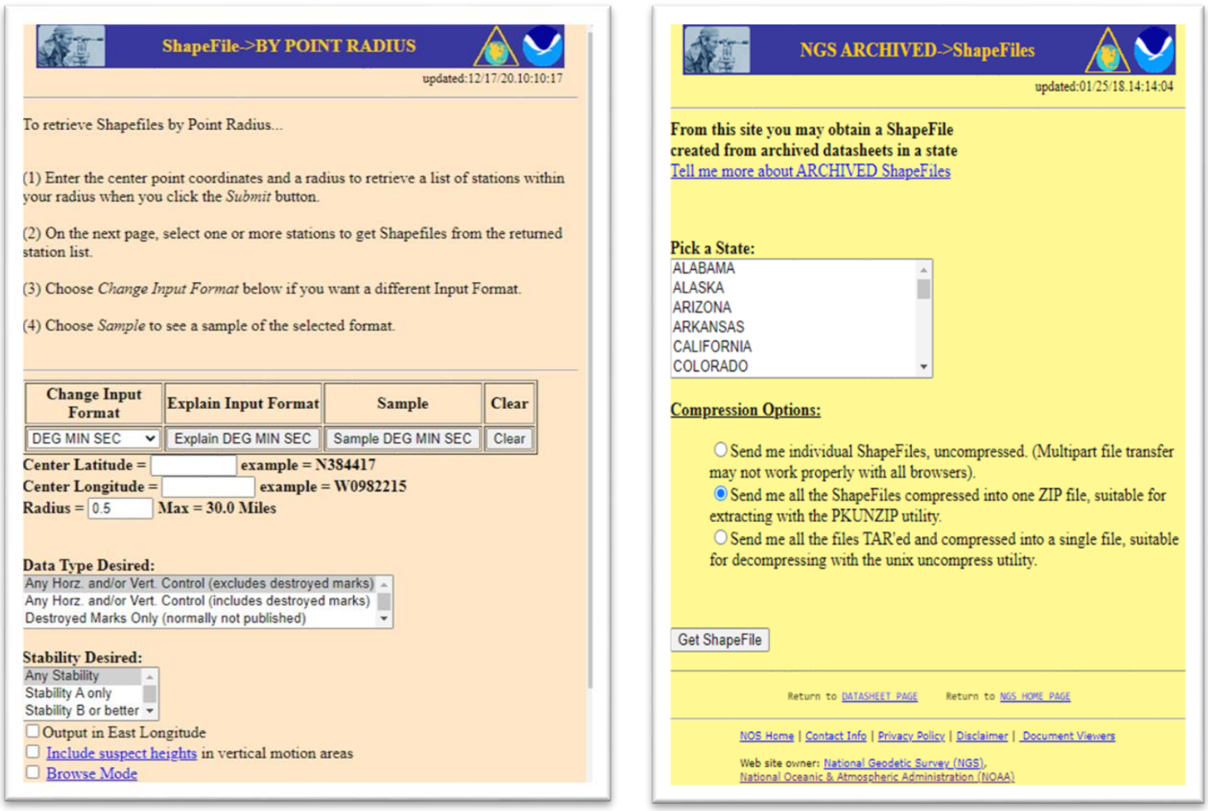


Figure 3-11. (L) Screen capture of radial search for shapefiles. (R) Screen capture of downloading state shapefiles.

The ease and speed with which positions can be shared has made OPUS a very rapidly expanding product. Although there are some blunder checks, these elevations are considered "no check" since they are individual observations. They are also not least squares adjusted with respect to other survey control in the area. Multiple OPUS Share solutions (and therefore positions) can co-exist for the same mark, so the user may have to exercise caution in choosing among available solutions. For example, the user may want to choose the most recent solution, compute the average of the available solutions, or otherwise choose coordinates with the lowest three-dimensional error.

OPUS shared solutions can be retrieved through the OPUS website[37] (Figure 3-12). As with the NGS IDB, you can conduct a search via initial position and radius or other methods, and you can export the data in either a text document (i.e., OPUS solutions) or shapefiles.

NGS supports another tool called DSWorld that works with Google Earth® and provides a user-friendly way of obtaining access to both physical coordinates and information sheets from either the NGS IDB or the OPUS shared solutions, although we recommend you search the NGS IDB first.

[37] geodesy.noaa.gov/OPUS/view.jsp

Figure 3-12. Screen capture showing OPUS "Shared Solutions" retrieval options and solution formats. Options include radial search, or search by county, zip code, as well as a map-based browser.

***Web navigation tips**: Visit* geodesy.noaa.gov

To find OPUS shared solutions:

1. Select "OPUS" from left menu.
2. Select "Shared Solutions" from left menu.

   Screen capture showing retrieval options and solution formats in Figure 3.12.

To download DS World:

1. Hover over "Tools" tab.
2. Select "Download PC Software" menu item.
3. Click the "User-Contributed Software" hyperlink (it is a red link under the tabular list).
4. Click on DSWORLD (Version 4.02) or the most recent version; it is an executable file that must be downloaded and installed.

To use DSWorld, you must download an executable file.[38] You can specify the area to search by providing latitude/longitude, state and county, or by using Permanent Identifiers (PIDs). Screen shots illustrating how to begin this search are in Figure 3-13. DSWorld will automatically open Google Earth if you already have Google Earth installed on your computer and you will be able to see the existing bench marks on the map (Figure 3-14). Note that if you search OPUS shared solutions, ALL solutions will be loaded into Google Earth® (they may take time to load!).

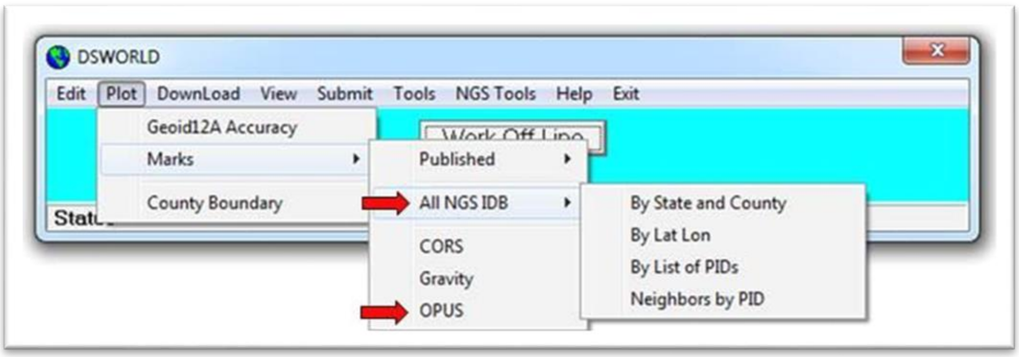


Figure 3-13. Screen captures showing how to search DSWorld for either all marks published in the NGS Integrated Database (IDB), or through On-Line Position User Service (OPUS) shared solutions.

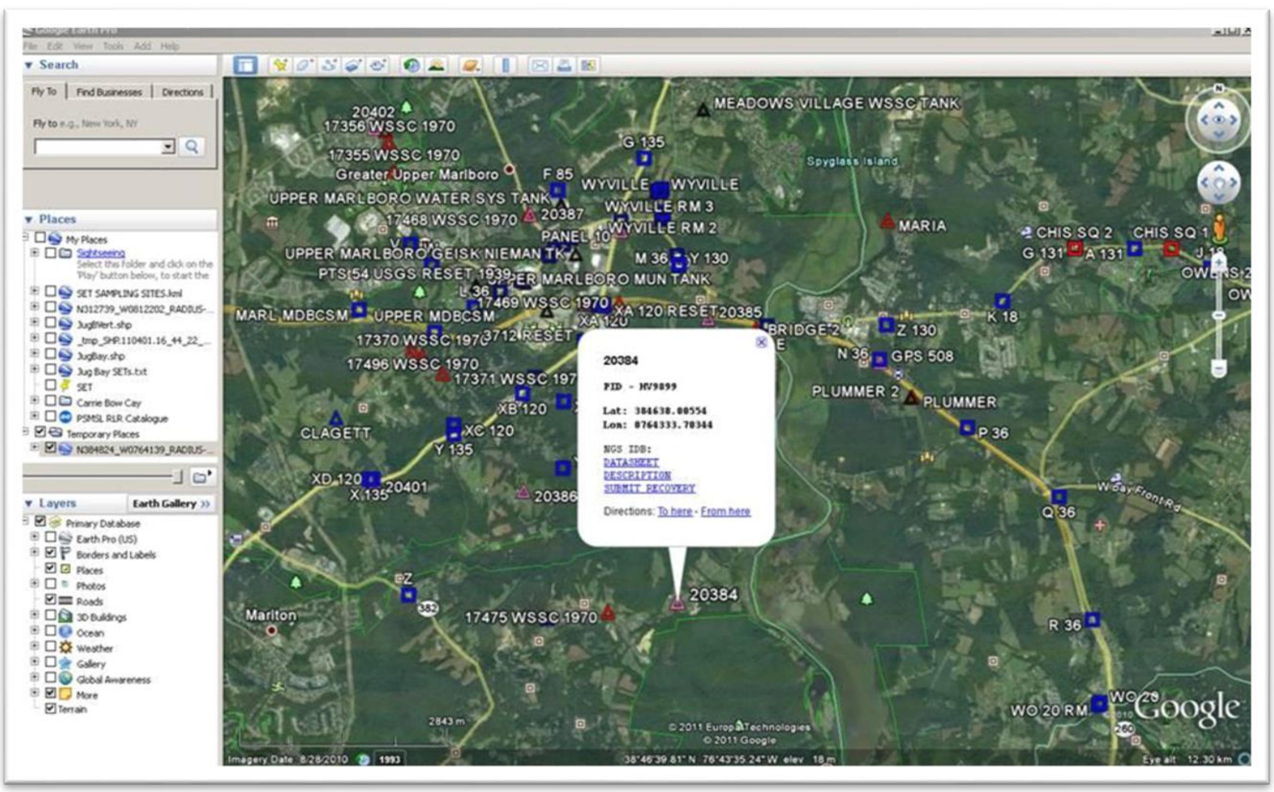


Figure 3-14. Screen capture of Google Earth showing output of marks from a DSWorld retrieval. Clicking on a mark will open the properties window, which will have a link to the mark's datasheet if it is available from the NGS IDB. Clicking on the link will open the datasheet in your internet browser.

38 https://geodesy.noaa.gov/PC_PROD/#WinDesc

The NGS IDB holds information on marks regardless of their origin (e.g., NGS, U.S. Army Corps of Engineers (USACE), U.S. Geological Survey (USGS), state departments of transportation, etc.) as long as the marks were part of a project that was submitted to NGS for processing and adjustment. Similarly, OPUS contains solutions submitted by users from numerous public agencies or private companies. However, there may be a number of other marks in existence that have not been incorporated into either of these two databases. These include tidal bench marks, USACE marks, USGS marks, as well as state marks, among others.

A tool that can help retrieve some of these additional marks is the USACE Survey Marker Archive & Retrieval Tool[39] (U-SMART). This program will not export the bench mark coordinates, so you will have to document the coordinate information to plot the marks in addition to any other metadata you record. After using some or all of the tools described earlier in this section, you should have the location of all available marks loaded onto your map.

Important Information
At the end of the inventory phase, your map should now show all pre-existing and planned monitoring infrastructure (Section 3.1), and all existing tidal (3.2) and geodetic (3.3) infrastructure. The next step is to look over the map and decide if any pre-existing geodetic infrastructure can be useful to support the monitoring infrastructure at your site.

3.3.2 Evaluating the inventory

Once you have an inventory map of pre-existing geodetic infrastructure in and around your site, you will evaluate its usefulness for a sea level change sentinel site. Reconnaissance can be a time-intensive task, so it is best to evaluate as much as you can at the office. At least three permanent Local Control Marks (LCMs) need to be identified for each site. These will be the marks for which you will obtain high accuracy coordinate information (horizontal and vertical) through a connection established with the National Spatial Reference System (NSRS).

Will existing bench marks be useful?

To evaluate the utility of an existing bench mark, gauge its distance to your monitoring infrastructure and the accuracy of its published elevation. Any mark within a kilometer of your site could be a good candidate for a LCM. Such a mark may be very useful, especially if it has a leveled orthometric height, and it can be connected to the sentinel site's vertical control network via leveling. Existing marks with accurate published elevations more than a couple of kilometers away (maybe too far away for leveling) may still be useful because these known points can be used in a GNSS campaign to augment the accuracy of your GNSS observations on unknown points through a process called a "network adjustment" or "network solution". This sort of analysis is possible through the use of OPUS-Projects mentioned earlier. Although beyond the scope of these guidelines, this network solution provides enhanced accuracy to GNSS solutions.

Next, evaluate the stated or implied accuracies of the marks based on how the orthometric elevation has been established. If you are working with shapefiles, then the attributes you want to focus on for this evaluation are "ELEV_DATUM" and "ELEV_SRCE." If you are not using shapefiles, you will need to use information from NGS IDB or OPUS datasheets.

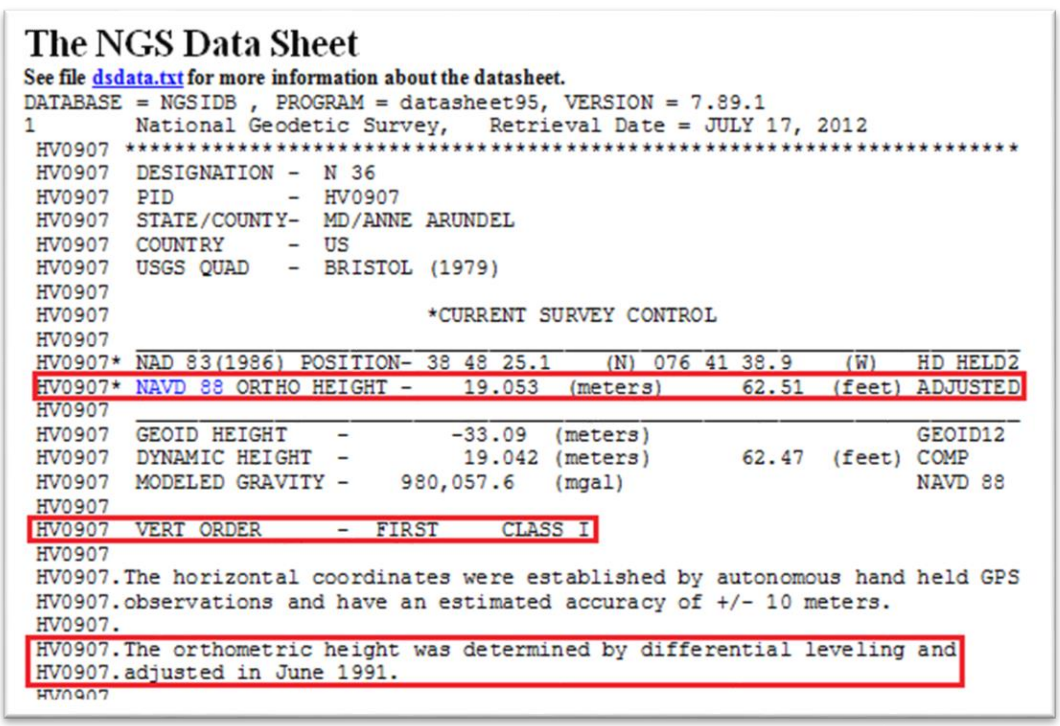
---

39 https://www.agc.army.mil/What-we-do/U-SMART/

On the NGS IDB datasheets, note whether or not a mark has an elevation assigned, and how the value was obtained. Figure 3-15 provides an example of a bench mark whose elevation was obtained via First Order, class I leveling (the highest accuracy leveling). Elevations that were originally obtained via leveling ensure a certain minimum error in comparing any two points except in high subsidence areas. An additional feature to look for is that the height has been included in a recent adjustment (the original adjustment for NAVD 88 was in June 1991). Figure 3-16 shows an example of an elevation that was estimated from a scaled topographic map (lowest accuracy elevation). Figure 3-17 provides an example of a mark with GPS-derived positions, including elevation. Figure 3-18 is an example of an OPUS shared solutions information sheet, showing where the vertical coordinates are found. GPS-derived NAVD 88 elevations have more inherent error compared to leveling. Not only is there error in the satellite-derived ellipsoid elevation (typically four centimeters (cm) at 95% confidence), but there is also error in the geoid model used to arrive at the orthometric height.

There are also a number of horizontal marks that do not have elevations assigned that can be incorporated into the site's bench mark network; a new accurate elevation will have to be obtained through surveying.

Important Information
If your site is located in a known subsidence area, the published heights of the bench marks may be suspect, even if the highest precision leveling was conducted in the past.



The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

```
DATABASE = NGSIDB , PROGRAM = datasheet95, VERSION = 7.89.1
1        National Geodetic Survey,   Retrieval Date = JULY 17, 2012
 HV0907 *********************************************************************
 HV0907  DESIGNATION -  N 36
 HV0907  PID         -  HV0907
 HV0907  STATE/COUNTY-  MD/ANNE ARUNDEL
 HV0907  COUNTRY     -  US
 HV0907  USGS QUAD   -  BRISTOL (1979)
 HV0907
 HV0907                       *CURRENT SURVEY CONTROL
 HV0907
 HV0907* NAD 83(1986) POSITION- 38 48 25.1     (N) 076 41 38.9     (W)    HD HELD2
 HV0907* NAVD 88 ORTHO HEIGHT -     19.053  (meters)       62.51  (feet) ADJUSTED
 HV0907
 HV0907  GEOID HEIGHT    -         -33.09  (meters)                      GEOID12
 HV0907  DYNAMIC HEIGHT  -          19.042 (meters)       62.47  (feet) COMP
 HV0907  MODELED GRAVITY -    980,057.6    (mgal)                        NAVD 88
 HV0907
 HV0907  VERT ORDER      -  FIRST      CLASS I
 HV0907
 HV0907.The horizontal coordinates were established by autonomous hand held GPS
 HV0907.observations and have an estimated accuracy of +/- 10 meters.
 HV0907.
 HV0907.The orthometric height was determined by differential leveling and
 HV0907.adjusted in June 1991.
 HV0907
```

Figure 3-15. Sample NGS IDB datasheet showing where to find the published NAVD 88 orthometric elevation and how that elevation was obtained. This elevation was obtained using First Order Class I differential leveling in June 1991. Additionally, the high level of precision that the elevation is reported to (0.001 m) also confirms this implied accuracy.

The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

```
DATABASE = NGSIDB , PROGRAM = datasheet95, VERSION = 7.87.6
1        National Geodetic Survey,   Retrieval Date = APRIL 18, 2012
 HV7226 ***********************************************************************
 HV7226  DESIGNATION -  PLUMMER
 HV7226  PID         -  HV7226
 HV7226  STATE/COUNTY-  MD/ANNE ARUNDEL
 HV7226  USGS QUAD   -  BRISTOL (1979)
 HV7226
 HV7226                        *CURRENT SURVEY CONTROL
 HV7226  ___________________________________________________________________
 HV7226* NAD 83(1991)-  38 48 08.68417(N)    076 41 20.19957(W)     ADJUSTED
 HV7226* NAVD 88     -        26.     (meters)      85.     (feet)  SCALED
 HV7226  ___________________________________________________________________
 HV7226  LAPLACE CORR-         -5.14  (seconds)                     DEFLEC09
 HV7226  GEOID HEIGHT-        -33.11  (meters)                      GEOID09
 HV7226  HORZ ORDER  -  SECOND
 HV7226
 HV7226.The horizontal coordinates were established by classical geodetic methods
 HV7226.and adjusted by the National Geodetic Survey in January 1992.
 HV7226.
 HV7226.The orthometric height was scaled from a topographic map.
```

Figure 3-16. Sample NGS datasheet showing elevation information obtained via a topographic map (mark was a horizontal mark, not vertical).

The NGS Data Sheet

```
DATABASE = NGSIDB , PROGRAM = datasheet95, VERSION = 7.87.6
1        National Geodetic Survey,   Retrieval Date = FEBRUARY 16, 2012
 AJ2087 ***********************************************************************
 AJ2087  DESIGNATION -  GC048
 AJ2087  PID         -  AJ2087
 AJ2087  STATE/COUNTY-  FL/CALHOUN
 AJ2087  USGS QUAD   -  ALTHA EAST (1994)
 AJ2087
 AJ2087                         *CURRENT SURVEY CONTROL
 AJ2087  ___________________________________________________________________
 AJ2087* NAD 83(2007)-  30 36 10.26373(N)    085 05 21.67979(W)     ADJUSTED
 AJ2087* NAVD 88     -        62.2    (meters)     204.     (feet)  GPS OBS
 AJ2087
 AJ2087  ___________________________________________________________________
 AJ2087  EPOCH DATE  -        2002.00
 AJ2087  X           -     470,346.029 (meters)                     COMP
 AJ2087  Y           -  -5,474,398.364 (meters)                     COMP
 AJ2087  Z           -   3,228,091.120 (meters)                     COMP
 AJ2087  LAPLACE CORR-           0.29  (seconds)                    DEFLEC09
 AJ2087  ELLIP HEIGHT-          33.909 (meters)          (02/10/07) ADJUSTED
 AJ2087  GEOID HEIGHT-         -28.38  (meters)                     GEOID09
 AJ2087
 AJ2087  ------- Accuracy Estimates (at 95% Confidence Level in cm) --------
 AJ2087  Type    PID    Designation                      North   East  Ellip
 AJ2087  -------------------------------------------------------------------
 AJ2087  NETWORK AJ2087 GC048                             2.49   2.12   9.66
 AJ2087  -------------------------------------------------------------------
 AJ2087
 AJ2087.The horizontal coordinates were established by GPS observations
 AJ2087.and adjusted by the National Geodetic Survey in February 2007.
 AJ2087
 AJ2087.The datum tag of NAD 83(2007) is equivalent to NAD 83(NSRS2007).
 AJ2087.See National Readjustment for more information.
 AJ2087
 AJ2087.The horizontal coordinates are valid at the epoch date displayed above
 AJ2087.which is a decimal equivalence of Year/Month/Day.
 AJ2087
 AJ2087.The orthometric height was determined by GPS observations and a
 AJ2087.high-resolution geoid model.
 AJ2087
 AJ2087.The X, Y, and Z were computed from the position and the ellipsoidal ht.
 AJ2087
 AJ2087.The Laplace correction was computed from DEFLEC09 derived deflections.
 AJ2087
 AJ2087.The ellipsoidal height was determined by GPS observations
 AJ2087.and is referenced to NAD 83.
 AJ2087
 AJ2087.The geoid height was determined by GEOID09.
```

Figure 3-17. Sample NGS datasheet showing elevation obtained via GPS observation. Note that the ellipsoid elevation is given, referenced to the NAD 83 ellipsoid. The date the height was adjusted is also given (i.e., 02/10/07).

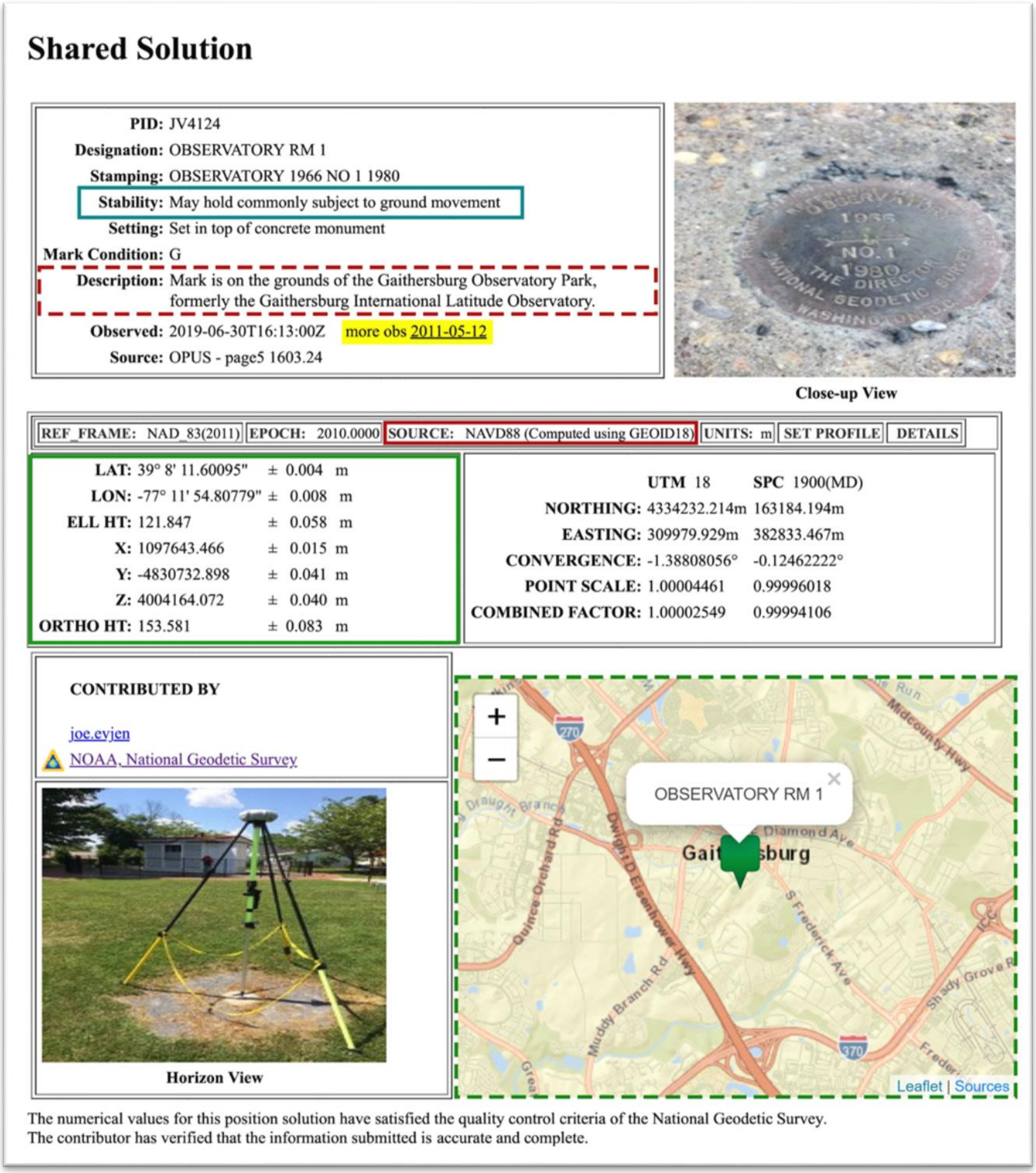


Figure 3-18. Sample OPUS "shared solution" mark information sheet (from 2014) showing positional information (lat/long and orthometric elevations) as well as the expected error (green box). Since the orthometric elevation is GPS derived, the geoid model used is designated in the red box. Other important information to note includes the mark description in the upper left-hand corner (dashed red box); both close-up and horizon photographs to help locate and identify the mark an interactive map to provide directions to the site (dashed green box). Note that the mark was previously observed in 2000; a link to this observation is highlighted in yellow. Stability information is in the blue box.

Next to consider is mark type and stability. For shapefiles and datasheets, the attribute of interest is stability. The information on mark type and stability can be found under the position information and above the recovery information on datasheets (Figure 3-19). Stability information is provided near the top of the OPUS shared solution (green box in Figure 3-18), but the description of the mark and the assignment of a stability code are not listed or verified.

Survey discs on rock outcrops or survey discs set in massive, permanent structures are ideal (stability code A); however, rod marks (stability code B) and concrete post marks (stability code C) can be considered for use in the local geodetic control network. Note that the highest stability is recommended for the LCMs (A or B). Bench marks of stability D can be included in the bench mark network, especially as temporary marks to support leveling efforts; however, these cannot be considered stable, and cannot be relied on to maintain a positional reference to support the position (elevation) of monitoring infrastructure (refer to Table 2-5).

So which bench marks should I try to recover?

To evaluate the recoverability of marks, examine the mark condition and the date last recovered. Shapefile attributes you should note are LAST_RECV and LAST_COND. If you are using an NGS IDB datasheet, read the recovery information listed under "History" and after the date created (See Figures 3-20 and 3-21). If the mark is labeled "MARK NOT FOUND" (e.g., Figure 3-21), then it is likely that the bench mark will not be recoverable. Keep in mind that bench marks are often along roads, and state highway authorities widen the roads over time resulting in destroyed marks. However, do not automatically reject a mark if it was labeled "not found." There is no guarantee the person searching for the mark did due diligence. There have been examples of professional surveyors finding marks that were previously labeled "not found." Label marks on your map that have a high probability of being recovered, but keep all the information handy, as you may in fact be able to find/recover more difficult marks.

If you are using an OPUS shared solution, all marks will have been visited fair recently. Still, you can note the observation date (see Figure 3-18). If a mark is not in any of the NGS databases, then the accuracy of the positional data assigned to the mark (assuming you can find it) is in question, and you will likely want to obtain a new position.

The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

```
DATABASE = NGSIDB , PROGRAM = datasheet95, VERSION = 7.87.6
1        National Geodetic Survey,   Retrieval Date = APRIL 18, 2012
 HV1525 ***********************************************************************
 HV1525  DESIGNATION -  C 18 RESET
 HV1525  PID         -  HV1525
 HV1525  STATE/COUNTY-  MD/ANNE ARUNDEL
 HV1525  USGS QUAD   -  SOUTH RIVER (1993)
 HV1525
 HV1525                         *CURRENT SURVEY CONTROL
 HV1525  ___________________________________________________________________
 HV1525* NAD 83(1986)-  38 55 27.6     (N)     076 34 07.6     (W)     HD_HELD2
 HV1525* NAVD 88     -        18.039   (meters)       59.18    (feet)  ADJUSTED
 HV1525  ___________________________________________________________________
 HV1525  GEOID HEIGHT-          -33.22  (meters)                       GEOID09
 HV1525  DYNAMIC HT  -           18.029 (meters)       59.15   (feet)  COMP
 HV1525  MODELED GRAV-     980,066.6    (mgal)                         NAVD 88
 HV1525
 HV1525  VERT ORDER  -  FIRST     CLASS I
 HV1525
 HV1525.The horizontal coordinates were established by autonomous hand held GPS
 HV1525.observations and have an estimated accuracy of +/- 10 meters.
 HV1525.
 HV1525.The orthometric height was determined by differential leveling and
 HV1525.adjusted in June 1991.
 HV1525
 HV1525.Photographs are available for this station.
 HV1525
 HV1525.The geoid height was determined by GEOID09.
 HV1525
 HV1525.The dynamic height is computed by dividing the NAVD 88
 HV1525.geopotential number by the normal gravity value computed on the
 HV1525.Geodetic Reference System of 1980 (GRS 80) ellipsoid at 45
 HV1525.degrees latitude (g = 980.6199 gals.).
 HV1525
 HV1525.The modeled gravity was interpolated from observed gravity values.
 HV1525
 HV1525;                    North         East    Units  Estimated Accuracy
 HV1525;SPC MD       -   139,695.      437,393.      MT  (+/- 10 meters HH2 GPS)
 HV1525                          SUPERSEDED SURVEY CONTROL
 HV1525
 HV1525  NGVD 29 (??/??/??)   18.281  (m)            59.98   (f) ADJUSTED    1 1
 HV1525
 HV1525.Superseded values are not recommended for survey control.
 HV1525.NGS no longer adjusts projects to the NAD 27 or NGVD 29 datums.
 HV1525.See file dsdata.txt to determine how the superseded data were derived.
 HV1525
 HV1525_U.S. NATIONAL GRID SPATIAL ADDRESS: 18SUJ6400809549(NAD 83)
 HV1525
 HV1525_MARKER: DB = BENCH MARK DISK
 HV1525_SETTING: 7 = SET IN TOP OF CONCRETE MONUMENT
 HV1525_SP_SET: SET IN TOP OF CONCRETE MONUMENT
 HV1525_STAMPING: C 18 RESET 1950
 HV1525_MARK LOGO: CGS
 HV1525_MAGNETIC: O = OTHER; SEE DESCRIPTION
 HV1525_STABILITY: C = MAY HOLD, BUT OF TYPE COMMONLY SUBJECT TO
 HV1525+STABILITY: SURFACE MOTION
 HV1525_SATELLITE: THE SITE LOCATION WAS REPORTED AS NOT SUITABLE FOR
 HV1525+SATELLITE: SATELLITE OBSERVATIONS - December 21, 2010
```

Figure 3-19. Example of mark type and stability setting for a published bench mark.

The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

```
DATABASE = NGSIDB , PROGRAM = datasheet95, VERSION = 7.87.6
1        National Geodetic Survey,   Retrieval Date = APRIL 18, 2012
 AJ8027 ***********************************************************************
 AJ8027  HT_MOD       -  This is a Height Modernization Survey Station.
 AJ8027  CBN          -  This is a Cooperative Base Network Control Station.
 AJ8027  DESIGNATION -  TAMERON AZ MK
 AJ8027  PID          -  AJ8027
 AJ8027  STATE/COUNTY-  MD/ANNE ARUNDEL
 AJ8027  USGS QUAD    -  SOUTH RIVER (1993)
 AJ8027
 AJ8027                          *CURRENT SURVEY CONTROL
 AJ8027  ______________________________________________________________________
 AJ8027* NAD 83(2007)-  38 54 08.21701(N)     076 35 14.76454(W)      ADJUSTED
 AJ8027* NAVD 88      -        44.29   (meters)      145.3     (feet)  GPS OBS
 AJ8027  ______________________________________________________________________
 AJ8027  EPOCH DATE   -         2002.00
 AJ8027  X            -   1,152,883.445 (meters)                       COMP
 AJ8027  Y            -  -4,834,594.814 (meters)                       COMP
 AJ8027  Z            -   3,983,887.619 (meters)                       COMP
 AJ8027  LAPLACE CORR-           -4.78  (seconds)                      DEFLEC09
 AJ8027  ELLIP HEIGHT-           11.055 (meters)            (10/15/10) ADJUSTED
 AJ8027  GEOID HEIGHT-          -33.21  (meters)                       GEOID09
 AJ8027
 AJ8027  ------- Accuracy Estimates (at 95% Confidence Level in cm) --------
 AJ8027  Type    PID    Designation                        North   East  Ellip
 AJ8027  -------------------------------------------------------------------
 AJ8027  NETWORK AJ8027 TAMERON AZ MK                        0.51   0.43   1.14
 AJ8027  -------------------------------------------------------------------
 AJ8027  ELLP ORDER  -  FOURTH    CLASS I

<CUT>

 AJ8027_U.S. NATIONAL GRID SPATIAL ADDRESS: 18SUJ6234807130(NAD 83)
 AJ8027
 AJ8027_MARKER: DD = SURVEY DISK
 AJ8027_SETTING: 7 = SET IN TOP OF CONCRETE MONUMENT
 AJ8027_STAMPING: TAMERON AZ 1996
 AJ8027_MARK LOGO: MD-003
 AJ8027_MAGNETIC: O = OTHER; SEE DESCRIPTION
 AJ8027_STABILITY: C = MAY HOLD, BUT OF TYPE COMMONLY SUBJECT TO
 AJ8027+STABILITY: SURFACE MOTION
 AJ8027_SATELLITE: THE SITE LOCATION WAS REPORTED AS SUITABLE FOR
 AJ8027+SATELLITE: SATELLITE OBSERVATIONS - July 13, 2010
 AJ8027
 AJ8027  HISTORY      - Date      Condition         Report By
 AJ8027  HISTORY      - 1996      MONUMENTED        MD-003
 AJ8027  HISTORY      - 20000522 GOOD              NGS
 AJ8027  HISTORY      - 20010817 GOOD              MDSHA
 AJ8027  HISTORY      - 20060621 GOOD              USPSQD
 AJ8027  HISTORY      - 20100713 GOOD              NGS
```

Figure 3-20. NGS datasheet showing recent recovery information, indicating the mark was in good condition.

The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

```
DATABASE = NGSIDB , PROGRAM = datasheet95, VERSION = 7.87.6
1        National Geodetic Survey,   Retrieval Date = APRIL 18, 2012
 HV0493 ***********************************************************************
 HV0493  DESIGNATION -  Q 52
 HV0493  PID         -  HV0493
 HV0493  STATE/COUNTY-  MD/DORCHESTER
 HV0493  USGS QUAD   -  BLACKWATER RIVER (1982)
 HV0493
 HV0493                         *CURRENT SURVEY CONTROL
 HV0493  ______________________________________________________________________
 HV0493* NAD 83(1986)-  38 24 59.     (N)     076 03 18.     (W)     SCALED
 HV0493* NAVD 88     -          0.742  (meters)        2.43   (feet)  ADJUSTED
 HV0493  ______________________________________________________________________
 HV0493  GEOID HEIGHT-         -35.27  (meters)                       GEOID09
 HV0493  DYNAMIC HT  -           0.742 (meters)         2.43  (feet)  COMP
 HV0493  MODELED GRAV-     980,006.0   (mgal)                         NAVD 88
 HV0493
 HV0493  VERT ORDER  -  SECOND    CLASS 0

<CUT>

 HV0493_U.S. NATIONAL GRID SPATIAL ADDRESS: 18SVH078525(NAD 83)
 HV0493
 HV0493_MARKER: DB = BENCH MARK DISK
 HV0493_SETTING: 7 = SET IN TOP OF CONCRETE MONUMENT
 HV0493_SP_SET: SET IN TOP OF CONCRETE MONUMENT
 HV0493_STAMPING: Q 52 1942
 HV0493_STABILITY: C = MAY HOLD, BUT OF TYPE COMMONLY SUBJECT TO
 HV0493+STABILITY: SURFACE MOTION
 HV0493
 HV0493  HISTORY     - Date     Condition        Report By
 HV0493  HISTORY     - 1942     MONUMENTED       CGS
 HV0493  HISTORY     - 1977     MARK NOT FOUND   USGS
```

Figure 3-21. Sample NGS datasheet showing a mark that was listed as missing.

3.3.3 Reconnaissance and recovery

Once you have identified which bench marks could be useful to your sentinel site and are likely recoverable, then it is time to go into the field. A basic list of recommended equipment is found in Table 3-1.

How do I find a mark?

The NGS IDB datasheet provides navigation from the nearest town or major intersection to the bench mark in the station description (Figure 3-22). On the OPUS datasheet, the description is in the upper left-hand box, and an interactive map with a link to a route and directions from a user-supplied starting point is also displayed.

For a complete description, NGS requires at least five measured distances from seemingly long-lasting objects. The idea is to triangulate to the exact mark location. Read through the detailed directions first. If the directions state the mark is above the ground, you might easily see it without the need for careful measurements. If it is flush with the ground or under the soil surface, then you will probably need both the tape and the probe. Using survey flags can help line up the positions (distance and direction) as you're following the directions.

Table 3-1. Recommended equipment and supplies for a reconnaissance and recovery.

Quantity	Description	Notes
1	Map	Your map showing approximate locations of your site(s) and all bench marks of interest
varies	Datasheets	Printed NGS IDB and OPUS datasheets (and any other datasheets from other agencies if so required)
1	Safety vest	Many bench marks are near roads, so you need to ensure you work safely
1	Sharp-shooter type spade (narrow) shovel	Can help uncover marks that may have become covered by dirt or vegetation over the years
1	Work gloves	
1	Probe (such as a long screwdriver)	Can help uncover marks that may have become covered by dirt or vegetation over the years
1	Measuring tape	Recommended 100' flexible measuring tape
1	Survey flags	Bright orange or pink survey flags to signal the location of the mark
1	Camera	Pictures are important to document the location of recovered marks
1	Rain-proof notepad and pencil	Field notes are critical for recovery
1	Dry-erase board with dry-erase felt tip pens	Can be used in photographs to designate in what ordinal direction the photo is being taken
1	Hand-held GPS	Help locate mark
1	Steel-tape measure	Should be used for precise measurement rather than a flexible measuring tape

1	Magnetic locator or metal detector	Can help recover buried or covered marks
1	Compass	Needed to measure distances along azimuths from listed reference points
1	Rag, wire brush, steel wool	Helpful in cleaning a brass disk for identification and photography

Remember, bench marks are often set along roads, many of which are widened over time, and state departments of transportation do not always reset destroyed marks. As a rule of thumb, spend only up to half an hour looking for one mark – certainly not more than one hour.

```
HV1523                          STATION DESCRIPTION
HV1523
HV1523'DESCRIBED BY NATIONAL GEODETIC SURVEY 1971
HV1523'3.8 MI NE FROM HARWOOD.
HV1523'ABOUT 3.75 MILES NORTHEAST ALONG STATE HIGHWAY 2 FROM THE
HV1523'SOUTHWEST END OF THE SOUTHERN HIGH SCHOOL AT HARWOOD, AT THE
HV1523'ALL HALLOWS CHURCH, AT THE INTERSECTION OF SOUTH RIVER CLUB
HV1523'ROAD LEADING EAST AND BRICK CHURCH ROAD LEADING NORTHWEST, 188
HV1523'FEET WEST OF THE CENTER LINE OF THE HIGHWAY, 118.3 FEET EAST OF
HV1523'THE SOUTHEST CORNER OF THE MORE WESTERLY OF 2 CHURCH BUILDINGS,
HV1523'71.2 FEET SOUTH-SOUTHWEST OF THE SOUTHEAST CORNER OF THE MORE
HV1523'EASTERLY OF TWO CHURCH BUILDINGS, 8.6 FEET EAST OF THE
HV1523'SOUTHEAST CORNER OF THE BRICK PILLAR ON THE EAST SIDE OF A
HV1523'BRICK SIDEWALK WHICH LEADS TO THE SOUTH ENTRANCE OF THE MORE
HV1523'EASTERLY BUILDING, 0.6 FOOT SOUTH OF THE SOUTH SIDE OF A
HV1523'1.7-FOOT HIGH BRICK WALL ON THE SOUTH SIDE OF THE CEMETERY AND
HV1523'THE MORE EASTERLY BUILDING, ABOUT 4 FEET ABOVE THE LEVEL OF
HV1523'THE HIGHWAY, AND ON THE TOP OF A COPPER COATED ROAD WHICH IS
HV1523'LEVEL WITH THE SURFACE OF THE GROUND AND IS PROTECTED BY A
HV1523'6-INCH TILE WHICH PROJECTS 1/2 INCH.  THE ROD WAS DRIVEN TO
HV1523'REFUSAL AT A DEPTH OF 52 1/2 FEET.  NOTE-- THIS MARK IS ALSO
HV1523'3.45 MILES SOUTHWEST ALONG STATE HIGHWAY 2 FROM THE NORTHEAST
HV1523'END OF THE HIGHWAY BRIDGE OVER THE SOUTH RIVER AT EDGEWATER.
HV1523
```

Figure 3-22. Example of mark description in the NGS IDB, providing detailed directions for finding the mark. Highlighted in red is the more obvious part of the description, noting that the mark is seven inches from the cemetery wall, and eight feet away from a brick pillar.

Once you have found a mark, place a survey flag near it to help you find it later. Next, take photographs of the mark (you may need to clean the surface of the mark with a rag, wire brush, or steel wool); take a close-up photograph, then a couple location shots showing structures around the mark. Using your dry-erase board can be helpful by writing the name of the mark on the board and placing the board behind the mark in these photos. Next, take some photographs of the horizon around the mark to document any obstructions that might cause problems in a GNSS survey. All of this documentation will aid future recovery and will allow you to share a new, GNSS-derived position on the mark via OPUS.

Next, make a sketch in your notepad showing where the mark is, but also noting any obstructions in the aerial view. In the northern hemisphere, we are more concerned about having clear skies towards the south than towards the north. Furthermore, any objects that are below an angle of

20° above the horizon will likely cause minimal obstruction to your GNSS observations. You should also note whether the area can support a survey tripod, and if the location is a safe place to leave equipment for an all-day GNSS observation. If any of the distances from the description no longer apply (e.g., the metal fence is no longer there), these should be noted. Finally, if you decide to include new descriptive text for describing the position of the mark, you should note the general location of the mark, the mark setting, the starting point, the azimuth, and the distance (to the nearest centimeter).

Conducting this reconnaissance completes the work needed to plan your survey, but it would be a wonderful habit to also fill out the NGS bench mark recovery sheets.[40] The form is mobile-friendly and you can upload photos directly from your mobile device. Mark recoveries and photos can also be uploaded using DSWorld. When you choose to submit photos, make sure to review and follow NGS photo submission guidelines.[41]These additional steps give something back to the surveying community: it is a great way to let others know that you found (or did not find) a given mark and its condition. All new or updated information on a mark can be submitted to NGS, and an updated recovery entry will be posted on the datasheet. Furthermore, if you eventually take GNSS measurements at a given mark, it would be great to update the NGS IDB or OPUS datasheets with your information because not all marks have high accuracy GNSS coordinates.

3.4 Survey Planning

The final step in the preparation process is to develop a detailed survey plan, which will indicate the scope of field work required to establish the sea level change sentinel site. The plan will provide a detailed description of where infrastructure needs to be installed, where observations need to be completed, and how the work will be carried out. First, update the map with your reconnaissance information indicating marks that were not recovered, those that are too far away for leveling, or that do not have open skies for GNSS observations.

Next, identify the three or more marks which will serve to anchor the local geodetic control network to the NSRS: these are the LCMs introduced earlier. All three (or more) marks should be relatively close together and close to the monitoring infrastructure. Review the recommendations given in Section 3.3 for selecting LCMs. You do not have to rely on pre-existing marks for your local vertical control network; it is relatively inexpensive, although labor intensive, to establish concrete post marks anywhere they are needed.

> Ideally, the three primary control bench marks will have open skies to ensure excellent GPS signal reception; if high accuracy elevations are brought in to the network via leveling, then the GPS requirement is not as important.

Next, the location of the water level sensor must be evaluated carefully. The water level sensor should be placed within easy leveling distance of at least three vertical control marks, ideally, one of them being a LCM.

[40] https://geodesy.noaa.gov/cgi-bin/mark_recovery_form.prl
[41] https://www.ngs.noaa.gov/web/surveys/photo_submissions/

You may end up with monitoring infrastructure clustered in widely separated areas (e.g., upstream and downstream sites separated by several kilometers). In such cases, you may need separate local vertical control networks for each location. The same general rule would apply as before: at least three stable marks within each separate geographic location to anchor the local network to the NSRS.

Deep rod SET foundations may serve as part of your local vertical control network even as one of your three (minimum) local control marks (LCMs), especially if the mark went very deep [e.g., 24+ meters (m) or 80+ feet (ft)]. Different techniques have been used over the years for establishing these SET marks. The early manual pile-driving technique probably resulted in shallower sediment depths and, marks installed using this method are correspondingly less stable compared to the more current method, which uses a 27-kg (60-lb) jackhammer, following NGS guidelines for setting deep rod marks (e.g., Smith, 2010).

The next step is to propose survey techniques (e.g., leveling or GNSS) to bring accurate elevations into your control network (Section 6), and from there to each of your monitoring components (water level gauge, SET marks, vegetation plots, etc.; Section 7). Leveling is the recommended survey method to transfer accurate elevations to the water level sensor; leveling is also recommended to connect other monitoring infrastructure as long as the physical separation between components is not too great. However, in certain cases leveling may be impractical or impossible. First, leveling will require access to at least two existing bench marks (ideally separated by at least 500 m) to begin the level line. Leveling is land-based, so you can cross creeks and streams, but crossing open bodies of water (>70 m across) is very difficult and may require specialized surveying instrumentation and methodologies. Additionally, leveling is difficult in soft, unstable soils such as wetlands (especially where the wetland is broken up). Whenever leveling is proposed, the techniques used and a target misclosure error is specified in the survey plan (Table 2-4). This will provide an expectation of precision and accuracy for the leveling in the project. When leveling is not possible, elevations can be transferred via GNSS-based techniques (e.g. Static GNSS or RTK GNSS). If planning to use GNSS, describe a plan for taking the required multiple ≥4-hour observations on the LCMs, and identify any/all simultaneous GNSS sessions.

If you plan to level from your local control marks to one or more monitoring components, it can be helpful to have additional local bench marks adjacent to the monitoring component(s). This way, you need only to make a one-setup connection between your network and a monitoring component. This will enable a rapid check on the vertical integrity of the connection and minimize potential errors if having to survey over long distances.

At this stage, your map should be complete, and we will turn our attention to the techniques used to build the geospatial infrastructure for the sentinel site. Once you feel comfortable with the methods, then we advise you to revisit the survey plan, review the specific techniques assigned to specific components, and revise them accordingly (if necessary).

When you have a fully developed geodetic and tidal control plan, you may have to submit it to your agency for approval. It is highly recommended that you also seek the advice of NGS and CO-OPS to review and comment on the plan, to make sure that the plan is sound and to ensure that the best techniques for the job will be used. An example of a successful survey plan is given in Appendix 2.

4. ESTABLISHMENT OF WATER LEVEL INFRASTRUCTURE AND AN INTRODUCTION TO WATER LEVEL ANALYSES

This section provides the guidelines for establishing your local water level sensor/water level gauge and provides preliminary information on what it will take to routinely analyze water levels and generate water level products. The goal of this section is to familiarize the reader sufficiently to enable appropriate investments, whether it be in the physical infrastructure, or in the software and training for analyses.

By the time the installation of any water level infrastructure is to begin, decisions have already been made regarding what kind of equipment and materials will be needed and where they will be placed. The type of water level sensor (including sensor deployment) and Local Control Marks you plan to install will have been included in the detailed survey plan discussed in Section 3 of this document. Section 5 provides guidance on establishing new marks if they are needed. Section 6 provides instructions on how to connect the local network of bench marks to the National Spatial Reference System (NSRS) to establish accurate positions, especially in the vertical dimension. Section 7 provides guidance on connecting all the sentinel site components locally, so accurate positions are established relative to each other.

4.1 Establishing Water Level Infrastructure

The first subsection (4.1.1) provides a brief synopsis of the major requirements for a CO-OPS water level station. If this is the infrastructure chosen, the reader is referred to official documentation for further details. Such installation and maintenance is very rigorous, but will provide data that will be comparable to the NWLON. The second subsection (4.1.2) provides guidelines for less expensive, commercially available water level systems such as those provided by YSI®. Regardless of the sensor and installation type, much of the basic installation infrastructure, stability, and reliance on local bench marks will be similar and will provide high quality water level data. As a result, you can follow and adapt many of the recommendations and best practices described throughout this section.

4.1.1. Establishing water level infrastructure to CO-OPS standards

If the intention is to install a water level station to CO-OPS standards, then you must follow CO-OPS specifications. The appropriate references for the installation and maintenance of a water level station, including references for computations are found here[42] (October 2013) on the CO-OPS website[43]. Below is a brief description of the essential elements of a CO-OPS water level station.

Basic components:

- A self-calibrating air acoustic, pressure (vented) or other water level sensor approved by CO-OPS collecting six-minute (i.e., :00, :06, :12, etc.) time series data and mounted on a stable platform.
- A data collection platform or data logger capable of acquiring and storing six-minute data along with the standard deviation from the averaging sample.

[42] https://tidesandcurrents.noaa.gov/publications/CO-OPS_Specifications_and_Deliverables_for_installation_operation_and_removal_of_water_level_stations_updated_October_2013.pdf
[43] https://tidesandcurrents.noaa.gov/pub.html

- A set of tidal bench marks established in the vicinity of the water level station, with high accuracy leveled connection to the gauge.
- Data transmission and communication [e.g. Geostationary Operational Environmental Satellites (GOES) transmitter, IP modem, phone, etc.].

The air acoustic sensor is established on the vertical face of a very stable pier or piling. The air acoustic sensor is housed in a secured "top hat," attached to a sounding tube enclosed in a PVC protective well and clamped to a large pier or piling such that it is stable (Figure 4-1a) and protected from impact and human disturbance. The sensor leveling point is the top of the collar on the sounding tube. The sensor is established at an elevation such that the sensor is able to record water level data lower than the lowest expected water level. Essentially, the sensor must capture all phases of the tide. This requires some knowledge of the tidal characteristics of the area (Section 3.2). In addition, the sensor's operating range is greater than the expected range of water levels, and the resolution is a function of the tidal range of the area of study.

Important Information
Sensor Resolution
- For tidal range **less than or equal to 5 m**: the required water level sensor resolution shall be 1 mm or better.
- For tidal range **between 5 m to 10 m**: the required water level sensor resolution shall be 3 mm or better.
- For tidal range **greater than 10 m**: the required water level sensor shall be 5 mm or better.

The vented pressure sensor is incorporated into a gas purge system. The orifice is mounted on the vertical surface of a piling, so that the precise elevation of the orifice outlet (orifice zero) below the orifice leveling point is measured with a steel-tape (Figure 4.1b). This orifice zero is also established at an elevation lower than the lowest expected water level. The orifice leveling point is established vertically above the orifice outlet. The orifice leveling point is included in the level run along with the tidal bench marks supporting this station. Some manufacturers design a leveling point on the sensor for this purpose; check with the manufacturer to verify where the point is, if present. The sensor (acoustic or pressure) must be accessible for annual and emergency maintenance.

The water level data are referenced to the calibrated "sensor zero" point. This zero point is also typically referenced to an arbitrary Station Datum (related to a local tide staff or height below pier, etc.) The Station Datum is connected to the local network of tidal bench marks, which is accomplished by leveling among the bench marks and the sensor leveling point. Once a NAVD 88 elevation is obtained on these tidal bench marks, it is transferred to the sensor leveling point and thereby provides a relationship between Station Datum and NAVD 88. Re-leveling to check stability is recommended every time the sensor is serviced/replaced or otherwise moved, or a strong storm is suspected to have moved the sensor. Refer to Section 7 for a description of leveling techniques. If the sensor has moved over the course of a deployment or if movement is identified during stability check leveling, then a linear offset can be computed and applied to the water level data to account for the vertical movement.

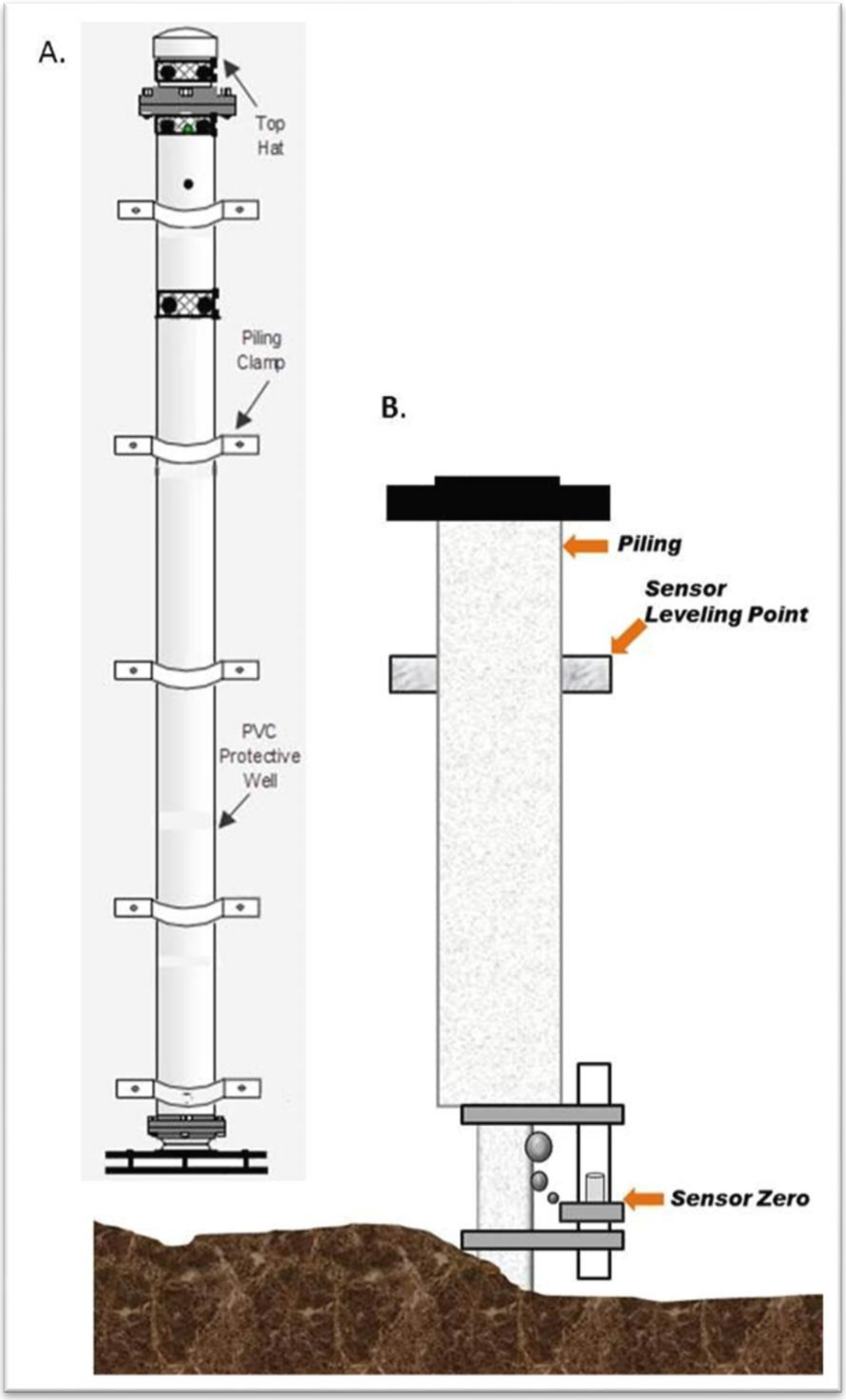


Figure 4-1. Examples of CO-OPS water level sensor installations: (A) air acoustic sensor within protective well; (B) vented pressure sensor attached to piling.

Continuous operation of a CO-OPS water level station requires access to continuous, uninterrupted power from either a battery or electricity. This requires a battery or access to reliable electrical power. Solar cells are often used to recharge batteries, especially if they are the main source of power. Telecommunications equipment is required to download the data, circumventing the problem of limited data storage onsite. Otherwise, data must be downloaded during onsite visits.

4.1.2. Establishing a YSI-type water level sensor

Basic water level infrastructure for a sentinel site will include:

- water level sensor with both precision and accuracy[44] at the three-millimeter (mm) level or better, a data collection and storage platform with adjustable data recording frequency and mounted on a stable platform.
- a set of tidal bench marks established in the vicinity of the water level station, with leveled connection to the gauge and sensor.

The sensor is typically deployed inside a sturdy PVC protective well with perforations or intake to allow unimpeded vertical water movement, yet protect the sensor from damage or accidental movement. The sensor must be installed in sufficiently deep water to avoid exposure during low water events. If the sensor becomes exposed during low waters, the water level data will have discontinuities. Therefore, some knowledge of the local tidal characteristics is very helpful prior to deployment (Section 3.2).

The protective well must be firmly anchored to a stable structure, such as a pier, piling or bulkhead (Figure 4-2). Ideally, the well is placed in a sheltered part of a pier, or even within the pier itself to avoid accidental disturbance, such as occurs with boat traffic. Once firmly anchored, the sensor must not move in the presence of wave and current action, with minimal vertical and horizontal displacement occurring. If the protective well or the entire structure to which the well is attached moves, so will the sensor. The result will be a jump in the data; although some vertical sensor shifts can be corrected (especially with good records of changes in the vertical position of the sensor through surveying), stability of the attachment structure is essential for high quality data.

In Figure 4-2, the stainless-steel bolt crossing through the diameter of the well (at the bottom) is used not only to anchor the well to the pier under water, but also to provide a stable resting place for the sensor enclosure. The top side of this bolt is a vertical reference mark for the pressure sensor if the distance between the bolt and sensor zero are known. The sensor zero is the theoretical point at which the sensor measures the data. The location of this point should be identified in the pressure sensors' manufactures specifications.

Important Information
Measuring to the Sensor Zero
During the installation of the sensor, measure and record the distance between the pressure sensor zero and the bolt on which the sensor enclosure rests. This measurement when applied to the elevation of the bolt with respect to the known datum (derived via leveling and steel tape measurements) will calculate the elevation of the sensor zero relative to the known datum.

[44] Accuracy assumes correction for local atmospheric pressure (vented probe or local atmospheric pressure data)

Once the pressure sensor is installed, a sensor leveling point needs to be established. The sensor leveling point is established at a point on or directly above the structure where the sensor is installed. In Figure 4-2, the metal rod is the sensor leveling point. The leveling point is described and included in the bench mark leveling scheme (this mark will not count as one of the three required bench marks for your water level station). This point is also leveled at the same defined frequency as the other bench marks in the network.

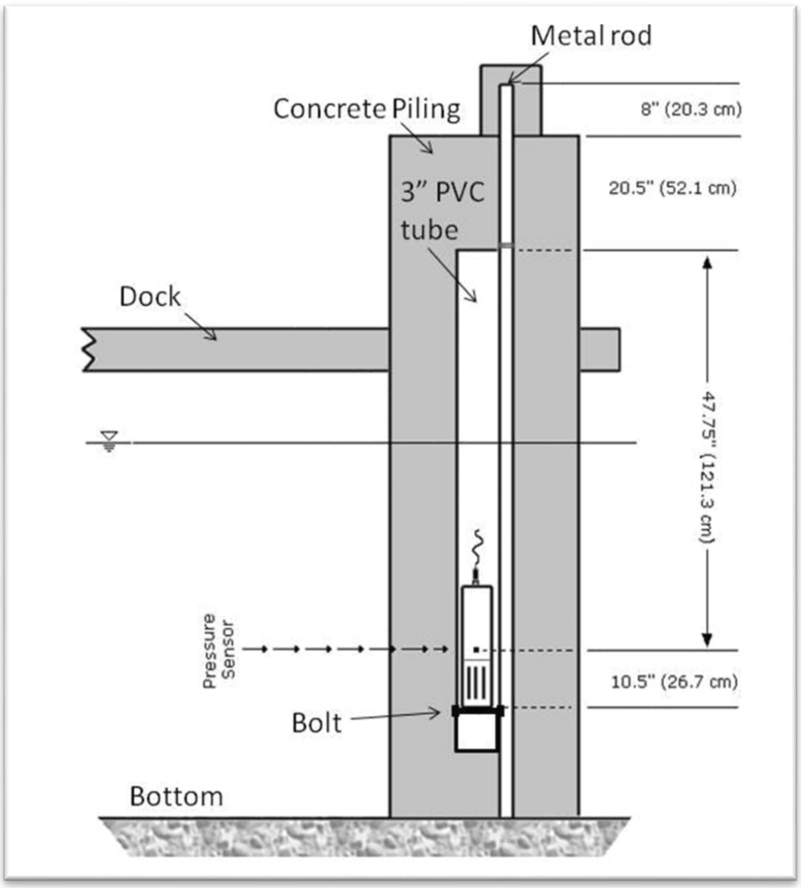


Figure 4-2. Diagram showing the protective well attached to the pier and pressure sensor resting on a bolt at the bottom of the well. Diagram courtesy of Tom Opishinski, the Smithsonian Institution.

After the pressure sensor leveling point is determined and a leveled connection is established to a known datum, the elevation of the bolt and the pressure sensor zero can be derived relative to a known datum as follows:

- Measure and record the distance, with a steel-tape, between the sensor leveling point and the top of the bolt.
- When this distance is algebraically applied to the elevation of the sensor leveling point (derived via leveling), the elevation of the bolt above the known data is derived.
- The sensor zero elevation can be derived relative to the elevation of the bolt.

Each time the sensor is serviced, or if there is any reason to suspect the sensor may have moved (e.g., after severe storms, impact to the pier, etc.), you should check the height of the bolt with respect to the sensor leveling point. If significant damage occurs to the sensor or the structure to which it is anchored, digital leveling between the sensor leveling point and a nearby tidal bench mark is recommended. Otherwise, check level connections between all supporting tidal bench marks and the sensor on a yearly basis.

At least three (3) bench marks will be leveled as part of the local water level station bench mark network. Refer to Section 7.1 for guidelines on leveling to the sensor leveling point. These bench marks can be a combination of existing bench marks, such as NOS tidal and geodetic marks or other agency bench marks. The deep rod of the surface elevation table (SET) can be incorporated into the (tidal) bench mark network. Other marks established as part of the local geodetic control network can also be used as part of the water level station network (they can be one and the same). For long-term deployments in remote areas and long-term wetland projects (e.g., several years or longer), the establishment of deep rod bench marks should be considered in the vicinity of the water level station to ensure long-term stable vertical reference control points. At least one of these permanent bench marks should be established in the open (preferably in a stable, upland setting) away from large trees, shrubs, telephone poles or buildings to ensure proper “horizon” for GNSS occupation (see Section 6).

The YSI-type water level sensors may be part of a larger multi-sensor assembly. Whereas the pressure sensor itself is relatively robust to fouling, the accompanying sensors may not be (especially, optical sensors). Therefore, if other, more sensitive sensors are also deployed, they may become fouled very quickly, resulting in much shorter deployment periods and a much higher frequency of sensor maintenance. This has important repercussions regarding sensor stability given the high frequency of sensor switch outs.

Ideally, the sensor will be configured to record data every six minutes, which will ensure highest accuracy tidal datum estimates, especially for higher high water and lower low water datums. Longer time intervals may lead to under-recording the necessary high and low water events needed to compute the higher and lower tidal datums. Due to sensor storage and/or battery capacity it may not be feasible to collect data at the same six-minute interval as with the NWLON sensors. Increasing the frequency of the data collection interval can result in rapidly filling available memory if memory is stored within the instrument itself or within an accompanying storage module. This leads to more frequent sensor maintenance. For this reason, it is recommended to either download the data to a separate but local data logger (or storage module) or transmit it directly via telecommunications equipment.

Continuous power is required to prevent unwanted data gaps. This might be an issue with extended deployments. Direct electric hookup is ideal, but battery backup is important in the case of power failure, such as during storms. Solar panels may allow backup batteries to keep their charge.

Recommendations related to pressure sensor type water level sensor

- For the most accurate water level readings from a pressure sensor, a correction for atmospheric pressure must be applied to the data. This can be done automatically using a vented pressure sensor. With non-vented sensors, water level is measured by a non-vented strain gauge and is calculated as pressure exerted by the water column minus atmospheric pressure. In this situation, water level data must be corrected using simultaneous atmospheric pressure readings from a nearby barometric pressure sensor. Otherwise, if no local data are available, atmospheric pressure can be obtained from the nearest meteorological station. However, the farther away the station, the greater the additional error. Some bias may exist if the sensors are at very different elevations. Note that the atmospheric correction does not change the sensor precision but does affect its accuracy.

- Factors influencing the deviation of depth from water pressure include barometric pressure, water density, and water temperature. For this reason, deploying simultaneous water temperature and salinity probes can help remove some error in the water pressure signal (calibration curves will have to be developed accordingly). Density changes are especially prevalent in tidal rivers where the saltwater wedge moves up and downstream with the tide. For longer deployments in some areas, the significant variation in water density occurs at seasonal time scales rather than with the daily tides, and water density should be monitored to provide correction where needed. Conductivity sensors would need to be deployed if variations in water density are a potential source of significant error. To derive height using the pressure equation (pressure = density × specific gravity × height), the local specific gravity measurement will be needed for the study area. The local surface gravity prediction can be found on the NGS webpage.[45]

Recommendations related to sensor calibration

- To obtain accurate water level data from pressure sensors, the sensors must be calibrated pre-deployment and the calibrations checked between re-deployments. Note that these types of instruments are subject to sensor drift, which must be corrected or accounted for during post-processing. For long-term deployments (i.e., of a year or more), the sensor should be swapped out with a newly calibrated sensor, and the old one should undergo a calibration check and major servicing before redeployment. Review the manufacturer's sensor specifications document for suggested calibration procedure and frequency. Calibration metadata should be stored in a database for future referencing.
- Optimally, pressure sensors should be operated for several hours prior to deploying the instrument to confirm the depth calibration (which is typically performed using barometric pressure offsets) as well as check for any sensor drift. In Figure 4-3, a typical YSI-type water level sensor is shown in a calibration bucket. By taking several hours of readings in the calibration bucket prior to deployment, one can check the depth (i.e., water level) measurements from the instrument (which should in this case be the distance H2) with an independent measurement of depth (using a steel-tape measure to measure the distance H2).

[45] http://www.ngs.noaa.gov/cgi-bin/grav_pdx.prl

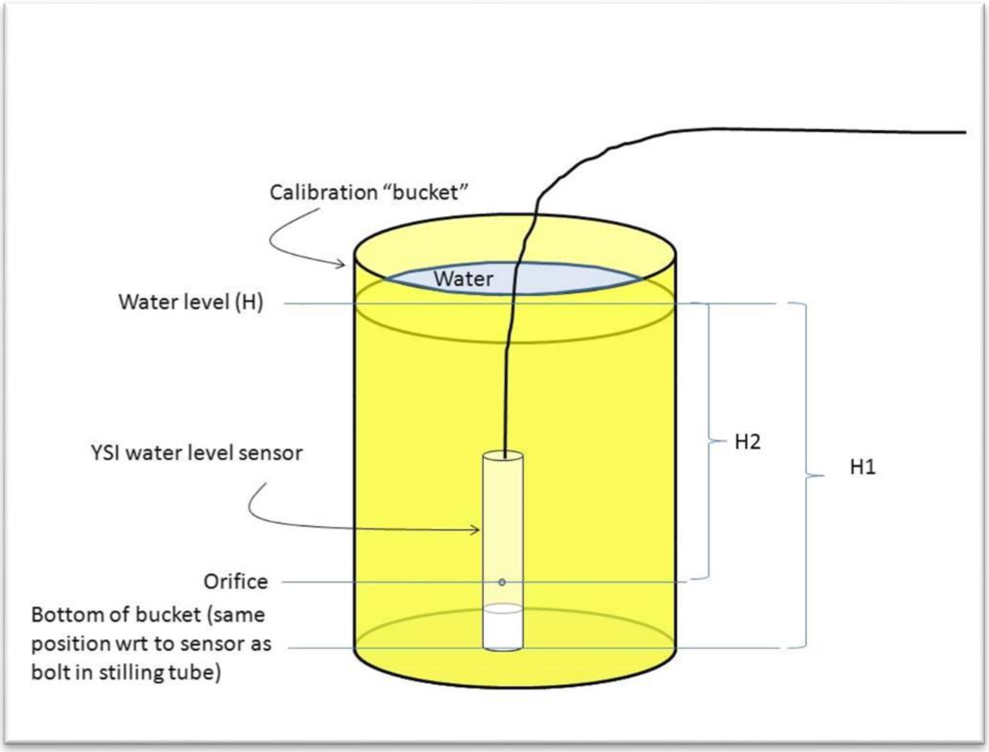


Figure 4-3. Pre-Calibration Technique for Vented (YSI Type) Water Level Sensor.

Recommendation related to local tidal bench mark network

- The elevation of the water level sensor zero (the pressure port or strain gauge) must be precisely measured to a physical sensor reference point on the supporting structure. This measurement must be done at installation and repeated on a periodic basis to check for vertical stability. This sensor leveling point should be located directly above the sensor on the supporting structure and can be a bolt head, a metal flange, a survey bar, a nail spike head, etc. as long as it is vertically stable and long-lasting. Steel tape measurements are acceptable for measuring from the sensor leveling point to the sensor zero or an established sensor reference mark. Note: It is good practice to describe and take a photograph of the sensor leveling point to ensure repeatability of this measurement.

Deployment Techniques

- Many of the project areas are located in remote wetlands away from roads and population centers. The recommended deployment technique is as described above, with a sensor located on a stable piling, close to a permanent, leveled tidal bench mark network. However, a number of other deployment techniques can be found in response to site-specific conditions and legacy water level programs. Examples range from protective wells attached to offshore structures (i.e. platforms or telephone pilings) (Figure 4-4) to sensors hanging from a chain or cable, which are not recommended methods. In some situations, the platforms on which the instruments are mounted are not stable or maybe too far offshore for more traditional surveying techniques (such as digital leveling or laser leveling). In addition, some instruments might be situated in an area that is intertidal and/or the sensor is positioned in the water column such that capturing the full range of the tide is unattainable. In these situations, the sensor would need to be re-established on a stable structure, at an elevation low enough to capture the full range of tide, and in a location suitable for differential leveling.

Figure 4-4. Examples of NERRS Water Quality Stations. Going from top left and moving clockwise. Offshore station at Mission Aransas NERR in Mesquite Bay, Texas (protective well is the red tube attached to the inside of the left piling). Shallow water station showing protective well in waters off of Goodwin Island Reserve Component of Chesapeake Bay NERR (CBNERRVA). Static GNSS occupation on survey bar of CBNERRVA Taskinas Creek water quality station. Radar Gauge, and water quality stilling protective at end of piling adjacent to Sweet Hall Marsh Reserve at CBNERRVA.

Summary of Best Practice Considerations when Establishing Water Level Stations

- Required:
  - documented vertical stability of the sensor
  - catching full range of tide
  - sensor zero referenced to local bench mark network
  - pre- and post-calibration of water level sensor

  - data sampling at any consistent interval with a frequency of one point per hour or higher if using simultaneous datum computation method is based on a NWLON station
- Recommended
  - use of protective stilling well for water level sensor
  - extra probes to measure salinity, temperature, etc.
  - 6-minute data acquisition/recording interval
  - location relative to other monitoring infrastructure
- Optional
  - in range of NWLON
  - vented water level pressure sensor
  - duration of time between sensor swap outs (dependent on field conditions)
  - external power supply
  - data acquisition or sampling rate (60 seconds, four seconds, etc.)
  - location of the sensor (inlet condition vs. more open shoreline)

4.1.3. Case studies of YSI-type water level station deployments from the NERRS

Case Study 1: North Carolina – Marsh Productivity Study

Objective: Provide support for wetland productivity/sea level change study – specifically examining relationships between tidal wetland biomass and elevation.

- Instrument: YSI600 LS (1 mm resolution with +/-3 mm accuracy)
- Pre- and post-calibration of water level sensor: Yes, following established protocols
- Vented sensor: Yes
- Atmospheric pressure correction: automatic (within sensor)
- External battery: Yes (Solar)
- Data acquisition window: 60-second sampling burst
- Data interval: 6 minutes
- Extra probes to measure salinity: Yes
- Use of protective well: Yes
- Sensor measuring full range of tide: Yes
- Time between instrument switch outs: four months
- Stability of sensor: on a stable platform
- Local bench mark network: Yes
- Sensor zero referenced to local bench mark network: Yes, and repeated elevation surveys every four months with each instrument maintenance event
- In range of NWLON station: Yes
- Location near transects/research: Yes

Outcome: Researchers were able to calculate an equivalent 19-year datum at the local water level station using CO-OPS protocols. This equivalent datum was plotted on a frequency and duration histogram along with ecological data to help describe how plant growth varies relative to the frequency and duration of high-water events. This work established a robust water level observing station that can monitor local water levels for the long term, with water levels referenced to NAVD 88.

Case Study 2 –South Slough Reserve, Oregon

Objective: Provide support for sentinel site network monitoring and in proximity to other wetland monitoring infrastructure such as SETS, vegetation plots, and groundwater wells and used for specific research projects for inundation.

- Instrument: YSI6600 V2 (1 mm resolution with +/-20 mm accuracy before atmospheric corrections)
- Pre- and post-calibration of water level sensor: Yes, following NERR System-Wide Monitoring Program (SWMP) protocols
- Vented sensor: No
- Atmospheric pressure correction: Yes
- External battery: No
- Data acquisition window: 4-second sampling burst
- Data interval: 15 minutes
- Extra probes to measure salinity: Yes
- Use of protective well: Yes
- Sensor measuring full range of tide: Yes
- Time between instrument switch outs: monthly
- Stability of sensor: stable; on a pier
- Local bench mark network: Yes
- Sensor zero referenced to local bench mark network: Yes, ran levels from a single point which was established using GNSS techniques; no repeat surveys at this time
- In range of NWLON station: Yes
- Location near transects/research: Yes

Outcome: Water quality station can now serve as a secondary water level station (>1 year and <19 years) and staff were able to calculate an equivalent 19-year datum at the local water level station; however, more error introduced than in Case Study 1 due to error from interpolating the 15-minute data to six-minute data (or calculating local datums for the simultaneous comparisons with 15-minute data), error due to the small data acquisition window (staff were not able to accurately discern lower lows of tides), and error introduced by having an unvented sensor (which requires collecting simultaneous barometric pressure data and making corrections). South Slough staff also use local water level station data to compare monthly means against the local NWLON station. This work established a robust water level observing station that can monitor local water levels for the long term, with water levels referenced to NAVD 88.

Case Study 3 – Chesapeake Bay NERR, Virginia

Objective: Part of Sentinel Site Monitoring Network at CBNERRVA. Specifically, a long-term study examining wetland change in a formerly tidal freshwater wetland due to sea level change, subsidence, and salinity intrusion issues.

- Instrument: YSI6600 V2 (1 mm resolution with +/-20 mm accuracy before atmospheric corrections)
- Pre- and post-calibration of water level sensor: Yes, following NERR SWMP protocols
- Vented sensor: No
- Atmospheric pressure correction: Yes
- External battery: No
- Data acquisition window: 4-second sampling burst
- Data Interval: 15 minutes
- Extra probes to measure salinity: Yes
- Use of protective well: Yes
- Sensor measuring full range of tide: Yes
- Time between instrument switch outs: two weeks
- Stability of sensor: stable: on pier
- Local bench mark network: Yes
- Sensor zero referenced to local bench mark network: Yes, local bench mark network established using GNSS and digital leveling techniques. No repeat surveys to this point.
- In range of NWLON station: No
- Location near transects/research: Yes

Outcome: This station cannot serve as a secondary water level station, and an equivalent 19-year datum at the local water level station will not be calculated (because this station is currently within an NWLON gap); however, hourly elevation, monthly means, high water events, and other tidal parameters can still be calculated and compared annually to compare water level trends to trends in wetland surface monitoring (through SETs) and wetland vegetation community changes. Potential options could be to transfer datums from the tidal bench marks of the historical Lestor Manor water level station (upriver), although no information is currently available on the condition of marks. This work established a robust water level observing station that can monitor local water levels for the long term, with water levels referenced to NAVD 88.

4.2 Water Level Analyses

Data collected from the field must be processed before tidal datums are computed; data processing includes quality control and assurance of the data, data editing, and filling gaps. After processing the data, the times and elevations of the high and low tides and the hourly elevations are tabulated. For more detailed descriptions of the processes described in Section 4.2.1, see Coast and Geodetic Survey (1965) and NOS (2013).

4.2.1 Data processing

Data Continuity: For computing tidal datums, it is very important to ensure a complete, continuous dataset over time. As is discussed below, small data gaps can subsequently be interpolated, however any interpolation will result in additional errors in the analysis (however this is better than no estimate at all).

Sampling: Six-minute water level data (e.g., 0:00, 0:06, 0:12, 0:18, etc.) provide highly accurate estimates of all tidal datums. Such high frequency enables an accurate determination of exactly when a high or low water event has occurred, which is important in tabulating the high and low water datums. Longer sampling rates can be used, however these intervals may truncate the tidal signal in strongly tidal areas and create large inaccuracies.

Six-minute data are required to use an NWLON station's tidal datums to calculate a NTDE equivalent tidal datum at the local water level station. Data recorded at longer frequencies must be interpolated to meet this requirement, which will introduce error in the tidal datum calculations.

Quality Control: The data should be checked against sets of tolerances that can be based on both the nearest NWLON data and the local observed water level data. Note that it is always useful to look at NWLON data and compare it to your local water level data, even if your local site is within an NWLON gap. The published NWLON data provide a reasonable estimate for tolerance checks, which include:

- Maximum expected water level elevation (information collected in Section 3.2)
- Minimum expected water level elevation (information collected in Section 3.2)
- Expected rate of change between data points (based on observed data)
- Data flats (expected number of sequential data points allowed to be the same, for instance five sequential 6-minute data points)
- Presence of data gaps

Data not meeting tolerance checks are reviewed to identify whether problems are due to instrument or data communication failure or to due anomalous conditions such as weather events (frontal passages), seiche, storm surge, tsunamis, etc. The reviewers use graphical and tabular summaries of simultaneous comparisons with (1) any available backup sensors, (2) data from nearby stations, or (3) predicted tides.

CO-OPS also takes advantage of information contained in each 6-minute sample of the acoustic primary sensors used in the NWLON. Each sample is the average of high-rate samples (181, 1-second samples in a 3-minute period) for the Aquatrak acoustic sensor, centered every tenth of an hour). The value of three times the standard deviation of the mean is used to reject individual 1-second samples. The reported 6-minute data include the re-computed mean, the standard deviation, and the number of rejected outliers. For pressure sensors, each 6-minute data point is the average of 36 samples taken every 5 seconds over the 3-minute period, instead of every 1 second, but a mean and standard deviation are still taken from the 3-minute time period centered every 6-minutes. The numerical values of standard deviation and outliers are typically a function of sea state, and values out-of-tolerance could indicate potential system problems. These statistics, which can be useful in quality control, may not be available with all sensor types.

Data Editing and Gap Filling: Invalid or bad data are edited or deleted, creating a gap. These manually created gaps and those caused by other problems (e.g., sensor malfunctioning) are then filled using a variety of procedures. Data may be plotted to examine the data quality and to determine what kind of gap filling may be required. If gaps are small, (<4 hours), then an interpolation of the missing data points using curve-fitting techniques is usually adequate. If gaps are up to three days, then the gaps may be filled with back-up water level data (if available), with predictions, or by comparison of data with a nearby station after amplitude gains and phase offsets are computed. It is standard procedure to avoid filling tidal time series for gaps longer than three days, as the reliability of these fills is questionable. Monthly means must not be computed if gaps are over three days.

4.2.2 Tabulation of the tide

Derived products from the water level data include the tabulation of the times and elevations of the high and low tide and tabulation of hourly elevations. Tidal parameters from these daily tabulations of the tide are then reduced to mean values, typically on a calendar month basis for long-term records or over a few days or weeks for shorter-term records.

The tabulation of the tides requires going through the process of picking them. This can be done by graphing the quality-controlled data and manually choosing the highs and lows corresponding to the expected tidal signal (diurnal, semidiurnal, or mixed tides; Figure 4-5). Care must be taken if picking the tides manually to ensure that all the appropriate diurnal or semidiurnal components are selected even when irregular conditions hold (e.g., meteorological tides). Private vendors and publicly available software products are available to pick tides according to tide type. CO-OPS uses a least-squares, third-degree polynomial curve fit to the 6-minute data around the time of each high or low water to select each tide. Some users fit even higher order polynomials. Note that the exact curve fit algorithm is not crucial, as long as the curve fit does not artificially reduce the tidal signal being tabulated. The purpose is to filter through the high frequency noise often seen in the 6-minute data due to wind waves and sea state without biasing the resulting selection of a high or low tide. Hourly elevations are simply every tenth 6-minute data point on the hour. There is no filtering or smoothing done to tabulate the hourly elevations.

For semidiurnal and mixed tide types, the higher highs and lower high waters are distinguished by pairing tides each tidal day sequentially throughout each calendar month to determine which one is the highest or lowest of the pair. To check the correct picks, plot the data separately for each month, adding the last day of the preceding month and the first day of the subsequent month, to make sure you can properly identify the first tide of the month. Figure 4-6 shows the result of having chosen higher high tides, high tides, low tides, and lower low tides for a semidiurnal tidal signal. For diurnal tides, CO-OPS uses a 25-hour algorithm to distinguish the higher highs from the lower lows by examining each 25-hour time period. This is necessary because in areas of diurnal tides, secondary lower highs and higher lows do not occur during many days in any given month.

HIGH/LOW WATER LEVEL DATA **March 2006 National Ocean Service (NOAA)**
Station: 8656483 **T.M.: 0 W**
Name: BEAUFORT, DUKE MARINE LAB, NC **Units: Meters**
Datum: Station Datum
Note: > Higher-High/Lower-Low [] Inferred Tide **Quality: Verified**

	High		Low			High		Low	
Day	Time	Height	Time	Height	Day	Time	Height	Time	Height
---	----	------	----	------	---	----	------	----	------
1	> 1.2	1.704	7.4	0.323	16	> 1.3	1.578	7.3	0.573
	13.8	1.688	> 19.8	0.319		13.6	1.535	> 19.3	0.586
2	> 2.0	1.754	> 8.4	0.357	17	> 1.9	1.641	7.8	0.646
	14.4	1.693	20.6	0.451		14.1	1.536	> 19.8	0.624
3	> 3.0	1.672	> 9.1	0.409	18	> 2.5	1.653	8.6	0.718
	15.4	1.651	21.2	0.551		14.7	1.497	20.4	0.659
4	> 3.6	1.816	10.2	0.538	19	> 2.8	1.635	> 9.4	0.584
	16.0	1.514	> 22.0	0.520		15.1	1.399	> 20.9	0.599
5	> 4.7	1.666	> 10.9	0.553	20	> 3.7	1.588	10.0	0.631
	16.9	1.404	22.9	0.557		16.0	1.345	> 21.5	0.592
6	> 5.4	1.566	11.9	0.634	21	> 4.6	1.549	10.6	0.725
	17.6	1.332				16.8	1.484	> 22.1	0.648
7	> 6.1	1.595	> 0.3	0.586	22	> 5.6	1.664		
	18.8	1.333	> 13.2	0.700		17.8	1.324	12.3	0.734
8	> 7.7	1.641	0.8	0.766	23	> 6.2	1.529	0.0	0.657
	19.8	1.355	14.1	0.815		18.5	1.256	> 13.3	0.629
9	> 8.4	1.523	> 2.1	0.652	24	> 7.5	1.557	> 1.1	0.610
	21.0	1.316	15.3	0.719		21.0	1.299	14.3	0.664
10	> 9.5	1.509	> 3.1	0.641	25	> 9.0	1.662	> 2.0	0.584
	22.1	1.270	16.8	0.659		21.1	1.501	15.1	0.674
11	> 10.6	1.387	> 3.9	0.520	26	> 9.8	1.740	> 3.3	0.546
	22.7	1.295	16.9	0.511		22.1	1.578	16.1	0.592
12	> 11.2	1.501	> 4.5	0.493	27	> 10.8	1.731	> 4.2	0.456
	23.5	1.380	17.3	0.543		23.2	1.700	16.9	0.463
13	11.9	1.497	> 5.3	0.499	28	> 11.6	1.715	5.4	0.392
			17.9	0.546		> 23.9	1.731	> 17.8	0.331
14	> 0.3	1.513	> 6.3	0.538	29			> 6.4	0.260
	> 12.5	1.544	19.0	0.593		12.4	1.638	18.4	0.308
15	0.7	1.469	> 6.1	0.435	30	> 0.8	1.806	7.2	0.350
	13.0	1.435	> 18.6	0.506		13.2	1.658	> 19.2	0.343
					31	> 1.7	1.831	8.1	0.432
						13.8	1.570	> 19.9	0.358

Highest Tide: 1.831 1.7 hr Mar 31 2006
Lowest Tide: 0.260 6.4 hr Mar 29 2006
Monthly Means:

MHHW 1.633
MHW 1.549 DHQ 0.084
MTL 1.048 **GT 1.117 HWI 0.18 hr**
DTL 1.075 **MN 1.001 LWI 6.34 hr**
MSL 1.046
MLW 0.548 DLQ 0.032
MLLW 0.516

Figure 4-5. Tabular example of a monthly tabulation of the tide.

Note for the purpose of computing an NTDE equivalent datum, you will also need the high and low tide data points from the NWLON station for the same period over which the data were observed at the local water level station. This can be obtained from the CO-OPS website,[46] by choosing a station, navigating to its water levels, and selecting H/L as well as the relevant time period in the plotting options.(Figures 3-3 and 3-4)

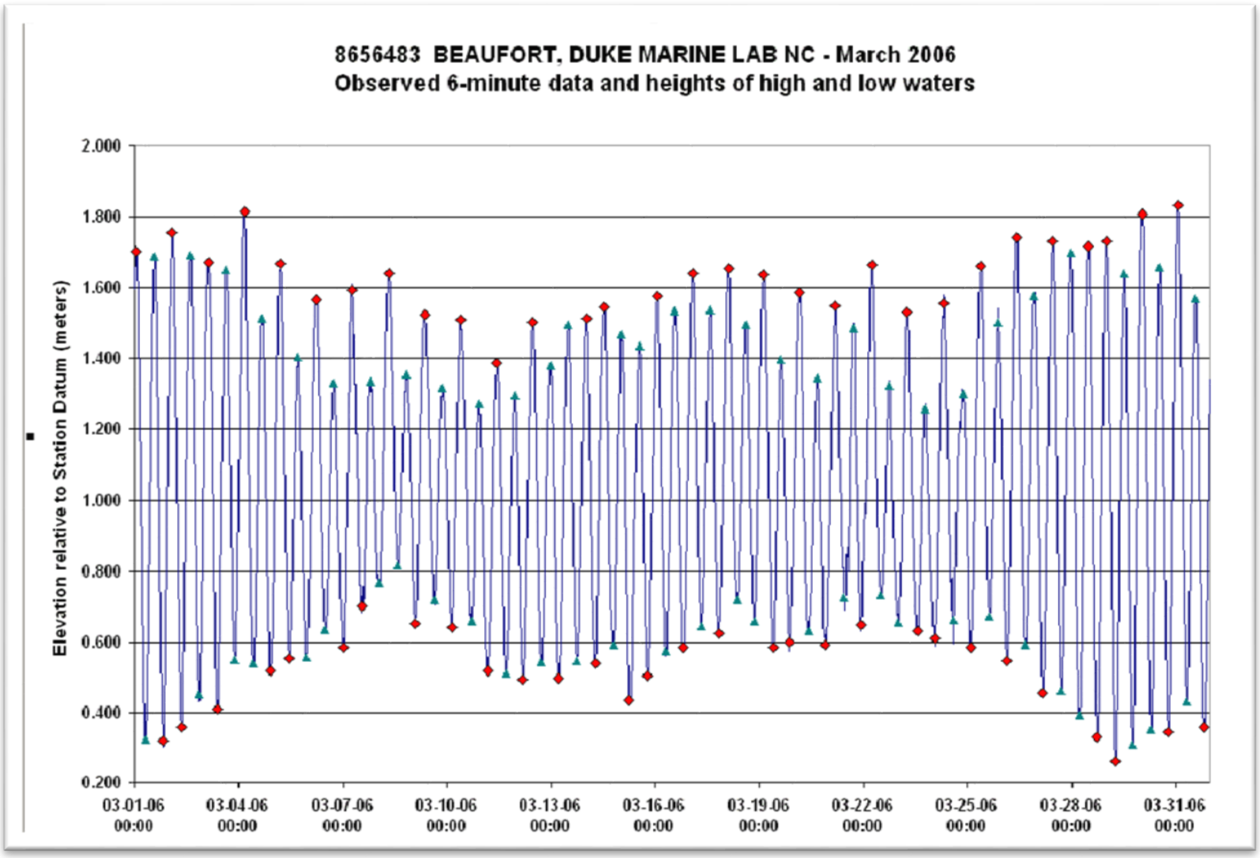


Figure 4-6. Graphical example of a monthly tabulation of the tide. The plot of one month of observed tides at Beaufort, NC shows the tabulated higher high waters and lower low waters as red diamonds and the lower high waters and higher low waters each day as green triangles.

4.2.3 Computation of tidal datums

Local tidal datums can usually be computed on an equivalent NTDE without requiring the full 19-year time series, so long as verified local water level data can be corrected to an equivalent mean value by comparison with a suitable control water level station (Marmer, 1951). The method is called “comparison of simultaneous observations.” See National Ocean Service (2003) for detailed procedures and calculations.

Conceptually, the method is outlined as follows:

1. Select the time period over which the simultaneous comparison will be made.

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[46]https://tidesandcurrents.noaa.gov/waterlevels.html?id=8656483&units=standard&bdate=20060301&edate=20060331&timezone=GMT&datum=MLLW&interval=hl&action=. You must select a station before drilling down to the High/low WL plot.

2. Select the appropriate control water level station (from the NWLON gap analysis) for your local water level station.
3. Obtain simultaneous data from your water level station and the control station and obtain or tabulate the tides and compute monthly means, as appropriate.
4. Obtain the accepted NTDE values of the tidal datums at the control station from CO-OPS via the website.[47]
5. Compute the mean differences and/or ratios (as appropriate) in the tidal parameters between your station and the control station over the period of simultaneous comparison.
6. Apply the mean differences and ratios computed in step 5, above, to the accepted values at the control station to obtain equivalent or corrected NTDE values for your local water level station.

If equivalent NTDE datums cannot be computed (e.g., the site is outside NWLON coverage), then local tidal datums can be computed, but these estimates will not be on the NTDE and will not incorporate the full 19-year Metonic cycle (so, they will have corresponding biases and errors due to short term phenomena). The local tidal datum with the most reliable estimate will be the local mean sea level. This tidal datum is based on monthly averaging of hourly elevations. As a sentinel site, tracking mean seal level is of great importance, so it is fortuitous that this datum is the most straightforward, easy to compute, and insensitive to the differences between 6- and 15-minute data.

CO-OPS recently released an online tool called the Tidal Analysis Datum Calculator (TAD) that allows users to compute tidal datums from their own data. TAD explores a new, fully automated method that uses a digital filter to remove high-frequency variability in water level data and then select the times and heights of the high and low waters from the filtered water level signal. Once the high and low tides are tabulated, a datum computation is performed using the same basic principles outlined above and can derive NTDE-equivalent datums if a control station is used. While TAD will compute datums for as little as 15 days of data, NOS strongly recommends that your data cover at least 30 days because that captures the period of one full lunar month. Accordingly, the differences between the automated method of TAD and NOS-published datums are greatest with shorter time periods and are reduced as the time series gets longer. To learn more about it, the tool, user guide, and technical report can be found here.[48]

4.2.4 Error budgets for tidal datum analyses

There are numerous instances where an error can enter into the computation of tidal datums, including:

- Accuracies of the water level sensor;
- Tidal datum computation;
- Geodetic connection between sensor zero and tidal bench marks; and
- Geodetic connection from tidal bench marks to vertical control network.

The following is a hierarchical listing of recommended courses of action to establish tidal datum references and water level measurements at specific sentinel site locations. Equations show how individual sources of error contribute to the overall error budget. The estimated errors for each component are at the one-standard deviation level and the final 95% confidence interval

[47] https://tidesandcurrents.noaa.gov/stations.html?type=Datums
[48] https://access.co-ops.nos.noaa.gov/datumcalc/

combined error is obtained by taking the square root of the sum of the squares of the individual errors and multiplying by 1.96.

1. If an existing CO-OPS NWLON station is located within or near the sentinel site (for example Beaufort Duke Marine Lab 8656483), it is recommended to use the existing published tidal bench mark elevations and bring vertical control into the project using high precision leveling. Note that this assumes homogeneous water level characteristics between the local NWLON and the sentinel site. Water level information for the desired time period can be downloaded from these operating stations off the CO-OPS website at http://tidesandcurrents.noaa.gov/. Preliminary or published elevation relationships of tidal and geodetic datums may be obtained from CO-OPS or NGS as well. If no geodetic connection exists, then one of the tidal bench marks should be included in a GNSS campaign (Section 6).

   Example:

   $$\varepsilon_S = \varepsilon_B + \varepsilon_L = 0.00 + 0.01 = 0.01$$

   Where:
   ε_S = error in tidal datum at project site (one standard deviation)
   ε_B = error on datum at Beaufort (0.00 m, one standard deviation)
   ε_L = error in transfer of datum from bench marks at Beaufort to project site using leveling (0.01 m one standard deviation)

2. If a historical CO-OPS station was deployed within or very near the sentinel site and the historical station has published bench mark elevations on the current tidal datum epoch, then it is recommended to use those published elevations and bring vertical control into the project area via high precision leveling as above. If the historical station does not have a geodetic datum connection, then a suitable existing bench mark should be occupied by GNSS survey grade equipment (Section 6). As above, this assumes homogeneous water level characteristics between the local NWLON and the sentinel site.

   Example (assuming historical gauge was a three-month tertiary gauge):

   $$\varepsilon_S = \varepsilon_T + \varepsilon_B + \varepsilon_L = 0.03 + 0.01 = 0.04$$

   Where:
   ε_S = error in tidal datum at project site (one standard deviation)
   ε_T = error in datum at three-month tertiary station (0.03 m, one standard deviation)
   ε_L = error in transfer of datum from bench marks at Beaufort to project site using leveling (0.01 m one standard deviation)

   Note that there are specific computations for estimating error from a tertiary tidal station (Bodnar Analysis), which are beyond the scope of this document but are available in National Ocean Service (2014).

3. If the conditions do not meet the criteria outlined in (1) and (2) above, then all datums will rely on the local water level station as outlined in this document. A minimum of one month of data is recommended with the data tabulated and tidal datums computed using simultaneous comparison with a NWLON station. A local bench mark network should be established as outlined in Section 4.1.2, and geodetic datum relationships established using leveling or static GNSS surveying (Section 6). If the sentinel site is outside

NWLON coverage, then all tidal datums will be locally derived and cannot be computed on the 19-year NTDE.

Can I use VDatum to establish tidal datums?

VDatum is a tool developed by NOAA to extend tidal datums away from, or interpolate in between the location of, water level stations for which these datums are published. VDatum uses hydrodynamic tidal models to perform the interpolations of the tidal datums. The online tool makes use of a number of geographic grids within which the sea surface topography is modeled to estimate relationships between tidal datums and geodetic datums. There are known issues with the VDatum grids such as not being able to provide information above the MHW line and inaccuracies in some shallow water areas of some estuaries, so the user is warned not to use these estimates in lieu of high accuracy measurements and direct tidal datum computations. Furthermore, general uncertainties were aimed to be within the 0.1 m range, which will likely result in a very low signal-to-noise ratio for any analyses depending on accurate water levels. The VDatum product will provide a gridded, variable uncertainty in future versions of the transformations. The VDatum home page (https://vdatum.noaa.gov/) provides the user with error estimates for each grid.

5. ESTABLISHING BENCH MARKS

Additional survey monumentation likely is needed to support your local geodetic network. Most low-lying coastal habitats may not have exposed bedrock, so a disk set in an outcrop generally is rare. Massive structures may also be hard to come by in a sentinel site. You may be able to use bridge footings, abutments, and piers, but in general, concrete monuments and deep rod marks will likely provide the best options; this section details their installation techniques.

5.1 Concrete Monument

A concrete monument is concrete poured into a deep hole with a bell-shaped bottom, which has been dug in the ground (Figure 5-1). A metal survey disk is cemented in place at the top/center of the mark (Figure 5-2). Local ground conditions may influence the depth of the monument: hard soil with subsurface rock might require more shallow monuments; soft soils may require deeper depths to assure stability. Table 5-1 provides a list of equipment and supplies required to install one concrete post mark.

Avoid setting concrete monuments in areas where erosion or other movement is likely (e.g., a sandy beach, a cut bank, or a steep slope).

1. Dig the hole with an auger or post-hole digger, and then backfill with mixed concrete. Place the excavated soil on a tarp, so you can remove the soil from the site. The hole is generally round in shape, about 0.3 m in diameter. The depth of the hole should exceed the frost line (typically about 1.3 m deep in temperate settings), and the hole is belled out at depth (see Figure 5-1) to help ensure stability. A long, narrow shovel may be handy to shape the hole and cut through roots. Generally, the hardest part of the digging is at the beginning/top, where the soil is the hardest (and where there typically are more roots).

   It might be impossible to dig a deep enough hole in sand or certain wetland settings, as the hole will cave in immediately. If the water table is very shallow (as in many coastal areas), water may start to fill the hole as you dig. If the hole is too unstable, a concrete monument may be impossible.

2. Once the hole is dug, fill with prepared concrete: first sprinkle enough dry mix at the bottom of the hole to absorb any water as well as help draw out moisture. Add clean fresh water to the dry cement mix according to recommended proportions. Try to keep the concrete on the dry side – avoid a mix that is too wet. Do not use brackish water for the mix, as it will weaken the cement. Add shovelfuls of concrete in the hole; after a few of these, use the long narrow shovel to mix the concrete in the hole. This helps the concrete settle and removes air bubbles.

   Once you reach the top, keep the concrete from coming out the sides; it might help to have the monument slightly recessed relative to ground level (e.g., 1 cm). Avoid creating any shoulders or mushrooming effect near the top of the monument, which might cause frost heave to move it. A cylindrical form, such as rolled black tar paper (felt paper) or a cardboard form placed at the top of the hole and extending about 0.4 m deep, will create a round shape and help support the upper portion of the concrete monument until the concrete cures. A smooth surface near the top of the monument is less susceptible to damage by frost or other forces than unfinished tops.

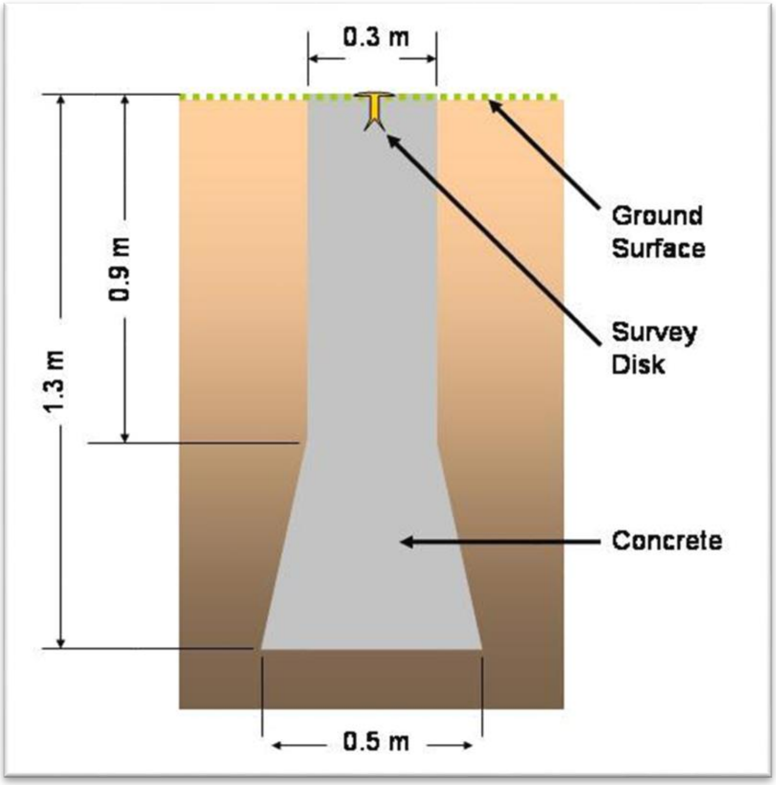


Figure 5-1. Diagram showing approximate dimensions of a concrete post bench mark.

Figure 5-2. Survey marker that is used atop a concrete post mark. Note that the mark is slightly domed (which helps for leveling), but also has a small survey mark punched at the top, to facilitate GNSS-derived positions.

Table 5-1. Equipment and supplies needed for a concrete post mark.

Quantity	Description	Notes
1	Large tarp	For holding excavated fill for off-site removal/disposal
1	Post hole digger	Scissor style is heavier, but provides better grip, especially within the narrow opening of the hole
1	Long narrow shovel	To bell out the bottom of the hole; also good for mixing concrete
1	Pair work gloves	
1	Portable cement mixer	Large plastic trough or 5-gallon buckets can be used
1	5-Gallon carboy-filled with clean water	For mixing with dry concrete mix
8 - 10	60-lb bags concrete mix (cement, sand, and aggregate)	Much easier to carry to the site compared to 80-lb bags!
1	Cement trowel	A small trowel is best to smooth the top of the mark. If possible, use a round-tip trowel
1	Domed metal survey marker	Make sure it is made for concrete post applications (it will have a flared tip)
1	Small bag Portland cement	To finish the top of the mark
1	Small level	To check position of disk and level of top of mark
1	Cloth rag	To clean the disk after installation
1	Witness post	To signal the location of the mark
1	Dust Mask	To prevent toxic inhalation when handling dry cement

Identification of the mark is very important: you may want to stamp the metal disk with an ID. You may also want to order all disks with an agency, location, or other uniform description or logo. If you stamp a site-specific ID on the disk, make sure you do this *prior* to setting the disk in the soft concrete.

3. Next, take the survey marker and fill the underneath with concrete before setting it at the top (this keeps air from being trapped under the marker; Figure 5-3, top right). Wiggle the marker a little bit as you place it in the concrete. Tap the disk in place. If the concrete is too wet, be careful not to tap too hard, but make sure some concrete actually covers the entire perimeter of the marker by a couple millimeters. This will protect the monument from prying hands – or screwdrivers – once it is set. The top surface of the concrete may draw water from underneath: to keep water from accumulating, sprinkle dry cement around the top. Use a rag to keep the marker clean and shiny. A small level can be used to make sure that the domed marker protrudes sufficiently from the top of the concrete, so

that a level rod can be placed on top without touching concrete (or it may be necessary to use a spacer in this situation). In addition, use the small level to make sure that the concrete top is level.

4. Make sure you leave the site as you found it. Remove the dirt fill and place it somewhere it can be used or won't be seen by passers-by. Clean your tools with water. Note that cement is hard on the hands (wear gloves) and can also kill vegetation; try to avoid contaminating the site.

   Concrete should be covered for several days after it is placed. This prevents the mark from drying too quickly, thereby decreasing its strength. It also prevents rain from eroding the fine mortar. The bag the concrete came in can be used as a temporary cover while the concrete cures. You may also try a trash can lid, a piece of wood, or even cardboard. This covering needs to be removed after several days. For more in-depth details on concrete mark setting (including cold-weather applications), see Floyd, 1978[49]; a more condensed version can be found in Smith, 2010[50].

Figure 5-3. Steps involved in finishing the mark: smoothing the top; inserting the marker; final touch-up smoothing the surface; the cured mark. Note witness post to the right of the mark, with flagging.

[49] https://www.ngs.noaa.gov/PUBS_LIB/GeodeticBMs.pdf
[50] https://geodesy.noaa.gov/PUBS_LIB/Benchmark_4_1_2011.pdf

5. Place a witness post (Figure 5-3) or another marker/post to facilitate returning to the mark. Make a careful description of where the mark is located, including azimuths and measured distances to at least three local reference objects. Try to avoid using trees as markers, as they will either grow or disappear over time. A nearby building is ideal, but in a coastal reserve, park, or refuge, it may be very challenging to get even two or three positions. Take as many photographs as possible, both close-up and farther away, to photo-document the mark, as well as how to locate it.

5.2 Deep Rod Mark Setting

Deep rod marks are based on 1.3 m (4 ft), 17 mm diameter (9/16 in) sectional stainless-steel rods that are threaded together and driven into the ground until refusal, or until a minimum driving rate has been achieved. The top-most rod section is rounded, and a datum point is punched. The upper meter of the monument is encased in a greased sleeve that is protected inside a 0.9 m long, 15 cm diameter PVC pipe that has been driven into the soil until the top is flush with the ground level and filled with sand. An aluminum cap is generally epoxied to the top of the PVC, protecting the mark. Figure 5-4 gives a cross-sectional sketch of the upper part of a deep rod monument; Table 5-2 provides a list of equipment and supplies needed.

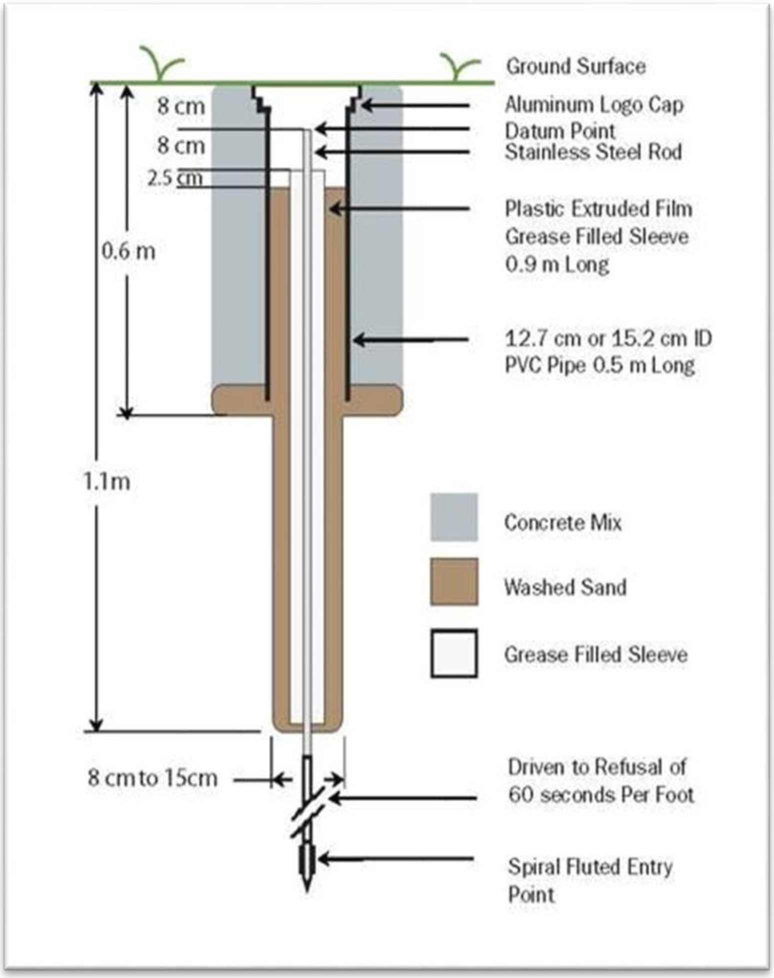


Figure 5-4. Diagram showing components and dimensions of a typical deep rod mark (from Smith, 2010).

Table 5-2. Basic equipment and supplies needed for one deep rod mark installation.

Quantity	Description	Notes
1	Post hole digger or auger and trough	Minimum diameter,15.2 cm (0.9 m) deep hole and use trough to remove sediment from site.
1	Fluted stainless steel driving point	
± 20	1.3 m (4 ft) sectional rods with threaded studs	Number depends on depth to bedrock or soil characteristics; one stud per rod (extra is good)
1	Driving head	This part gets threaded on top rod, to protect rod from impact during driving
1	Gasoline-powered jackhammer (or acceptable alternative)	To drive rods; need to bring gasoline or gas/oil mix
2	Lock-jaw pliers (vice grips)	To tighten rods together
2 pairs	Gloves	To protect hands while using jackhammer
3 pairs	Hearing protection	One pair for each crew member (typically 3)
1	Angle grinder	18 V battery powered is ideal – used to cut remaining rod section and make rounded top
1	Sheet coarse sandpaper	To polish rounded top
1	Hole punch	To make datum point on top of rod
1	Mallet/hammer	To strike hole punch
1	15 cm (1 m) diameter Sch 40 PVC pipe	Outer encasement for deep rod mark
1	0.9 m Greased sleeve	Inner casing for rod – see text for details
1	Food-grade grease	To fill the greased sleeve
1	50-lb bag of sand	To fill the PVC tube after sleeve is in
1	15.2 cm cap	To protect rod mark from disturbance
1	Epoxy	To glue cap on 15.2 cm PVC
1-2	60-lb bag of concrete	To pour into space between PVC tube and sides of hole to provide extra stability
1	Dust Mask	Personal protective equipment when handling concrete

1. Use a post hole digger to make a round hole in the ground about 15 cm to 30 cm in diameter and approximately 0.5 m to 1 m deep. Near the end of the installation process, place the 15 cm diameter PVC pipe in the hole, and fill in the space between the PVC and the surrounding sediment with concrete to stabilize it (in upland settings). In the case of wetland soils, a smaller (15 cm diameter) hole is specified. If it is difficult or impossible to dig the full 1 m deep-hole due to the hardness of the substrate or large rocks, a 0.5 m hole may be sufficient. If roots are present, cut them to get the full depth. Place the fill to the side or in a trough (to be disposed of later).

2. After the initial hole is dug, take a sectional rod and thread a fluted point to the tip using threading sealant to secure the fit (you may need to add a threaded stud first, depending on the supplier). This will help the rod assembly drive through hard substrate, such as rocks. The fluting also helps tighten the rods as they go down. Tighten the tip onto the rod with vice-grips. You may be able to push most of the first rod section into the soil by hand. Use a rubber mallet to tap it in, if desired. Once it has gone in, you may be able to thread another rod and keep inserting by hand (remember to place sealant on the threads). Tighten the rods together tightly. In wetland soils, it is not uncommon to push four to six rods in by hand. Whatever you do, do NOT hit the top of the rod directly with a steel hammer or any object that can mar the threads. If you use a hammer, first thread on a pounding head (purchased separately, or use a spare cut section of rod).

3. Once you have inserted the rods in as far as you can by hand, use a jackhammer to drive the rods the rest of the way. The idea is to drive the rods into the ground until you cannot drive them anymore. The mark is then considered to have reached stability. Evidently, different hammering tools and techniques with differing amounts of impact applied will arrive at different stopping points. Two variables help determine the vertical impact: static weight and driving force. NGS guidelines specify a static weight of 25 kg (55 lb) and a driving force of 24.0 newton meter (N-m) (17.7 ft-lb). Typically, a gasoline-powered jackhammer meets the guidelines. If the static weight guideline is not met, the tool may bounce on the rod without transferring enough of its energy down on top of the rod to result in effective driving. If this is the case, the operator(s) will need to increase the effective weight by putting their own weight to bear down on the hammer. Unpublished field trials have shown that tools as light as 17.7 kg (39 lb) [but which have a 46.1 N-m (34 ft-lb) driving force] will perform identically as the jackhammer, so long as the operator(s) applies their own weight in the driving. Before using the jackhammer, you need to make sure that the threaded part of the rod is protected with a driving head and that the driving head is securely tightened onto the rod (e.g. use vice grips). If it is loose, it can easily damage the threads; there is also a greater risk that the threaded stud between the two might break.

4. Once you start joining rods together, make sure that they are very tightly secured. A pair of lock-jaw pliers (vice grips) or pipe wrenches is ideal: fix one to the top of the bottom rod, and the other on bottom of the top rod, and tighten. Apply threading sealant to ensure a lasting coupling.

   It is helpful to have a field crew of three for driving rods: two people to lift and operate the jackhammer, and one person to prepare the rods (Figure 5-5). The one who prepares the rods can also make sure the rods have threaded studs in place (with thread locker applied), as well as keep track of how many rods have gone in.

Bring extra threaded studs with you to the field; they can often fall off when you unscrew the driving head; they can also get bent. Having extra is always useful. It is also a good practice to leave the threaded stud on the rod already driven into the ground, and use a new threaded stud each time you re-attach the driving head to the new rod as a precaution for stressing and potentially breaking the threaded stud while in the rod (which can be very difficult to remove).

Figure 5-5. Field crew setting a deep rod mark in a Chesapeake Bay wetland, Maryland. Note use of platform to avoid disturbance on wetland soil.

Once you've started driving rods, don't stop. Stopping for any significant period of time may cause the rods to seize in the ground, resulting in a shallower depth than is optimal.

At first, the rods will spin in the ground if you try to tighten them with only the top pliers. As you drive the rods, you will start feeling resistance, and the rods will no longer spin as easily. Eventually, they will not turn at all. This is a good sign that you are making progress. Going through layers of rocks and boulders might cause the driving point to be deflected off to one side (finding the path of least resistance). You may see this as the top rod begins to tilt markedly to one side. If there is significant lateral stress on the rod assembly, it may eventually break – usually at a stud. Breaking a rod section is unfortunate, as there is usually no way to retrieve more than the upper section or two of rods. If the rod you are hammering bends to the side and the driving rate has slowed down markedly, be very careful, as this is where breakage typically occurs. If you have a break, you must begin a new installation.

Tip: Drive the rod so only 10–15 cm remain at the top of the hole, if possible, so that you won't have to lift the jackhammer so high above your head after threading on the next rod. Also, have one person lift the jackhammer from the handles, while the other grabs the driving head and places it on the driving head of the rod. Otherwise, it can be difficult to

It is ideal to drive the rods until refusal (when driving abruptly stops). In many situations, this is never reached. Instead, the driving rate keeps slowing down. For this reason, NGS guidelines specify "substantial resistance" when the driving rate is equal to or less than 1 ft per minute. If you reach this rate, then stop the driving. Otherwise, if more than 22 rods have been driven without reaching "substantial resistance," the mark can be left overnight. The subsequent day, you can attempt to drive the remaining rod section. If the rods do not twist AND do not move down after continued pounding, then you can call the job finished.

5. To finish the installation of a deep rod mark, cut any remaining rod section so that it is about 8 cm (about 3 in) below the soil surface. A hydraulic bolt cutter can also be used, but a cordless 18 V angle grinder is also very practical. After cutting, center-punch a substantial dimple at the top/center, to create the datum point. Then use the angle grinder to make the top surface of the last rod section round at the top (Figure 5-6). You can use coarse sandpaper as needed to make a smooth top. This way, the point of a tripod/bipod can occupy the dimple. If you drive the mark to the end of a rod section, then there is nothing to cut; you will need to screw a spherical datum point onto the top of the uppermost rod (use thread sealant to lock in place).

Figure 5-6. Using a cordless angle grinder to create a dome at the top of the rod.

6. Once the rods are in, place the PVC pipe in the hole (Figure 5-7). You may need to pound it in (take care not to damage soft PVC). Next, insert the greased sleeve. Note that you can make your own greased sleeve with 2.5 cm PVC pipe with 17 mm holes drilled in caps on both sides of the tube, which are cemented into place. Otherwise, plastic finned sleeves are available from survey supply distributors. Fill the sleeve ¾ full of food-grade grease; check local listings or online (look under "food-grade grease") for distributors. Once the sleeve is filled with grease, place it over the rod to allow about 8 cm (3 in) of rod to be exposed above the sleeve. After the sleeve is in, you can fill the remaining space with clean sand or gravel.

7. The last step is to affix a protective cap (Figure 5-8). Survey supply distributors sell caps to fit a 15-cm diameter PVC tube. You can order the caps with inscribed identification, and caps can be affixed to the PVC using a marine grade epoxy or PVC glue. For marks in upland settings, pour concrete around the exterior of the tube to stabilize it in the hole (Figure 5-8).

Figure 5-7. Inserting 15 cm PVC pipe in hole after section rods have been driven.

Figure 5-8. Completed deep rod mark, shown with logo cap in open position. Note rod with datum point extending out of greased sleeve; rod assembly is below the soil surface.

Remember, to assist with future recovery of the mark:

- Place a witness post, flagging, or other marker.
- Take photographs of the finished mark (cap on) both up close and at a distance (from the path you'll take to approach it).
- Document if possible five distances and azimuths to the mark from permanent structures, again to assist recovery.
- Obtain accurate locational information with a GPS handheld unit.

See Floyd, 1978[51] and Smith, 2010[52] for two NOAA publications describing more information on NGS guidelines for deep rod marks.

Wait at least two weeks after marks have been installed prior to conducting any surveying activities; this allows time for any initial settling.

5.3. Deep Rod Setting: SET Marks

Important Information
This guidelines document assumes that deep rod SET marks can serve as Local Control Marks in the establishment of a local geodetic control network.

Since the early 2000s wetland scientists have used a form of "deep rod marks" as foundations for SETs (Cahoon et al., 2002). Although these SET marks use the same section stainless steel rods as a deep rod mark, the goal at that time of their installation was not to establish a Local Control Mark (LCM). As a result, there have been slight differences in how the two types of rod marks have been installed.

In the case of the SET mark, the entire 15 cm PVC pipe encasing the mark is filled with concrete, whereas in the geodetic mark, a greased sleeve isolates the rod from the surrounding soil (usually sand) filling the tube. Over ten years of SET data across hundreds of marks from the Gulf Coast into Canada have not shown any evidence of frost heave-induced elevation change (Donald R. Cahoon, USGS, personal communication). Since these marks are primarily found in unconsolidated, flooded wetland soils, frost action is likely to result in the wetland surface itself sliding along the external PVC pipe encasing the rod. The matter of mark stability has not been conclusively addressed, although at the time of this writing, an initial study conducted by NGS suggests that there is no difference in short-term stability between traditional geodetic three-dimensional deep rod marks and their SET counterparts. For this reason, this guidelines document assumes that deep rod SET marks can serve as local LCMs in the establishment of a local geodetic control network.

A SET mark was traditionally installed differently than a traditional deep rod mark. The original insertion technique relied upon a hand-held, cast-iron pile driver (Figure 5-9, top left). By 2003, a lightweight electric demolition hammer was gaining widespread use due to the much greater

[51] https://www.ngs.noaa.gov/PUBS_LIB/GeodeticBMs.pdf
[52] https://geodesy.noaa.gov/PUBS_LIB/Benchmark_4_1_2011.pdf

ease of insertion (Figure 5-9, top right). The demolition hammer typically weighs less than 14 kg (30.9 lb), and operators would often apply their own weight to the instrument during installation.

In late 2011, an initial study was conducted to compare the effective depths of insertion of deep rod marks in wetland soils using the three most widely used techniques of insertion: the hand-held, cast-iron pile driver, the 10 kg-Bosch 11316EVS demolition hammer, and the 25-kg Atlas Copco “Cobra” jackhammer. Increases in insertion lengths of 46% and 98% using the demolition hammer and the jackhammer, respectively, compared to the manual method were obtained. The implication for stability is that the traditional jackhammer technique may lead to more stable marks. For an in-depth step-by-step manual on installing deep rod SET marks, please refer to Lynch et al. 2015.

Deep rod SET marks have a different vertical point of reference (VPR) compared to three-dimensional deep rod marks, and they are typically located in the middle of research plots, which complicates approaching and setting up on the mark. For these reasons, typical surveying procedures must be modified to successfully connect SET deep rod marks to the local vertical control network and the NSRS. This document provides a review of these essential modifications (Section 6); however, Geoghegan et al. (2010) provide in-depth techniques for connecting any kind of SET mark to the NSRS via GNSS observations.

Wait at least two weeks after marks have been installed prior to conducting any surveying activities; this allows time for any initial settling.

Figure 5-9. Three techniques for setting deep rod marks (or deep rod SET marks). These include using a hand-held pile driver (top left), a lightweight electric demolition hammer (top right), or a self-contained gasoline powered jackhammer (bottom).

6. CONNECTING THE LOCAL VERTICAL CONTROL NETWORK TO THE NSRS

In this section, we present two techniques to connect your local vertical control network to the National Spatial Reference System (NSRS): differential leveling and static Global Navigation Satellite System (GNSS) observations. A high precision connection to the NSRS provides a number of benefits, including:

- Ability to monitor vertical stability of the local vertical control network.
- Ability to monitor vertical stability of individual control marks.
- Ability to compare elevations and all other vertically referenced observations/data across different sites.

The connection to the NSRS is made on a chosen subset of vertical marks in the local control network. These marks, referred to as “Local Control Marks” (LCMs) (Section 3), typically include at least three of the most stable marks widely distributed around your local network (Figure 6-1). An LCM should also support each water level station (acting as the primary tidal bench mark). Refer to Section 3 for guidance on selecting these marks.

Differential leveling and static GNSS observations both have their strengths and weaknesses when connecting to the NSRS. These two techniques are briefly compared in Table 6-1. Note that if you can bring high-accuracy elevations into your entire network via leveling from an existing level line, a GNSS connection to the NSRS is not required. However, if in an area of vertical land motion (subsidence or uplift) and the level line is old (and never re-observed), the published NAVD 88 elevations may have a degraded accuracy. For this reason, it is recommended that you include GNSS observations as part of a leveling campaign. If an existing high-accuracy published level line is not available, then a GNSS-based connection to the NSRS is required. If you can level among all components of your local control network, you only need one good connection to the NSRS. Please see Figure 6-2 to view these options as a tiered outline.

At the end of this effort, you will have established NSRS connections to each of your local LCMs in your local network. Section 7 provides information on how to then transfer the elevations to the other marks in the network and your monitoring infrastructure (water level station, Surface Elevation Tables (SETs), groundwater wells, etc.).

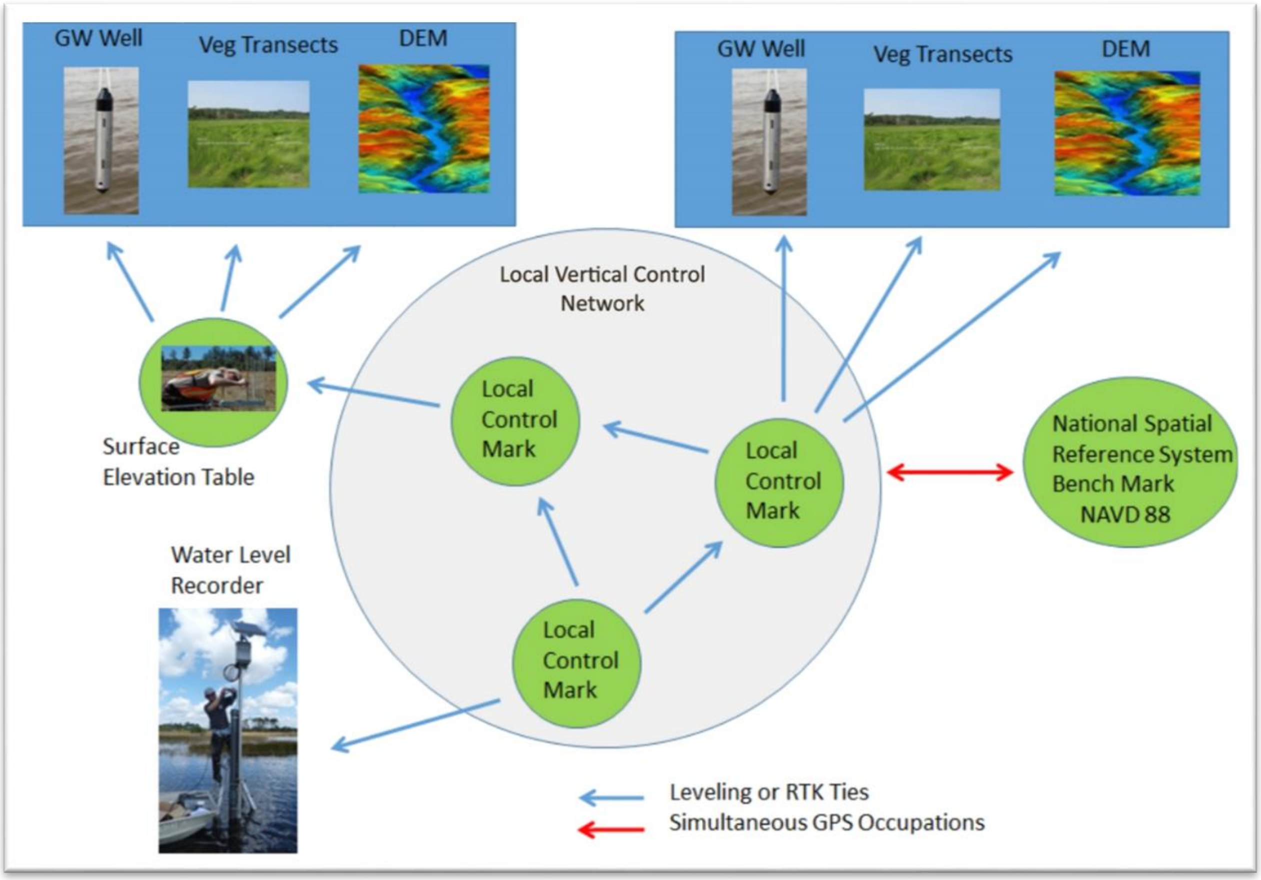


Figure 6-1. Conceptual diagram showing sentinel site data sources and how they can be connected to the local vertical control network (minimum of three local control marks) via leveling or RTK GPS. In addition, the graphic shows how the local control network itself can be tied to the National Spatial Reference System via simultaneous GPS occupations.

Table 6-1. Comparison of two techniques for establishing a local connection to the NSRS.

Survey Characteristics	Leveling	GNSS
Direct connection to NSRS	NAVD 88	NAD 83
Precision	$\pm 4\ mm\ \times \sqrt{km\ distance}$	±20 mm (1 σ) for 4-hr static observation sessions[53]
Connection to orthometric datum (NAVD 88)	Direct	Indirect (apply geoid; thus, add 20 mm more error, 1σ)
Requirements	NGS published vertical line nearby with at least 2 existing stable bench marks	Open skies, ≥ 3 CORS stations with clean data, preferably within 50 - 100 km
Level of difficulty	Moderate to high	Low
Time required	Many days (training + survey)	Two ≥ 4-hour sessions

[53] Estimated according to Snay et al., 2011

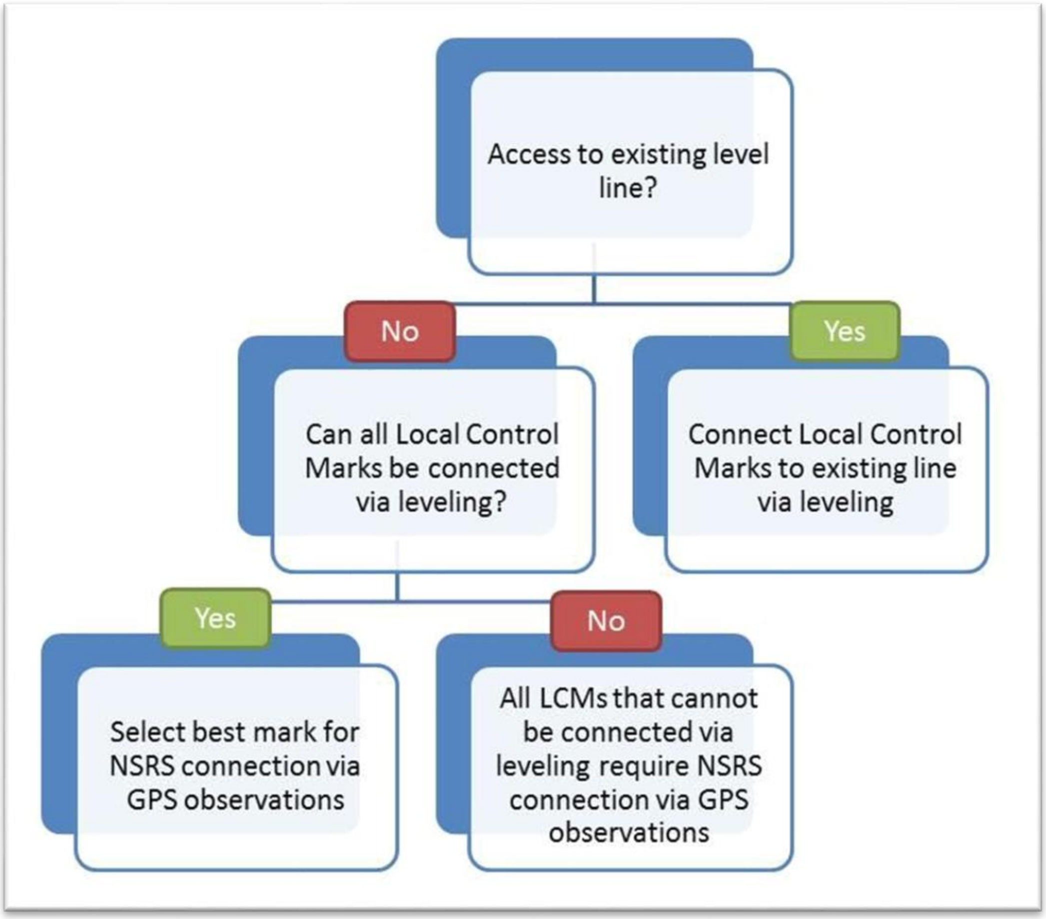


Figure 6-2. Decision tree to help decide best technique to connect local vertical control network to the NSRS.

6.1. Geodetic Differential Leveling

Geodetic differential leveling will achieve the most precise connection to the orthometric vertical datum (Table 6-1). There are standards and specifications associated with different implied levels of precision accuracy for geodetic leveling (Bossler, 1984). These generally have been developed for professional surveyors conducting large leveling projects; in contrast, most sentinel site work involves very small, geographically limited projects. Given the perceived needs of our intended audience in establishing a sea level change sentinel site, we therefore recommend the following specifications, taken from a combination of different orders and classes of leveling (Table 6-2).

Table 6-2. Recommended leveling specifications for sea level change sentinel sites

Item	Specification
Average bench mark (BM) spacing	200 m ≤ BMs ≤1.6 km
Bench mark type	Local Control Marks: NGS 3D deep rod mark Other marks: combination of other mark types, including concrete posts, outcrops, disks set in concrete structures
Turning points	On land: metal spikes or plates In wetland: semi-permanent stakes driven into soil, topped with double-headed nail
Instrument and rod resolution	0.0001 – 0.001 m
Level	Digital barcode or optical, 1.0 mm or less vertical accuracy per km, double-run
Rod	Digital barcode or optical, ideally constructed from one-piece invar.
Maximum collimation error, single line of sight	±0.05 mm/m (±10''0)
Level rod maintained vertical to within	10 ft (0.3048 m)
Minimal observation method	Digital: precise setting (0.0001 m rounding or better) Optical: 3-wire tie or micrometer
Section running	Double-run
Setup imbalance	Routinely ≤2 m, no more than 5 m
Sight length	Routinely ≤40 m, no more than 70 m
Temperature readings	Beginning and end of each section
Maximum section misclosure	$4\sqrt{D_{km}}$
Maximum loop misclosure	$4\sqrt{D_{km}}$

These specifications are achievable with commercially available equipment. Regardless of the methods followed and specifications applied, fully document the actual specifications used, so that the expected error can be properly evaluated.

Leveling does have practical limitations. Leveling is a relatively slow process; leveling routes, route distances, and availability of personnel must be considered. For example, after a couple of weeks, a persistent three-person crew might expect to achieve 2–5 km of leveling per day, depending on the conditions along the route. Long leveling routes, routes that cross expanses of unstable soil (marsh), and/or open water tend to become impractical rather quickly and open the door to alternative strategies.

Basic concepts

Differential leveling entails measuring elevation differences between two permanent marks and then checking to make sure those differences are correct (Figure 6-3). Differential leveling can therefore transfer a known/published elevation into a new local vertical network by summing up the elevation differences along the level line. A *setup* consists of a level instrument centered between two rods resting upon or directly referenced to stable points in the ground. "Stable point" usually means a permanent, recoverable mark or temporary turning point (e.g., a turning pin or a "turtle" –see 6.1.2). A leveling *section* is the set of all setups required to level from one permanent mark to another. Sections may consist of one to dozens of setups. The general procedure describes the basic steps in running a section.

1. Start with two NSRS recovered/known bench marks with second order, class II or better elevations. This will usually be the first section of your leveling project and consists of a check-tie to ensure the starting bench mark (BM) has not moved over time.
2. Setup 1
   a) Level Rod 1[54] is placed on BM A and level Rod 2 is placed on a temporary turning point (e.g., *pin*; Figure 6-3).
   b) The level instrument is placed half-way between the two rods, for the initial *setup*.
   c) The level instrument operator records a reading on Rod 1 (*backsight*, or BS), turns the level around to face Rod 2, and records a new reading (*foresight*, or FS). The simple formula BS minus FS produces an *elevation difference* between BM A and the turning pin. *Whenever a setup is complete, the forward rod's turning pin must always remain undisturbed until after the* ***next*** *setup is complete.*
3. Setup 2
   a) Rod 2 remains on the turning pin while Rod 1 is now "leap-frogged" ahead (to a new mark or turning point), and the level instrument is again centered between the two rods.
   b) A new backsight is taken to Rod 2, and a foresight is taken to Rod 1, providing a new elevation difference between these two points.
4. The method is continued, with the rods and level instrument leap-frogging each other until the final setup, when the Rod 1 is placed atop the new mark and the final foresight is taken.

When all these intermediate measurements are summed, we arrive at the cumulative elevation difference between the known point and the unknown mark. In this manner, we can take the published elevations on a BM (i.e., the NAVD 88 orthometric elevations from the NGS datasheets), and work through the elevation differences to assign new elevations to the LCM's in our local network.

Important Information
This document assumes that you will not be publishing your leveling data through NGS; you will not be making the results of your leveling project public through the NGS IDB. If you want to publish your results, you are directed to other publications that document this procedure: Challstrom, 1994; Schomaker and Berry, 1981.

[54] If only one rod is used, Rod 1 = Rod 2

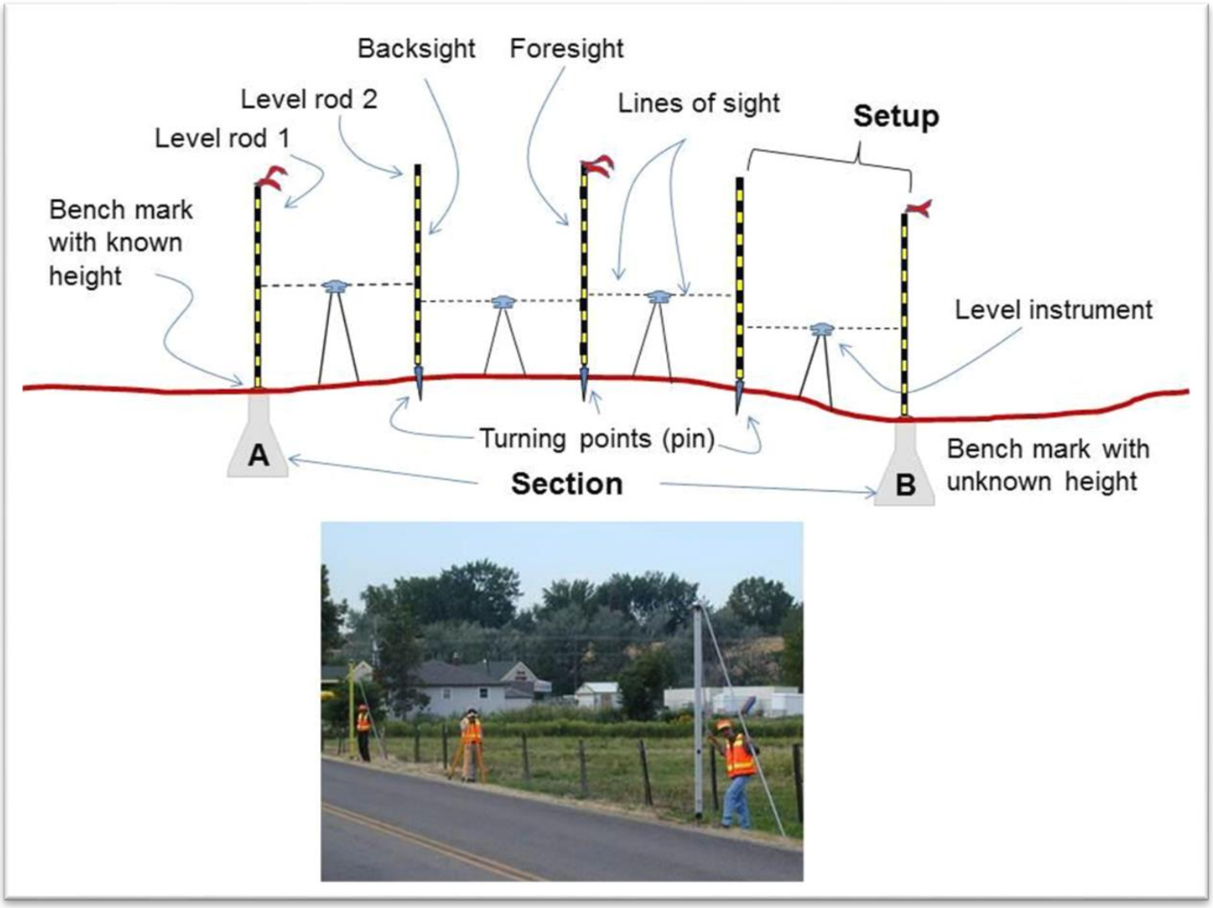


Figure 6-3. Diagram showing the transferring of elevations via leveling. Diagram identifies many of the terms used in leveling. Photo shows leveling being completed with 3 m rods.

Differential leveling entails the careful attention to detail and the following of guidelines aimed at reducing error. Most importantly, differential leveling means the work is always done twice: once going forward (forward run) and a second time running exactly in reverse (backwards run). The elevation differences on both forward and backwards runs for each section should match within target tolerance according to Table 6-2 (the difference is called *misclosure*). Careful adherence to the techniques outlined below will often result in smaller error.

Strengths and Weaknesses:

- Strength: Differential leveling (from a previous NGS published level line) provides a direct tie to the existing orthometric datum NAVD 88 along an existing level line with elevations published in the NGS's database. Differential leveling ensures that your site will be connected to this existing level line with known error tolerances of less than one centimeter per square root of the kilometers of distance traveled.
- Weakness: Although differential leveling will provide a higher precision connection to NAVD 88, it will not correct for regional land movement, such as regional subsidence (i.e., all marks are moving in the same amount vertically).
- Weakness: Leveling requires training and experience, and it can take a lot of time. It is therefore best done over relatively short distances (i.e., one to several km). If you have

to cross over water that is more than about 70 m across, then leveling may not be a good option.

- Weakness: Connecting your local network to the NSRS through differential leveling requires the presence of an existing and local high accuracy NGS level line, as well as the ability to survey the line into your site and to at least one of your LCMs. If the nearest high accuracy level line is 5–10 km away, you may want to inquire about contracting professional surveyors to conduct the work (although this may be expensive).

Important Information
This document assumes that you and your field crew will take some training – both in the classroom and hands-on, prior to conducting any leveling. Such training is offered by NGS (see http://www.ngs.noaa.gov/corbin/index.shtml for schedule of upcoming classes, or to request a class); another point of contact might be your state land surveyors' association. Hopefully, this document will provide you with enough theory and practical guidance, so that you will know what you are getting into.

You may decide either to contract this work out to local professional surveyors or take some training and do the work yourself. If you conduct this work yourself, this document will provide important information specific to the tasks at hand and help ensure that standard practices are followed across the user community. If you contract out for this work, it is important to obtain the services of a company that can clearly demonstrate proficiency in this area. Note that very few professional surveyors have the necessary equipment and experience to perform geodetic leveling.

6.1.1 Running levels

The instructions in this section are a general guide to complete differential leveling. Digital barcode leveling using Invar® rods provides the greatest accuracy, but good results can be obtained using non-Invar rods, laser, or optical levels. These instructions are intended to be general enough to guide a user regardless of the type of leveling equipment being used. Before you go out into the field, make sure you consult the recommended equipment in the check-list below (Table 6-3).

Table 6-3. Equipment recommended for geodetic leveling.

Quantity	Description	Notes
1	High accuracy level	Digital barcode levels provide the greatest accuracy, but good results can be obtained using laser[55] levels or optical levels.
1	Level tripod	You should use a tripod with fixed length wooden legs with steel stomp-plates at the tips; calibrated flat surface on top to mate with level.
2	Level (stadia) rods	Two level rods are recommended: one for the backsight, one for the foresight. Recommend using one-piece rods that have attached circular vials (bubble levels) and brace poles, Check digital barcode level rods for consistency among each other and test and calibrate circular vial as needed.
2	Turning points (pins; maybe also turning plates if on concrete/stone)	Pins are generally safer, as they are less likely to be bumped and moved; semi-permanent stakes with double-headed nails are useful in wetland soils – see 6.1.2.
2	Soft-faced or dead-blow mallets	To drive in turning pins.
Many	Wooden stakes (2″ × 2″ × 24″) with 10d nail or double-headed nail at top	For temporary points on the wetland, instead of turning pins.
Many	Leveling recording sheets + pencil	For taking careful field notes.
1	Hand-held temperature probe	To monitor ambient air temperature at the start and end of each section.
	Standard field equipment	Hat, sunscreen, raincoat, drinks, cell phone, etc.
	Umbrella	Optional- To shade the level and when dealing with low sun angles.

Complete Collimation test (Kukkamaki method):

Prior to conducting the leveling, make sure that the level and the stadia rods have acclimated with the ambient air (leave the equipment outside where you will be leveling for 10-20 minutes). The first measurement of the day is the *collimation test* (also called the C-shot or peg test). This checks the internal characteristics of your level's optics, ensuring that they are properly aligned according to the instrument's standards. Typically, the internal lenses of a leveling instrument will have some small amount of misalignment, which can be accounted for by correcting the data for this collimation error. Although it is ideal to keep collimation to within 10 arc seconds (±0.05 mm/m; Schomaker and Berry, 1981), our recommendations regarding balanced setups and short sighting distances should help reduce the influence of collimation error, even if it is greater than recommended. Re-calibration of your level instrument is best done by a professional

[55] Note that laser observations cannot be submitted for inclusion in NSRS (i.e., "Blue-Booked").

repair technician. However, keeping track of collimation and its changes through time will provide an indication of whether the instrument will need to be serviced (e.g., collimation getting worse and worse). The procedure outlined below is for the Kukkamaki method: your level may come with another recommended technique (follow your owner's manual).

1. Set up your tripod on firm, level ground and set the level on the tripod: plumb the level.
2. Pace 10 m on both sides of the level and place a turning point or a pin in the ground at these locations (Figure 6-4). Make sure the turning point/pin is stable before placing a stadia rod on it (on concrete, stomp on the turning plate with your foot).
3. Have an assistant hold the stadia rod on the point labeled Rod 1 in Figure 6-4, with the calibrated surface facing the level. The rod should be held plumb (see Section 6.1.2)
4. Check the distance between the level and the rod with the level instrument.
5. Repeat steps 3 and 4 for the second turning point/pin (Rod 2 in Figure 6-4).
6. Check the distance from the level to Rod 2; make sure your level is half-way between the two rods (within 1 m).
7. Take a backsight to Rod 1, then a foresight to Rod 2. Record the elevation difference. Note that the rod sighting order may vary with equipment manufacturer (recommendation: follow the sequence suggested by your level instrument).
8. Pace out 20 m from Rod 2, in line with the two rods. Set your tripod at the 20 m mark (level is now 20 m away from Rod 2 and 40 m away from Rod 1).
9. Take a backsight to Rod 2 and a foresight to Rod 1. Note that the distances between the level and each rod are NOT the same. This is on purpose, as it will provide an estimate of collimation error.
10. Record the elevation difference between Rod 2 and Rod 1.

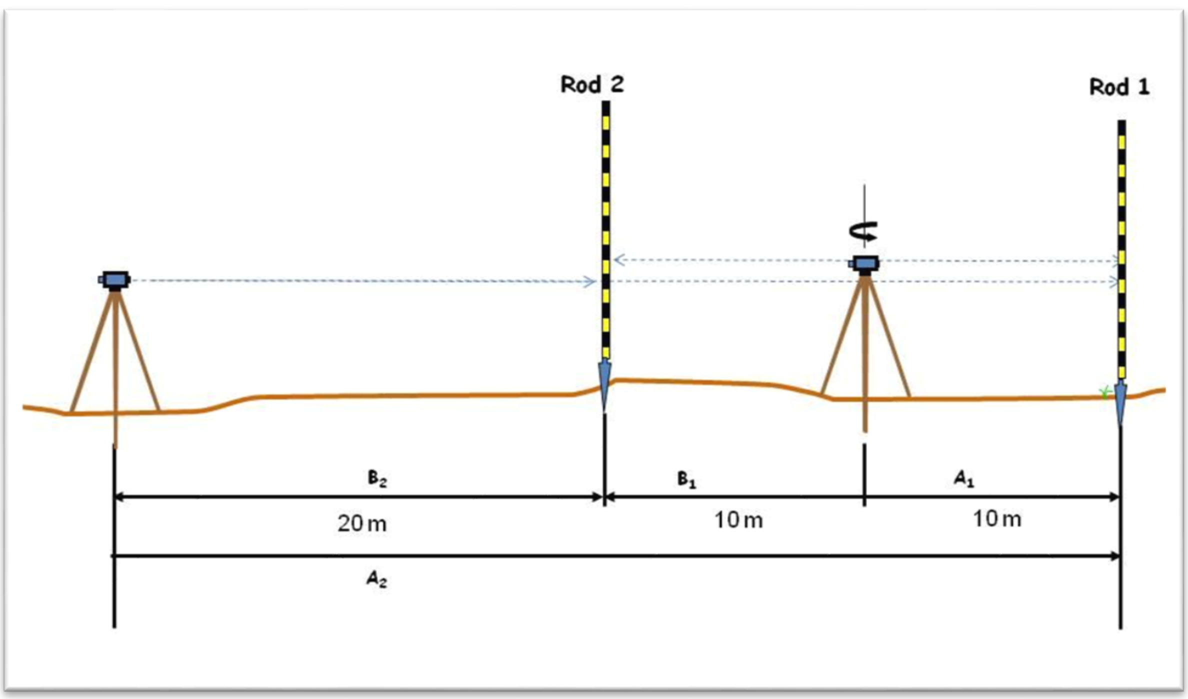


Figure 6-4. Kukkamaki method for testing collimation.

The elevation differences (e.g., Rod 1 – Rod 2) from both setups should be within 1.2 mm to satisfy the 10 arc seconds tolerance.

Example:

First reading with balanced sights (10 m/10 m):	Rod 2 - Rod 1	= -0.1239 m
Second reading with unbalanced sights (20 m/40 m):	Rod 2 - Rod 1	= -0.1250 m
Difference between two differences		= -0.0011 m

If the difference in the two height differences is well outside of 1.2 mm, you should consider having your level serviced. If not, you will need to pay extra attention to having *balanced setups,* meaning that your level instrument should be separated by the same distance between the two stadia rods (this is always a good practice; see the next subsection for further explanation). The recommendation is to keep the distance imbalance to no more than 2 m per setup, less if the collimation does not meet specifications.

Observe your double-run level line:

To level into your site, you will have already identified at least two leveled (or better) vertical marks, which are part of an existing level line near your site with published, high accuracy elevations (Section 3.3.2). The bench marks must be spaced at least 0.5 km apart. To verify that the two marks have not been damaged or moved, begin your survey by differential leveling among these marks (Figure 6-6).

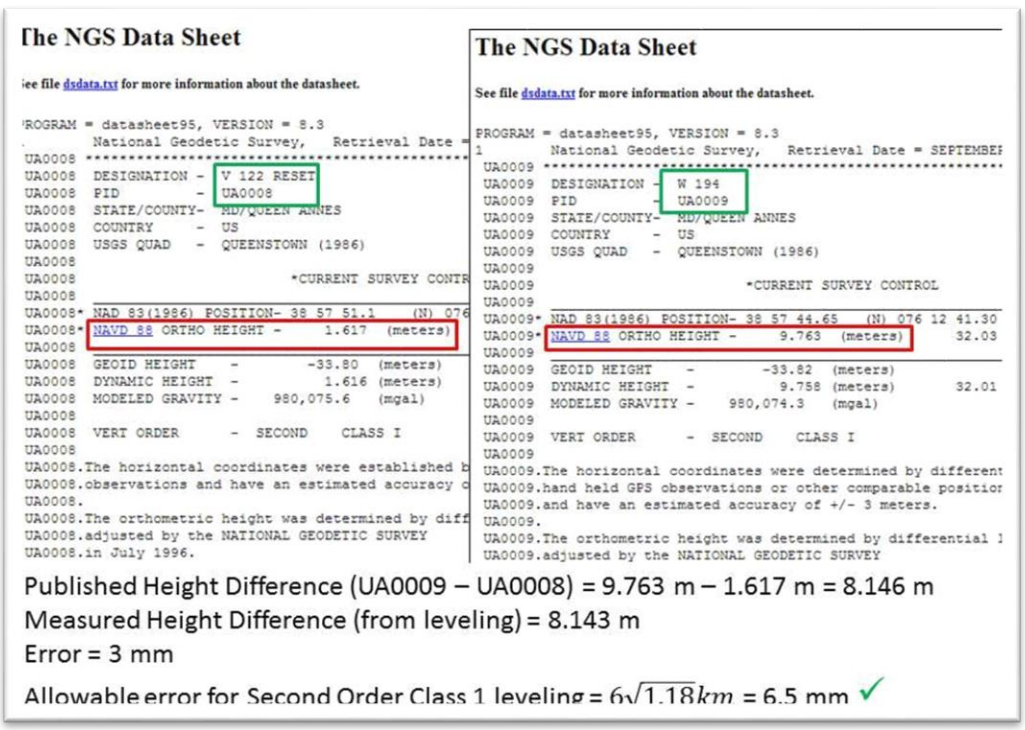
1. Start your level line at the farthest bench mark from your site.
2. Begin filling out a leveling recording sheet identifying the starting mark, which rod is on the mark, the time of day, etc. (see appendix 3). Record ambient air temperature at the start of the section.
3. Read the backsight on your starting mark (e.g., Rod 1), and your foresight on the turning or temporary point (e.g., Rod 2). Record on datasheet.
4. Move Rod 1 forward to the next setup; swivel Rod 2 so it faces the new level position. It is recommended to have even numbers of setups between marks. For example, if you started with Rod 1 on the starting mark (e.g., Q51 in Figure 6-7), it is ideal if Rod 1 ends up on the next mark (R51 in Figure 6-7). Starting and ending with the same rod will minimize error caused by any slight vertical differences between Rod 1 and Rod 2. Repeat steps 3 and 4 until you reach the second mark. Record all intermediate and final rod heights (backsights and foresights); record ambient air temperature at the end of the section.
5. Once you have reached the second mark, sum up the leveled observations and compute the elevation differences between the two marks.
6. Compare this computed elevation difference to the published elevation difference (taken from the published datasheet – see Section 3.3.2 and Figure 6-5). The differences will likely not match perfectly, but they should be within the misclosure allowed for the specific order and class of leveling identified in the datasheets. In the example given in Figure 6-5, the allowable misclosure for Second Order Class I leveling (given in millimeters) is $6\sqrt{D}$, where D is the distance, in kilometers, between the two marks. A table of allowable misclosure is given in Table 6-4. If misclosure is out of specification, run the levels back to the first mark, and compare. As long as one level run meets specifications, you may continue. If the second run also fails, you may have to look for a third mark, or consider tying to the NSRS via GNSS, and then leveling from GNSS-based positions.

Table 6-4. Allowable misclosures for different orders and classes of leveling.

Order and Class of Leveling	Allowable Misclosure (mm)
1/1	$3\sqrt{D}$
1/2	$4\sqrt{D}$
2/1	$6\sqrt{D}$
2/2	$8\sqrt{D}$

It is recommended to have even numbers of setups between marks. That way, the same rod which started on the first mark will finish on the next mark in sequence. Starting and ending with the same rod will minimize error caused by any slight vertical differences between Rod 1 and Rod 2.

Checking height differences will not ensure that the published orthometric heights themselves are still accurate – the whole region may have subsided or uplifted since the level lines were first established. This might not be a problem if all your vertical data have the same bias. Contact your Regional Geodetic Advisor for additional information.



The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

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.        National Geodetic Survey,   Retrieval Date =
UA0008 ***********************************************
UA0008  DESIGNATION -  V 122 RESET
UA0008  PID         -  UA0008
UA0008  STATE/COUNTY-  MD/QUEEN ANNES
UA0008  COUNTRY     -  US
UA0008  USGS QUAD   -  QUEENSTOWN (1986)
UA0008
UA0008                         *CURRENT SURVEY CONTR
UA0008
UA0008* NAD 83(1986) POSITION- 38 57 51.1    (N) 076
UA0008* NAVD 88 ORTHO HEIGHT -      1.617  (meters)
UA0008
UA0008  GEOID HEIGHT    -        -33.80  (meters)
UA0008  DYNAMIC HEIGHT  -          1.616 (meters)
UA0008  MODELED GRAVITY -    980,075.6   (mgal)
UA0008
UA0008  VERT ORDER      -  SECOND    CLASS I
UA0008
UA0008.The horizontal coordinates were established b
UA0008.observations and have an estimated accuracy o
UA0008.
UA0008.The orthometric height was determined by diff
UA0008.adjusted by the NATIONAL GEODETIC SURVEY
UA0008.in July 1996.
```

The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

```
PROGRAM = datasheet95, VERSION = 8.3
1        National Geodetic Survey,   Retrieval Date = SEPTEMBEI
 UA0009 ***********************************************************
 UA0009  DESIGNATION -  W 194
 UA0009  PID         -  UA0009
 UA0009  STATE/COUNTY-  MD/QUEEN ANNES
 UA0009  COUNTRY     -  US
 UA0009  USGS QUAD   -  QUEENSTOWN (1986)
 UA0009
 UA0009                         *CURRENT SURVEY CONTROL
 UA0009
 UA0009* NAD 83(1986) POSITION- 38 57 44.65   (N) 076 12 41.30
 UA0009* NAVD 88 ORTHO HEIGHT -      9.763  (meters)        32.03
 UA0009
 UA0009  GEOID HEIGHT    -        -33.82  (meters)
 UA0009  DYNAMIC HEIGHT  -          9.758 (meters)        32.01
 UA0009  MODELED GRAVITY -    980,074.3   (mgal)
 UA0009
 UA0009  VERT ORDER      -  SECOND    CLASS I
 UA0009
 UA0009.The horizontal coordinates were determined by different
 UA0009.hand held GPS observations or other comparable positior
 UA0009.and have an estimated accuracy of +/- 3 meters.
 UA0009.
 UA0009.The orthometric height was determined by differential l
 UA0009.adjusted by the NATIONAL GEODETIC SURVEY
```

Published Height Difference (UA0009 – UA0008) = 9.763 m – 1.617 m = 8.146 m

Measured Height Difference (from leveling) = 8.143 m

Error = 3 mm

Allowable error for Second Order Class 1 leveling = $6\sqrt{1.18km}$ = 6.5 mm ✓

Figure 6-5. Comparison of height differences among two published vertical marks with leveled height difference. Example shows that the recorded 3 mm error lies within the allowable misclosure error for Second Order, Class I leveling ($\boldsymbol{6\sqrt{D}}$).

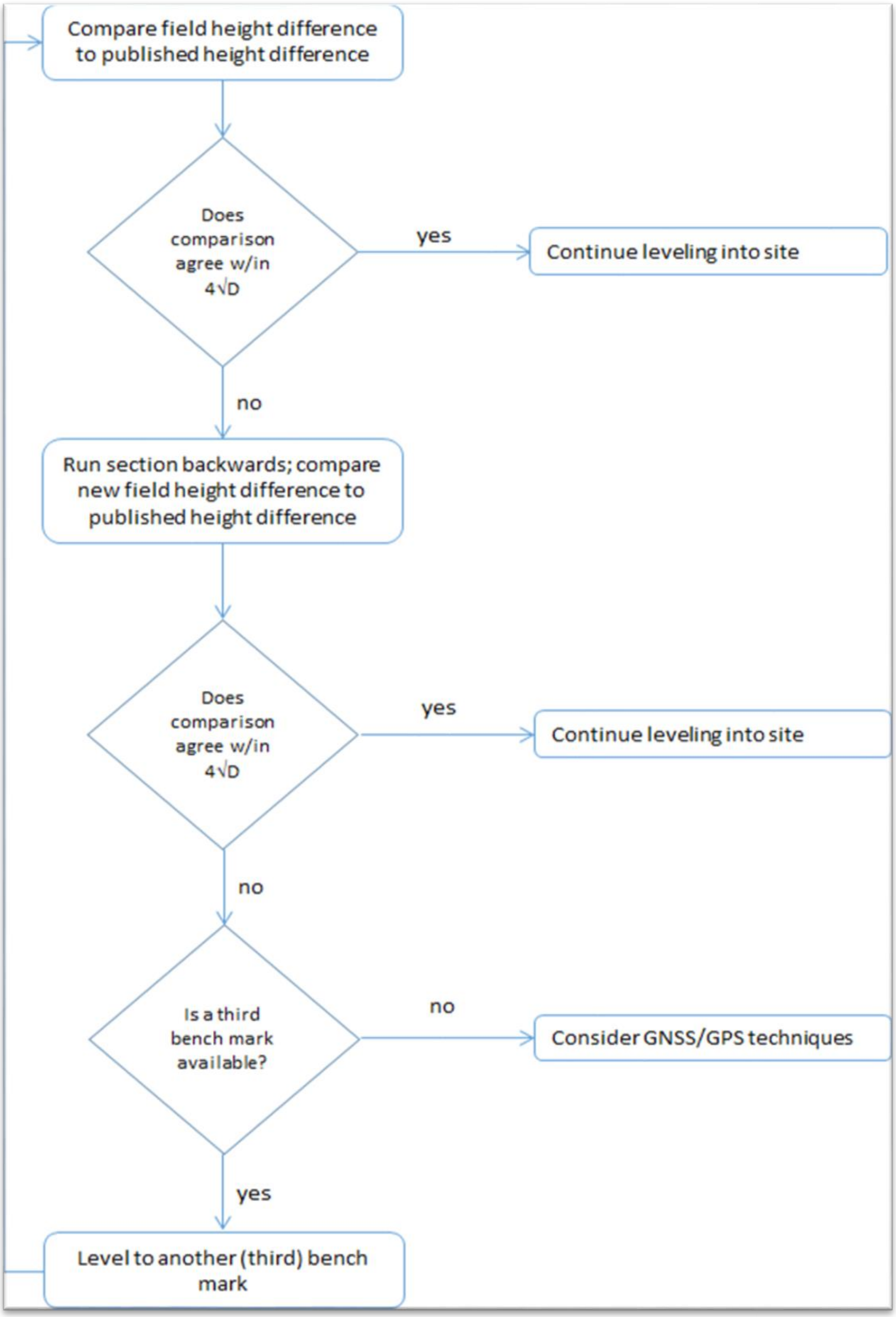


Figure 6-6. Flow chart for making the initial two-mark tie at the start of a level run. Published heights are obtained from the bench mark data sheets (Section 3.3.2); field heights differences are computed from leveling measurements in the field. Allowed misclosure depends on the published order and class of leveling.

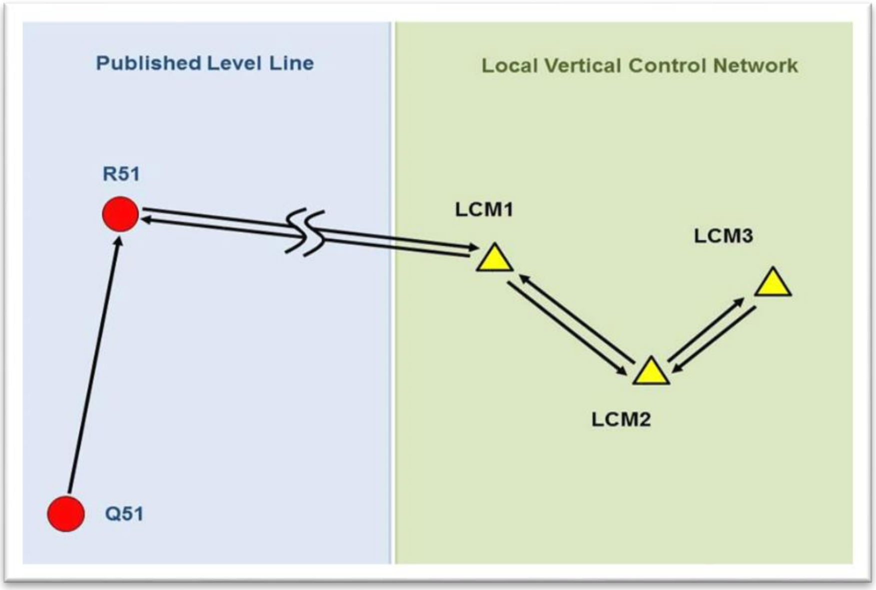


Figure 6-7. Conceptual diagram showing leveling among two published control marks (red circles) at the start of a level line. Two measured elevation differences can be checked against those expected from published elevations (e.g., Q51-R51). The example shows a linear level line continuing into the local vertical control network, connecting three LCMs (yellow triangles). The arrowed double lines starting at R51 and continue to the LCMs 1, 2, and 3, respectively, showing the forward and reverse measurements taken of the survey runs.

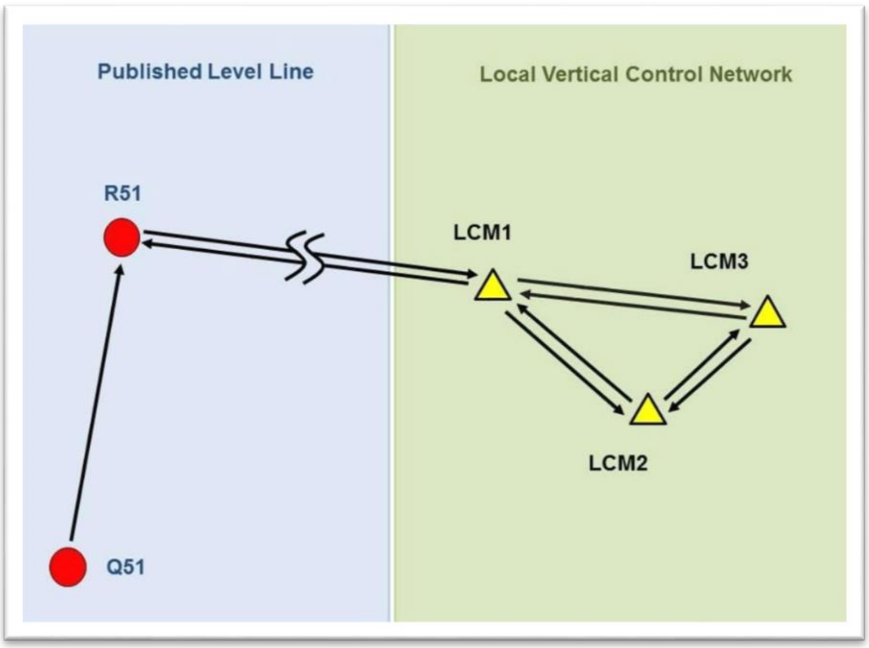


Figure 6-8. Example of leveling a loop within a local vertical control network. The arrowed double lines start at R51 and continue to the LCMs 1, 2, and 3, respectively, but LCM 1 and 3 are now connected via both forward and reverse survey runs.

Once you have leveled through all your local marks and have gone from start to finish, it is time to run the entire survey line again, but in reverse. This will provide an independent check to make sure your measurements of each section are correct.

Compare the pairs of elevation differences between the forward and backwards runs for each section (denoted by the arrows in Figures 6-7 and 6-8). This is best done while you're still in the field, so you can quickly re-survey if needed, see guidance below: (Figure 6-9 shows an example of the calculations involved.)

1. If the difference in millimeters are less than or equal to the target misclosure (e.g., $4\sqrt{D}$), then you successfully verified the section elevation differences (you will retain the average difference in subsequent computations). You can now move onto the next section, if applicable.
2. If the differences in millimeters is more than the target misclosure, then you have a *busted section*, otherwise called *section misclosure*. This means that the error is more than our recommended tolerances, and you will have to run that particular section again (backwards run) and make your calculation again.
   - If the new comparison (forward run – new backwards run) is still too large, then re-measure the section in the forward direction. Compare the new forward to the new backwards run and compute misclosure. If there is still misclosure, repeat alternating between forward and backwards until you get appropriate closure; but you must end up with at least one forward and one backward run that agree favorably for each section.

Examine the data

Back at the office, transfer your field notes to a computer, and double-check section misclosures (Figure 6-9). If misclosures fall within the target error, compute the average height differences for each section from forward and backwards runs (Figure 6-10). The next step is to assign a height to one of the marks in the level line and compute heights on all other marks by applying the average leveled height differences (Figure 6-10). If leveling into your site from an existing level line, use the published orthometric height of the mark nearest your local network that checked correctly (step 7 - *Observe your double-run level line*, above) to set the vertical control. Otherwise, you may obtain the orthometric height of a LCM via static GNSS observations (see Section 6.2).

A number of factors can introduce error in leveling data, such as using different equipment with different operating characteristics and collimation, different operators, scale imperfections on the level rods, refraction, curvature of the earth, tidal accelerations, and changes in the earth's gravity. Such errors typically build up over large distances (tens to hundreds of kilometers), so most of these should not accumulate much if you level over relatively short distances (on the order of one to several kilometers). In addition, keeping your setups balanced and taking short shots will further reduce these errors.

By following the recommended specifications given in Table 6-2, you will be assured of high-quality leveling data sufficient to make high accuracy vertical connections among your sentinel site bench marks and monitoring infrastructure, as well as monitor the network for vertical change. Regardless of exactly what specifications are followed, careful documentation of methods and misclosures is critical to evaluate the accuracy of the leveling data.

Line Leveling at Jug Bay
Instrument: Leica DNA03 s/n 338438
Date 4/29/2011
Collimation -10.1

Backsight - Foresight

4√D(km)

Forward Run

Section	Backsight (m)	Foresight (m)	Height Diff (m)	Distance (m)	Section Diff (m)
SET3 - SET5	1.46685	1.33934	0.12751	46.40369	
SET5 - SET4	1.28672	1.48954	-0.20282	42.76176	
SET4 - Pin	1.49527	0.86716	0.62811	40.38305	
Pin - Prop Mrk 1	1.29245	1.36043	-0.06798	98.41964	0.56013
Prop Mrk 1 - Stone	1.09741	1.17354	-0.07613	107.24857	
Stone - SET7	0.85752	1.33112	-0.4736	38.39266	
SET7 - SET8	1.11349	1.0986	0.01489	38.56826	
SET8 - Pin	1.0432	0.40887	0.63433	43.54988	
Pin - Prop Mrk 2	1.46717	1.48138	-0.01421	81.20458	0.62012
Prop Mrk 2 - Nail	1.71612	1.60659	0.10953	108.2093	
Nail - SWMP	1.4911	0.62269	0.86841	80.18841	

Backwards Run

Section	Backsight (m)	Foresight (m)	Height Diff (m)	Distance (m)	Section Diff (m)	Error (mm)	Allowable Error (mm)	Check
SET3 - SET5	1.29414	1.42152	-0.12738	46.69394		0.13	0.86301	PASS
SET5 - SET4	1.50869	1.30576	0.20293	42.34571		0.11	0.82514	PASS
SET4 - Pin	0.82509	1.43657	-0.61148	40.47276				
Pin - Prop Mrk 1	1.31884	1.26679	0.05205	98.42128	-0.55943	0.7	1.49049	PASS
Prop Mrk 1 - Stone	1.25838	1.18268	0.0757	107.22128		0.43	1.30987	PASS
Stone - SET7	1.11495	0.6411	0.47385	38.59658		0.25	0.78480	PASS
SET7 - SET8	0.90171	0.91681	-0.0151	30.7118		0.21	0.74447	PASS
SET8 - Pin	0.40234	1.06648	-0.66414	45.07388				
Pin - Prop Mrk 2	1.38371	1.33957	0.04414	80.67269	-0.62	0.12	1.13799	PASS
Prop Mrk 2 - Nail	1.55687	1.66646	-0.10959	108.20137		0.06	1.31578	PASS
Nail - SWMP	0.67012	1.54032	-0.8702	80.231		1.79	1.13285	FAIL

Height readings from level rods

Figure 6-9. Example of worksheet showing how elevation differences and misclosure errors are calculated for double-run (forward and backward) leveling.

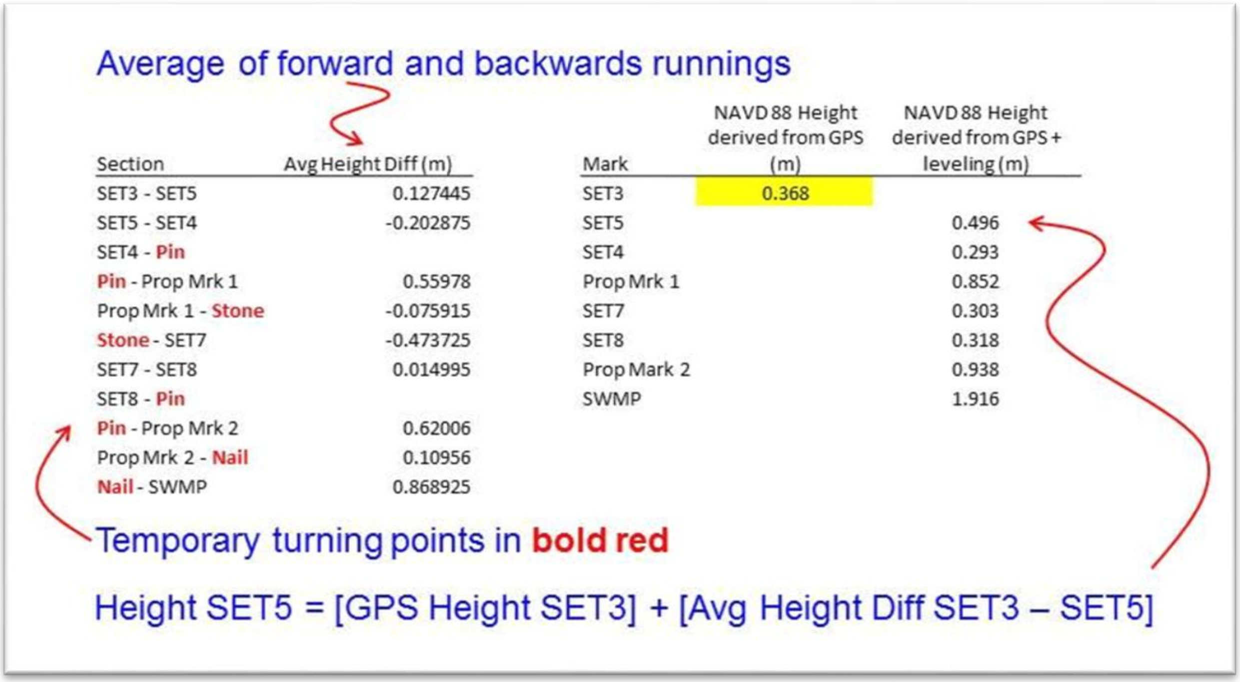


Figure 6-10. Example showing how to transfer heights to reference marks using leveled height differences. In this example, SET3 was a local control mark whose height was determined via static GNSS observations. Leveled height differences were applied from this mark to all other marks in the local vertical control network.

If you plan to routinely conduct leveling operations, you may want to look into training on processing leveling data, which can remove many of the errors mentioned above. This involves writing description files for each mark that is leveled to and running a correction procedure. NGS provides the software[56] *WinDesc* for writing description files and *Translev* for correcting. At the time of this writing, *WinDesc* is a necessary input to *Translev*, so the training is typically given together. Note that corrections require additional data, such as positions (lat/long – can use hand-held GPS) and ambient temperatures at the beginning and end of each section.

6.1.2 Best practices for geodetic leveling

Finding the Vertical Point of Reference (VPR)

The level rod is always placed on the vertical point of reference (VPR), which is usually the top-most surface of a domed brass disk (Figure 6-11). It should also be the point on the metal marker or rod where GNSS-derived elevations are determined (often marked by a dimple, punch mark, cross or X). This is also usually the center of the marker (Figure 6-12). If the center is not the highest point on the marker, or if metal marker is recessed and the level rod cannot make contact with the VPR, then a calibrated spacer (i.e., *plug*) should be used on the VPR, so that the level rod can connect to it (Figure 6-13). One plug is placed on the VPR of the mark in question: the level rod is placed directly on top of it. It may take two people to make sure the plug is placed correctly on the monument, and it is roughly in the center of the bottom plate of the level rod. A

[56] http://www.ngs.noaa.gov/PC_PROD/pc_prod.shtml

matching plug (plugs come as a set of two) is also placed under the other level rod, even if a foresight was already taken without a plug. Now, both the backsight and subsequent foresight will have plugs, and the effect of the plugs will cancel out the height offsets. Plugs must be used in pairs! If the foresight on the next setup does not need a plug, then both plugs must come off. Matching plugs may come in the level kit; otherwise contact your survey supplier.

If you use a deep rod Surface Elevation Table mark (SETs) as a LCM, it is customary to level to the top of the stainless steel receiver; the receiver is the machined rod that is milled and threaded to accept the base of a Rod SET measuring instrument. It usually protrudes from a concrete base (6" PVS pipe filled with concrete; Figure 6-12). It is not recommended to level to any metal survey/identification disk cemented at the base of the Deep Rod SET monument. Such a disk bears no constant vertical relationship with the top of the receiver, and it is not directly affixed to the rod; so it does not have the same inherent stability as the rod (it is merely set into the top of the concrete). Placing a level rod on the exposed top of the receiver will naturally find the top (don't forget to remove the plastic top; Figure 6-14).

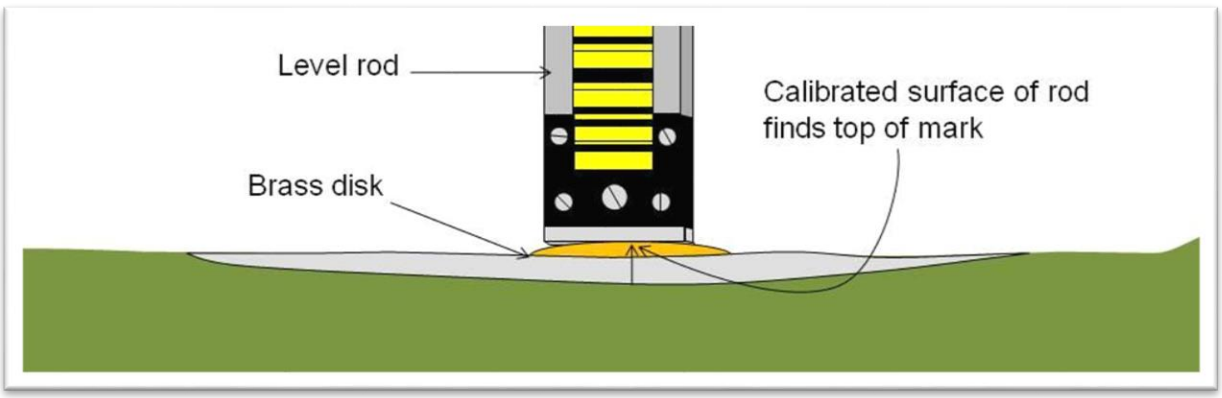


Figure 6-11. Diagram showing how calibrated surface of the level rod will naturally sit on the top-most part of the mark, the vertical point of reference (VPR).

Figure 6-12. Examples showing different types of survey monuments and the location of the vertical point of reference (green arrows). A: typical domed brass disk; B: leveling disk with raised center; C: Brass cap on metal rod encased in pipe; D: deep rod mark with domed datum point.

Figure 6-13. Matching (calibrated) 2-cm magnetic plugs used to place rod on vertical point of reference (VPR) where VPR is recessed, and calibrated end of rod cannot make direct contact. Both plugs must be used in the same setup (both backsight and foresight).

Figure 6-14. Close-up of level rod placed atop a deep rod SET receiver (bench mark). The vertical point of reference is the top-most side of the receiver. The cap to the receiver is shown and has been removed before leveling to the SET.

Stability

Ensure that no component of a level shot move within a setup (e.g., turning points, level rods, level tripod). This means that the tripod holding the level has to be on stable ground, and the operator has to be very careful not to bump the tripod or otherwise move the level. Hard, stable ground is not always possible in coastal habitats, so extra care must be exercised. If you need to place the tripod on unstable ground, stomp on the tripod legs firmly prior to plumbing the level and be careful to keep your body weight from tilting the tripod. Check the circular vial on the level to make sure it hasn't moved. If it is out of plumb between backsight and foresight, cancel the shot and retake the backsight. Try to get the level more stable.

Turning points must be stable - at the very least between the foresight of one setup and the backsight of the next. Only after the foresight of the next setup has been successfully taken can you pick up and move the rod and turning point.

Everything plumb

The level instrument and level rods must be plumb (parallel to the local gravity field). Normally, the level instrument will be auto-compensating, meaning that within several degrees, the optics inside the level will be plumbed automatically. You still need to adjust the level instrument, to make sure that the auto-compensation is within an appropriate range. The level rods may or may not have built-in bubble gauges. If they do, it is good practice to check their adjustment on a yearly basis. Refer to the equipment manufacturer for instructions. If your rods do not have bubble gauges, then you will have to use a high-quality level. Level rods may have brace poles attached (e.g., Figure 6-15). This makes it much easier to keep the rod plumbed and immobile over the time it takes to take the measurement.

Tips to plumb a level rod with brace poles (Figure 6-16):

1. Place the calibrated base of the rod gently on center/VPR of the mark; try to keep the rod plumb.
2. Extend each brace pole out and down, pushing the pointed end into the soil or ground.
3. Look at the bubble gauge: make an imaginary plane defined by the level rod and one brace pole and note the relationship between the bubble and the plane.
4. Grasp the release mechanism of the other brace pole with two hands: one hand can hold the release mechanism of the brace pole, the other can let out or take in the pole extension.
5. Let out or take in the extension, until the bubble crosses the imaginary plane defined above.
6. Repeat now with the first brace pole, but bring the bubble in line with the imaginary plane defined by the level rod and the second brace pole.
7. Alternatively, bring the bubble in line with the plane (axis) of the other brace pole to plumb the bubble quickly and accurately.

Figure 6-15. Three-meter tall-digital barcode level rod set on turning point, showing brace poles in action. Brace poles ensure immobilization of rod during the leveling operation, keeping the rod plumb.

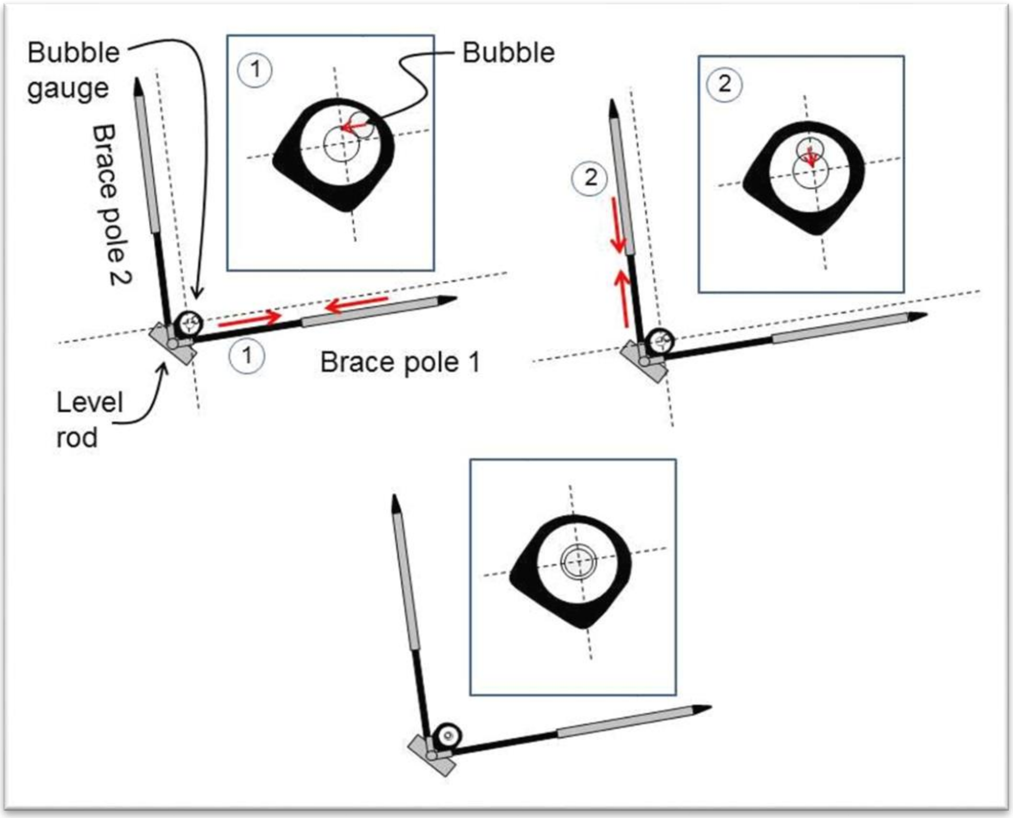


Figure 6-16. Conceptual diagram showing how to plumb a level rod with two brace poles.

Turning points and temporary points

Turning points are temporary marks that allow the surveyor to keep the rod at exactly the same height while turning the rod to face the new leveling position. There are two basic kinds of turning points: those that lay flat on the ground (turning plate or "*turtle*") and pins that are pounded into the ground (Figure 6-17). Pins are generally preferred, as they are more stable and less prone to accidental movement. You will need a rubber-faced mallet to pound it in (cap on); the mallet is also useful to get the pin out: you tap the sides of the pin to loosen the soil around it, making it easier to pull out. The most important thing is that the turning point be stable for the duration of two consecutive setups.

Figure 6-17. Pins and turtles used as turning points during a leveling section.

Important Information
Regardless of the kind of turning point you use, do NOT move the point between TWO (2) consecutive setups – between the time a rod is the foresight to the time it is a backsight. Only after the backsight has been successfully taken can you pick up the point. Do this only when the level operator has signaled you to move. Removing a point before the backsight is taken will result in losing the entire level section (you'll have to start back at the last mark occupied).

Level sections can be long and involve the difficult task of leveling across a wetland, through tall vegetation, etc. Temporary points can save a lot of time, as you can pace out and mark all rod and level placements. In addition, you will be able to compare the intermediate calculations along an entire section, so you can pinpoint exactly where any misclosure error occurred. That way, you only have to redo one or two setups. Temporary points need to be a stable physical structure that can support the weight of the level rod without moving - at least during the duration of the level run. An example is exposed rocks or boulders in the ground or in other hard structures - something with a definite top side, or an area that can be marked as a vertical point of reference. Other examples are an exposed nail head on a pier, bridge, or road, a pre-existing property marker, or a wooden stake with a sturdy 10d nail on top. For wetland temporary points, 2 inches × 2 inches × 24 inches (or longer) wooden stakes can work well. Make sure they go in far enough to be stable and do not protrude much above the ground (use flagging so you can find them later!). Placing temporary points may also allow you to pinpoint where the level should go to ensure balanced shots. This can all be done in advance of the leveling.

For the novice surveyor, it may be convenient to use as many temporary points (TPs) as possible, instead of turning points. Temporary points can be stakes driven in the ground, with survey (PK) nails or 10d nails hammered into the top (after hammering the stake into the ground). Temporary points can also be a chiseled mark on a rock outcrop, concrete structures, or any other structure that is both stable and whose height will not change with temperature and humidity, especially over the course of the leveling project. Also consider marking the locations of each setup (where the tripod and level were placed to ensure balanced shots). This affords several benefits:

- Less chance of pulling up a pin before it is time.
- Faster reverse run, as you won't have to pace between setups.
- If a shot is "busted" on the reverse run (see below), you won't have to do the entire section, just a setup or two. Height differences must have been recorded.

Distance

With both optical and digital levels, error tends to increase with the distance from the level to the rod. For this reason, we recommend a maximum distance (between rod and level) of 70 m; shorter distances are more accurate.

- For optical leveling, we recommend you keep shots short enough to clearly see the divisions along the level rod - again to keep error at a minimum.
- In shortening the shots, the quality of the elevation readings improve, but you also are requiring more setups, which can also introduce error. You are also spending more time.
- Some compromises need to be made between distance and time. For example, if you can make a one-setup section between two marks (especially on the wetland surface, where stability is difficult), you may want to allow for a longer shot just to avoid setting up twice.

Balanced shots

It is important to place the level instrument the same distance away from each rod (e.g., distances BS ≈ FS in Figure 6-18) to minimize errors. The level does not have to be in a straight line with the rods—in fact, there are many occasions in the field when you may get a better shot if the level is moved to one side. The key is to have the distances the same on both sides of the level. We recommend no more than 5 m of imbalance per multi-setup sections. For two-setup sections, you should be within 1–2 m.

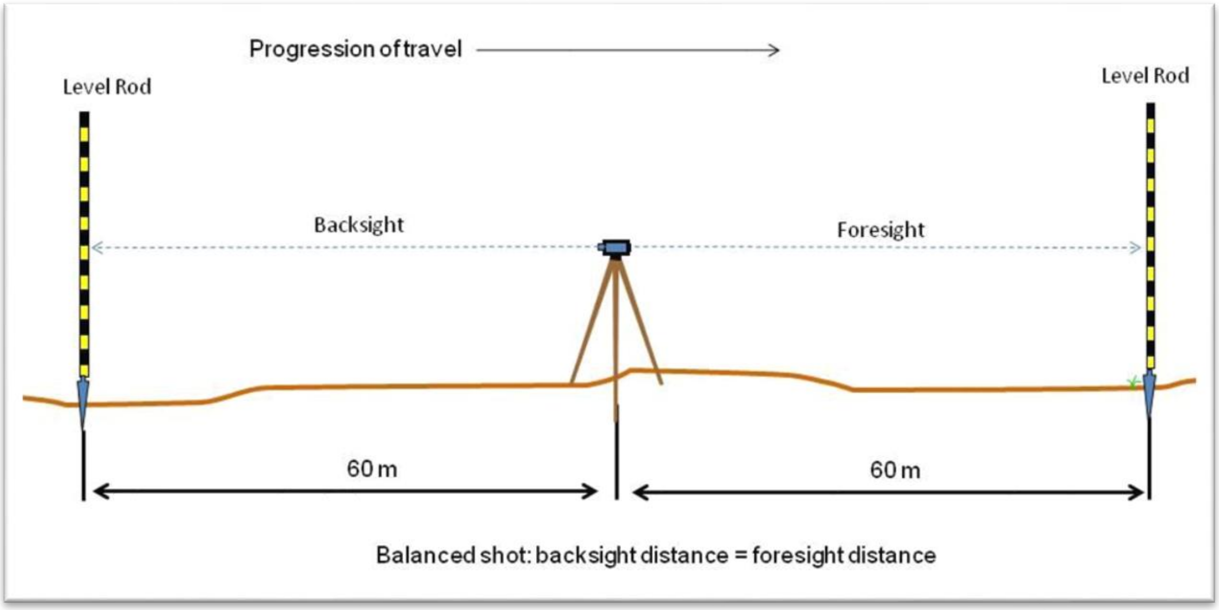


Figure 6-18. Sketch showing concept of a balanced level shot.

How to ensure balanced shots

- Careful pacing (good)
- Optical distance measurement (better)
- Electronic distance measurement (best)

An adequate geodetic leveling party generally consists of four people: the chief of party generally operates the level instrument; two team members operate the rods, and the fourth person can serve to pace distances and keep field notes. Accurate pacing comes with experience, so you can expect the pacing to be somewhat unreliable at the start.

The novice surveyor should use the built-in distance meter on digital levels to check for out-of-balance. This step may add 30 seconds to a shot but may well be worth it for keeping shots very balanced. Balance can also be gauged on an optical level by measuring the range on the level rod between the top and bottom cross hairs (but this takes somewhat more time and practice). If you find that the imbalance is more than a meter or two, either move the level in the required direction, or have the foresight (NOT the backsight!!) moved accordingly. If you are using temporary points instead of turning points, then you must move the tripod. Once the setup is balanced, mark the location of the level, so you will not have to measure distances on the backwards run.

Sloped surfaces

Occasionally you will have to go up an incline. If your stadia rod is long enough, you may be able to place the tripod half-way up the slope and still be able to read both the top and bottom rods (Figure 6-19). Be careful in setting up the tripod on the slope (two legs down, one leg up) to make sure it is stable. Also, make sure that all three crosshairs in the sighting scope are on the stadia rod. This will ensure that you get accurate readings both top and bottom. If this is not possible, then simply shorten your setup by moving your forward rod back an appropriate distance. If you are in an area with a lot of relief and inclines/declines and are considering purchasing or renting leveling equipment, it might be worth the extra cost to buy the longer (3 m) rods.

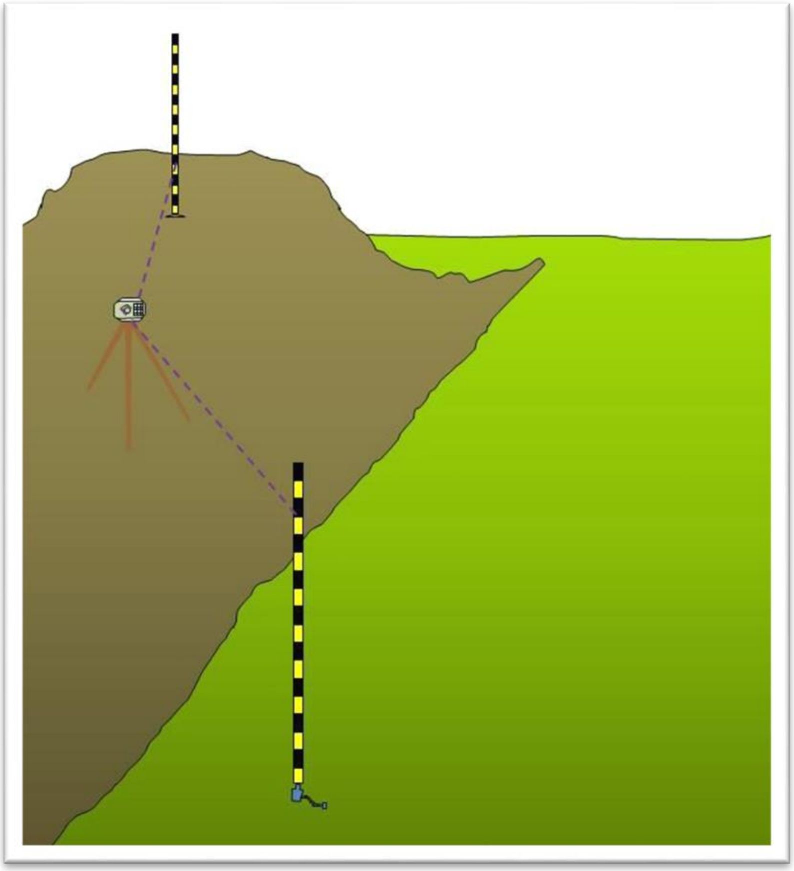


Figure 6-19. Diagram showing how you can place a level midway up a slope to read both upper and lower survey rods.

Leveling across the wetland

Leveling on unconsolidated surfaces can be very challenging due to the difficulty in keeping everything stable and plumb. Turning points or temporary points can be made stable enough by driving long stakes into the soft mud. Probably the most difficult part of leveling in a wetland is finding a stable surface on which to place the leveling instrument and ensuring it does not move between backsight and foresight.

Suggestions to keep leveling instrument stable in a wetland:

- Splay out the tripod legs to between 45° and 60° or so (Figure 6-20).
- Place barbell weights under each tripod leg. Make sure you wrap flagging tape or a rope to each weight, or they'll quickly disappear.
- Place each tripod leg on a clump of vegetation. Grasses like *Spartina* and rushes like *Juncus* grow multiple stems from a central node just under the ground surface: oftentimes, the node is sturdy enough to keep the tripod steady.
- Stay as far away from the tripod legs as possible. If you have to take the measurement optically, consider setting up a board on the marsh surface to distribute the weight of the

observer; if you are using an electronic level, then try to make the measurement with your body as far from the level as possible (Figure 6-21).

- If possible, set up the instrument lower than normal and in a spot where both rods can be seen by craning your neck around while leaving your feet planted.

Figure 6-20. Leveling in the wetland: note splayed legs of tripod between 45º and 60º to enhance stability.

Figure 6-21. Leveling in the wetland: Operator(s) standing away from tripod, while activating electronic measurement.

Another difficulty in wetlands can be the height of the vegetation. In freshwater wetlands, cattail (*Typha* spp.) can easily grow to a height of 2 m. Similarly, in brackish wetlands, the common reed (*Phragmites*) can also grow in excess of 2 m. Such vegetation quickly obscures line-of-sight, rendering leveling virtually impossible.

Several recommendations to help you level through tall vegetation:

- Keep your setups short.
- Create a line of sight by using stakes and rope to tie back the vegetation.
- Conduct leveling operations in the late winter or early spring, after last year's growth has fallen down to the soil and before new growth has begun. You may still have to tie or knock back some vegetation, but it'll be a lot easier than when fresh growth is 2 m tall!
- Use an optical level; a digital level requires that a larger section of the rod is visible and your eye can often see more clearly through moving vegetation than the laser.

Leveling in the wetland requires patience and care. Whatever you do, don't drop the level instrument in the mud! Make sure you rinse the rods with clean, fresh water, and wipe everything down clean and dry (do not scratch the markings on the rod). Make sure the level instrument is clean and dry when you put it away. If you remove salt or other deposits with a moist rag, make sure you wipe the instrument dry; any moisture will get inside the level and ruin the internal electronics or mechanisms.

Record keeping

Careful record keeping is essential to avoid mistakes. General data descriptors for a leveling project include project name, date, level operator, instrument type and level rods (note all serial numbers) and collimation readings, including computations. If leveling data are not being recorded electronically (e.g., in the level instrument), then make sure to record by hand (best practice is to record even if data are being recorded electronically). The data that should be recorded for each section include:

- Beginning Bench mark/ID, and which level rod is on it
- Beginning time and air temperature[57]
- Direction of travel (forward/backward)
- Section elevation differences
- Total section distance
- Number of setups
- Accumulated imbalance
- Backsight rod reading/distance, foresight rod reading/distance Ending Bench mark/ID, and corresponding level rod
- Ending time and air temperature[58]

At the end of a section, it is also good practice to note wind and sun codes (0 = none, 1 = some, 2 = high); this will allow eventual leveling adjustments using the software noted earlier (beyond the scope of this document).

Leveling data recording sheets are available from NGS for different types of leveling equipment. Appendix 3 provides an example of a field datasheet for one particular vendor's digital barcode level. This kind of sheet provides spaces for writing down all necessary field notes that would be required for subsequent corrections. Although other datasheets exist for optical leveling (e.g.,

[57] Time and temperature are required if adjusting leveling data using surveying software (not covered here). If computations will be done by hand/spreadsheet, temperature compensation will not be used; times may be useful for recordkeeping but would not be used in the computations.
[58] Same as (42) above.

three-wire method); these likely specify more records than would be required for the kind of leveling prescribed in this document.

6.2. GNSS Static Surveying

In many, if not most sentinel site locations, static GNSS surveying will be required to establish a geodetic connection between the local vertical network and the NSRS. Although leveling has greater precision, many locations will be tens of kilometers away from an existing high accuracy level line or require water crossings greater than 70 m. In addition, even if you can bring high accuracy elevations into your network via leveling, you may still need to conduct static GNSS surveying in some remote locations in the site or to obtain good geometric positions (latitude, longitude, and ellipsoid height).

The recommended procedures for connecting the local vertical control network to the NSRS via GNSS rely on two or more 4-hour (or longer) static GNSS sessions on the LCMs that you plan to observe. The observation sessions should occur on at least two separate days and over different times of day (e.g., Day 1 8 a.m.–2 p.m., then Day 2 12 p.m.–6 p.m.). If you are observing more than one LCM, it is recommended to observe them simultaneously. The data is processed using the NGS Online Position User Service (OPUS).

Basic Concepts

Static GNSS surveying involves placing a dual-frequency (L1 and L2 bands) differential GNSS antenna on a tripod atop a survey mark for a long enough time to obtain high-accuracy results. “Static” means that the antenna does not move during an occupation on a mark. The GNSS antenna receives time and positional information continuously from one or more arrays of satellites circling the earth: over the course of a day, the satellites cross over the sky, constantly changing the geometry of the arrays. These changing arrays provide any number of different triangulations to the survey mark. For example, the array of GNSS satellites in the morning hours will be different from that of the afternoon, as different GNSS satellites come into and out of the field of view of the GNSS antenna. A large number of different configurations in the array will produce a more robust geometric solution for the position on the ground – which is why a long observation session is needed.

The high accuracy positions obtained via GNSS observations are the result of processing GNSS data (after the sessions are completed) with data recorded at the same time by a number of nearby Continuously Operating GNSS Reference Stations, or CORSs. The CORSs receive similar GNSS satellite information as your GNSS antenna in the field; since the position of the CORS is well defined, the information received at the CORS at any given time can be used to provide corrections for atmospheric influences on the GNSS signals. OPUS chooses from among the nearest CORS to your observed mark to provide you with the best estimate for your mark’s position. As a result, a 4-hour or longer GNSS observation can yield vertical accuracies of about 2 cm (Figure 6-22). Note that OPUS requires at least 2 hours of continuous GPS data; longer observations lead to even lower positional errors.

These guidelines recommend simultaneous GNSS observations on multiple LCMs to minimize error among the relative positions of these marks. Simultaneous GNSS occupations ensure that each mark “sees” the same GNSS constellations with the same atmospheric conditions. Atmospheric errors will likely affect all your GNSS antennas in a similar way (resulting in a potential bias in the positions), so *relative* positions will be less affected. Averaging positions from multiple days will reduce the effect of the biases.

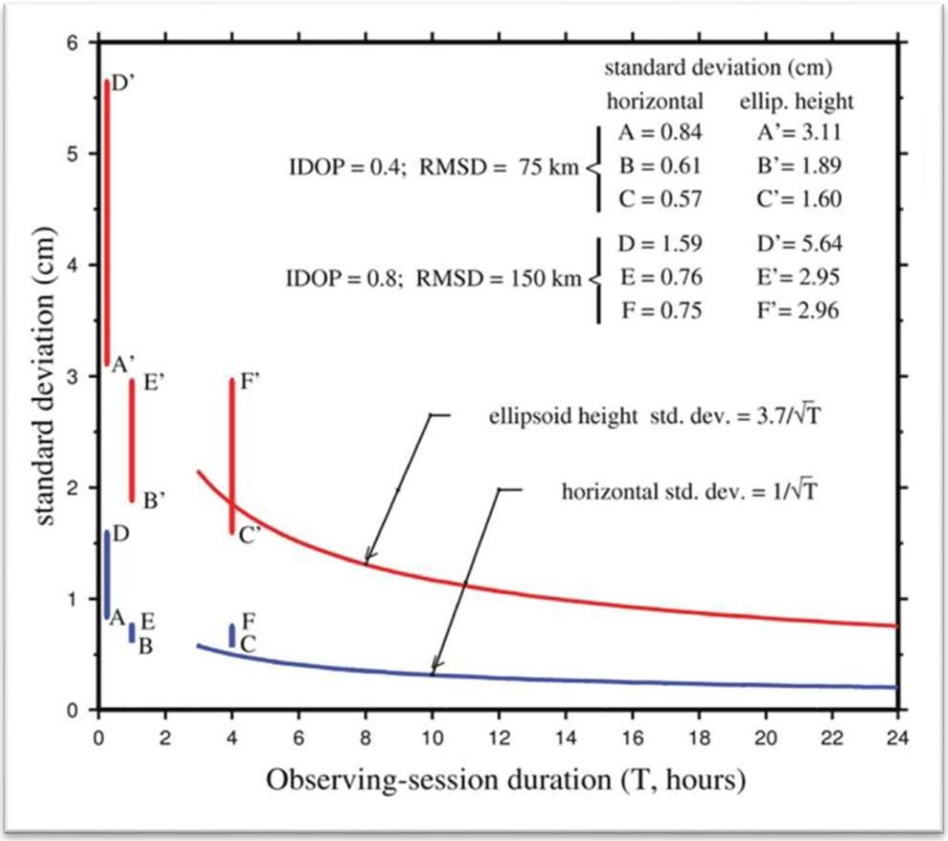


Figure 6-22. Accuracies of static GPS-derived positions (given in units of standard deviations, centimeters) in relation to length of observation (hours). Taken from Snay et al. (2011).

Strengths and Weaknesses

- Weakness: GNSS provides a connection to the ellipsoid datum NAD 83 with centimeter-level error. Through the application of a hybrid gravity model ("geoid"), an equivalent NAVD 88 elevation (i.e., orthometric elevation) can be computed from the GNSS data (adding an additional component of error).
- Strength: GNSS, because it computes a contemporary position, reflects where the current mark is with respect to an established geodetic datum.
- Weakness: GNSS will provide a more contemporary connection to the NSRS, but at the time of this writing, GNSS-derived NAVD 88 elevations will have vertical errors on the order of several centimeters. GNSS equipment is also expensive, but it is very easy to use, and you will only need it for a couple of days. These units, along with the necessary accessories, such as tripods and data loggers, can be rented from surveying equipment distributors.

Important Information
Even if you bring leveled elevations into your network, you should still conduct a GPS survey at some stage of the project to bring accurate horizontal positions to your local network (e.g., photo control or other ground control points). You may also rely on Real-Time Kinematic (RTK) GPS to transfer elevations from the LCMs to your environmental monitoring infrastructure, which requires similar GPS equipment.

6.2.1. Planning a GNSS survey

Your GNSS survey plan should be included as part of your overall geodetic control plan (Section 3.4). As such, you will have conducted the bench mark recovery both in the office and in the field, and you will have proposed which marks you will observe, for how long, and on what days. For a minimum accuracy standard, the following recommendations are given for planning the GNSS survey:

- Observe LCMs with static GNSS for as long as possible.
- Use survey-grade GNSS units.
- Complete simultaneous GNSS occupations on all LCMs if possible. If this is not possible due to lack of equipment, you may still be able to occupy pairs of points simultaneously and sequentially move one unit to another point over time (e.g., leap-frog method).
- Complete a minimum of 4-hour observations on all marks.
- Complete a minimum of two observations per mark. If only one GNSS unit is available, then take as many observations as possible on each mark (more than two is recommended).
- Plan observation periods on separate days and span different times of the day.
- Alternate GNSS equipment on marks for repeated observations.

Important Information
Make sure that your GPS antenna has been calibrated by NGS – this will be important when you process your GPS data. To make sure your antenna is calibrated, check the web page: http://www.ngs.noaa.gov/ANTCAL/.

Modern "survey grade" (dual frequency, differential) GNSS units generally come as one-piece units, combining both antenna and receivers (Figure 6-23). Older assemblies typically have separate antennas connected to a larger receiver via a coaxial cable (Figure 6-24). In both cases, the antennas are placed atop a GNSS tripod which is typically a 2 m, fixed-height tripod with a fourth, central leg, which is placed on the VPR of the survey mark.

GNSS equipment can be costly, but it may also be rented from survey equipment retailers. Most GNSS units operate in very similar ways, but it is always best to get trained on the equipment and software that your vendor is supplying. If you are associated with a university, you may have access to equipment through your geomatics or survey engineering departments. If you are a state institution, your state departments of transportation or state surveyor's office might be able to provide you with some assistance. Consider contacting your NGS regional advisor[59] for information on what is available, and suggestions for running your survey. It is ideal to obtain enough GNSS antennas and receivers to ensure simultaneous occupations on all your LCMs (at least those that you cannot level among). Ideally, all antennas and receivers should be the same model to reduce errors. Without additional receivers and antennas, your survey will take much longer as you alternate equipment on different marks for multiple sets of simultaneous occupations.

Ideally, select the LCMs to ensure an unobstructed view of the sky. Marks that are next to buildings or trees, especially if they obscure the southern sky, are problematic. In the best case, you need open skies down to about 10° above the southern horizon (Figure 6-25). This is roughly equivalent to the height of your two fists, one on top of the other, extended at arm's length. You might need tripod extensions to ensure that the antennas remain above obstructions such as vegetation; otherwise, you should consider temporarily pushing vegetation aside or waiting until leaf-off or stem-down conditions (late winter or early spring) to hedge your chances of getting sufficiently good GNSS signals.

In the northern hemisphere, open skies are most needed above and to the south.

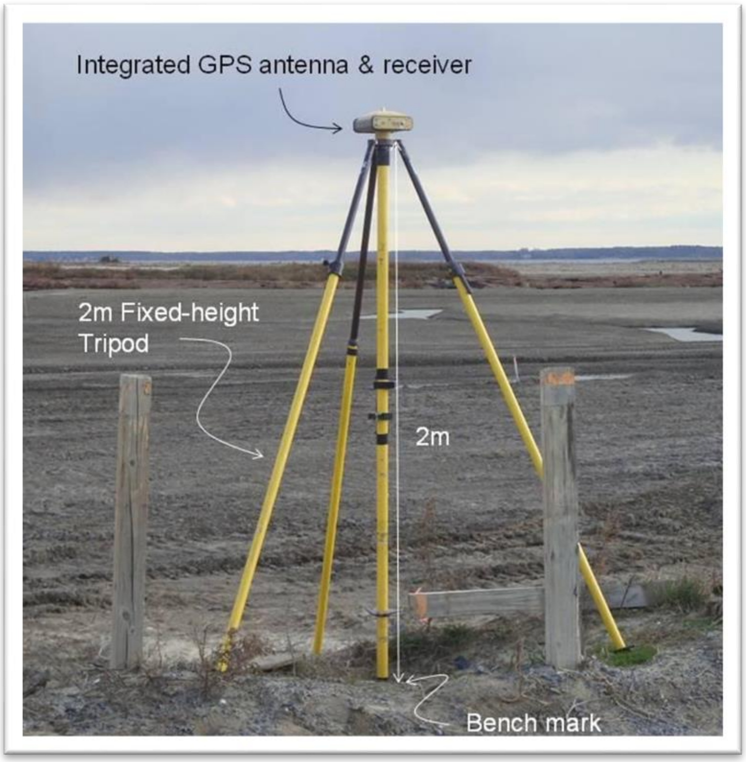


Figure 6-23. Integrated GNSS antenna and receiver atop a two-meter fixed-height tripod during a static occupation at Poplar Island, MD.

[59] https://geodesy.noaa.gov/ADVISORS/

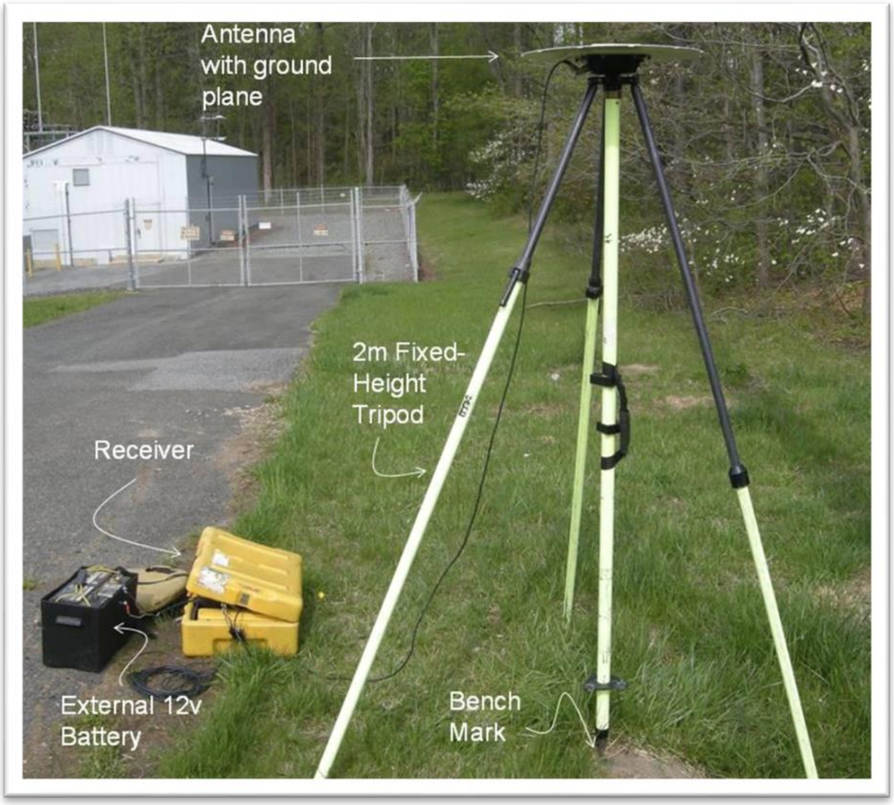


Figure 6-24. GNSS antenna with ground plane atop a 2 m, fixed-height tripod. Note that in this case the GNSS receiver is a separate unit, connected to the antenna via a coaxial cable.

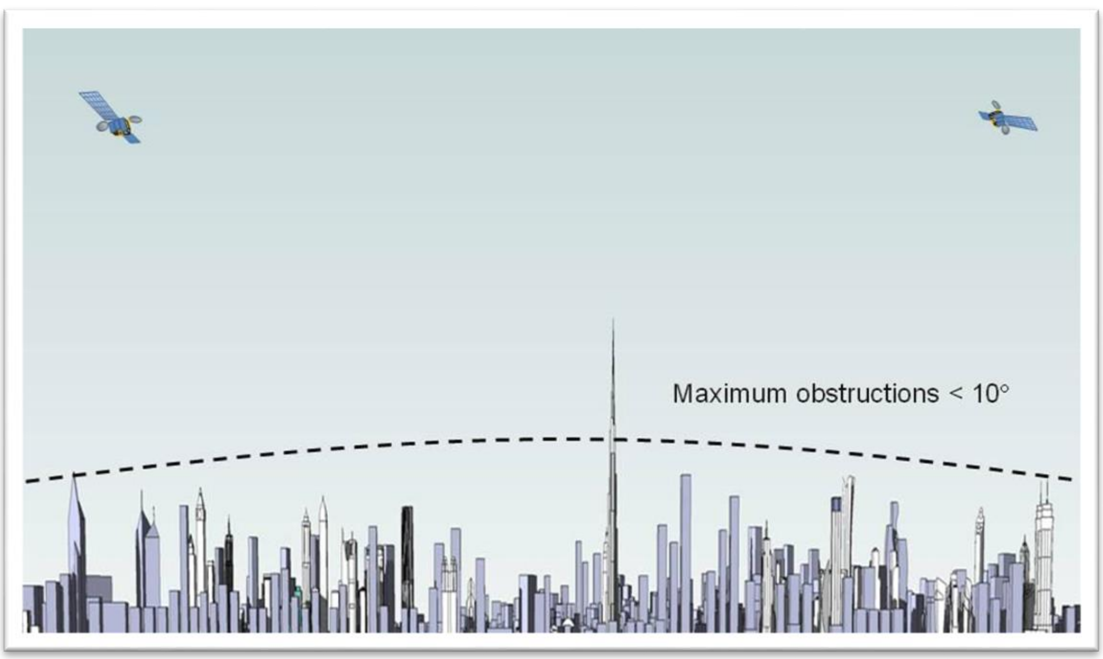


Figure 6-25. Conceptual diagram showing the need to estimate the degree of vertical obstructions between the GNSS antenna and GNSS satellite orbits. Anything more than about 10° is less than ideal.

If you have open skies, then you probably do not need to worry about using GNSS planning software (available through private vendors). Such software is available to assist in cases of an obstructed view, so you can plan your GNSS sessions for when satellites will be in view of your restricted location. Based on your position and date, the program can tell you at what times of the day you will "see" a good enough GNSS constellation to obtain high-quality data. Even with no obstructions, this software can help you maximize data quality by helping you time your observing session to when there are the greatest number of widely dispersed satellites in the viewing sky. For GPS, there are now over 30 satellites in orbit, so their geometries are generally good.

Additional considerations to ensure successful planning:

- "Babysitting" the GNSS: In public areas frequented by passers-by, you need someone guarding the equipment during the entire occupation to avoid theft and ensure data integrity (the equipment is expensive, and so are your data!).
- Teamwork: If it takes a long time to get from one site to another, divide your party into teams, one per mark. That way, most marks can be observed at about the same time.
- Budget extra time: Add a day because your first session might expose unforeseen problems with setting up the survey (it is common to make mistakes in setting up when you are new to this!) Then add a couple more days to the plan to make sure you can account for poor weather. Typical GNSS units can remain out in a drizzle, but it is best not to observe in a downpour – your equipment could be damaged.
- For more in-depth tips on GNSS survey planning: Please see the NGS online lesson GNSS Positioning: Survey Planning and Data Acquisition.[60]

6.2.2 Running the GNSS survey

A GNSS survey is conceptually very simple: you set up a GNSS antenna on a tripod over a mark, plug it into a receiver, turn it on, and let it run for a number of hours. However, in reality, there are numerous ways a session can go wrong, resulting in either no data or just not very good data. The trick is paying close attention to details and ensuring you are well prepared. We won't go into every detail of static GNSS surveying but will hopefully provide you with enough information to successfully conduct your survey. A short video on how to minimize errors in GNSS surveying can be found here.[61]

More information can be obtained from two earlier NGS guidelines for GPS-derived elevations: NOAA Memorandum NOS NGS-58 (Zilkoski et al., 1997) and NOAA Memorandum NOS NGS-59 (Zilkoski, 2008). Note that these documents do not assume the use of OPUS, so the calculation methods assume knowledge of advanced geomatics. You may also refer to GPS training provided by NGS for more information on best practices.[62] No matter what guidelines document you decide to follow, make sure you consult the recommended equipment in the checklist in Table 6-5. Also, make sure to complete the equipment checks described below before you go into the field.

[60] https://geodesy.noaa.gov/web/science_edu/online_lessons/gnss-positioning.shtml
[61] https://geodesy.noaa.gov/corbin/class_description/Reducing_Error_Sources
[62] http://www.ngs.noaa.gov/corbin/class_description/GPS_Derived_Heights_Zilkoski.shtml

Table 6-5. Recommended equipment for a static GNSS survey.

Quantity	Description	Notes
3+	Survey grade GNSS antenna-receivers	Can be a small all-in-one unit, communicating via Bluetooth to handheld device, or a separate antenna and receiver (with required cables and battery). Ideally, one unit per local control mark (LCM).
3+	Survey grade 2 m fixed-height tripods	Used to fix antenna at a known elevation above a mark.
3+	External 12V batteries + cables	One fully charged battery per GNSS unit; lawn mower batteries work well. Make sure you have appropriate cable ends to fit onto the battery and plug into the GNSS receiver. Crimp or weld appropriate ends as needed.
3+	Portable solar panels	Allows long GNSS observation sessions by recharging external batteries during daytime.
1	12 V marine/car battery charger	To recharge batteries between occupations.
1	Tool kit	Extra wires, fuses, pliers, wrench, screwdrivers, stripping/crimping tool, electrical tape, metric measuring tape, light oil, assorted crimp-on wire connectors, and terminal ends.
3+	Weatherproof containers	To house the separate GNSS receivers – one per unit (not needed for all-in-one units).
1	Field notebook, pencil	For documenting leveling equipment, antenna heights, recording start/stop times, and any other pertinent information.
3+	GNSS recording sheets	Optional
	Folding chairs	Optional -To sit comfortably while babysitting the GNSS.
	Umbrella	Optional -To shade the battery or GNSS receiver – or the babysitter.
	Standard field equipment	Hat, sunscreen, raincoat, drinks, cell phone, and bug repellant.

Check your equipment

Verify the vertical offset of each survey tripod (as deployed on the mark) to make sure that when you process your GNSS data, you are providing the true vertical offset value (measure to the nearest millimeter):

1. Make sure the survey tip is securely fastened to the middle tripod leg.
2. Measure the distance between the antenna attachment surface and tip of the center tripod with a steel tape – at least twice.
3. Write down the average length (in meters) on a label and include the date.
4. Place the label on the tripod, so you'll know the vertical offset and when it was last checked.

Check to make sure that the circular vials of your tripods are reasonably calibrated. See subsection below (*Check your mark*) for discussion on the effect of being out-of-plumb:

1. Plumb the vial (bubble in middle of circle).
2. Rotate the tripod shaft (or instrument containing the vial) 180° (if you were facing it before, not it's facing away from you).
3. Check to see if the bubble is still in the middle of the vial. If not, then use the vial adjusting screws (typically under the vial or on the flange holding the vial) to bring the bubble half-way towards the middle again. Use the regular leveling thumbscrews to bring the bubble the remaining distance to the center.
4. Rotate the tripod shaft/instrument 180° again.
5. Check the vial; repeat adjustment as necessary (may take several attempts).

Important Information

Check to make sure your GPS unit is in working order:

- GPS unit turns on and has sufficiently charged batteries for 4+ hours of operation.
- GPS can lock onto satellites, and it can record data to memory.
- Memory card is cleared, and memory in the GPS is ready to accept a full >4-hr session.

Check your mark

Make sure you are observing the correct mark! Many marks look alike, and several may be found in the same area (e.g., both vertical and horizontal marks). In addition, a brass disk is not necessarily the vertical reference mark (Figure 6-26). Take a close-up photograph of the mark, as well from a distance to provide some geographic context. Make any pertinent notes regarding the condition of the mark, difficulties with access, and anything blocking an open view to the sky. Refer to the NGS field survey forms: https://geodesy.noaa.gov/surveys/forms/.

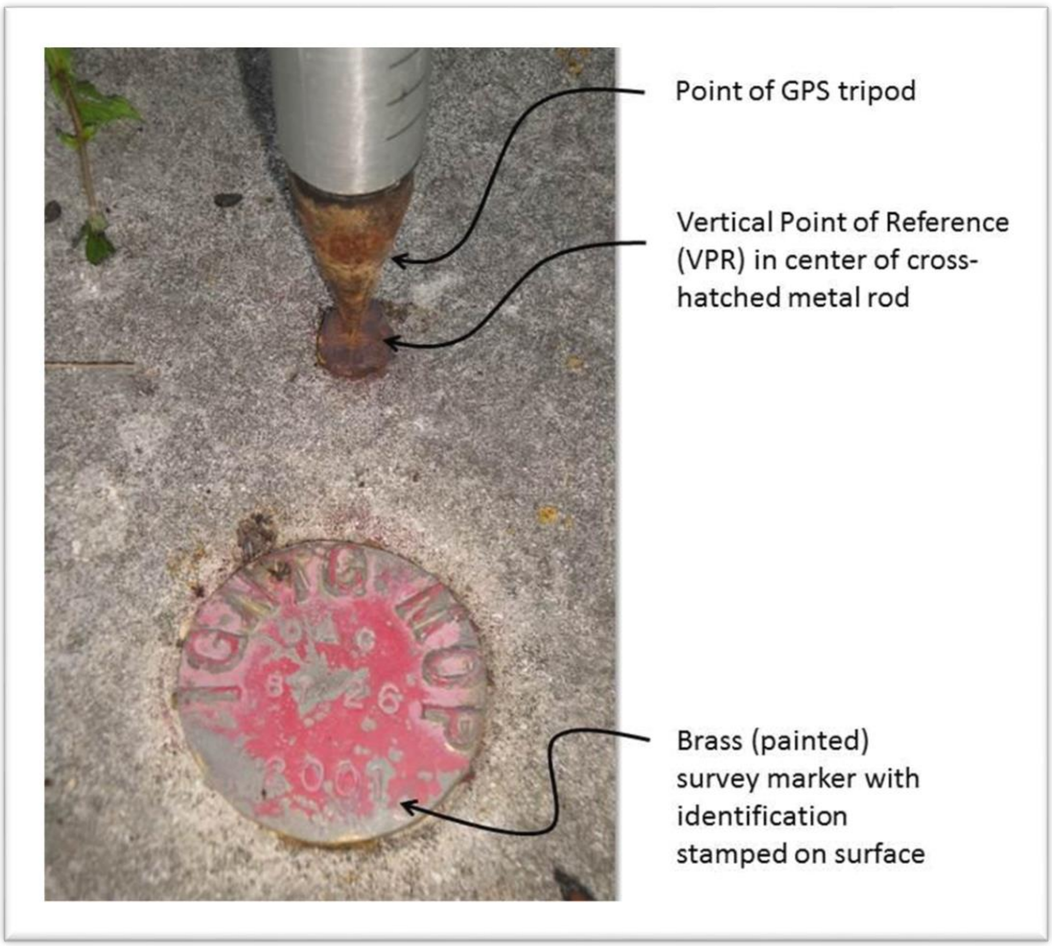


Figure 6-26. Example of a mark where the Vertical Point of Reference (VPR) is NOT on the brass disk.

Set-up your instruments

First, you need to set up your tripod. A GNSS tripod has a central (4th) leg, which provides the vertical reference line from the GNSS antenna to the mark. This leg ends in a sharp "survey" point, which is placed on the VPR of the mark being occupied (Figures 6-27, 6-28). The distance from the tip of the point to the flat upper mounting surface is typically 2.000 m; whatever its distance, it should be noted to the nearest millimeter (make sure the tip is securely fastened). Plumbing the tripod can be the most frustrating part of setting up a GNSS session, so some tips are listed below:

1. Remove the brass plug from the top of the tripod – you will need that later to attach the GNSS antenna to the tripod.
2. Place survey tip of the (fully extended) central leg on VPR of mark. For a typical metal marker, there is a central recess (Figure 6-26); for a deep rod mark, there is usually a dimple at the top of the rod; for chiseled marks, it is the intersection of two grooves; if in doubt, always find the top of the mark.
3. Extend the two adjustable legs with the quick-release/adjusting levers (you now have three legs down); splay them out, and stomp the tips firmly in place.
4. Using the quick release/adjusting levers (Figure 6-28), adjust their lengths so as to plumb the central leg (use the circular vial or a survey rod level); Refer to Figure 6-29 for technique.
5. Once the central leg is plumb, gently extend the remaining leg to the ground. Keeping it loose, stomp the tip into the soil. Make sure the central leg is still plumb, and then tighten the locking screw on the third leg. Your tripod should now be in place.

To set-up your instruments on a reference point, you may have to excavate or remove grass or debris. Clean the reference point as best as you can, and when you finish the occupation, return the site as you found it.

The error incurred for being slightly out of plumb is actually rather small, typically less than 0.1 mm. The horizontal position may easily be off by much more (e.g., several centimeters). It is always good field practice to check the calibration and other performance characteristics of your equipment, but a slight out-of-plumb will not be detrimental to your data.

If you are not using a standard GNSS tripod, you will need to both plumb the top plate and carefully measure its height above the mark. A tribrach can be used to create a plumb surface atop a tripod, but it is not a fixed height, so you will have to measure the thickness of the plumbed tribrach at its three corners to derive its height above the center of the tripod (Figure 6-30).

If for whatever reason the tripod gets off plumb in the middle of an observation, make a note of it, but do not correct it: you may easily do more harm than good because being slightly off plumb will result in a very small offset.

Figure 6-27. The survey point of a tripod is placed on the vertical point of reference of a typical metal survey disk.

Figure 6-28. Plumbing a 2 m, fixed-height GNSS survey tripod. Left panel shows how to grasp the leg release levers. Note that the third leg is not deployed until the tripod is plumb. Right panel shows the two-handed technique for fine-tuning the adjustment.

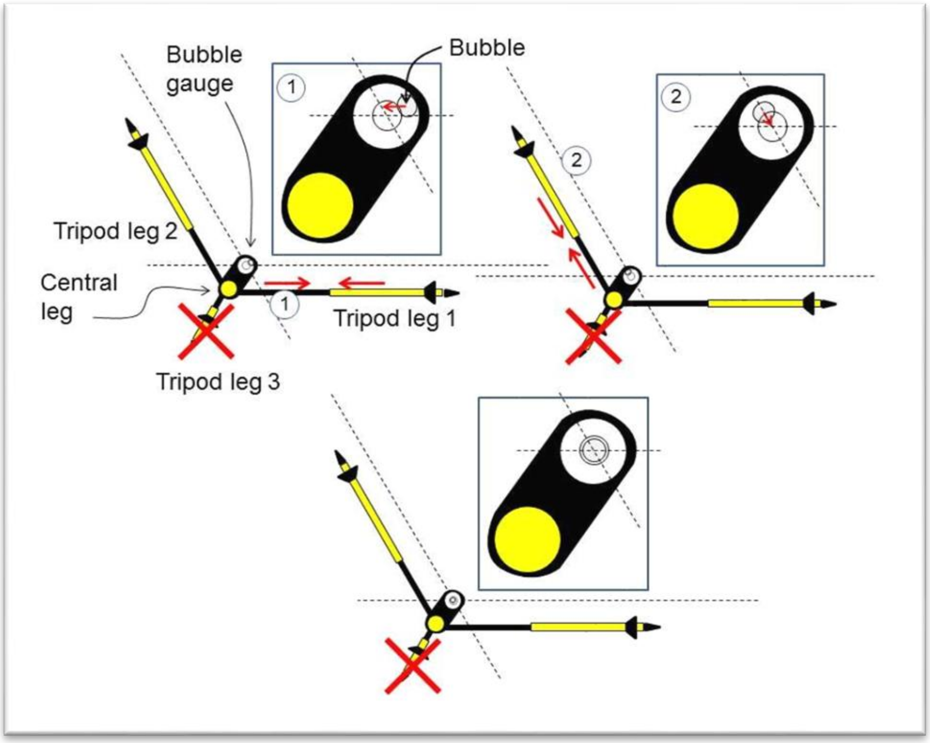


Figure 6-29. Steps taken to plumb survey tripod. Step 1: adjust one leg to bring bubble in line with axis of second leg. Step 2: adjust second leg to being bubble in line with first axis. Repeat. Within a couple reps, you should be able to get the bubble in the middle; your tripod is plumbed.

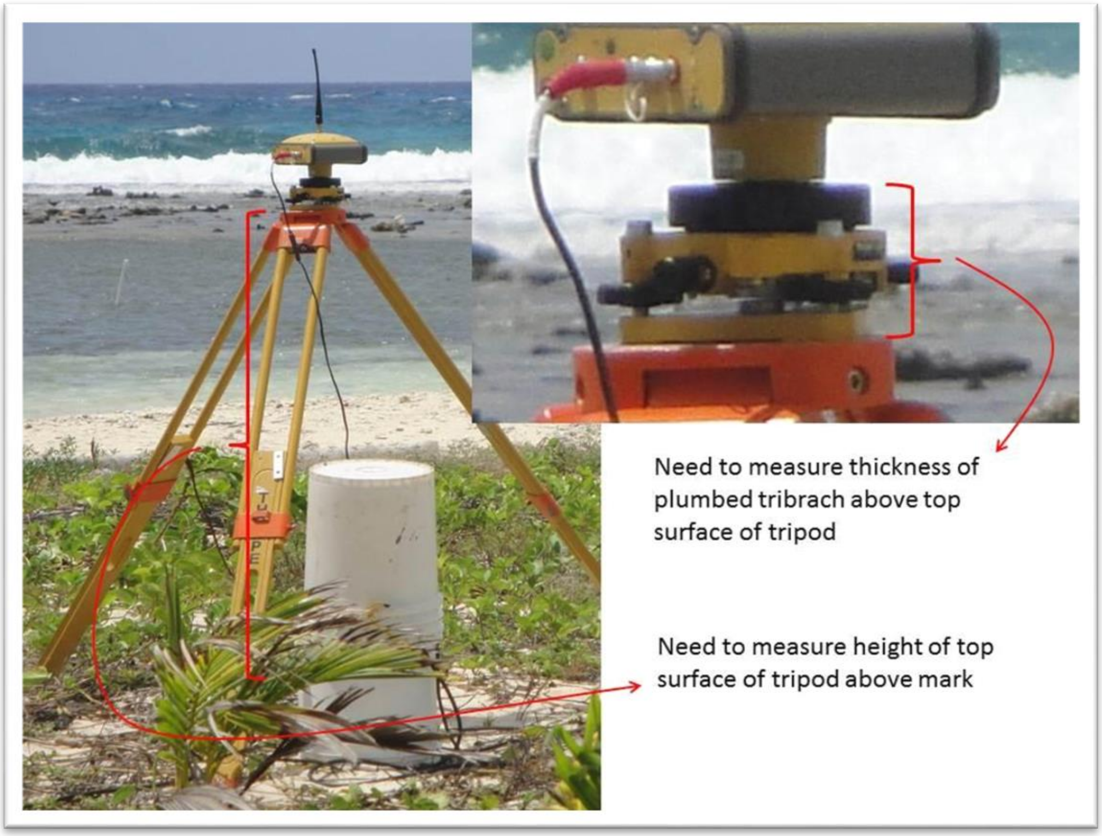


Figure 6-30. If using a non-GNSS tripod for GNSS observations, be sure to carefully measure both the height of the top plate of the tripod, as well as the thickness of a plumbed tribrach (if used).

Next, place your GNSS antenna at the top of the tripod. Before setting it up, write down in your field book the antenna serial number, as well as that of the receiver. If it is a combined antenna/receiver, there is one common number for the entire unit. After recording this information, complete the following steps:

1. Screw the brass plug (threaded insert) that you removed earlier into the base of the antenna. If the antenna is separate from the receiver, connect one end of the coaxial cable to the antenna. Make sure there are no kinks in the cable as you screw the connector in; this can damage the cable.
2. Once the brass insert and the coaxial cable are good and tight, gently place the antenna into the recess at the top of the tripod. If you are not tall enough, don't hesitate to step on a stool or have someone taller put the antenna in place. This is not the time to fall on the tripod you've just spent some time adjusting!
3. If your antenna has an arrow pointing north, go ahead and point it in a northerly direction (many tripods come with a compass attached to the central leg). Whether or not the antenna faces north will not be detrimental to your positioning solution, but having all your antennas oriented in the same manner may help reduce a small fraction of your within-network error.
4. With the antenna in place, tighten the knurled knob to keep it from moving.
5. If you have a separate receiver, plug the other end of the coaxial cable into the receiver.

Extra care must be taken when placing a GNSS unit on a SET mark. These marks contain a vertical structure, extending several centimeters above the concrete base, to which the SET instrument is mated (the "receiver"); the top-most side of this receiver is the VPR (Figure 6-31). For a GNSS occupation, you may be able to use a tripod, especially if there is a dimple on the top edge of the receiver. Otherwise, it is recommended to use (or fabricate) a custom-made GNSS antenna adapter (Figure 6-32). Since the vertical offset of the adapter may be altered through the task of making it vertical in the field, special techniques apply to accurately measure this offset. Consult the publication "Guidelines for Connecting SET Bench Marks to the NSRS[63]" to understand the tools and techniques involved.

Important Information
If setting up a GPS on an SET plot, discuss your survey plan with the manager of the SET plot, to make sure that you will not disturb the site.

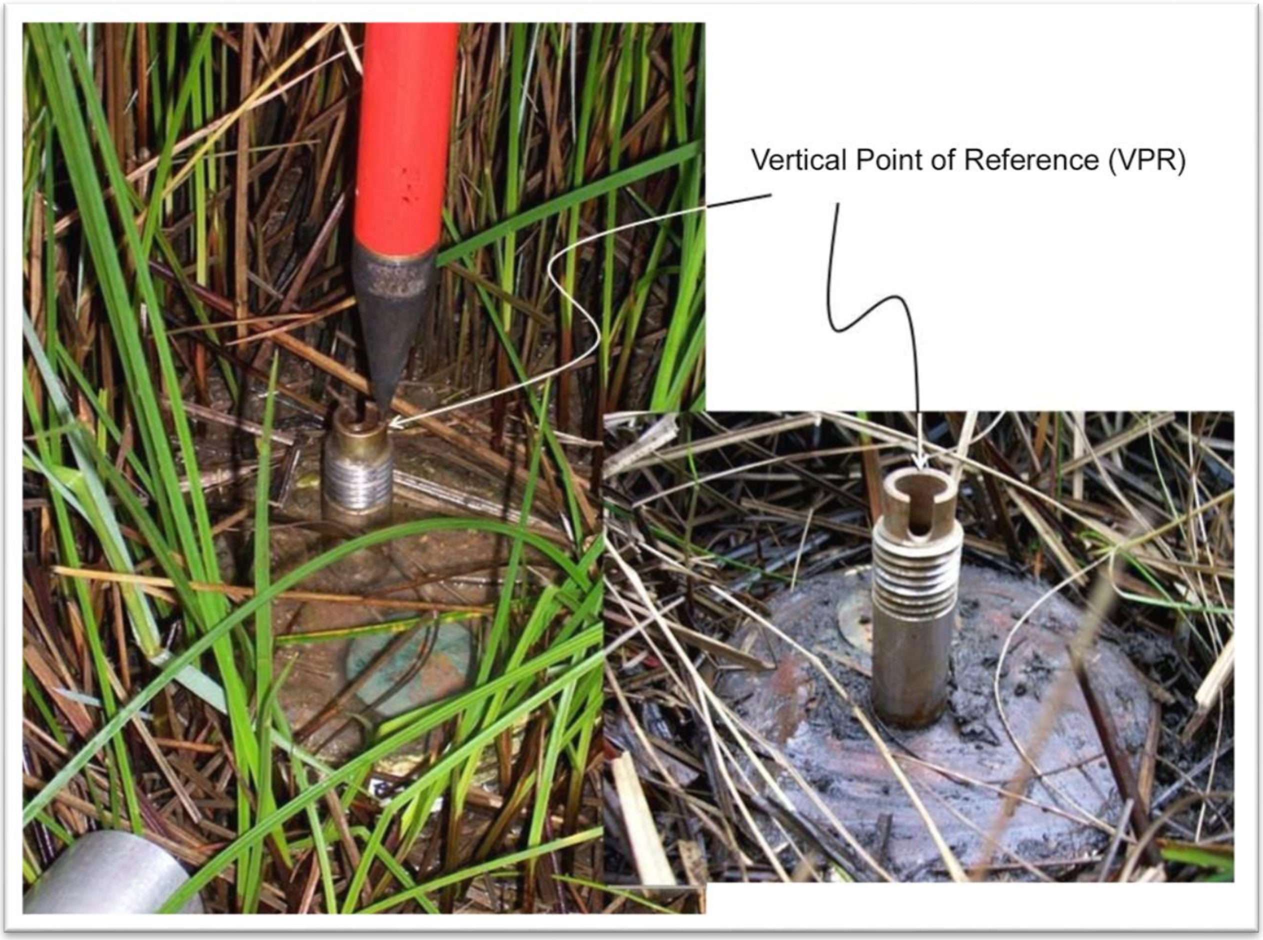


Figure 6-31. Deep rod surface elevation table (SET) mark, indicating the vertical point of reference as the top-most side of the SET receiver (NOT the brass disk, which can be seen on the concrete surface at the base of the receiver; right photo courtesy Don Cahoon USGS).

[63] https://www.ngs.noaa.gov/web/science_edu/ecosystems_climate/SET_Guidelines.pdf

Figure 6-32. Special equipment needed to observe with static GNSS on a deep rod SET mark.

Powering your Session

Ideally, you should record GNSS data for two, independent, extended (4 6-hour) sessions. Replication provides an estimate of precision; independence can be obtained by observing on different days and at different times of day. If it is not feasible to run replicate surveys, you can leave a GNSS session running for 48 hours or even 72 hours. For such long occupations, it is recommended to set up your receiver's configuration file so that it automatically ends an observation file after a pre-determined number of hours (or at a certain time, such as 0:00UTC), and immediately starts a new file. This will remove the need for editing the observation file after the survey. If the file is too large to be processed in OPUS, you can split it up into 24-hour sessions (with each session integrating many variables influencing GNSS observations over the course of a day). Using either vendor-specific software or the free software program WinTEQC[64]. WinTEQC is a PC-based program that uses the UNAVCO's TEQC[65] DOS program.

For extended static GNSS sessions, the internal batteries of your GNSS unit are probably not sufficient. Check with your vendor, as well as the digital output of your receiver, to verify how long your static session can run using internal batteries. We recommend you always use an external power source, such as an automotive or marine 12 V 18 Ah battery. A solar panel can also be used to recharge the battery during daylight hours, in the case of multi-day deployments. This will ensure you do not run out of power during a long occupation. Smaller batteries will also work well for 8 10-hour sessions. Marine and lawn mower batteries have terminals that lend themselves very well to simple eyelet electrical connectors (Figure 6-33). Also, make sure that your connections to the battery are tight, the contacts are clean, and power is reaching your receiver. There should be a fuse (15 Ah) on the positive cable to protect the GNSS unit in case of

64 https://www.ngs.noaa.gov/web/science_edu/ecosystems_climate/SET_Guidelines.pdf
65 https://www.unavco.org/software/data-processing/teqc/teqc.html

a short (Figure 6-33). Additionally, most GNSS receivers have a built-in fuse, and you may have to replace it if you have inadvertently crossed the wires.

Over the course of your static occupation, periodically check the power meter, if present, on the GNSS receiver. If you are draining power quickly, you may be running on the internal battery instead. Check connections to the external battery. If you need to change batteries, you should connect a fresh battery in parallel with the old one by connecting the positive terminal of the draining battery to the positive terminal of the fresh battery while maintaining the connection to GNSS intact. Likewise, connect the two negative terminals.

Any lack of power, even momentary, may inadvertently end a GNSS session. Ending a GNSS session closes the data file that was being recorded (see subsection *Collect observations* below). Once power is restored, a new session will automatically begin, and a new data file will be created; therefore, two separate sessions will be recorded in the receiver's memory for that day. When you download the data, make sure you pick up both files. If you have two files for one GNSS occupation, you may have to combine them into one sequential file, so that your data span the minimum time required (>4 hr). Consult your vendor software or consider using WinTEQC.

> ***Important Information***
> **Continuous power** is very important; any break will cause loss of data. This is a common yet easily avoidable mistake.

Figure 6-33. External 12V lawn mower-type lead-acid battery, with connectors to power a GNSS receiver.

Collect observations

> ***Important Information***
> Only the most general principles governing GPS session configuration are covered here. Refer to your particular unit's user guide for specific instructions on setting up a GPS job file.

With the tripod deployed, the antenna in place, the antenna cable attached to the receiver, and the receiver connected to the external battery, you can now turn the unit on. Right away, the receiver will go through internal checks on its operating system. After the checks are complete, the receiver will start looking at the sky and lock on the "space vehicles" (SVs, which are satellites) in the next minute or two. Once the receiver has found enough satellites to get a solution for its position, it may begin recording. We recommend you make sure the GNSS antenna is locked onto at least four separate GNSS satellites. If you are using an integrated unit and do not bring a hand-held sensor into the field, you might not be able to see the actual number of satellites that are locked on by the receiver. As good practice, you should review the user manual and make sure you understand how to complete these steps using your own equipment.

Record metadata in a field book at the start of each session. This can also be set up in the GNSS receiver's memory. With late model all-in-one units, setting up a survey job is typically done via a hand-held data sensor with a Bluetooth connection to the GNSS unit (Figure 6-34). With older models, there is typically a screen and touch pads or buttons (Figure 6–35). Creating the job configures GNSS data and metadata files, and typical parameters that you will select when creating a job are included in the call-out box below. If you do not create a job using your GNSS unit, then you must take special care to record the metadata yourself and verify that the receiver is, in fact, logging data. Even if you do create a job, it is good practice to keep a copy of all metadata in a separate field notebook.

GPS field notes/metadata:

- Job name (including mark being observed and date)
- Type of GPS observation (should be “static”)
- Date/time observation begins (and ends)
- GPS equipment that is being used (both antenna and receiver if they are separate)
- Height of antenna above mark (typically tripod height of 2.000 m)
- GPS recording interval (recommended 15 or 30 seconds)
- Elevation mask (recommended 10-15 degrees)
- Sketch of location, orientation, and potential obstructions

Note: Take photographs of your setup from both close and far—and take close-up photos of the mark (fine to have tripod point on middle of mark).

Figure 6-34. Hand-held data logger used to set up the job file and communicate with late model GNSS units.

Figure 6-35. Older GPS unit featuring small interface screen and combination navigation/editing buttons.

During the GPS session, it is good practice to check the vital signs:

- ***Check power:*** make sure connections are tight and you are not draining batteries too fast; prepare to swap new batteries as needed.
- ***Satellite reception***: make sure you have not dropped to less than four satellites; if you see very few satellites, you may have an obstruction (check open sky).
- ***Check memory:*** make sure data are being recorded into memory (i.e., memory not full yet).
- ***Monitor PDOP (positional [3D] dilution of precision):*** a measure of how dispersed the satellites are in the sky. A smaller PDOP value is better; a value less than four is good, and a value less than two is excellent. You cannot change the PDOP, but it is good information to note regarding the quality of the observations.

When you are ready to stop the session, follow the receiver-specific session-ending sequence (often just powering down suffices). The receiver should provide you with the information on how long the session lasted. This is a good check that you recorded sufficient data. Note the time at which you stopped the session and take down the site.

When you repeat observations, it is recommended to switch the antennas/receivers around among your geodetic control points. This way, each mark will see a different combination of GNSS antenna, receiver, and tripod. If there is a slight error (e.g., bias) in any component, the average solution will tend to remove it.

6.2.3. Post-processing the GPS data

Your first step in post-processing is to download the raw GNSS data. Your GNSS receiver should come with the cables and software needed to download the observation file(s) onto a personal computer. For older units, the software may be freely available on the internet (e.g., Trimble Data Transfer). Older units may also have a serial data port, but newer laptop computers generally no longer support this kind of port, opting instead for USB. If this is the case, you will have to use a serial-to-USB connector, which may require software installation. Alternatively, if you use a hand-held data logger, you can export the GNSS file from the receiver to the hand-held via the Bluetooth® connection or data cable using the file export function. Then, you can transfer the files from the hand-held logger to the computer.

The trick to downloading GNSS data is having the right software and specifying the correct connection settings. If your connection settings are wrong (e.g., wrong port, wrong speed, wrong transfer settings), you may get frustrated very quickly. Sometimes trying a different port (e.g., serial setting or USB port) can work. Do not hesitate to ask your IT department for assistance.

Save multiple copies of your raw GNSS data. You may need to reprocess the data at a later time to make the data compatible with newer reference frames as they are realized. Without the raw data, your ability to measure change may be compromised. Also, if you encounter any problems processing the data, a surveying professional needs to see the raw data file.

Next, submit your data to OPUS. First navigate to the OPUS web page[66] (Figure 6-36) and complete the following steps:

1. Enter an email address where you will receive the post-processed solutions.
2. Upload your GNSS data file. Most native GNSS file formats are directly read by OPUS; if you cannot load your file, convert it to RINEX (Receiver Independent Exchange format) or another format supported by UNAVCO's TEQC[67] program. Most likely, your GNSS system's software will have a feature to convert the data to RINEX.
3. Select the type of GNSS antenna used, noting that the names are often abbreviated. This is why you checked to make sure the antenna was calibrated by NGS (Section 6.2.2); if it was not, the antenna will not be on the list, and you will not be able to use OPUS.
4. Provide the correct antenna height in meters, reported to the nearest millimeter.
5. Click on "Upload to Static.[68]" After a few minutes, you will receive the upload confirmation.

Web navigation tips for using OPUS:
1. Visit geodesy.noaa.gov
2. Select "OPUS" from left menu.
Screen shots illustrating OPUS Web page are shown in Figure 6.36 below.

Important Information
Effective July 2012, OPUS uses the latest realization of the horizontal datum, NAD 83 (2011) epoch 2010.00.

If you have already processed earlier data with the NAD 83 (CORS96), you should re-process older data using NAD 83 (2011), and then continue using NAD 83 2011) for all subsequent work. Note that you cannot mix different realizations for the same project.

Note that you may receive an error message from OPUS if your solution has failed. Generally, OPUS will provide you with some information suggesting where the problem may have occurred (e.g., your observation length was too short for a static solution, or there were insufficient satellite observations). If you get an error message, you may have to run quality control on your data file. Consult your vendor software or consider using WinTEQC. Also note that these programs can allow you to edit the RINEX file, break up the file into shorter observation sessions, or even combine two (or more) files together.

After you receive your OPUS solution via email, examine the OPUS report (Figure 6-37) to evaluate the quality of the results through several statistics.

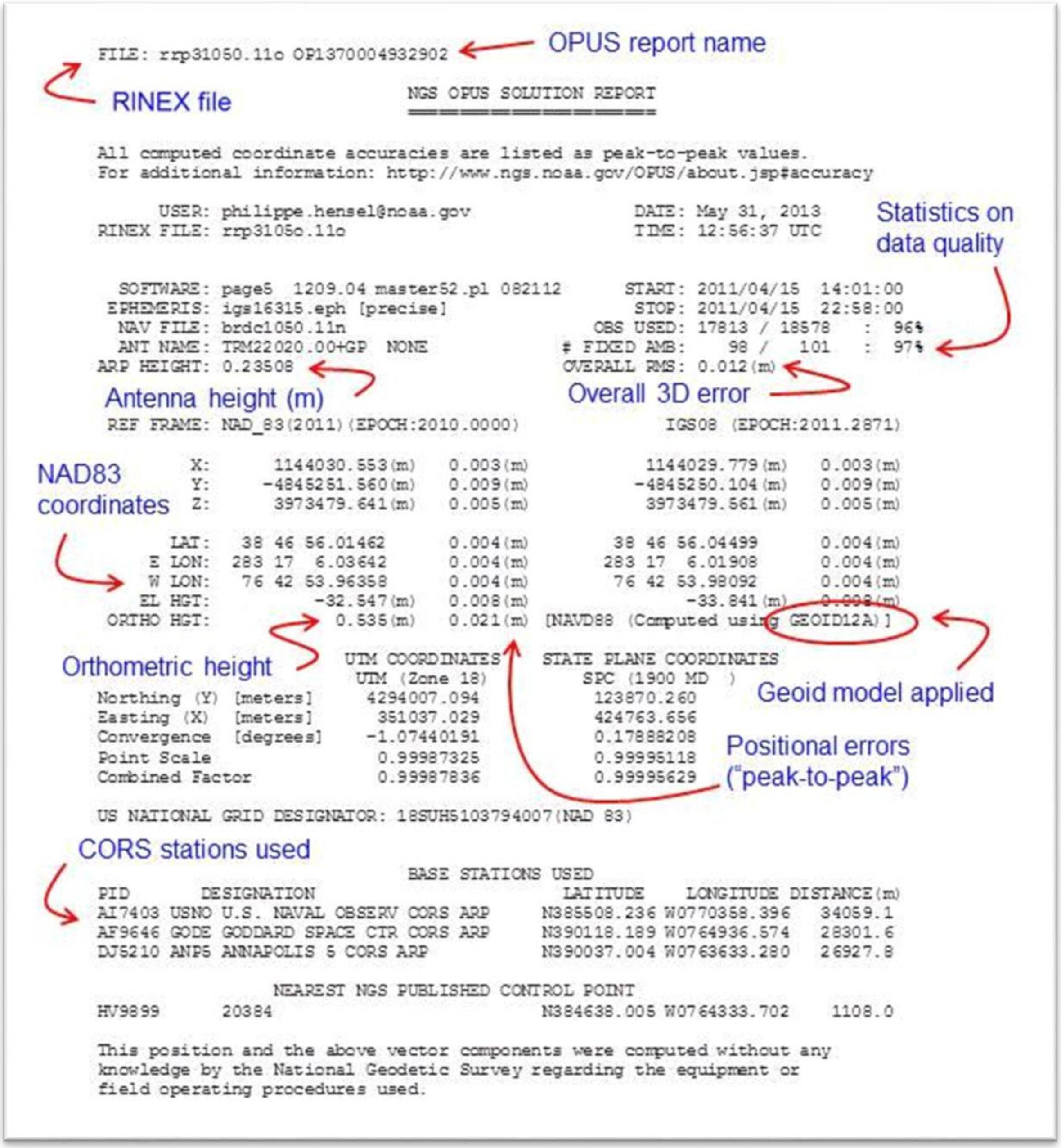
- ***Antenna height:*** Make sure the antenna height was written correctly.
- ***Observations used***: This tells you how many observations were rejected (e.g., satellite was seen, but data not received). The percentage should be greater than 70%.

[66] http://www.ngs.noaa.gov/OPUS/
[67] See https://www.unavco.org/software/data-processing/teqc/teqc.html or WinTEQC
[68] If for whatever reason your GPS file is <2 hours long (but ≥15 minutes), the data will automatically be redirected to OPUS Rapid Static.

- ***Fixed ambiguities***: This value should be greater than 70%.
- ***Three-dimensional (3-D) error***: This value combines error in all three dimensions (i.e. latitude, longitude, and height), and an error of less than 0.03 m (3 cm) is good. Although you are primarily interested in the vertical dimension, the 3-D error gives a good indication of the overall precision of the solution based on the particular CORS selected.
- ***Vertical error***: Recommended orthometric height error ("peak to peak") should be ≤0.08 m (8 cm).

Figure 6-36. The OPUS home page (2021), showing input fields.

The OPUS solution provides the coordinates according to different reference frames. Within the continental US, you should use the NAD 83 coordinates. Note that the NAD 83 coordinates are based on the "realization" of the datum at the time the data were processed. Realizations change over time, as models become more precise and accurate. As of 2021, the latest realization is NAD 83 (2011) epoch 2010.00; this superseded the previous realization NAD 83 (CORS96) epoch 2002.00. If you want to compare coordinates among different realizations, you need to know the respective realizations and convert to a standard realization. Otherwise, you may be introducing error. The recommended way to get all coordinates on the same realization is to re-process all older GPS data using the newer datum realization (instead of merely transforming the coordinates).



```
FILE: rrp31050.11o OP1370004932902

                     NGS OPUS SOLUTION REPORT
                     ========================

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: http://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

      USER: philippe.hensel@noaa.gov                DATE: May 31, 2013
RINEX FILE: rrp3105o.11o                            TIME: 12:56:37 UTC

  SOFTWARE: page5  1209.04 master52.pl 082112      START: 2011/04/15  14:01:00
 EPHEMERIS: igs16315.eph [precise]                  STOP: 2011/04/15  22:58:00
  NAV FILE: brdc1050.11n                        OBS USED: 17813 / 18578   :  96%
  ANT NAME: TRM22020.00+GP  NONE              # FIXED AMB:    98 /   101   :  97%
ARP HEIGHT: 0.23508                          OVERALL RMS: 0.012(m)

 REF FRAME: NAD_83(2011)(EPOCH:2010.0000)              IGS08 (EPOCH:2011.2871)

         X:      1144030.553(m)   0.003(m)          1144029.779(m)   0.003(m)
         Y:     -4845251.560(m)   0.009(m)         -4845250.104(m)   0.009(m)
         Z:      3973479.641(m)   0.005(m)          3973479.561(m)   0.005(m)

       LAT:   38 46 56.01462      0.004(m)        38 46 56.04499      0.004(m)
     E LON:  283 17  6.03642      0.004(m)       283 17  6.01908      0.004(m)
     W LON:   76 42 53.96358      0.004(m)        76 42 53.98092      0.004(m)
    EL HGT:          -32.547(m)   0.008(m)               -33.841(m)   0.008(m)
 ORTHO HGT:            0.535(m)   0.021(m) [NAVD88 (Computed using GEOID12A)]

                        UTM COORDINATES    STATE PLANE COORDINATES
                         UTM (Zone 18)         SPC (1900 MD  )
Northing (Y) [meters]     4294007.094           123870.260
Easting (X)  [meters]      351037.029           424763.656
Convergence  [degrees]    -1.07440191           0.17888208
Point Scale                0.99987325           0.99995118
Combined Factor            0.99987836           0.99995629

US NATIONAL GRID DESIGNATOR: 18SUH5103794007(NAD 83)

                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
AI7403 USNO U.S. NAVAL OBSERV CORS ARP     N385508.236 W0770358.396   34059.1
AF9646 GODE GODDARD SPACE CTR CORS ARP     N390118.189 W0764936.574   28301.6
DJ5210 ANP5 ANNAPOLIS 5 CORS ARP           N390037.004 W0763633.280   26927.8

                  NEAREST NGS PUBLISHED CONTROL POINT
HV9899      20384                          N384638.005 W0764333.702    1108.0

This position and the above vector components were computed without any
knowledge by the National Geodetic Survey regarding the equipment or
field operating procedures used.
```


Figure 6-37. Sample OPUS report, showing post-processed positional information, including peak-to-peak errors.

Note that the solution given in Figure 6-37 gives both ellipsoid and orthometric heights. The ellipsoid height is the earth-centered reference for the GNSS satellites; the orthometric height has the gravity model applied (the hybrid GEOID12A, in this example) to the ellipsoid height. The orthometric height therefore refers to gravity and how water levels relate to land. For purposes of a sentinel site, you want all observations on the orthometric datum. However, for purposes of monitoring vertical stability of a mark, there is less error involved if you compare ellipsoid heights (only for GPS-derived heights). Therefore you should keep track of both height measurements. In the continental US, the national orthometric datum is the National Vertical Datum of 1988, or NAVD 88. For a refresher, refer back to Section 2.

The “positional error” reported with an OPUS solution is the “peak-to-peak” value, which corresponds to the maximum range of solutions arising from the three CORS solutions chosen. Strictly speaking, it is not a standard error, but studies have shown this peak-to-peak value provides the most robust estimate of positional error of a solution (Soler et al., 2006). Ideally, the NAVD 88 error peak-to-peak should be within ≤0.03 m (3 cm), but this might be difficult to obtain for any given mark. Figure 6-38 provides a graphical interpretation of the errors involved with an OPUS-derived solution.

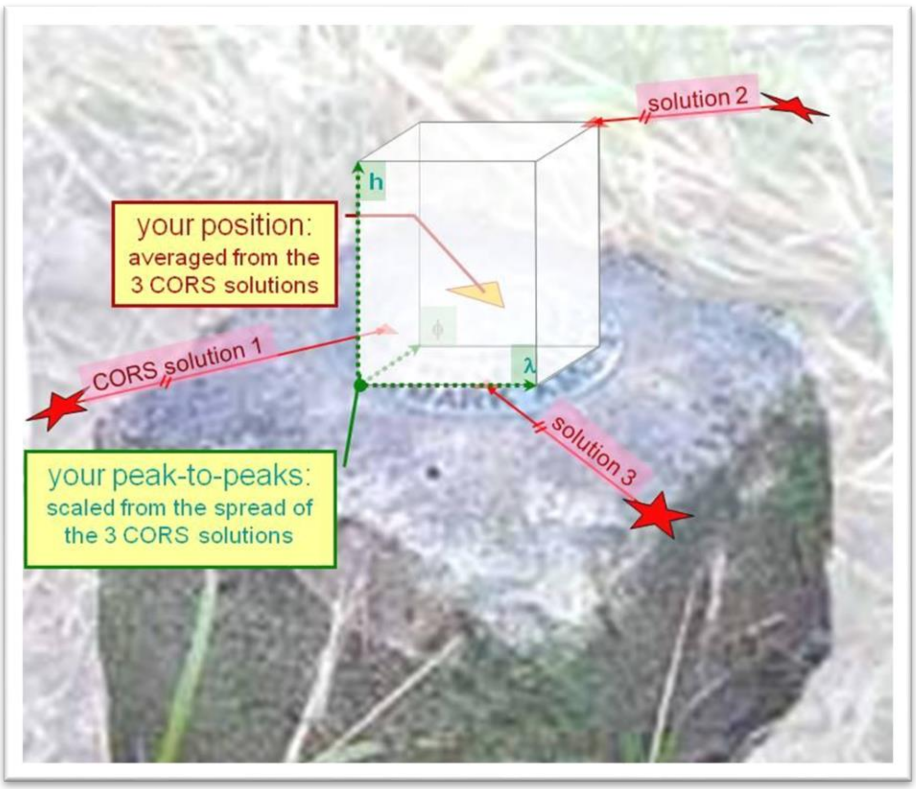


Figure 6-38. Schematic showing concept of accuracies and errors involved with a GPS derived position using OPUS.

The three CORSs chosen for the solution are printed near the bottom of the printout, as well as their positions and distances to your mark (computed baselines). As you process more GPS data from a particular site, keep track of which CORSs are being used and which ones provide good solutions. Ideally, the three nearest CORS would always be used, but for a number of reasons, any given CORS might not provide the best fit on any particular day. Keeping track of which CORS are consistently chosen may help you understand when a solution cannot be found (OPUS error message sent to your email), or when a particular solution is not as good as expected.

The CORS data provide your connection to the NSRS, but the simultaneous GNSS observations also connect your LCMs together. Two concepts should therefore be considered when post-processing GNSS data. First, the solutions with least error may provide better connections to the

NSRS. Second, processing data using different selected CORS might increase the relative error among your different marks.

Constraining CORS

If you are unable to establish vertical connections among the different LCMs in your project via leveling, you may consider selecting individual CORS, so that you are using the same CORS for each OPUS solution. In that way, although you may not get the very best solution for any one LCM, you will be maximizing the accuracy of the relative height differences between them. In other words, the height with respect to the vertical datum (e.g., NAVD 88) may have somewhat more error, but the network height relationships will be strengthened. Note that this strategy works best where the LCMs are clustered in space relative to the CORS. Generally speaking, distances of less than 20 km separating all LCMs are good candidates for selecting a consistent set of individual CORS for OPUS processing.

First, process all the data files without manually selecting any CORS, and see if there is any pattern to the chosen CORS and error estimates. If so, identify the three CORS that are associated with consistently good solutions. Then, you can reprocess all your GNSS data files using the advanced option of selecting which CORS to use in the processing. To use advanced options and customize your solution, select the "Options" button when you are on the OPUS submission page (Figure 6-39).

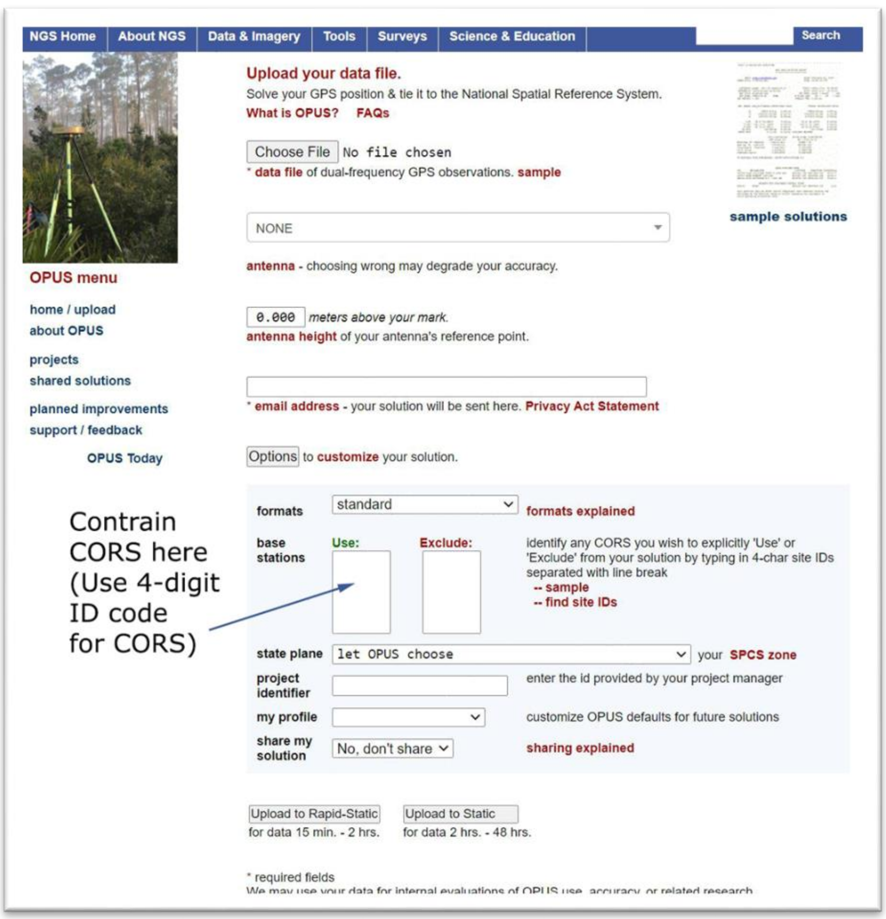


Figure 6-39. Advanced options in NOAA's On-Line Position Users Service (OPUS).

Finally, you should assign positions to your LCMs. For each LCM in your local network for which you have obtained GNSS observations, you will have conducted at least two separate GNSS sessions, which will provide separate OPUS solutions with slightly different coordinates, including elevation. Assuming both solutions are good, you will want to calculate average coordinates using a weighted-average approach. The inverse of the orthometric vertical error will be the weight (see "peak-to-peak errors" for orthometric elevation; 0.021 m in Figure 6-37), and the basic formula is as follows:

$$Elev = (z_1 w_1 + z_2 w_2)/(w_1 + w_2)$$

Where $w = error^{-1}$

Where z = *ortho height*

A similar weighed average can be computed for horizontal positions as well.

In the end, the weighted average positions will be the ones you assign to your LCMs. There may be instances in which any two OPUS solutions for a given mark are very different from each other (e.g., by more than 4 cm). If so, then you will want to re-observe that mark to make sure you have two good OPUS solutions from which to compute an average height. The more observations you have for a mark (and the longer the observations), the greater the confidence in the computed position.

If you are able to level among your LCMs, and you took GNSS observations on more than one of them, you will find that the leveled height differences do not exactly match the GNSS-derived elevation differences. In this case, you should choose one LCM as the primary connection to the NSRS. This might be the most centrally located mark within the site, or the inherently most stable mark, the one with easiest access, with the best view to the sky, or the one with the consistently best OPUS solution. Height differences from leveling are then applied to the averaged OPUS height for this mark.

7. CONNECTING SEA LEVEL CHANGE SENTINEL SITE COMPONENTS

This section provides guidance to connect the water level sensor (water level station) and ecosystem monitoring infrastructure to the local vertical control network. First, we will discuss leveling techniques, specifically for connecting a water level sensor, Surface Elevation Tables (SETs), groundwater wells, and vegetation plots. Then, we will present guidelines for Real-Time Kinematic (RTK) GNSS techniques as an alternative to leveling.

Differential leveling provides better error control than GNSS-based techniques when establishing vertical connections among sentinel site components. The leveling techniques presented here should provide vertical errors in the range of 4–6 mm per square root of kilometer of leveling. Leveling is therefore the recommended technique for acquiring high accuracy elevations on vertical measurement systems such as SETs, any water level sensors, stream gauges, or groundwater wells. Other sentinel site measurement infrastructure, such as vegetation transects, dune profiles, digital elevation models (DEMs), and remote sensing ground truth points are good candidates for the much faster but less accurate RTK GNSS technique.

Leveling provides additional challenges because the technique is laborious and not feasible for sections separated by water or widely dispersed in the habitat. RTK provides a good way to establish elevation differences among your sentinel site components for which leveling is impractical or impossible. Regardless of which technique you use, it is highly recommended to develop detailed survey plans for each part of the project. These survey plans should be included in the overall geodetic and tidal control plan (Section 3), so they can be reviewed appropriately.

7.1 Geodetic Differential Leveling

7.1.1. Connecting a water level sensor to vertical control network via leveling

We strongly recommend you use differential leveling to establish the vertical relationship between the water level sensor and the local vertical control network. Applying this vertical relationship to the water level data enables you to relate the data (and derived tidal datums) to the other vertical observations in your network. Section 6, Table 6-2 provides recommended leveling specifications. Following these recommendations should ensure high accuracy results, and careful documentation of equipment and techniques used along with observed misclosure will allow you to assess the accuracy achieved. The equipment, methods, and target misclosure need to be specified in the survey plan described in Section 3.

The level line includes the water level sensor leveling point (see below) and at least two additional marks that are part of the local control network (two marks are allowed only if one of them is a deep driven rod or another type of mark with very high stability; see Section 3.3.2 for additional information). Consistent with leveling procedures described in Section 6, you must run the level line twice when it is first established; once forward, once backwards. Then, check the forward and backwards runs for tolerance for targeted misclosure [misclosure (in millimeters) e.g. $4\sqrt{D}$].

After establishing the leveled connection, perform routine leveling to maintain and verify water sensor stability over time in the following instances:

- At specific, user-defined intervals (e.g., CO-OPS re-levels annually).
- When a sensor jump is noted in the data (e.g., jumps +/- in the water level data).
- After major storms.
- Whenever a boat runs into your dock or any other disturbance to the water level sensor from others (e.g., an area with heavy recreational users).
- Whenever you service the sensor. If servicing occurs very frequently (e.g., every two weeks) at the very least measure from your sensor leveling point to your sensor zero where this measurement can be easily done. For some installations, this may not be practicable without introducing even more error.

When conducting routine leveling, check if the forward run matches (within error tolerance) the previous/original value. If so, then there is no need to run the section backwards.

The water level sensor leveling point depends on the sensor type and installation technique. Variations include a bolt to which the stilling well is attached, or a survey mark next to the well (Section 4.1.2). After establishing a leveled connection from the sensor leveling point to the nearest bench mark, temporary mark, or turning point, take a steel-tape measurement between the sensor leveling point and the bolt that the sensor is resting on at the bottom of the well. The distance between the sensor zero and the bolt (resting on the sensor at the bottom of the well) will be a known distance measured during the installation of the sensor or back in the laboratory. Due to different sensor specifications and mounting infrastructure, it may be necessary to tailor a leveling and maintenance plan allowing for sensor stability checks and verification.

When using an active NWLON water level station as the sentinel site water level sensor, it may be necessary to contact CO-OPS if a NAVD 88 elevation is not referenced to station datum. In such cases, you can request the NAVD 88 elevation of the water level sensor. Note that this might not be available at all NWLON stations. CO-OPS preliminary and verified water level data are available on the CO-OPS[69] website.

Important Information
Unlike publicly accessible tidal bench marks, NWLON water level gauges are secured and should not be accessed without CO-OPS permission.

There may be situations in which it is impossible to level to the water level sensors, such as when the sensor is on a piling out in a large body of water (e.g. an embayment). In such cases, using static GPS (Section 6.2) might be the next best option to connect your water level sensor and vertical control network.

[69] https://tidesandcurrents.noaa.gov/

Figure 7-1. Digital barcode leveling from local vertical control network to the protective well of the water level sensor**.**

7.1.2. Computing vertical relationships among geodetic and tidal datums at the tide station

Once you compute the vertical distance between the sensor leveling point and the sensor zero (see Section 7.1.1), apply this distance to the sensor leveling point elevation derived via leveling. If the local vertical control network has been connected to the NSRS, leveling from a LCM allows a geodetic vertical datum (e.g., NAVD 88) to be applied to the water level data. The following equation will transfer water level data to your geodetic datum:

Water level data on geodetic datum:

Elevation of LCM (or known bench mark on geodetic datum)
Plus elevation difference between LCM and sensor leveling point
Minus height of sensor leveling point above sensor zero
Plus observed water level

In the case of an NWLON station, the relationship between Station Datum and the geodetic datum NAVD 88 is often available on the datums page of the CO-OPS website. The relationship between NAVD 88 and tidal datums may be listed on the bench mark sheets for that station (if a geodetic connection has been made). The NAVD 88 elevation is shown only on the "Elevations of Tidal Datums Table Referred to MLLW" when two or more of the bench marks listed have published NAVD 88 elevations, and when the appropriate CO-OPS surveying procedures have been followed and maintained at that particular station. Unfortunately, some NWLON stations (and secondary or tertiary water level stations) may not have a published (or listed) NAVD 88 elevation relative to station datum (or the station's tidal datums). However, you can make an estimate of this relationship in most cases from known information and possibly some on-the-ground surveying.

If you know the vertical relationship between station datum and a published tidal datum (e.g., MHW), as well as the relationship between a NAVD 88 tidal bench mark and the same tidal datum (e.g., MHW), you can algebraically determine the difference between NAVD 88 and station datum. Applying this calculated difference in elevation to the water level data, at the NWLON station, will result in the water level products referenced to NAVD 88. See the examples below for an explanation of the procedure.

Example 1 Computing a NAVD 88 height at Yorktown NWLON Station

Station of interest: Yorktown US Coast Guard Station on the York River, Virginia (Station ID: 8637689). Tidal datum elevations with respect to MLLW are given in Table 7-1 (from bench mark sheets):

Table 7-1. tidal datums for NOAA tide station 8637689, the Yorktown United States Coast Guard (USCG) station on the York River, Virginia.

Datum	Height (m)
Highest observed water level	2.089
Mean higher high water (MHHW)	0.786
Mean high water (MHW)	0.727
Mean tide level (MTL)	0.382
Mean sea level (MSL)	0.378
Mean low water (MLW)	0.037
Mean lower low water (MLLW)	0.000
Lowest observed water level	-0.580

At this site, there are three tidal bench marks (out of ten), which are also published NGS marks (and are tied to the NSRS). These are as follows:

- Tidal Bench mark Station 52: (PID# GV5961)
- Tidal Bench mark Station 51: (PID# GV5960)
- Tidal Bench mark Station FUEL: (PID# AE4257)

Unfortunately, the elevations of these tidal bench marks are not accurate. They are either scaled from a topographic map (rounded to the nearest meter) or estimated using a conversion from the outdated NGVD 29 datum. Knowing the vertical relationship between tidal datums and NAVD 88 is very important to the Chesapeake Bay National Estuarine Research Reserve in Virginia (CBNERR-VA). A GPS campaign was therefore conducted on three of the ten tidal bench marks (Stations B, EL, and 51) one of which was also in the NGS database (Station 51) as indicated above. As a result of the survey, a GPS-derived NAVD 88 height was computed for several marks. The marks now have both NAVD 88 heights as well as heights with respect to the tidal datums (from the bench mark sheets; Table 7-2).

Table 7-2. Derivation of the relationship between NAVD 88 and MLLW at the Yorktown water level station (Station ID: 8637689) based on GPS observations.

Mark	Height above MLLW (a)	NAVD 88 Height[70] (b)	Height of NAVD 88 above MLLW (a) – (b)
Station B	3.481	3.042	0.439
Station EL	3.990	3.527	0.463
Station 51	17.056	16.606	0.450

As can be seen from Table 7-2, the vertical relationship between NAVD 88 and MLLW can be computed by subtracting the newly derived NAVD 88 height from the published bench mark heights above MLLW. These heights should theoretically be the same since there is only one true relationship between NAVD 88 and MLLW at the water level station. The variability in the estimates (about 2 cm) is mostly due to uncertainties in the GPS solution (although a small amount of error may be attributed to the leveling by CO-OPS as well as the geoid model that was applied to the GPS-derived ellipsoid height). Therefore, the most stable mark closest to the water level station was chosen to determine the tidal-to-geodetic datum relationship (Station ID: B = 0.439).[71]

Example 2 – Using Published Data to Approximate NAVD 88 at the Gloucester Point NWLON Station (Historical Station with Published NAVD 88 Value)

Tidal datums from published bench mark sheets for the historical NOAA water level station at Gloucester Point, Virginia (Station ID: 8637624) are given in Table 7-3 (heights with respect to MLLW).

Table 7-3. Published tidal datums for a historical water level station with respect to MLLW (Gloucester Point, Station ID: 8637624).

Tidal Datum	Height (m)
Highest observed water level	1.908
Mean higher high water (MHHW)	0.820
Mean high water (MHW)	0.760
North American Vertical Datum of 1988	0.487
Mean tide level (MTL)	0.398
Mean sea level (MSL)	0.394
Mean low water (MLW)	0.035
Mean lower low water (MLLW)	0.000
Lowest observed water level	-0.957

[70] Orthometric (NAVD 88) height is obtained from an OPUS solution based on applying the hybrid geoid model to the ellipsoid height, which is derived from the GPS observations.
[71] Subsequent to the GPS survey, precise leveling was conducted by CO-OPS and the separation between NAVD 88 and MLLW for the station is now published at 0.468 m., which closely matches the estimated value for Station EL.

Elevations of tidal bench marks above tidal datums are published along with the tidal bench mark datasheets (Table 7-4).

Table 7-4. Published elevations of tidal bench marks with respect to MLLW, MHW, and NAVD 88 at water level Station ID: 8637624.

Bench Mark Designation	Elevation above MLLW (m)	Elevation above MHW (m)	Elevation above NAVD 88 (m)
NO 4 1918	10.160	9.400	9.675
NO 9 1959	9.305	8.546	8.828
D 457 1971	4.310	3.550	3.823
G 298 RESET 1981	1.704	0.944	1.23
C 457 1971	8.732	7.972	8.244

From the information presented in Tables 7-3 and 7-4, we can compute the height of NAVD 88 at the water level sensor (Table 7-5):

- Average from five tidal bench marks in Table 7.5 = 0.482
- CO-OPS derived value for the Gloucester Point Historical Station is 0.487.

Table 7-5. Approximating NAVD 88 at the Historical Gloucester Point Station from published bench mark heights with respect to tidal and geodetic datums.

Bench Mark Designation	Computation
NO 4 1918	10.160 (MLLW) - 9.675 (NAVD88) = 0.485
NO 9 1959	9.305 (MLLW) – 8.828 (NAVD88) = 0.477
D 457 1971	4.310 (MLLW) – 3.823 (NAVD88) = 0.487
G 298 RESET 1981	1.704 (MLLW) – 1.230 (NAVD88) = .474
C 457 1971	8.732 (MLLW) – 8.244 (NAVD88) = 4.88

Additional Information:

Appendix I in National Park Service (2011) contains additional examples.[72]

7.1.3. Connecting Surface Elevation Tables (SETs) via leveling

SET foundations that were chosen as part of your vertical control network were most likely a form of deep rod marks (deep rod SET marks). As shown previously in Figure 6-12, the wide, flat base of the level rod will automatically find the vertical point of reference (VPR) at the top of the receiver. Older, first generation SET foundations will be somewhat more problematic for leveling: the 5 cm (2-inch) diameter top of the mark will not fit entirely under the calibrated end of the rod (Figure 7-2). For this reason, you have to find the top side of the mark and stamp/etch/mark the VPR. The technique is relatively simple (Figure 7-3):

1. Apply a carpenter/torpedo-type level to the side of the insert pipe.
2. Rotate the level around, noting consistent movement of bubble.
3. The top of the monument will be where the bubble is facing directly away from the axis going through the center of the mark.
4. Mark/etch/stamp the top of the mark at this location.

[72] https://www.ngs.noaa.gov/web/science_edu/ecosystems_climate/Elevations_CoastalNationalParks.pdf

Helpful tips

To ensure the level rod is touching the VPR, place one corner of the level rod base on the point, with the rest of the base of the rod hanging off the edge. Make sure the level rod is plumb (Figure 7-3). If using brace poles, make sure they do not land within the SET plot. For more information on SETs, please review "The Surface Elevation Table and Marker Horizon Technique: A Protocol for Monitoring Wetland Elevation Dynamics" (NPS, 2015).

When establishing leveled height differences between the vertical control network and monitoring infrastructure, proceed with both forward and backward runs as you would with leveling along a line. Leveling in a loop provides a more robust connection than a single line, as it can more accurately estimate accumulated error along the entire line. Compute height differences of both forward and backward runs and compare them (and any loop closures) to the target misclosure (e.g., $4\sqrt{D}$). If the difference is greater than allowed, then repeat observations as explained in Section 6.1.

Providing leveled connections to your SETs might be an ideal occasion to measure the vertical offset of your SET instrument. Detailed instructions for conducting this measurement via leveling are available in Lynch et al. (2015).

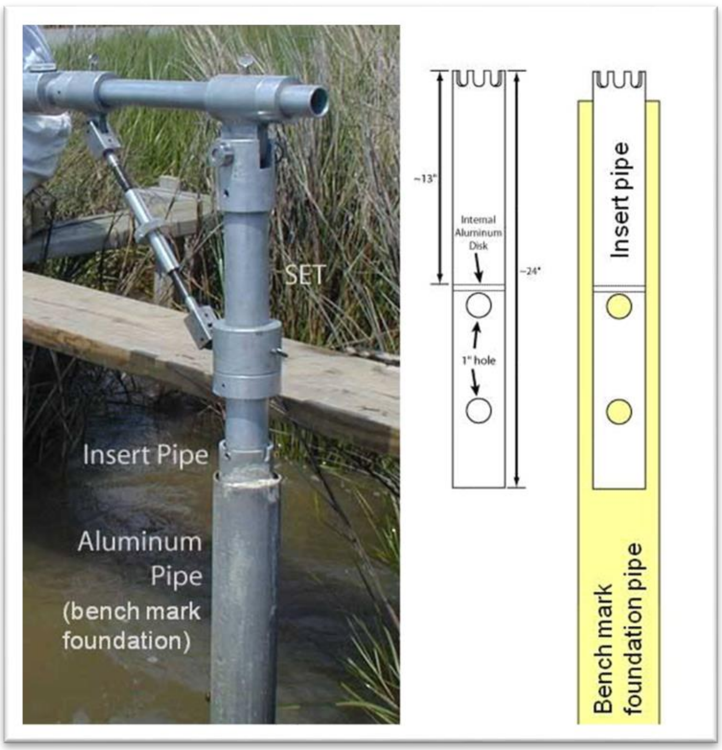


Figure 7-2. First generation SET foundation, insert pipe, and measurement instrument in place in the field (left panel). Right panel is sketch of insert pipe and insert pipe within bench mark foundation pipe. Photos and diagram courtesy of Donald Cahoon, USGS.

Figure 7-3. Procedures for finding and leveling to vertical point of reference of a first generation SET foundation.

7.1.4. Connecting groundwater wells to vertical control network via leveling

Groundwater protective wells are typically constructed of PVC or other pipe material, which protrude from the ground at variable elevations, generally under 2 m (Figure 7-4).

Since narrow-diameter PVC tubing is typically flexible, you should not place a level rod on top. Additionally, placing the rod at more than about 30 cm above the wetland surface may cause problems reading the rod. For these reasons, it is best to place a reference mark at the base of the well. Make the leveled connection to this mark, and using a steel tape, carefully read the distance from the mark to the VPR of the groundwater well (read three times and take the average).

As before, you should take both forward and backwards runs connecting each groundwater well to the local control network. If both runs agree (in millimeters) to within the target misclosure, then you have established a good vertical connection. Otherwise, repeat observations as you would along a level line (Section 6.1).

Figure 7-4. Examples of different groundwater well constructions.

7.1.5. Connecting vegetation plots to vertical control network via leveling

Leveling techniques generally assume measuring elevation differences between survey marks, either permanent or temporary. Vegetation plots are typically marked by flags or poles, but the reference surface is the soil itself (Figure 7-5). Therefore, do not perform a combination of forward and backwards runs; just the forward run from a local control mark will suffice.

Figure 7-5. Leveling to a corner of a vegetation plot.

Vegetation plots may require measuring several locations on the soil surface within each plot. In this case, then the measurements for any one plot may be taken as multiple foresights from an initial backsight (ideally, to a local control mark). Some digital barcode levels have a special program for "cut and fill" operations that expedite taking multiple spurs off one reference mark, in which you should follow these steps:

1. Place the level such that it can read the nearest reference mark in addition to several plots (typically along a transect).
2. Take a backsight to the reference mark.
3. Take numerous foresights to each elevation point within each given plot.
4. Take a final foresight to the reference mark (effectively, a backsight). This should read a similar height as #2 (to within a millimeter or so).

This technique is recommended, as it will speed up the process of taking multiple shots within each plot. However, you must keep shots as balanced as possible by positioning the tripod, so that the distance from the local reference mark to the plots is about the same. Frequent checks back to the reference mark will confirm that no movement in the level has taken place.

Another concern with leveling to the wetland surface is the difficulty of obtaining a good line of sight through tall vegetation (Figure 7-5). If vegetation interferes with digital barcode leveling, try using the optical technique, as your eye may be able to see through the vegetation more easily than the digital method.

7.2. Real-Time Kinematic GNSS

Real-time positioning (RT) uses GNSS technology to produce and collect three-dimensional (3-D) positions relative to either a fixed (i.e., stationary) base station (Real-Time Kinematic, or RTK), or relative to a network of base stations (Real Time Network or RTN). RTK or RTN positioning provides a good way to establish elevation differences among your sentinel site components for which leveling is impractical or impossible. RTN techniques are simpler and easier than RTK, and do not require the establishment of your own base station. Consult your local RTN provider for instructions on how to access the network (most networks require a subscription fee). This section of the manual focuses on RTK techniques.

> At the time this document was first created, Real-time networks (RTNs) were in their infancy. They have now matured and offer a viable technique for rapid, centimeter-level positioning. Consult your Regional Geodetic Advisor for more information on RTNs available in your region.

Basic Concepts

When GNSS signals are processed by a GNSS receiver, there is always some error in the resulting position due to any number of variables acting in the atmosphere/troposphere/ionosphere to change how the GNSS signals arrive at the GNSS antenna (Henning, 2011). CORS data are used in post-processing of static GNSS data (Section 6.2) to correct for these errors because every CORS has a NGS published position.

For example, at any one moment in time, the instantaneous position calculated at a CORS might be different from its published position due to atmospheric conditions. If you draw a vector from the instantaneous position to the published position, this vector can be considered a corrector for the instantaneous position. If you are collecting GNSS data at that same moment in time and in the general vicinity of the CORS, that same corrector can be applied to your data to account for those same atmospheric conditions. This corrector is applied in post-processing the GNSS data.

With RTK, we obtain similar atmospheric correctors, but without post-processing. Instead of the CORS, the correctors come from a companion GNSS base station, which has been set over a point with known, high-accuracy coordinates (Henning, 2011). A base station is a survey-grade, dual frequency GNSS unit deployed on a 2 m survey tripod, and it receives GNSS signals during your RTK survey. These signals are processed to generate a position for that point (latitude, longitude, and elevation), but with error due to atmospheric conditions. The base receiver's software differentiates the calculated position from the known position it is placed upon and derives its own corrector. That corrector is transmitted via radio waves to the GNSS unit that is being deployed in the field, called the rover (Figure 7-6). Since the base station is near the rover, the atmospheric conditions can be assumed to be identical. Therefore, the rover can get a very accurate elevation difference with the base station (generally at the centimeter level) in just a few minutes. The elevation difference is not the same thing as the elevation referenced to NAVD 88; the accuracy associated with NAVD 88 is typically much worse, at the 4–6 cm level. In other words, RTK GNSS is similar to leveling in that both techniques transfer elevations through measured elevation differences. However, RTK accuracies are at the centimeter level, whereas leveling produces accuracies at the millimeter level.

Accuracy classes have been established by NGS for real-time derived positions. For the purposes of connecting sentinel sites components to the local geodetic control network, we suggest the highest order accuracy: RT1 (Henning, 2011). There are several factors that influence the accuracy class in our surveys, including the number of satellites seen during data recording, how they are distributed in space (their geometry), and the duration of time observed.

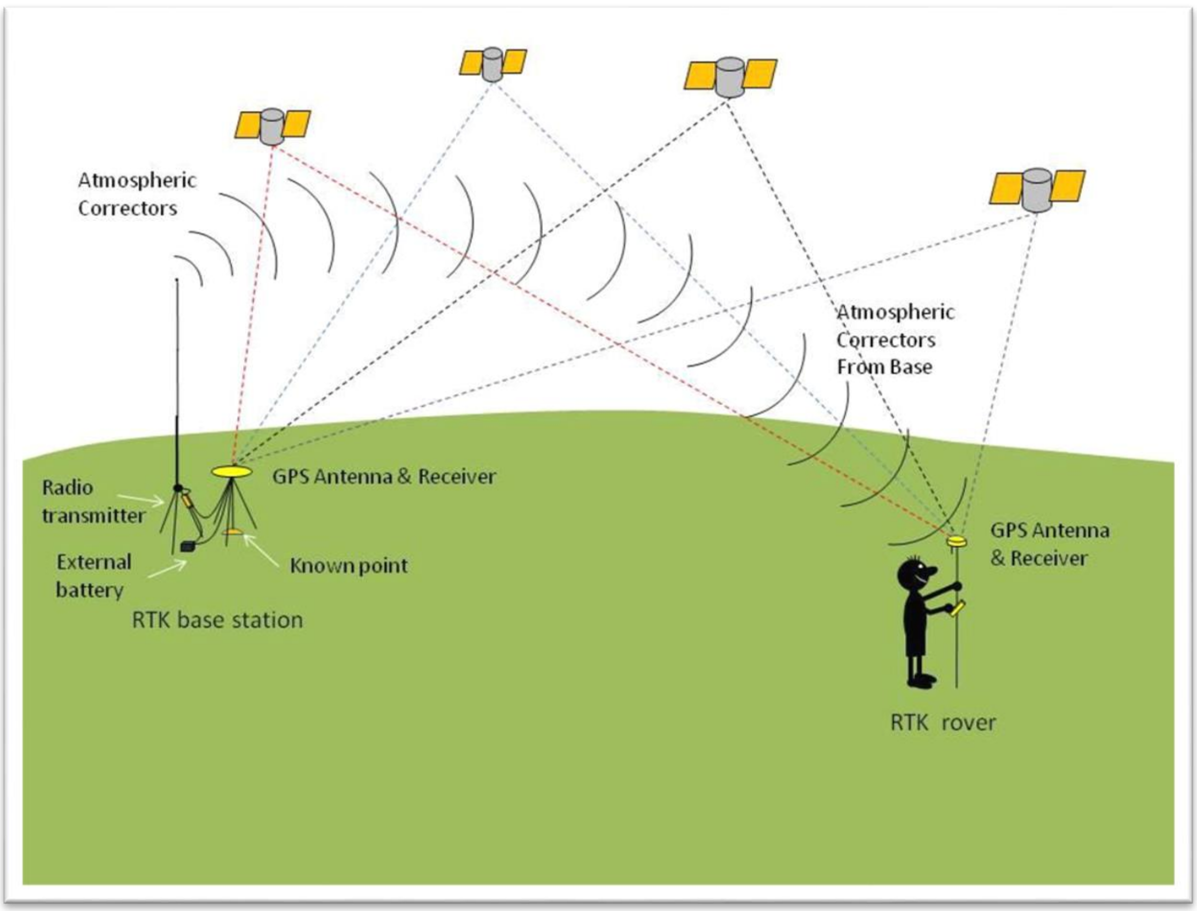


Figure 7-6. Illustration showing concept behind RTK technology: the broadcasting of positional correctors from the base on a known point.

Important Information

This document assumes that you and your field crew will take some training – both in the classroom and hands-on, prior to conducting any RTK surveys. Such training is offered by NGS (see http://www.ngs.noaa.gov/corbin/index.shtml for schedule of upcoming classes, or to request a class); you may also obtain training from your vendor or survey supply distributor. Hopefully, this document provides you with enough theory and practical guidance, so that you will know what you are getting into.

You may decide to contract this work out to local professional surveyors or take some training and do the work yourself. In case you conduct this work yourself, this document will provide important information specific to the tasks at hand, and will ensure that standard practices are followed across the user community. If you contract for this work, it is important to obtain the services of a company that can clearly demonstrate proficiency in this area. Note only a small percentage of professional surveyors have the necessary equipment and experience to perform RTK GPS surveying.

7.2.1 Running an RTK survey

Running an RTK survey can be quite a daunting process at first. A very useful resource is the NGS "User Guidelines for Single Base Real Time GNSS Positioning" (Henning, 2011). This document is not meant to replace the real-time positioning guidelines, but it covers the most important considerations involved with this kind of surveying. It highlights considerations for making necessary geodetic connections among sea level change sentinel components and provides tips/cautions to help you get the job done correctly and safely.

The modern GNSS RTK units for both the base station and the rover are generally all-in-one antenna/receivers; however, older units can be the same used for static GNSS (i.e., with a separate antenna and receiver). RTK guidelines recommend using a separate geodetic GNSS antenna for the base, so that a choke ring can be used to guard against multipath errors (GNSS signals bouncing off reflective surfaces (Henning, 2011). However, any geodetic GNSS dual-frequency antenna with multipath rejection, including an all-in-one unit, can be used. Regardless of which type of base you use, it is critical for the base to communicate the correctors to the rover. Furthermore, the vendor software is typically designed to work with the vendor GNSS units. As a result, in most cases the RTK equipment will come as a matched base and rover pair. Table 7-6 provides a list of recommended equipment for RTK surveying.

Table 7-6. Recommended equipment for RTK surveying.

Quantity	Description	Notes
1	Matched pair of RTK GNSS units	Must include base and rover GNSS units; can use all-in-one or separate antenna/receiver units
1	GNSS 2 m fixed height survey tripod	Used to position based on known mark
1	External radio transmitter	Make sure you have the necessary cables to GNSS receiver and to radio transmitter
1	Radio antenna	
1	External battery with power cables	Needed to power both radio and base GNSS
1	Radio tripod	
1	Rover range pole with bipod legs for stability	
	Survey point and topo foot attachments	For rover range pole
1	Data logger	
	Standard field equipment	Hat, sunscreen, raincoat, drinks, cell phone, bug repellant

To get started, use one of your local control marks (LCM) as the base. This would preferably be the mark chosen in Section 6 as the connection point to the NSRS, since it has the most accurate height and hopefully has a clear view of the sky. With the base GNSS on one LCM, you will bring the rover to each of the other LCMs in your system and check their positions. If they match the elevations assigned to these marks within 3 cm, then continue over to your monitoring infrastructure and record the positions (Figure 7-7). After successfully obtaining positions, repeat the survey for redundancy but only on fixed points such as SETs, groundwater wells, and the like (not for sediment surfaces, such as vegetation plots).

If the elevation displayed on your data sensor is off by more than 3 cm for either LCM, then you have a problem and will need to troubleshoot.

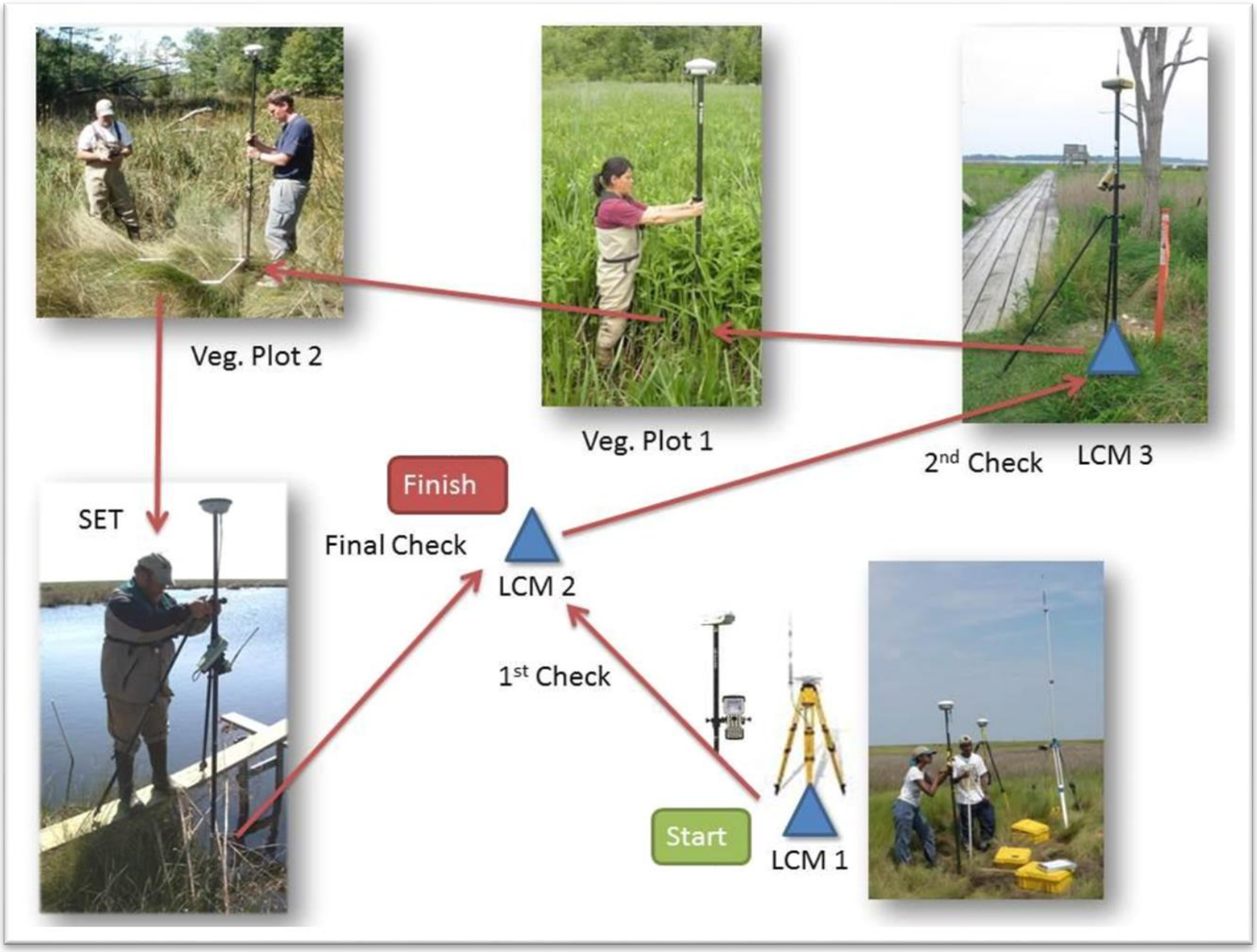


Figure 7-7. Diagram showing the RTK rover method. The base is set on an LCM; the rover checks the two other LCMs prior to establishing new positions in the field. At approximately 4-hour intervals (and at the end of the day), known points are re-checked for confirmation/closure.

Setting up the RTK Survey

Setting up the RTK survey is the most complicated part of the whole process. It can be very frustrating at first, as there are a number of ways in which an RTK survey can go wrong. For example, forgetting to specify one setting, such as the radio channel, may cause your rover to be disconnected from your base. Forgetting to specify the antenna height can cause the wrong correctors to be sent to your rover.

The key to success is practice. With enough experience, you will soon become familiar with all components, and you will be able to set up everything quickly, check that everything is fine, and complete your survey. Once you have everything functioning, it is rare that you will get a serious problem. The steps below outline general procedures shared by most RTK equipment. Most differences in setup and operation are due to differences in the software controlling the survey. Different software will have its own menus, tabs, and input screens, as well as a particular sequence of operations. The steps outlined below are therefore meant as a general reference, not a true user manual. Your particular steps may be in a slightly different order.

Before setting up the tripod, complete a few quick equipment checks:

- Make sure that the center pole is in good working order, and that the (pointed) tip is tightly placed.
- Measure the length of the middle pole, from its tip to the surface on which the GNSS antenna sits. Record the length to the nearest millimeter (most survey tripods have a 2 m setting).

Next, assemble your equipment following the basic steps below. Remember that the base will only work if it can see satellites, and we recommend choosing one of your LCMs as the base.

1. Remove the brass plug from the top surface of the GNSS tripod.
2. Extend and splay the two adjustable legs of the tripod; place the tips on the ground and stomp them firmly in place.
3. Place the middle pole (4th leg) of the GNSS tripod on the vertical reference point (VPR) of the known point that will be your base (LCM).
4. Plumb the tripod (Refer to Section 6.2.2 for detailed instructions on plumbing a GNSS tripod).
5. Screw the brass plug into the base of the GNSS antenna, attach any cables required for the function of the antenna (e.g., antenna cable or data/power cord), and gently place antenna atop GNSS tripod; tighten knurled knob to keep it in place. Make sure the central leg is still plumb.
6. Connect power to the receiver.
7. Assemble radio tripod and radio antenna (note: the base station GNSS may come with a small whip-antenna: this is NOT needed for the base).
8. Extend the radio antenna and fix it to the top of the tripod with the included washer and plate and hand-tighten.
9. Note that a higher antenna height leads to a longer range. However, if your antenna is more than 25 feet high, you need a low-loss cable (typically a much fatter, heavier cable) to attach the antenna to the radio unit.
10. Hang the radio on the radio tripod; there is usually a bracket built into one of the legs for this purpose (Figure 7-8).
11. Plug the radio antenna cable into the transmitter antenna port.

12. Plug the data end of the power/data cable from the GNSS unit into the radio transmitter.
13. Once the antenna cable and the GNSS data cables are attached, you can then plug the power end of the radio cable into the battery.

Important Information

Caution: the antenna with its extensions may easily extend into overhead electric wires. When in the field, **LOOK UP** and make sure antenna is free of any wires, branches, etc.

Note that we first assembled the radio antenna and plugged it into the radio; this is to make sure that if the radio gets power accidentally, the radio will not get fried (power will be transmitted through the antenna).

Caution: Make sure plugging into the radio battery is the last step! You never want to have power to the antenna while you are still touching it - you could get shocked and seriously burned.

Different manufacturers have slightly different setups. Some have separate external batteries for both the GPS and the radio. If so, first plug in the battery for the GPS, then the radio (make sure radio antenna is plugged in).

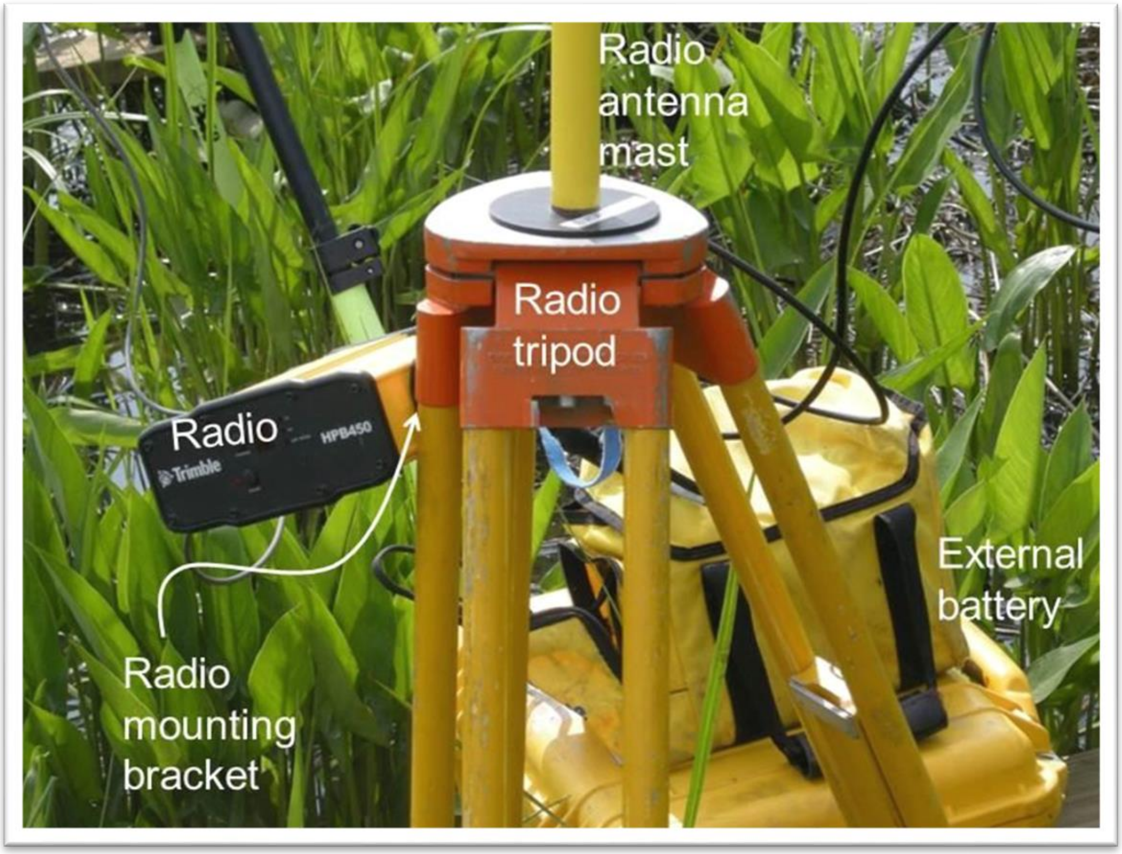


Figure 7-8. Close-up view of RTK radio, attached to radio antenna tripod. Bottom part of antenna mast shown.

You should now have all components assembled (Figure 7-9). At this point you can turn on the RTK GNSS base, and it should lock onto available satellites. The next step in preparing for your survey is to set up your rover pole following the steps outlined below:

1. Screw on either a survey point or topo foot (see green box below and Figure 7-10).
2. Attach the brace (bipod) poles and the data sensor clamp to the rover pole (if desired).
3. Carefully screw the GNSS unit on top of the rover pole: place the bottom of the pole on the ground and stabilize it with the brace poles. Note: you might find it helpful to slant the rover pole – that is fine.
4. Turn the GNSS rover unit on, so it initializes and begins to see satellites.

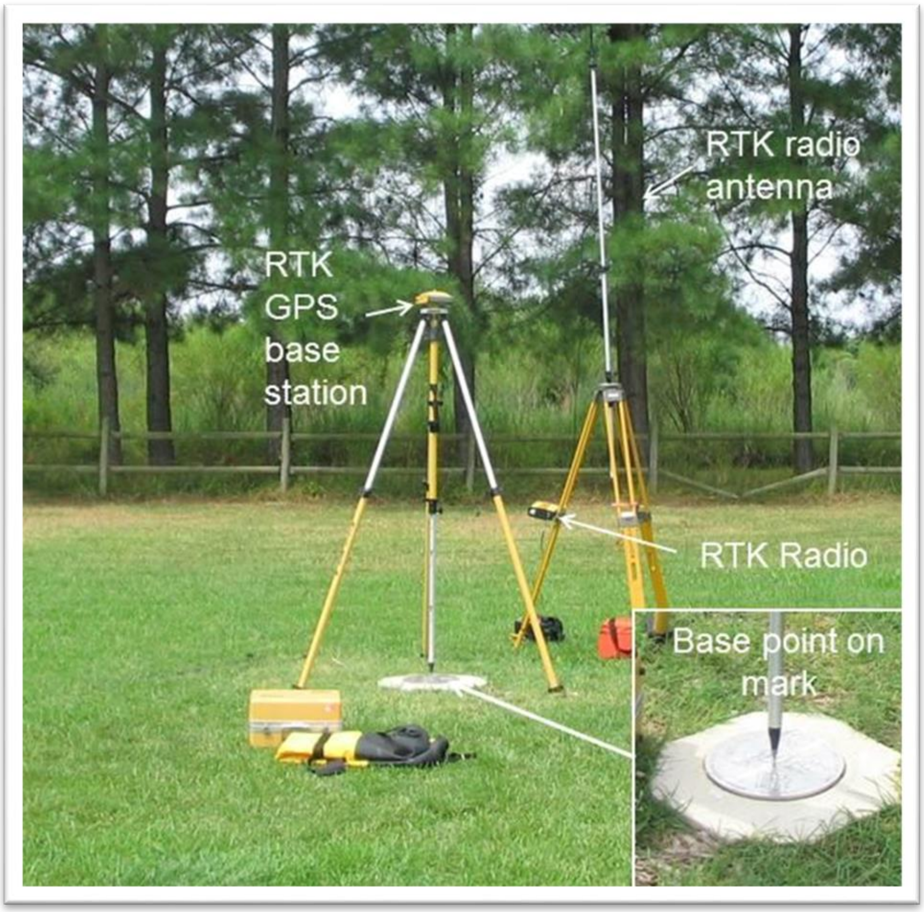


Figure 7-9. RTK GNSS base station setup.

Survey point or topo foot? For getting a position on a marked vertical point of reference (a center punch on a metal marker, rod, survey nail, etc.), the survey point will be best. For placing the rover pole on the ground, or on an object that does not have a vertical reference point, the topo foot is recommended (Figure 7-10).

Figure 7-10. Close-up of two different kinds of rover tips. Left panel: survey point on mark; right panel: "topo foot" on ground. The base of the topo foot is approximately 2.5 inches in diameter.

Collecting RTK observations

At this point, your tripod and GNSS should be set up on the known point that will be your base. Start the RTK session using the data sensor and following the general steps below:

1. Turn on the hand-held data sensor and start a new job, making sure to create or note the file name.
2. Configure the RTK session, which involves setting the coordinate system/reference frame used and the geoid model. It is best to use the latest realization of the reference frame and the latest geoid; however, you may be limited by options currently available (loaded) in your data sensor, or by the reference frame used in defining the position of the mark at the base. In any event, positions will be adjusted and corrected during post-processing.
3. Configure the RTK base station and the radio, **so make sure you specify the correct channel**. Also, input the assigned coordinates including height for the base. You can run an RTK session without knowing the position ahead of time, but this is not recommended because the data will have to be post-processed.
4. Check the radio to make sure it is transmitting. Make your radio check within sight of the base to ensure that obstructions or long distances are not causing a problem. If your rover is more than about 2 km away from the base, you need to augment the power by using a special thicker (low loss) cable and possibly a taller antenna.
5. Configure the rover by setting the height of your rover pole and making sure it is receiving from the same radio channel that the base is transmitting on.
6. Set up the rover on a known point (e.g. another LCM), begin recording, and monitor the observation. You want to make sure that:
   a) PDOP (Position Dilution of Precision) ≤ 2.0 parts per million
   b) Rover is seeing ≥ 7 satellites
   c) RMS (Root Mean Square) ≤ 0.01 m
7. Stop the observation after three full minutes of fixed data. If the rover becomes autonomous during that time (loses the connection to the base), you may have to extend the observation time.
8. Compare the coordinates given on the rover with the known coordinates of your mark. If they agree within 3 cm, you have successfully passed the check.
9. Repeat the check on a second known point. If both marks check fine, you may continue with your RTK observations. Otherwise, you will have to troubleshoot (see below).

Now that your base and rover are set and you have confirmed that everything is functioning correctly, you can go to the new points that you want to have connected (i.e., your surveying monitoring infrastructure).

10. Place the rover survey point on the vertical point of reference (VPR); if you are using a topo foot, place the foot on top of the ground or structure.
11. Plumb the rover, using the brace poles for stability as needed.
12. After making sure that the data logger is connected to the rover and that your job is open/active, enter the new point name on the new point screen and press the **"start"** button to begin recording and monitor the observation. As before, you want to make sure that
    a) PDOP ≤ 2.0 parts per million
    b) Rover is seeing ≥ 7 satellites

c) RMS ≤ 0.01 m

13. Stop the observation after three full minutes of fixed data. If the rover becomes autonomous during that time, you may have to extend the observation time.
14. After a position is obtained, move to your next point, and repeat steps 10–13.
15. After a 4-hour interval between each mark, return the rover to a known point (published bench mark or LCM) to check the accuracy of the position.
16. After all points are observed, repeat the observing sequence (only on fixed points – not soil surface points such as for a digital elevation model, or along transects), so that you get two different (and hopefully independent) solutions for each point. "Independent solutions" can be assured if at least four hours have passed between your observations on the same point.
17. Note that you may have to replace the internal batteries in your rover receiver. This might require you to reconnect to the base (or even restart the survey).
18. Compare each of the two solutions you have obtained for each point. If they are within 3 cm, then you can average the two positions. If they are different by more than 3 cm, then you should obtain one more reading for that point.
19. At the end of your day's survey, return to one of the LCMs you checked into at the beginning. Make sure that the new coordinates are similar to the old ones. If not, it is recommended to repeat the survey.

The reference frame (and geoid) used to define the mark at the RTK base might not coincide with what is available on your RTK data sensor. If that is the case, post-processing is required to align the reference frames.

Troubleshooting

If you are experiencing no communication between rover and base, we suggest you check for the following potential issues:

- You have open skies and are within range of the base radio (<2 km).
- Rover is listening to the same radio channel you selected on the radio.
- Data sensor is connected to the rover and not the base.
- Radio is on. Remember, if the rover was far from the base, the radio should be in the "high" mode.
- Base is transmitting through the radio (verify the transmission light).
- External battery for the radio is charged.
- Base is seeing satellites and is generating coordinates.

If none of these seem to be the problem, try resetting/restarting the rover and/or the base.

If your real-time coordinates for known point are way off (e.g., more than 6 cm), then answering the following questions can help you figure out why:

- Are you occupying the correct mark (e.g., an azimuth mark or reference mark instead of the actual station)?
- Are you not using the same projection or datum? Make sure they are the same, and in same units.
- Is the height off by 2.0 m? If so, you forgot to input the antenna or rover height.

- Was there a blunder in inputting base coordinates?
- Is the base station tripod correctly positioned on the mark?
- Can you check another known point and see if that one is off? Maybe you recorded the wrong coordinates.

You can appreciate that there are many steps in setting up an RTK survey, and any error along the way can cause real problems with the survey and the data. At the start, you may find yourself calling the vendor/technical assistance from the field to resolve an error. Familiarity with your RTK equipment is key. After a few trials, you will find yourself pulling off a flawless survey.

7.2.2. RTK-derived elevations on SET marks

There are several versions of SET foundations (marks). First generation marks used a 5 cm (2 inches) diameter aluminum insert pipe, which was cemented into a large metal pipe that was inserted into the soil (Figure 7-11). The insert pipe is wide enough at the top (5 cm) that a topo foot might have a hard time landing on the true top of the pipe. If the topo foot does not fit entirely atop the insert pipe, then you will have to find the vertical point of reference (VPR) on top side of the mark using a rod level (red bubble gauge in Figure 7-11) or small torpedo level. Swivel the level around the insert pipe and note the apparent tilt direction of the pipe. The top side will be where the bubble is lying away from the pipe exactly in line with both the center of the bubble gauge and the center of the pipe. Mark this spot with a hole punch, chisel, file, etc., and note its location on the pipe with respect to landmarks or a cardinal direction (write in field notebook). This will be your vertical point of reference (VPR). Once marked, it would be best to use the survey point instead of the topo foot (Figure 7-11). Since many SET plots use permanent platforms to avoid site disturbance, you might find it helpful to place the legs of the brace poles on a wooden plank: once the rover pole is plumbed, the brace poles will help keep the range pole steady (Figure 7-12).

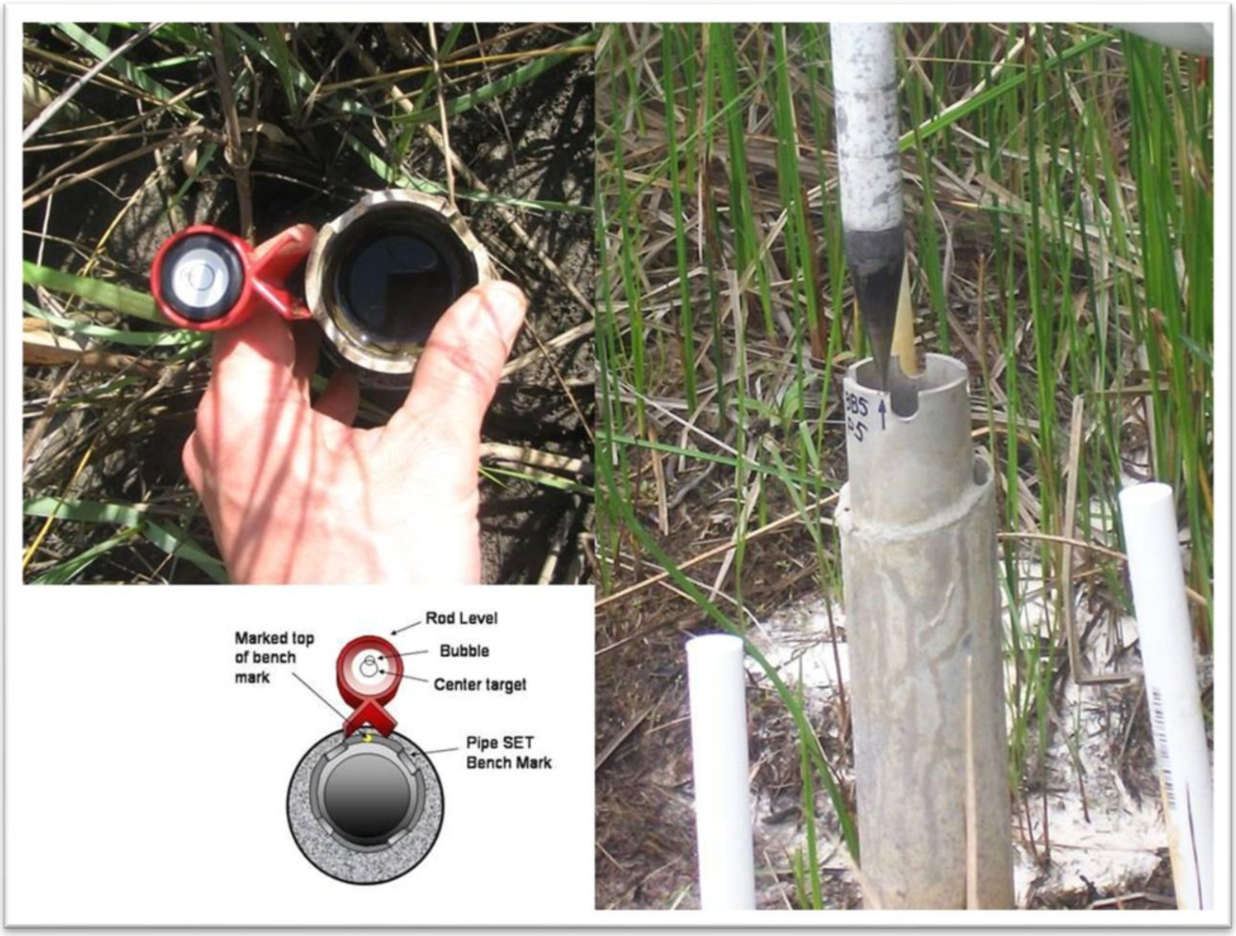


Figure 7-11. Finding the vertical point of reference on a first-generation SET monument. Top side of the mark is where the bubble lies to the outside of the insert pipe, perfectly in line with an axis going through the center of the pipe. Note: survey point is used for RTK.

Since about 2005, most new installations have used the traditional deep (survey) sectional rod monument (Section 5.2.2). The SET monument terminates in a receiver, which is milled from 1inch stainless steel rod stock. The receiver is usually protected by a small plastic cap, which needs to be removed for surveying. Although the same theory applies as with the original pipe-based monument, the small diameter of the receiver makes it much easier for a topo foot to automatically find the top of the mark. This is the same idea as seen previously with the level rod (Figure 6-12). However, if you do not have a topo foot, you should follow the same concept as with the older SET marks (Figure 7-13). Note that Figure 7-13 shows the presence of a small brass disk on the concrete surface of the SET monument. This often and incorrectly has been confused with the survey (datum) point. The brass survey mark traditionally was used by some agencies to label the mark, and it is NOT the survey point. The vertical point of reference is always the top side of the SET receiver. Regardless of SET foundation type, take two RTK readings at least four hours apart at each SET foundation for redundancy. Check for consistency. If the readings agree within 3 cm, the readings are considered adequate.

Figure 7-12. RTK on a SET foundation in the wetland. Note: that the RTK rover brace poles can rest on a wooden platform for stability.

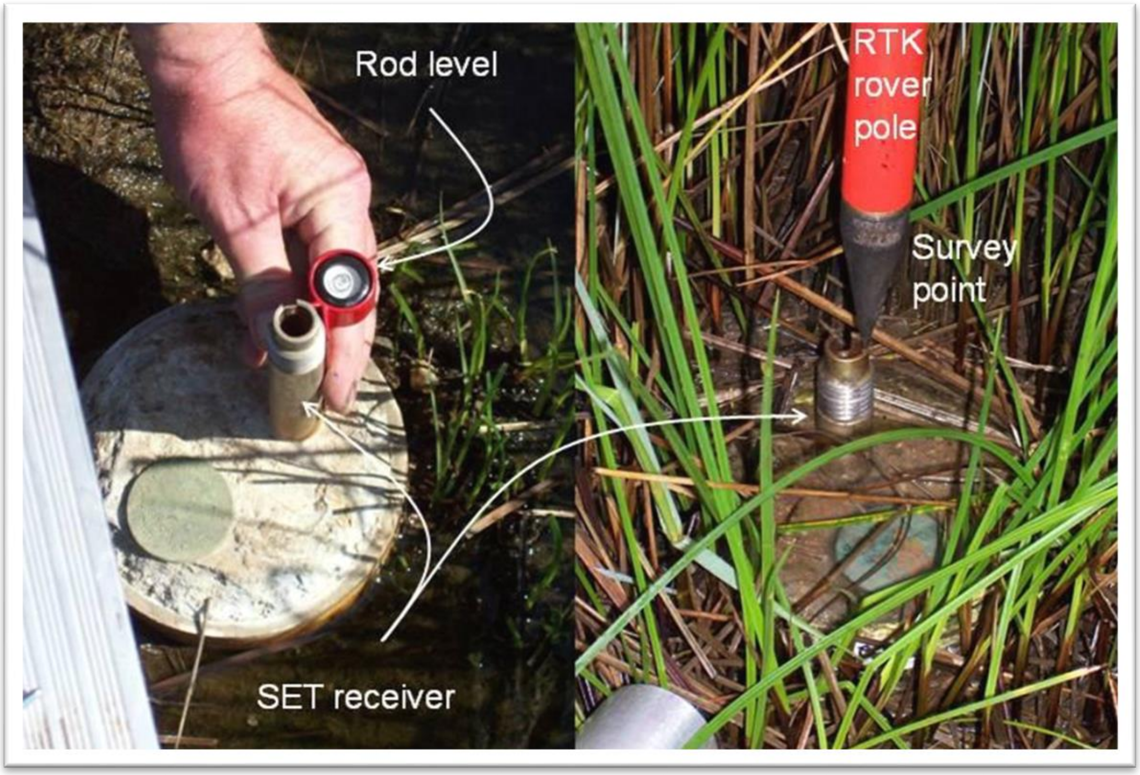


Figure 7-13. Finding the vertical point of reference (VPR) on a deep rod SET monument (left panel); RTK rover point on VPR.

7.2.3. RTK-derived elevations on groundwater wells

Groundwater wells share many similarities with water level sensors. A PVC protective well normally sticks a meter or more above the wetland soil, topped with a protective cap (Figure 7-14). A vertical point of reference (VPR) may be located on the PVC tube in the form of a notched mark on the rim or another reference mark along the tube. However, as was seen with leveling, it is usually impractical to place a rover pole atop the PVC. Instead, survey to a temporary vertical reference mark at the base of the PVC and then use steel tape (or something similar) to measure from the temporary vertical reference mark to the vertical point of reference on the top of the PVC tube. Take two RTK readings spaced four hours apart for redundancy on each reference mark. Check for consistency between observations at the same mark. If the readings agree within 3 cm, the readings are considered adequate.

Once the coordinates have been obtained for the VPR, the distance between the VPR and the sensor zero of the water level sensor must be carefully measured in a process similar to measuring to the sensor zero of water level stations.

7.2.4. RTK-derived elevations on vegetation plots

Most vegetation plots are identified by PVC poles, stakes, or other markings that locate at least one geometric reference for the plot. Most plots tend to be squares; if poles or stakes do not mark all four corners, then there usually is a consistent scheme of identifying the size and orientation of the plots with respect to the marker (e.g., Figure 7-14).

RTK coordinates on vegetation plots are generally obtained on the soil itself, not on a specific repeatable mark. At least four RTK points are recommended (one per corner of the plot). Figure 7-14 shows the surveyor taking an RTK position at one (unmarked) corner of a vegetation plot. Since these are not fixed points, there is no need to survey twice. Rather, the multiple observations per plot will serve to provide a reliable estimate of surface elevation.

In soft, wetland soils, be very careful not to let the RTK pole sink into the sediment. You must use a topo foot, and try to keep the foot from sinking in.

Figure 7-14. RTK GNSS within wetland vegetation plots. Note that only one corner of each plot is marked with the PVC cap; consistent field procedures need to be followed to approach sites and take positions at each corner.

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APPENDIX 1: DICHOTOMOUS KEY FOR DERIVING TIDAL DATUMS

Dichotomous Key for Determining "Procedures" for Deriving Tidal Datums	
Step	
1a	You want to determine a local tidal datum at a Sentinel Site - Go To Step 2
1b	You want to determine accurate water levels (relative to North American Vertical Datum (NAVD) 88 at a Sentinel Site - Go To Step 12
2a	Site is within Active National Water Level Observation Network (NWLON) Coverage with or without Historic Stations (see NOAA CO-OPS Gap Analysis) - Go To Step 3
2b	Site is within Active NWLON Gap (See NOAA CO-OPS Gap Analysis) - Go To Step 12
3a	Active NWLON Station within Sentinel Site (i.e. similar or homogenous tidal characteristics) with Datums on National Tidal Datum Epoch (NTDE) - Go To **Option 1**
3b	Active NWLON Station nearest Sentinel Site (i.e. tidal characteristics NOT homogenous with area of interest) with Datums on NTDE - Go To Step 4
4a	Bench marks at NWLON within leveling distance of local Sentinel Site bench mark network - Go to **Option 2**, also consider Step 5
4b	Bench marks at NWLON NOT within leveling distance of local Sentinel Site bench mark network - Go To Step 6
5a	Bench marks at NWLON part of published leveled Go To Line or bench marks can be used as part of Sentinel Site bench mark network - Go To **Option 3**
5b	Bench marks at NWLON NOT part of published level Go To Line or have no value in Sentinel Site bench mark network - stay with **Option 2**
6a	Historic Stations found within Active NWLON Coverage Area - Go To Step 7
6b	Historic Stations NOT found within Active NWLON Coverage - Go To **Option 2**
7a	Historic Stations on Current NTDE - Go To Step 8
7b	Historic Stations NOT on Current NTDE - Go To Step 10

8a	Bench marks from Historic Stations recovered and in good condition - Go To Step 9
8b	Bench marks from Historic Stations can't be recovered or have been compromised - Go To **Option 2**
9a	Bench marks within Digital Leveling Proximity to Sentinel Site - Go to **Option 2**, Also Consider Step 5
9b	Bench marks not within Digital Leveling Proximity to Sentinel Site - Go To **Option 2**
10a	Bench marks from Historic Stations recovered and in good condition - Go To Step 11
10b	Bench marks from Historic Stations can't be recovered or have been compromised - Go To **Option 2**
11a	Bench marks within leveling proximity to Sentinel Site - Go to **Option 2**, also consider **Option 3** and **Option 4**
11b	Bench marks not within Digital Leveling Proximity to Sentinel Site - Go To **Option 2**
12a	Establish a Permanent Water Level Station - Go To **Option 5**
12b	Establish a Temporary Water Level Station - Go To **Option 6**
Option 1 - Use datums from NWLON station and connect site bench mark network to NWLON bench mark network via digital leveling	
Option 2 - Use a local water level sensor and use simultaneous datum comparison to derive/update local tidal datums referenced to current NTDE;	
Option 3 - Connect tidal BM network to sentinel site BM network via leveling if NWLON bench mark network is part of a published level line or marks can be used as part of your local network	
Option 4 - Reoccupy historic station with new water level station and use simultaneous datum comparison to derive/update local tidal datums referenced to current NTDE	
Option 5 - Establish a permanent water level sensor and BM network connected to NAVD 88 and derive local tidal datums estimates	
Option 6 - Establish a temporary station (3 months to 1 year) and local BM network connected to NAVD 88, derive local tidal datums estimates to study inundation and identify high water line	

APPENDIX 2: EXAMPLE OF A VERTICAL CONTROL PLAN FOR THE JUG BAY COMPONENT OF THE CBNERR-MD

Plan to Establish a Local Geodetic Control Network at Jug Bay - 2011

There is a current need to develop high accuracy local geodetic control networks within the Chesapeake Bay National Estuarine Research Reserve in Maryland (CBNERR-MD), in support of the NERRS Sentinel Sites Program Guidance for Understanding Climate Change Impacts. Currently, a number of monitoring infrastructure components have already been established within the Maryland reserve, and environmental monitoring programs have already been in place for some time. One important infrastructure currently lacking is the local geodetic control network required to bring all observing systems, from local water level recorders to wetland Surface Elevation Tables (SETs) and permanent vegetation plots –onto the same, consistent vertical datum. The establishment of geodetic connections among these observing systems would not only enable this reserve to become a sentinel site for sea level change but would also provide an important mechanism to understand the impacts of water level changes on this coastal ecosystem.

CBNERR-MD is a multi-component reserve, with three sites distributed geographically around the Chesapeake Bay. The component with the most advanced sea level change monitoring infrastructure is Jug Bay, located on the banks of the upper Patuxent River in both Prince George's and Anne Arundel Counties. The component includes permanent vegetation transects, SETs, groundwater wells, and water level recorders.

The objective of this plan is to outline the specific needs and propose approaches to establish vertical control at Jug Bay. After the successful implementation of this plan, the next objective would be to establish similar infrastructure at the other two Reserve components: Monie Bay and Otter Point Creek. Separate vertical control plans would be devised for each of the remaining components.

Inventory and Assessment of Local Sentinel Site Infrastructure for Jug Bay

Continuously Operating Reference Stations (CORS):

According to the NOAA's NGS website, there are more than four national CORS within approximately 30 km from Jug Bay:

- LOYF, Loyola. Located at 27.5 km from Jug Bay; records data every second
- ANP5, Annapolis. Locate at 28.0 km from Jug Bay; records data every five seconds
- ANP6, Annapolis. Locate at 28.0 km from Jug Bay; records data every five seconds
- GODE, Greenbelt. Located at 30.3 km from Jug Bay; records data every 20 seconds

There are a number of other CORS within the region that can provide very nice baseline coverage for the site (Figure A2.1). CORS play a very important role for establishing a geodetic control network via GPS technology; some or all of these stations would be utilized for the purpose of post-processing GPS data.

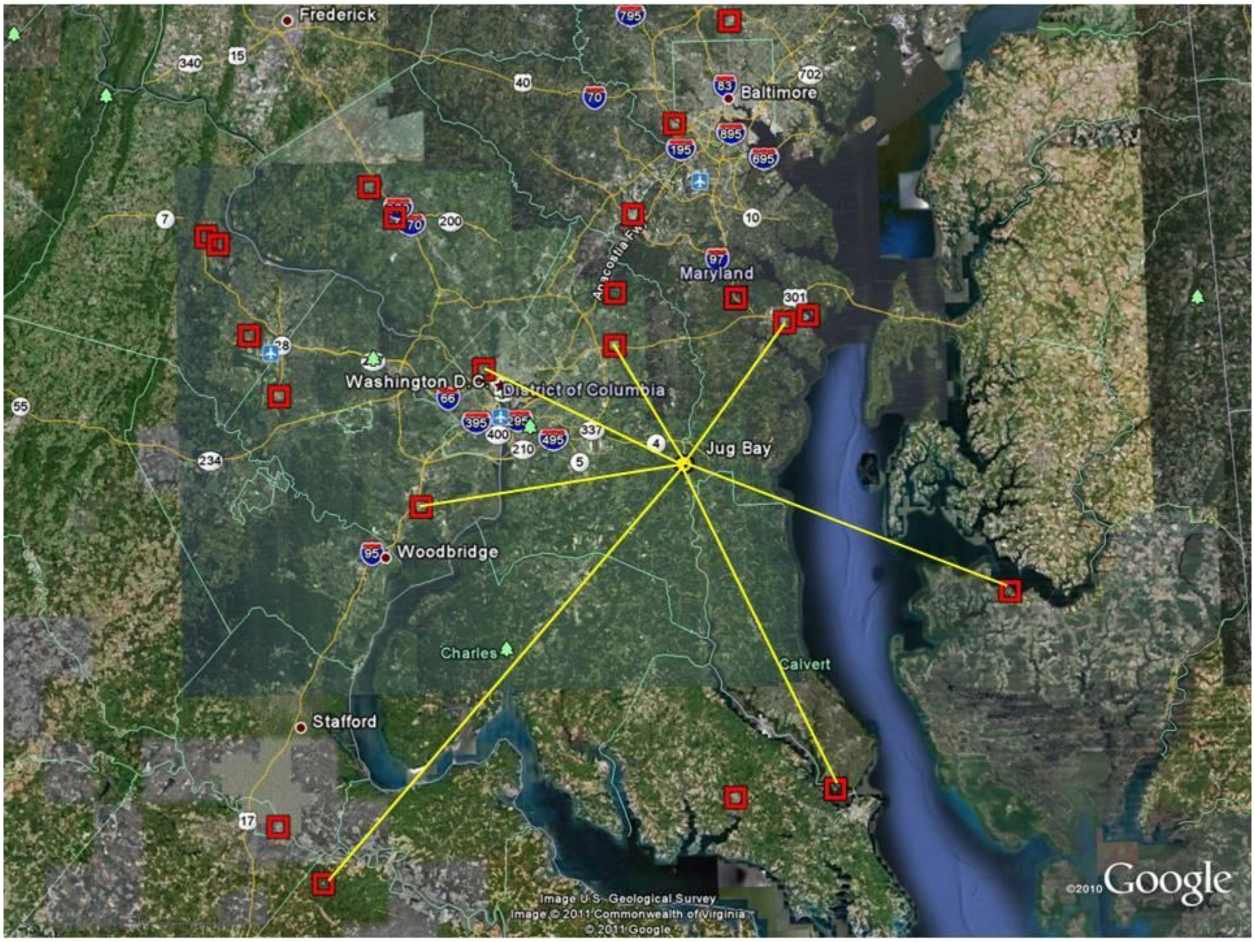


Figure A2.1. GPS CORS coverage for the Jug Bay component of the Chesapeake Bay Maryland National Estuarine Research Reserve.

Survey Monuments:

A series of existing survey monuments have been identified around Jug Bay using NGS website. A map showing the location of the ones nearest to the wetland sites is presented in Figure A2.2; the locations are given in the attached appendix. The need to recover some of these monuments would have to be determined as well as the need to establish new bench marks. It is important to note that in 2008, a team from NOAA-NGS came to Jug Bay to establish two Class C (concrete post) bench marks; one was located by the Jug Bay Wetlands Sanctuary Visitor Center and the other one was established along the Otter Point Trail. Both of these marks could potentially be used to bring vertical control to this Jug Bay area.

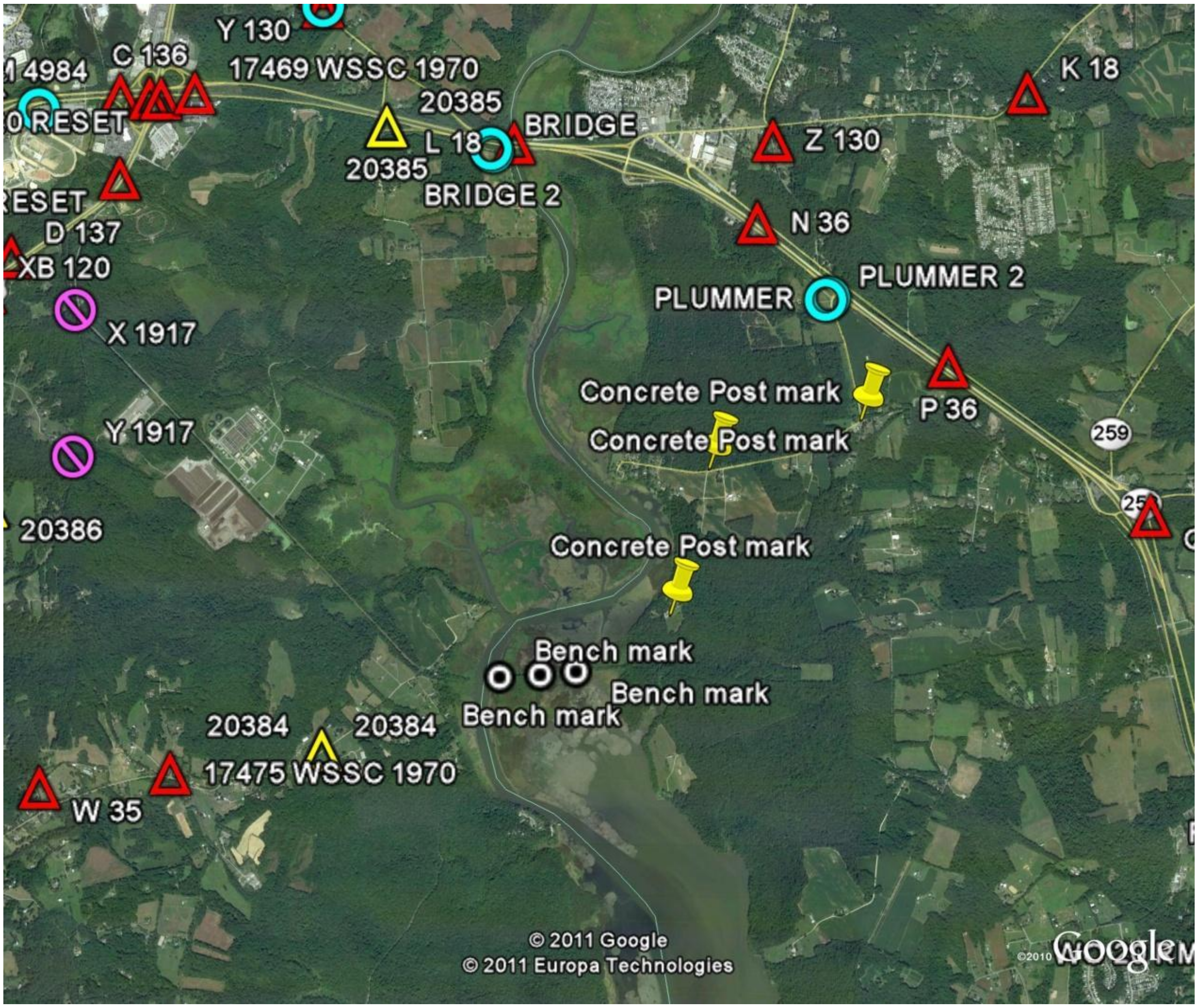
CO-OPS Water Level Stations and the National Water Level Observation Network (NWLON):

NOAA operates several different kinds of water level stations. The typical long-term NWLON station is a permanent data acquisition system that makes up the backbone of the country's water level station network, providing real-time data, tidal datums, and sea level trends (among other products). CO-OPS also deploys temporary stations for specific projects or to complement the NWLON with additional geographic coverage. Tertiary water level stations are such an example.

Several permanent and temporary CO-OPS water level stations have been established around the Jug Bay area (Table A2.1, Figure A2.3); three of them were placed along the Patuxent River estuary: Lower Marlboro, Trent Hall Point and Solomon's Island. The other nearby stations were established in very different hydrodynamic settings, such as the main stem of the Chesapeake Bay. Lower Marlboro (8579542) was established twice: the first time for about one year in the early 70's, and then for a five-year period between 2005 and 2010. Tidal datums are not currently available for this station. Trent Hall was in operation for only one year (2007–2008); computed tidal datums are not publicly available. Solomons Island, on the other hand, has one of the area's longest records (1937–present), and would be the closest water level station from which both verified tidal datums and long-term sea level trends are available.

Table A2.1. Location and status of NWLON stations near Jug Bay.

Tide Station	Station ID	Longitude (W)	Latitude (N)	Date Established	Removed/Status
Lower Marlboro	8579542	76° 41'	38° 39.3'	Jul 10 1972	**Oct. 11 1973**
				Mar. 24 2005	**Dec 16 2010**
Trent Hall Point, Patuxent River	8579023	76° 39.8'	38° 28.4'	Jan 1 2007	**Last data: 2/28/08**
Chalk Point	8575939	76° 32.5'	38° 50.2'	Mar 1 2007	**Last data: 2/28/08**
Poplar Harbor Island	8572271	76° 22.5'	38° 45.5'	Oct 1 2006	Active
Solomons Island	8577330	76° 27.1'	38° 19'	Nov 5, 1937; Present installation: Dec 18 1990	Active



°	Vertical mark with level connection	c	New concrete post mark
°	Vertical mark with GPS connection	r	Mark not found
@	Horizontal marks	H	Reference mark of unknown origin (& questionable stability)

Figure A2.2. Map showing the location of survey monuments within the Jug Bay area.

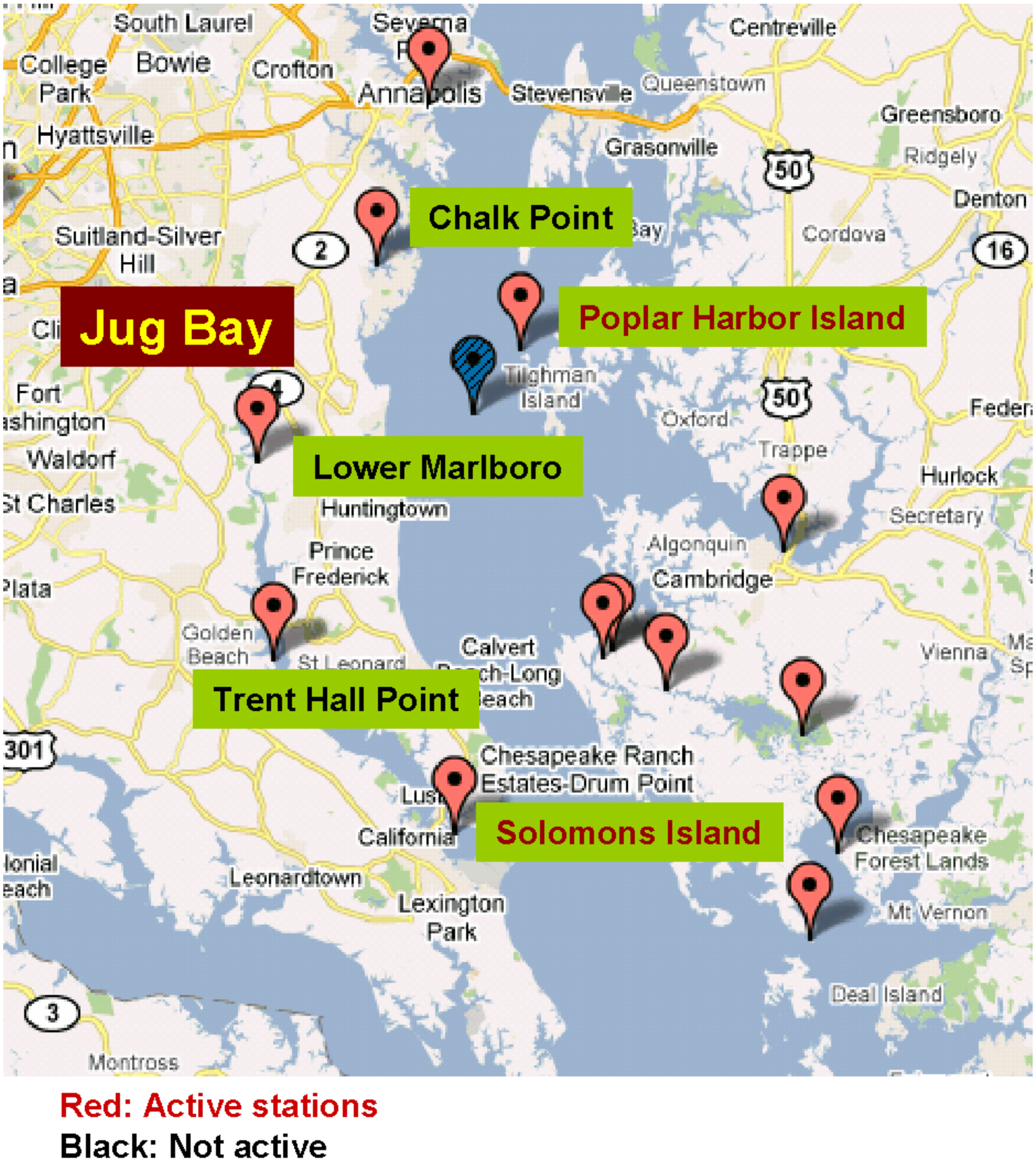


Figure A2.3. Map showing the location of NWLON stations near Jug Bay.

CBNERR-MD is a NWLON Gap:

In 2007 a preliminary desktop assessment was conducted by the NOAA CO-OPS to determine whether tidal datums could be extended from current or historic water level stations to each reserve within the NERR system. Results of this assessment for CBNERR-MD are presented in Figure A2.4. This information highlights the fact that Jug Bay, as well as the other CBNERR-MD components, are within NWLON gaps. If Jug Bay were to become a true sea level sentinel site, an investment in the necessary hardware, software, and operational support to establish an NWLON would be highly recommended. Some of the reasons to justify this recommendation are:

- This is one of the largest tidal freshwater systems of the north east coast of the U.S. and especially vulnerable to sea level change. A slight increase in flooding and salinity would probably lead to changes in species composition, particularly those with narrow tolerance levels.
- As of spring 2011, this component is close to having all of the basic infrastructure requirements for a sentinel site for climate change as defined by NERRS.
- The location of this reserve component within the larger DC Metropolitan region makes it very accessible to a host of universities, governmental and private research laboratories, from which researchers and students come to conduct research. Much of the resulting environmental research would greatly benefit from local, on-demand, high accuracy water level and tidal datum information.

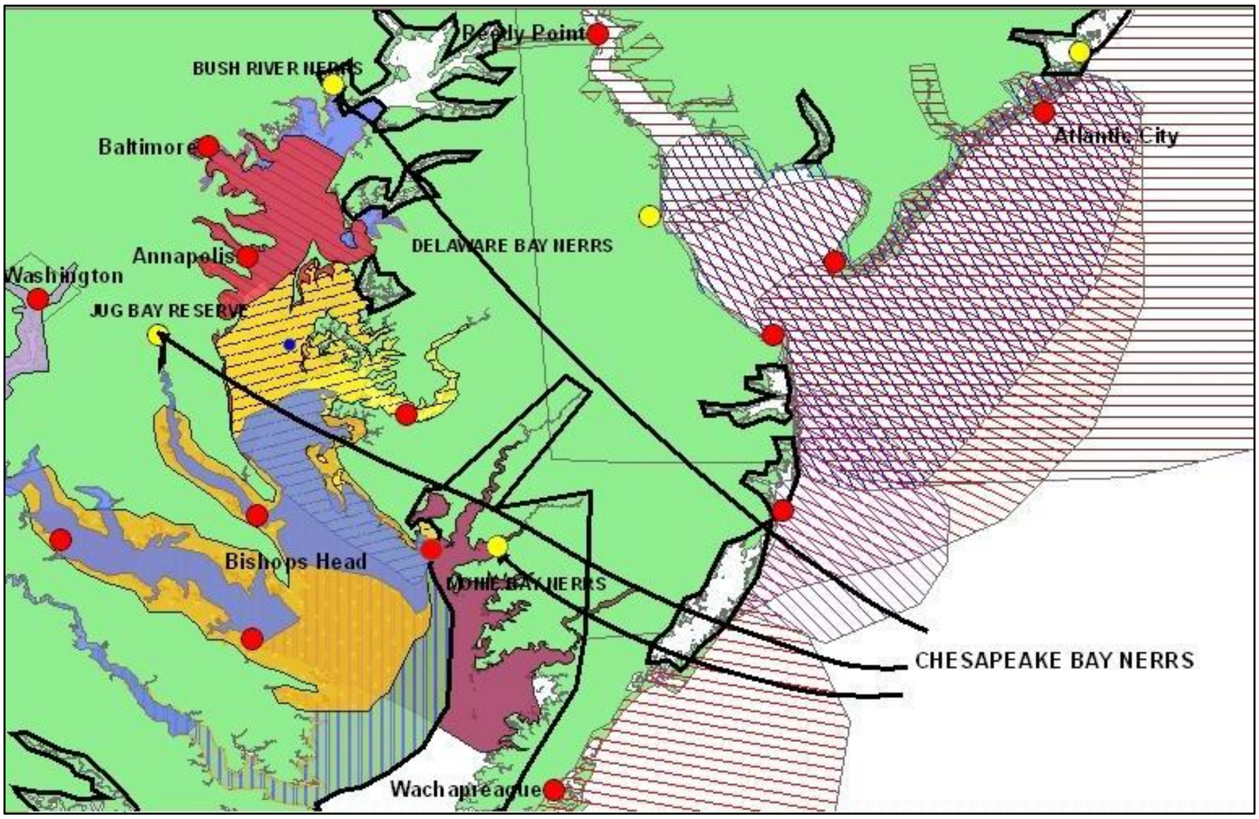


Figure A2.4. Assessment of NWLON station within or near the Chesapeake Bay National Estuarine Research Reserve in Maryland (CBNERR-MD). The areas covered by existing NWLON are presented in cross hatching; the areas in an NWLON gap are outlined in bold black.

Weather and SWMP Stations:

A weather station and a total of three continuous water quality monitoring stations (part of the NERR System Wide Monitoring Program - SWMP) have been established in Jug Bay at three main study areas: Iron Pot Landing (Western Branch), Railroad Bed, and Mattaponi (Figure A2.5). These three areas are the primary study areas of interest within this Reserve component.

The weather station was established in 2004 and the SWMP stations, as located at their current positions, were established in 2003. A SWMP station was operating at Jug Bay from 1995 to 2002, but at a different location.

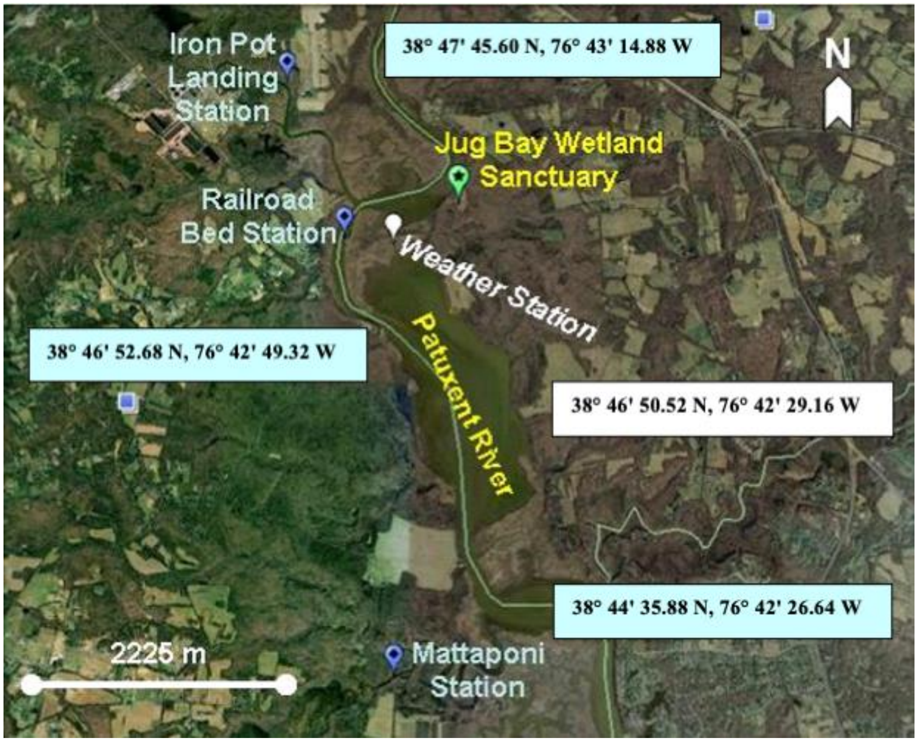


Figure A2.5. Map showing the location and GPS location of a weather station and three continuous monitoring stations (CONMON) at Jug Bay: Iron Pot Landing, Railroad Bed, and Mattaponi.

Emergent Vegetation Transects and SET Stations:

Following NERRS protocols (Moore, 2009), five emergent vegetation transects were established in 2008 at each of the three Jug Bay study areas where a SWMP station was located (Western Branch, Railroad Bed, and Mattaponi), for a total of 15 transects (Figure A2.6, Table A2.2). Within each of these three Jug Bay areas, two SET stations were established in 2010 along each of two of the vegetation transects. One SET was located within the low marsh zone and a second SET was located within the mid-high marsh zone, for a total of four SETs within each Jug Bay study area and a total of twelve SETs for the entire Jug Bay component (Figure A2.5, Table A2.3).

In addition to these twelve SET stations, twelve additional “legacy” SET stations (older, pipe-based technology) had been established by a previous researcher in 1999 within the Railroad Bed; these were measured for three years (until 2002) and then re-measured for two more years between 2007 and 2009. From these twelve SET stations, five will continue to be measured as part of the sentinel site effort since these are spatially associated with two of the permanent vegetation transects described above (T1 and T2 at the railroad bed in Figure A2.6, Table A2.3). All the SET stations, including the five legacy ones at the Railroad Bed area, are measured twice a year, during the fall (start of the non-growing season) and during the spring (start of the growing season).

The three established study areas at Jug Bay are considered reference sites and are used to evaluate the long-term potential impacts of development and climate change on this tidal freshwater system. Because of the Reserve’s long-term objectives in monitoring these areas, and due to the investment in monitoring infrastructure, it is of great interest to the Reserve’s research program to establish a local, high accuracy geodetic control network that encompasses these three main areas.

The overall layout of SWMP stations, vegetation transects, and SET stations within the same area facilitates 1) any potential correlation of water quality, vegetation, and marsh surface elevation data and 2) the establishment of a local geodetic control network which will tie all these physical and biological monitoring systems (SWMP stations, vegetation transects, SETs) to the NSRS.

Lidar data:

If needed, 2009 lidar imagery for Jug Bay is available, which includes both the portion within Anne Arundel County and the portion within Prince Georges County. This imagery could be accessed from the Maryland Department of Natural Resources.

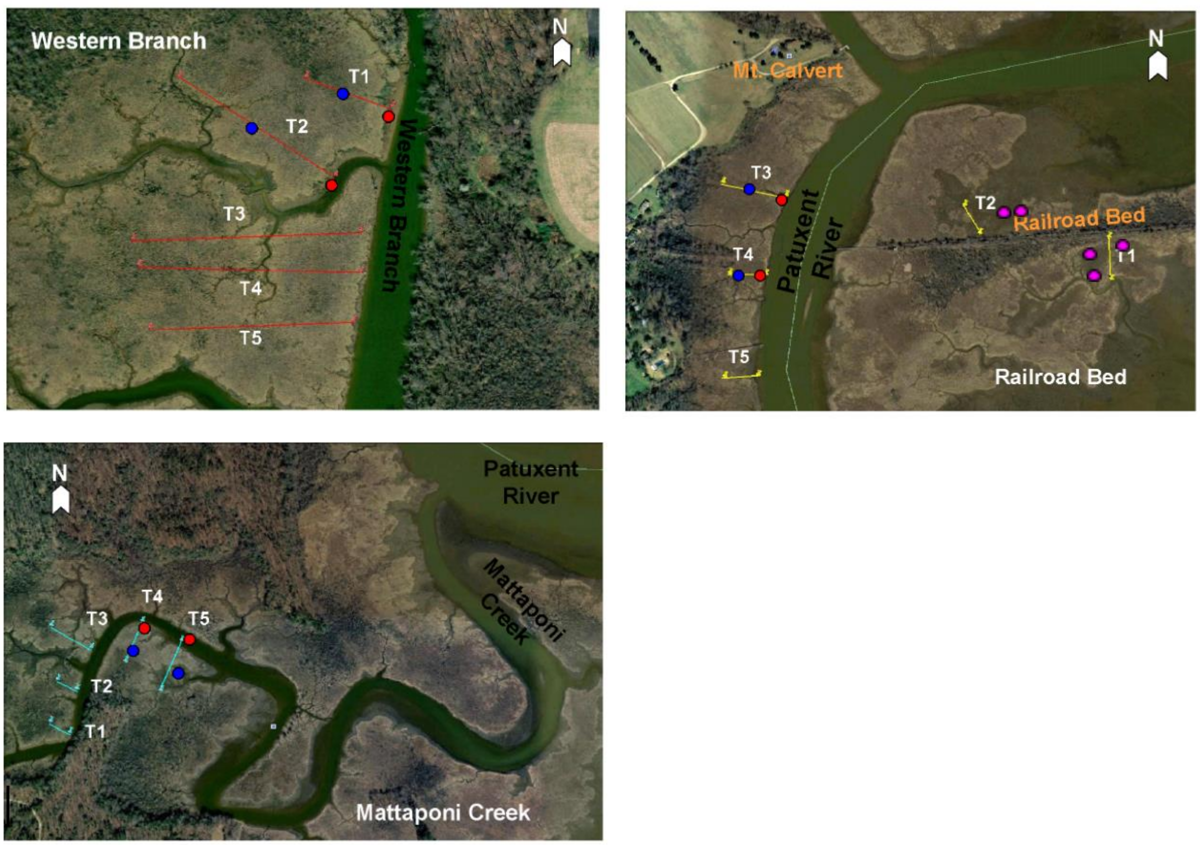


Figure A2.6. Location of emergent vegetation transects (lines) in the Western Branch, Railroad Bed, and Mattaponi Creek areas. Dots represent the location of SET stations along vegetation transects. The red dots correspond to SETs located in the low marsh zone and the blue dots correspond to SETs located in the high marsh zone; pink dots correspond to five “legacy” SETs located within the Railroad Bed study area.

Table A2.2. GPS location of emergent vegetation transects of the three main Jug Bay study areas: Western Branch, Railroad Bed, and Mattaponi. Location is based on the location of the first plot of each transect.

Western Branch Transects			Mattaponi Creek Transects			Railroad Bed Transects		
	GPS location			GPS location			GPS location	
Transect	N	W	Transect	N	W	Transect	N	W
JPT1	38.79434	76.72070	MPT1	38.74412	76.70547	RRT1	38.78067	76.70814
JPT2	38.79383	76.72115	MPT2	38.74491	76.70539	RRT2	38.78152	76.71071
JPT3	38.79342	76.72095	MPT3	38.74568	76.70515	RRT3	38.78223	76.71459
JPT4	38.79312	76.72095	MPY4	38.74619	76.70411	RRT4	38.78076	76.71494
JPT5	38.79276	76.72101	MPT5	38.74582	76.70326			

Table A2.3. GPS location of SETs at the three main Jug Bay study areas: Western Branch, Railroad Bed, and Mattaponi.

Transect		GPS location	
		N	W
Western Branch SETs			
IPT1	Low marsh	38.79434	76.72070
	High marsh	38.79441	76.72092
IPT2	Low marsh	38.79383	76.72115
	High marsh	38.79411	76.72157
Mataponi Creek SETs			
MPT 1	Low marsh	38°46.874	76°42.484
	Low marsh	38°46.875	76°42.494
	High marsh	38°46.851	76°42.492
MPT 2	Low marsh	38°46.905	76°42.627
	Low marsh	38°46.914	76°42.636
MPT 4	Low marsh	38.74619	76.70411
	High marsh	38.74590	76.70425
MPT 5	Low marsh	38.74582	76.70326
	High marsh	38.74540	76.70337
Railroad Bed SETs			
RRT 3	Low marsh	38.78223	76.71459
	High marsh	38.78225	76.71491
RRT 4	Low marsh	38.78076	76.71494
	High marsh	38.78078	76.71519

Preliminary Survey Plan for Jug Bay

None of the published bench marks nearest to the reserve were recovered. They appear to have been destroyed during road widening and never reset. The nearest level line is therefore about 4.5 miles (7.25 km) away –to one group of primary control points. Other infrastructure components (SWMP/SET/vegetation stations) are even farther away from a published leveled line. Given these remote locations, we plan to establish NSRS connections at one deep rod SET mark in each of three study areas (Figure A1.6) via static GPS occupations. An additional two older pipe-based SET marks would be observed along either side of the railroad bed, bringing the total to five SET marks observed simultaneously with GPS. Since four deep rod SET stations exist within each area, one station in each area will serve as the Local Control Mark (LCM). Following the NGS procedures for connecting SET bench marks to the NSRS, we will install "Kendapters" with tribraches on each LCM, and place dual-frequency GPS antennas after measuring (with Leica DNA03 digital barcode level) or calculating the vertical offset from the top of the SET bench mark (the SET receiver) using calipers. The antennas will be hooked up to their respective receivers with external 12V automotive-type batteries and allowed to run for a period of ≥ five hours in the field. This procedure will be repeated on each of three separate days. During each of these three days, simultaneous GPS observations will be made on four nearby published control points, specifically CHELTENHAM_2, AE120, J18 and P132 (Figure A2.7). These simultaneous occupations will allow for the eventual use of OPUS-Projects to provide a network adjustment to the GPS observations. Reserve staff will assist with the deployment of GPS receivers and will ensure the safety of the equipment during each observation period.

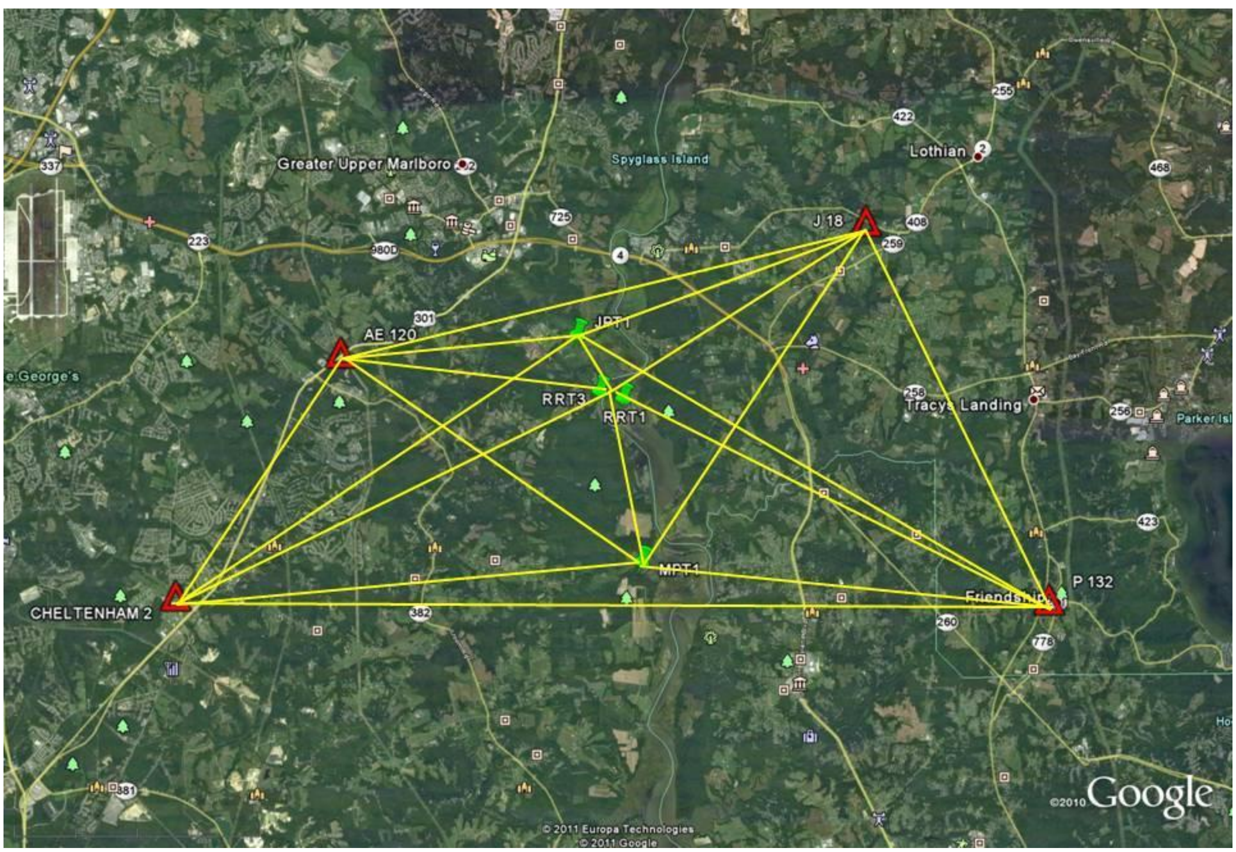


Figure A2.7. Map showing locations of four static GPS survey locations within Jug Bay, and four static GPS locations on published marks outside the reserve.

The four published marks have been recovered and appear to have adequate open skies. Obstruction diagrams and updated descriptions and photos will be made.

At the end of each of the three survey days, the GPS data collected during each ≥5- hour session will be downloaded, backed up, and submitted to OPUS for post-processing. After the survey, the operating characteristics of the nearby CORS will be evaluated, so correction to the set of chosen CORS can be made. Additionally, the data will be re-submitted once the precise orbits have been published. A weighted average of vertical and horizontal positions will be calculated for each LCM based on all OPUS solutions, using the inverse of peak-to-peak error as weighing.

Subsequent to the static GPS campaign, geodetic leveling (digital barcode leveling with Invar rods, Second-Order, Class II methods followed) will be used to transfer elevations from each LCM to the adjoining SET bench marks and SWMP water level recorder within each study area. Geodetic leveling will also be used to connect the local network of concrete post marks on the Anne Arundel side of Jug Bay, where the NGS commemorative mark is located. The geodetic leveling will be conducted in collaboration with NGS, which will provide hands-on training in the field.

Real-Time Kinematic (RTK) GPS will be used to transfer elevations from each LCM to the entire length of each permanent vegetation transect. As needed, RTK will also be used to generate Digital Elevation Models (DEM) of characteristic portions of each study area. Separate RTK deployments will be made within each study area in Jug Bay. For each deployment, a base station will be established atop the LCM. The position of the base will be checked with respect to the average position from the static GPS campaign. The rover will then be placed atop a local SET monument, using the leveled elevation difference as a check on elevation. Once the checks have been successfully verified, the rover will be deployed on the marsh surface along each vegetation transect. Once each area has been thus surveyed, the static observations from the base will be submitted to OPUS-RS as a check on the position.

The static GPS campaign will begin around April 15 and is expected to last until April 19. Digital barcode leveling within the individual study areas is expected to take place from about April 20–22. The RTK campaign is expected to take place from April 25–27.

APPENDIX 3: SAMPLE LOG SHEET FOR DIGITAL BARCODE LEVELING

(geodesy.noaa.gov/heightmod/Leveling/Forms/BackupRecordingSheetv2.pdf)

PRECISE DIGITAL LEVELING – BACKUP RECORDING SHEET

LINE	PROJECT	FILENAME	PAGE
L-			OF

CODE 1 – BEGINNING OF DAY OR CHANGE IN OBSERVER OR EQUIPMENT

INFO 1 DATE (MMDDYY)	**INFO 2** OBSERVER #	OBSERVER INITIALS	**INFO 3** INST TYPE	**INFO 4** TEMP CODE

CODE 2 – EQUIPMENT USED

INFO 1 INST S/N	**INFO 2** COLLIMATION "	ROD CODE	**INFO 3** ROD 1 S/N	**INFO 4** ROD 2 S/N

CODE 11 – BEGINNING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**DIR** F / B

CODE 99 – ENDING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**INFO 4** W / S

SECTION OBSERVATION INFORMATION

TOTAL SETUPS	TOTAL DISTANCE (KM)	ACCUMULATED IMBALANCE (M)	ELEVATION DIFFERENCE

CODE 11 – BEGINNING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**DIR** F / B

CODE 99 – ENDING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**INFO 4** W / S

SECTION OBSERVATION INFORMATION

TOTAL SETUPS	TOTAL DISTANCE (KM)	ACCUMULATED IMBALANCE (M)	ELEVATION DIFFERENCE

CODE 11 – BEGINNING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**DIR** F / B

CODE 99 – ENDING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**INFO 4** W / S

SECTION OBSERVATION INFORMATION

TOTAL SETUPS	TOTAL DISTANCE (KM)	ACCUMULATED IMBALANCE (M)	ELEVATION DIFFERENCE

CODE 11 – BEGINNING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**DIR** F / B

CODE 99 – ENDING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**INFO 4** W / S

SECTION OBSERVATION INFORMATION

TOTAL SETUPS	TOTAL DISTANCE (KM)	ACCUMULATED IMBALANCE (M)	ELEVATION DIFFERENCE

CODE 11 – BEGINNING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**DIR** F / B

CODE 99 – ENDING SECTION INFORMATION

SPSN #	BENCH MARK STAMPING	**INFO 1** TIME	**INFO 2** ROD/MK	**INFO 3** TEMP	**INFO 4** W / S

SECTION OBSERVATION INFORMATION

TOTAL SETUPS	TOTAL DISTANCE (KM)	ACCUMULATED IMBALANCE (M)	ELEVATION DIFFERENCE