User’s Guide to Vertical Control and Geodetic Leveling for CO-OPS Observing Systems

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A CO-OPS Vertical Control Committee was created in 2017 to update, with current practices, the *1984 Users Guide for Installation of Bench Marks*. The committee met on a bi-weekly basis to document current practices and procedures for installing and surveying of bench marks. Through many months of collaborative efforts with National Geospatial Survey, the committee provided their input into this guide. The committee's participation in writing this document is greatly appreciated.

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Chapter 1 – Preface

1.1 Introduction

The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) is responsible for the management of a national water level measurement program. The foundation of this program is the operation and maintenance of the National Water Level Observation Network (NWLON), a network of approximately 200 continuously operating data collection stations in the U.S. coastal oceans, the Great Lakes and connecting waterways, and in U.S. Trust Territories and Possessions. The data and information from this network represent one of the most unique and valuable geophysical data sets available. The network provides for the determination and maintenance of vertical reference datums used for surveying and mapping, dredging, coastal construction and restoration, water level regulation, marine boundary determinations, tide prediction, and determination of long-term water level variations (e.g. trends). The station platforms and telemetered data are used to support major U.S. Government programs such as the NWS Tsunami Warning System, the NWS storm surge monitoring programs, the U.S. Army Corps of Engineers (USACE) national dredging program, the USACE/Canadian Great Lakes regulation program, and the NOAA Climate and Global Change Program.

This guide provides references to several National Geodetic Survey (NGS) documents related to the standard methodologies and tools used to derive geodetic elevations using differential and trigonometric leveling. These references do not supersede the information in this document as this document is specifically written to determine and monitor water level sensor and bench mark network elevations for the determination of tidal datums and subsequently the sea level trend.

1.2 Purpose

Vertical control at a water level station enables the establishment and continuity of tidal and water level datums over time, regardless of any change in sensors. This is accomplished through an array of locally established permanent bench marks which are the foundation of a water level station's vertical control network. Through this established network, differential and trigonometric geodetic leveling can be used to establish precise and accurate height differences between each bench mark and each sensor. Therefore, datums can be maintained at the tide station over time even in the event that the sensors or bench marks are destroyed by coastal storms or other phenomena. The purpose of this document is to provide guidance and list specifications for monitoring and documenting the associated metadata pertaining to the stability of the water level sensor(s) and the associated bench mark network via differential geodetic and trigonometric leveling and/or static GPS observations. Documenting the stability of the water level sensor(s) and of the bench mark network, provides great confidence in the accuracy of the data collected and that it is free of bias via vertical land motion or movement from the structure of which the water level sensor is mounted on. Therefore, frequent leveling to the bench mark network and water level sensor(s) aids in documenting vertical land motion as well as the movement of the water level sensor(s).

A known source of land movement is regional vertical land motion. This motion is attributed to phenomena such as glacial isostatic adjustment, uplift, subsidence, and erosion. Through differential leveling of networked bench marks, CO-OPS intends to account for vertical land motion and remove its influence from the water level data. Furthermore, through differential leveling, CO-OPS will derive and maintain a local datum (station datum) to reference water level and meteorological sensor heights. Through this guide, important concepts and instructions are detailed to maintain a local datum.

1.3 Tidal Epochs and Reference Epochs

Tides are caused by the gravitational pull of the Moon and the Sun and can be influenced by a range of factors including bathymetry, hydrodynamics, and local oceanographic and meteorological conditions. Tides vary over a range of time scales from days to thousands of years due to cyclical changes in the Earth, Moon, and Sun system. The longest and most dominant such cycle that is important to consider for tidal prediction is the 18.6 lunar nodal cycle caused by changes in the Moon's orbit relative to the Earth (Parker, 2007). The slight changes in the geometries of these orbits at various phases of this cycle affect the gravitational force, the primary driver of the tides. This 18.6 year cycle necessitates the use of a tidal epoch or the specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums (Gill and Shultz, 2001). Standardization of these tidal datums is necessary because of the periodic and apparent secular trends in sea level. The National Tidal Datum Epoch is generally considered for revision every 20-25 years and the present Tidal Datum Epoch is 1983 - 2001. Tidal datums in certain regions with anomalous relative sea level change (Alaska, Gulf of Mexico) are calculated every 5 years using a modified procedure for tidal datum computation (Gill et al., 2014).

As an exception to the NTDE, the Great Lakes relies on the establishment of a reference epochs using a combination of water level observations and survey measurements gathered by efforts of both the United States and Canada. These reference epochs consist of 7-year observation periods and form the basis of the International Great Lakes Datum (IGLD) for specific years. The IGLD has been updated in the years of 1955 and 1985, consisting of observations performed between 1952-1958 and 1982-1988 respectively. Water level stations established in the Great Lakes are part of the basis for establishment of those datums (Coordinating Committee on Great Lakes Basic Hydraulic & Hydrologic Data, 2017).

1.4 Datums

A datum references a plane from which heights or depths are realized. A tidal datum is a standard elevation defined by a certain phase of the tide at a particular location. Tidal datums are used as references to measure local water levels and should not be extended into areas having differing oceanographic characteristics without substantiating measurements. Some examples of water level datums are Mean Lower Low Water (MLLW), Mean Sea Level (MSL), and Mean High Water (MHW) (see Parker, 2007 and Gill and Schultz, 2001). Water level observations and survey measurements are additionally used to form the basis of the IGLD for the Great Lakes water level stations. Due to the variability of water level datums (see tidal epoch), CO-OPS uses a Site Datum or Station Datum (SD) at water level stations, which is a local and arbitrary reference plane, but does not change with water level datum updates. This is also often referred to as a reference zero. For Great Lakes stations, the reference plane is defined as the current IGLD value. In order that datums may be recovered when needed, they are referenced to fixed and stable points on land called bench marks. Tidal datums are also the basis for establishing privately owned land, state owned land, territorial sea, exclusive economic zone, and high seas boundaries (e.g. Gill and Schultz, 2001).

For locations with less than 19 years of data, a comparison of simultaneous observations is made with a primary control tide station, which is a station that has established datums over the current 19 year period. This allows derivation of the equivalent of a 19 year datum (NOS 2000; Marmer, 1951). The shorter the time period of observations compared to a 19 year time period or tidal epoch, the greater the uncertainty in the tidal datum determination (Swanson, 1974). Full definitions of all terms relating to tidal datums can be found in the NOS Tide and Current Glossary.

1.5 Primary Water Level Sensors

CO-OPS installs, operates, and maintains water level stations consisting of primary, redundant, and/or backup water level sensors and additionally a network of bench marks. Some stations also collect meteorological data. CO-OPS incorporates at least one of the five approved water level sensor technologies at each stations. The primary water level sensors are the Aquatrak, ParoScientific sensor (in a single or dual orifice set up), Shaft Angle Encoders (SAE), and the Microwave (MWWL) Radar sensor. Each of these sensors have an identified sensor leveling point that must be included in each leveling survey. For the MWWL sensor when installed on elevated platforms or CO-OPS Single Pile Instrumentation Platforms (SPIPs), it is necessary to establish a sensor leveling point that can be included in the leveling survey. For the ParoScientific sensor, the sensor leveling point must be established vertically above the orifice outlet (described as the orifice zero in this document) to facilitate an exact measurement from the sensor leveling point to the orifice zero. The same sensor leveling point can be used for multiple ParoScientific sensors provided they are all mounted vertically below the leveling point. This measurement must be taken using a National Institute of Standards and Technology (NIST) approved steel-tape measure with millimeter granulations. For MWWL sensors on elevated platforms or SPIPs, a steel-taped measurement from the sensor leveling point to the sensor mounting plate is required. Section *2.7 Temporary Bench Marks* provides more information on leveling to the sensor leveling point per sensor type.

1.6 Bench Mark Networks

All water level stations require a network of bench marks. The number of bench marks per network depends on the purpose of the stations. Currently all CO-OPS long-term stations to include NWLON stations require a network of ten bench marks with at least three of the marks having stability class B or higher. Short-term stations (i.e. stations with a defined operational cycle) require a minimum of five bench marks of variable stability class, however, at least one mark should be class B or higher (see Section 2.2 Types of Bench Marks). Bench mark networks containing class B or higher bench marks should maintain stability over time and have a better chance of surviving severe storm events, or other environmental disturbances

Chapter 2 Bench Marks provides more information and background on the requirements related to bench marks, the infrastructure required to set the different types of bench marks, and best practices when establishing and performing work on marks within a network. *Chapter 3 Leveling* provides the requirements for performing digital and optical leveling at water level stations. The water level station bench mark and leveling documentation requirements are also noted in this chapter along with additional reference documents that provide detailed information and requirements. Chapter 4 mentions the requirements for static geodetic observations and provides additional references for more detailed requirements.

Chapter 2 - Bench Marks

2.1 Definition

Bench marks are long-lasting, fixed points of reference used to observe vertical stability. They consist of a physically identifiable marker which can be recovered and surveyed on a recurring basis. A bench mark's primary purpose is to hold as a stable point which can serve as a point of reference to one or more vertical datums. Through surveying and measuring points of interest relative to a bench mark, elevations of those points can be determined (*NOAA Manual NOS NGS 1* 1978). When surveying is done on a recurring basis, vertical control can be established as bench marks and associated points of interest are monitored for movement.

There are a variety of objects used to represent a bench mark. These objects and the surrounding infrastructure are described later in this chapter. Most notably among the objects used are brass disks stamped with the agency or organization responsible for setting the mark. Other objects include metal rods, bolts, chiseled marks, and stone monuments. The key feature of the mark is that it is capable of being repeatedly and consistently measured while being sufficiently robust to be considered a permanent fixture.

The bench marks must be established in a stable surrounding infrastructure. The overall monumentation refers to both the underlying infrastructure and the disk itself. When set, the bench mark contains the referenced elevation by a surface, line, or point on whatever object is denoted as the mark. Separate from the physical object used as the mark, the monument associated with a bench mark refers to the surrounding infrastructure. The purpose of the monument is to establish the permanence and robustness of the mark to ensure it does not move. A bench mark is considered permanent unless designated as a temporary bench mark (TBM). Precautions should be taken to ensure bench marks are long-lasting. They are expected to hold a stable elevation and are expected to not be readily disturbed by factors such as construction, demolition, or vandalism. However, bench marks themselves are not immune to weathering and other factors.

2.2 Types of Bench Marks

The most common type of bench mark is a survey disk. The standard bench mark used by CO-OPS is a 3 5/8 in. (9.21 cm) diameter brass disk with a stem about 3 in. (7.62 cm) long. The disk contains the inscription, or engraving, such as NATIONAL OCEAN SERVICE together with other individual identifying information. Numerous bench marks of predecessor organizations to NOS, or parts of other organizations absorbed into NOS, still bear the inscriptions, U.S. COAST & GEODETIC SURVEY, U.S. LAKE SURVEY, CORPS OF ENGINEERS, and U.S. ENGINEER OFFICE. The typical engraving has not changed format. For comparison, a newer mark following the current format is presented in Figure 2.1 and an older mark is presented in Figure 2.2. Another common type of mark is a stainless steel rod mark. These marks are rods driven deep into the ground to refusal or substantial resistance.

Figure 2.1: Photo of a tidal bench mark disk located at the tidal station 8594900 Washington, DC. Note the organization stamping, National Ocean Service, and the bench mark naming convention, 4900 P 2016.

Figure 2.2: The photo depicts an older National Ocean Survey bench mark set for the tidal station 9453220 Yakutat, AK. While originally established in 1977, the format of the stamping is largely identical to present methods.

Bench marks utilized by CO-OPS are fairly standardized, however, the foundation of where each mark is set varies significantly. The surrounding foundation is key to assessing potential vertical stability of a mark. As a result, bench marks are classified into categories of expected stability based on where they are monumented. This classification system is a risk assessment scale based on mark monumentation which assesses a mark's ability to hold stable elevation after it is set. Marks are subjected to numerous sources of potential instability, both on the near-surface (above 15 m) and sub-surface levels (below 15 m) (*NOAA Manual NOS NGS 1* 1978). Mark classifications are ordered by letter (from A to D) and are as follows:

Table 2.1: Stability classes and their general definitions: This reflects anticipated stability, not the actual stability of the mark. This is used as a tool to manage and assess risks to a network by grading stability. More information can be found in the *Geodetic Control Descriptive Data - Appendix P* (*Input Formats and Specifications of the National Geodetic Survey Data Base* 2016).

Stability Class	Anticipated Stability
Class A	Most reliable, expected to hold elevation well
Class B	Will probably hold elevations well
Class C	May hold elevation well but subject to surface ground movements
Class D	Unknown or questionable stability.

Class A bench marks are expected to hold elevations well and are of the most reliable nature. They are typically installed in bedrock, bedrock outcrops, or structures with very deep foundations or bedrock foundations. Class B bench marks are anticipated to likely hold elevation fairly well. These marks typically consist of stainless steel rod marks driven deep into the ground to refusal and marks installed on large concrete footings/foundations. Class C bench marks may hold elevations well but are commonly subjected to surface ground movements. These marks are usually installed in concrete monuments or similar structures. Class D bench marks are marks of unknown or questionable stability. These marks are installed in curbs, sidewalks, pavements, porches, and small seawalls. They should generally **not** be used as these structures may not hold stable elevation. These marks should **not** be set as they are of limited utility. These structures move due to soil, moisture, and frost action. Additionally, they are expected have a relatively short life expectancy.

This stability classification system is used when assessing station risks, assigning a Primary Bench Mark (PBM), and assigning a bench mark to be considered for Global Positioning System (GPS) observations. The station bench mark selected for GPS observations shall be of stability code A or B, and in the rare case of stability C only when NGS has previously acquired static GPS observations on that mark. GPS observations on the PBM are preferred (if the PBM has either stability code A or B) and if it is suitable for satellite observations.

2.3 Class A Bench Marks

2.3.1 Bench Mark Disks Set in Bedrock

Bench marks disks set in outcrops of bedrock (not boulders) are the most stable and among the easiest bench marks to set. However, a bedrock foundation is not always available in a readily accessible location. An example is shown below in Figure 2.3. If bedrock or bedrock outcrops are available and near a station, they make an ideal stable location in which to set a mark.

Figure 2.3: Example of a survey disk set in an outcrop (Class A stability).

To set a bench mark of this type, a 7/8 in. (2.22 cm) diameter, 3 1/4 (8.26 cm) deep hole is drilled into the rock to accommodate the stem of the disk. This is done with a powered rock drill with the countersink bit as part of the drill bit or by hand using a star drill and hammer. The rock is then wetted to prevent absorption of water from the cement paste. Cement paste is placed in the hole and on the underside of the disk to prevent air from becoming trapped in the concave portion. The cement paste should have a stiff consistency but still be workable. The pre-stamped disk is then tapped into the drill hole and made level using a small line level. The uppermost convex side of the disk should protrude from the rock. The excess paste is removed, and the mark is cleaned by rubbing dry cement powder over the finished mark. In hot weather, a wet cloth placed on top of the disk will help prevent the cement paste from drying too fast and cracking.

2.3.2 Bench Marks in Large Structures with Bedrock Foundations

Disks set in large structures typically only meet Class B stability. However, exceptions are made if those structures have bedrock foundations. If a bench mark is set into a structure with bedrock foundations, it may be classified as Class A stability. The most common example of this would be a large multi-story building (greater than three stories) established on a bedrock base.

Setting these marks is largely identical to establishing a mark in bedrock (see *2.3.1 Bench Mark Disks set in Bedrock)*. However, see section *2.4.3 Bench Marks in Large Man-Made Structures* for further details on what constitutes a large structure, setting information, and additional details.

2.4 Class B Bench Marks

2.4.1 Stainless Steel Deep Rod Bench Marks (3D)

These bench marks are commonly referred to as deep rod marks. They consist of a 9/16 in. (1.43 cm) diameter stainless steel rod driven vertically into the ground. Historically, a specially adapted pre-stamped disk was crimped to the top of the rod. Current installations use the rounder top of the rod as the datum point. A center-punch is used to facilitate a GPS range pole if the mark is to be used for GPS observations. The mark is protected by a 5 in. thick (12.7 cm) PVC pipe that often extends below ground by approximately 3 feet (0.9 m). The rod and PVC pipe are typically surrounded by a concrete kickblock. Deep rod bench marks are known to provide very good stability. They are second only to bench marks set in bedrock and large structures with deep foundations.

Figure 2.4: Example of a deep rod mark (Class B stability). Logo cap is shown open, to reveal uppermost section of rod mark, greased/finned sleeve, and sand-filled PVC pipe.

The rods used are segmented sections joined tightly with internal threaded couplers and pipe compound. Each rod segment is either 4 ft (1.2 m) or 5 ft (1.5 m) long. The rods are driven deep into the ground using a 56 lb or heavier impact hammer (or jackhammer) or a 30 lb manual drop hammer having a minimum drop height of 2 ft (0.6 m). Using these tools, the rods are driven to refusal or substantial resistance. Substantial resistance is defined as less than 1 ft (0.3 m) of movement per minute.

To set a rod mark, it is important to identify the proposed general bench mark location and file a dig-locate ticket with local utility companies so that local utilities can identify their underground services before driving a rod. A short section of rod (securely threaded on top) is used as a driving head. A clockwise torque of ½ turn every 5 ft (1.5 m) is applied, by pipe wrench, as the rod is driven into the ground. This is to prevent loosening of threaded couplers. A pointed end section of rod facilities the driving of the rod. The use of a greased sleeve is recommend to ensure vertical stability in frost-prone areas. The use of a finned grease sleeve can also ensure horizontal stability (Floyd 1978). See section *2.10 Frost Penetration* for further information.

2.4.2 Thermopile Bench Marks

In the Arctic and areas of extreme cold, "Thermopile" marks are often used as an added way to preserve the vertical stability of rod marks. These marks consist of a 10 ft (3.0 m) sealed metal tube, pressurized with nitrogen. The nitrogen gas conducts cold from the bottom of the tube, which keeps soil surrounding the pipe frozen. This prevents frost heave. As a result, these marks have proven to be stable in permafrost and should be considered if setting marks in the Arctic or similar environments. To set these marks, a large auger is needed, similar to what is needed to install a power pole.

2.4.3 Bench Mark Disks in Large Man-Made Structures

Buildings generally over three stories high, towers, bridge abutments, and other large structures tend to be suitable for establishing bench marks. These structures, as a group, tend to be the next most stable locations for bench marks. Typically, bench marks set in large structures are classified as Class B and are known to provide good stability. However, disks set in large structures with deep foundations or bedrock foundations are to be classified as Class A. These marks are useful to establish in areas of more urban development, where acceptable locations to install new bench marks are often quite limited. However, as a note, most buildings near CO-OPS water level stations may not have foundations that would meet these qualifications to be considered the highest class of stability. Most structures would largely fall under Class B stability.

Setting these marks is largely identical to establishing a mark in bedrock (see *2.3 Bench Mark Disks set in Bedrock)*. However, additional precautions need to be taken to avoid damaging the surrounding structure. Marks must be set neatly as to not deface the structure. Additionally, permissions need to be obtained to establish these marks from the land owners. Permission will usually be granted for the installation of a disk when its use is explained to the owner or appropriate authority.

As a note, most new buildings will settle. The rate of settlement decreases with time. Most of the settlement occurs in the first few years; therefore, **marks are never to be set in structures less than 5 years old**. In areas with expansive soils, most surface structures (even large buildings with shallow foundations) are subject to heaving and settling.

2.5 Class C Bench Marks

2.5.1 Concrete Monuments

Concrete monuments have historically been among the most frequently used supporting monuments. Despite being more stable than marks set in other concrete fixtures (e.g. curbs, sidewalks, pavements, porches, etc.), these marks can show some signs of movement due to frost heave, expansive soils, and their own weight causing the monument to settle *(NOAA Manual NOS NGS 1, 1978)*. As a result, CO-OPS does not tend to set these marks. These marks are seldomly installed today, however, those that have a history of remaining stable over time continue to be used. If the concrete monuments are installed in well-drained, coarse-grained soils, they should hold stability *(NOAA Manual NOS NGS 1, 1978).* **The monuments, if used, must be at least 2 weeks old before leveling in order to allow time for initial settlement.** This is another limiting factor when attempting to use these marks, as that settlement time must be considered when planning work.

To set these marks, concrete is placed in a 1ft (0.3 m) diameter hole about 3-4 ft (~1 m) deep. If frost action requires a deeper foundation, the hole may be deeper (see section on *2.10 Frost Penetration*). A bell-shape is dug at the base of the hole in order to reduce the possibility of heaving or settling. The monument should be formed at the top and free from projections. See Figure 2.5 below for an idealized cross section of a mark of this type.

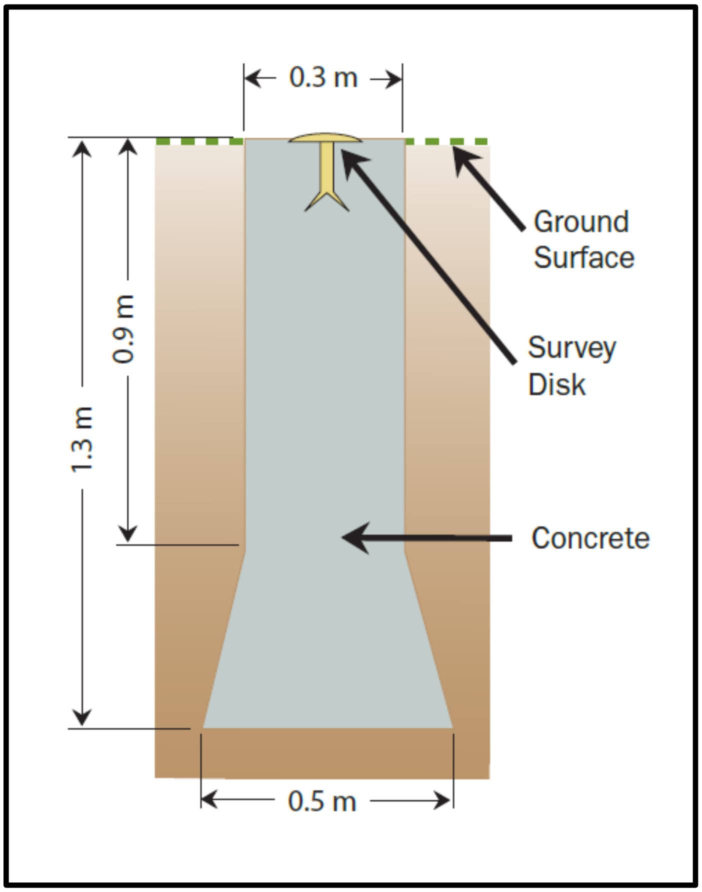


Figure 2.5: Idealized cross-section of a concrete monument. (Class C stability).

In order to ensure stability, the concrete used must be of a specific strength and durability. To produce mixture needed, a 1:3:2 (one part cement, three parts sand, and two parts gravel) shall be used. The mix should be stiff and rodded in place. The sand and gravel must be clean and sound. Ready-mix concrete sold in bags generally has a poor aggregate gradation and low cement content. If ready-mix is used, extra sand and cement shall be added as needed. Concrete mixing water should be potable water. Seawater can be used, but it will cause a reduction in strength of about 20 percent. The reduction in strength can be offset to some degree by either increasing the cement content and/or reducing the seawater content. Strength of concrete is increased by decreasing the water content as much as workability allows. A water-cement ratio is the weight of water to the weight of cement used in a concrete mix. Water-cement ratios of 0.45 to 0.60 are more typically used. A lower ratio leads to higher strength and durability, but it may make the mix the difficult to work with and form. Full hydration and maximum strength is obtained at an ideal 0.45 water/cement ratio and is recommended.

Setting the mark itself into the concrete monument is nearly identical to the procedure in setting a bench mark in bedrock (see *2.3.1 Bench Mark Disks Set in Bedrock).*See figures 2.6 and 2.7 for the establishment of a concrete monument and final product.

Figure 2.6: Surveyor completing the establishment of a concrete post mark (Class C stability). Note the hand level, which was used to ensure that the top-most surface of the disk was free of obstruction, level to enable successful leveling measurements. Also note the presence of a witness post to assist in mark recovery.

Figure 2.7: Finished product of a slightly weathered brass survey disk set in concrete monument.

2.5.2 Bench Mark Disks on Pipes

This type of mark is made from prefabricated pipe or a section of 9/16 in. diameter metal rod with a disk on top and a base plate on the bottom (Figure 2.8). The pipe is set in a hole backfilled with compacted earth. This type of bench mark is no longer set by CO-OPS. However, an existing bench mark on a pipe can still be used for leveling purposes.

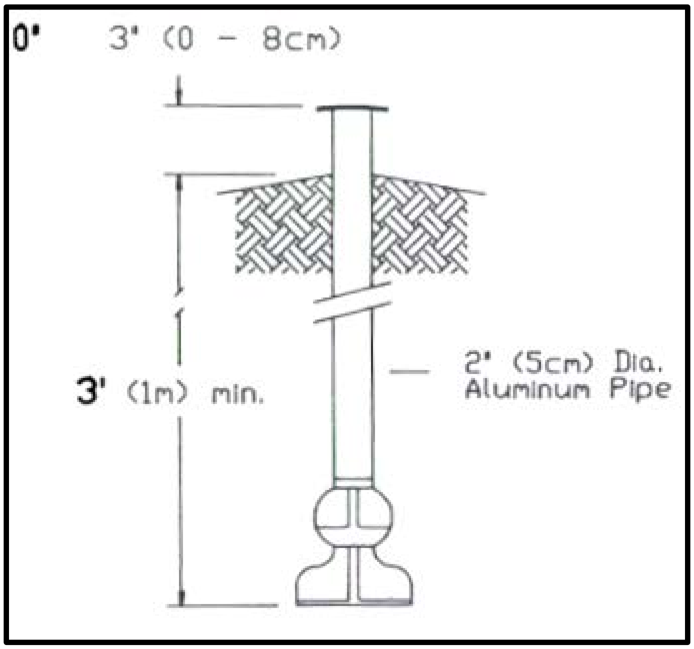


Figure 2.8: Sample of a bench mark disk on an aluminum pipe. Note the bench mark disk set on the top of the structure.

2.5.3 Bench Mark Disks set in Medium Structures or Small Buildings

Many marks that CO-OPS uses are established in medium-sized structures that are not as large as a multi-story buildings, bridge abutments, and towers. Examples of medium sized structures include flag pole bases, light pole bases, box culverts, small buildings (typically less than three stories), concrete headwalls, retaining walls, etc. **These structures do not include sidewalks or other pavements. Sidewalks and pavements are considered Class D stability marks.**

The method for installing bench marks in these structure is identical to the procedure listed in 2.3.1 *Bench Mark Disks Set in Bedrock.* Additionally, the same precautions of acquiring the necessary permissions and taking care not to deface the structure from *2.4.3 Bench Mark Disks in Large Man-Made Structures* apply to these structures as well.

2.6 Class D Bench Marks

CO-OPS does not set Class D bench marks as these marks are assumed to have questionable or unknown stability. Usage of these bench marks constitutes a risk to a bench mark network due to the potential instabilities these marks may introduce. These marks have been included in some station bench mark networks and some marks have appeared stable over time. The stability classification system does not reflect individual mark stability as it is a risk assessment tool. Some Class D marks still in use have shown evidence of stability. When taken as a whole, on average these marks do not meet stability requirements for CO-OPS usage. Examples of these marks include disks set into sidewalks, pavements, light structures, clay tile pipes, and others. Usage of these marks is highly discouraged when adding a mark to an existing bench mark network or when establishing a new bench mark network.

2.7 Temporary Bench Marks

Temporary bench marks (TBMs) are considered non-permanent marks that are used to transfer and reference elevations per leveling run. TBMs are not intended to maintain its elevation or structural integrity. They are typically less robust than a normal bench mark and are not to be used for historical elevation references. Many TBMs are leveled on a routine basis, much like individual bench marks. However, they are not considered when assessing the overall stability of a bench mark network.

Often times, TBMs are a point which can be reused and easily accessed during a single leveling run. The mark itself still must be consistently and repeatedly measured, however, there is no requirement that this must be permanent or maintain stability over time. Often times, a spike or nail is considered adequate to be considered a TBM. Additionally, CO-OPS considers the level point of a water level sensor to be a TBM. **A TBM is used to reference and transfer elevations only.** Certain types of TBMs are listed in subsequent subsections.

2.7.1 Sensor Leveling Point

The sensor leveling point is the point on a water level sensor that connects the sensor to the bench mark network via geodetic leveling. This connection to the sensor is required to transfer the water level datums derived from sensor observations to the entire bench mark network. The leveling point differs depending on the water level sensor being used and where the sensor zero is located. The sensor zero describes the point from which the water level measurement starts. This is the key point that needs to be related to the bench mark network. In order to accomplish this, an offset is often supplied by the sensor manufacturer and validated in labs by CO-OPS Engineering Division. This relates the sensor leveling point to the sensor zero, thus, allowing the connection of sensor observations to the bench mark network. Electric tape gauges (ETG) are covered later on in section *2.7.3 Electric Tape Gauge*. Further information on sensor leveling points and sensor zeroes is available in the *Standing Project Instructions for Coastal and Great Lakes Water Level Stations* (*Standing Project Instructions for Coastal and Great Lakes Water Level Stations* 2017).

The point that is to be leveled each year depends on the sensor involved. In the case of an Aquatrak sensor, the leveling point rests on the top edge of metal collar. This is accessible after the removal of the head of the sensor as depicted in Figure 2.9. For MWWL sensors, the leveling point is quite similar as it is the top edge of the geodetic leveling collar. The leveling point is inscribed on the collar as a triangle as depicted in Figure 2.10.

Figure 2.9: The photo depicts an Aquatrak water level sensor and its associated leveling point. In order to access the leveling point, the cap and head must be removed from the sensor setup depicted on the left. After removal, the top edge of the collar should be accessible for leveling.

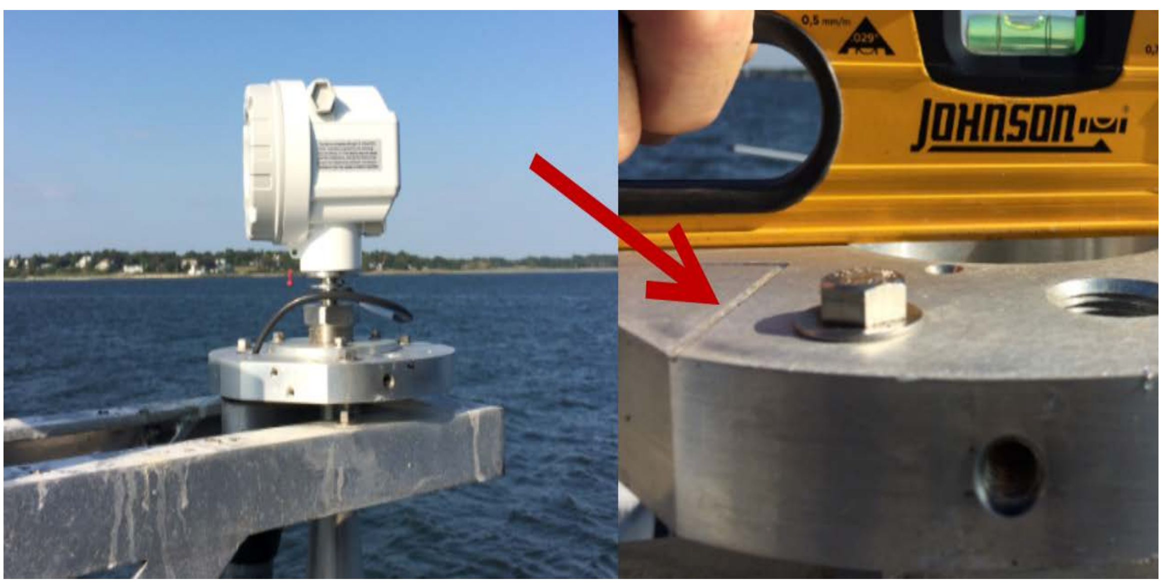


Figure 2.10: The photo depicts the sensor leveling point for a MWWL sensor represented by the inscribed triangle.

ParoScientific pressure sensors are rather different when compared to both Aquatrak and MWWL sensors due to operating underwater. As a result, the sensor zero is often only accessible via diving. A bolt or another object that is vertically in line with the sensor and plumb is often designated as the sensor leveling point. This is often interchangeably referred to as an orifice leveling point for this specific type of sensor. Figure 2.11 shows an example station where two orifice leveling points are represented by the top of a bolted boards. The same leveling point can be used for multiple ParoScientific sensors if they are both vertically below the leveling point. In order to relate the orifice leveling point to the sensor zero, a tapedown measurement must be performed. The steel tape must be held plumb to prevent error. This is why the leveling point established must be vertically in line with the orifice. Tapedown measurements should be performed whenever levels are performed as vertical movement may not be consistent between the orifice leveling point the sensor zero. It is necessary to ensure and validate sensor stability.

For a Paros sensor with a V-notch orifice (as depicted 2.12), the sensor zero is the vertex of the V-notch located at the bottom of the pipe orifice. The V-notch helps prevent a meniscus from forming at the bottom of the orifice. For a Paros sensor with an orifice consisting of parallel plates, the bottom of the upper parallel plate is to be used for the sensor leveling point. A parallel plate type orifice is presented Figure 2.13. A calibrated steel tape measurement must be made between the sensor zero and the orifice leveling point in order to relate the sensor zero to the bench mark network.

Figure 2.11: The photo depicts a host of water level sensors located at 1619910 Sand Island, Midway. Two ParoScientific pressure sensors are located underwater. The orifice leveling points (circled in blue) are the tops of two wooden boards directly above where the sensors are located.

Figure 2.12: The photo depicts a tapedown measurement to a ParoScientific pressure sensor with a with a V-notch orifice. In this case, the notch is readily visible. However, the amount of growth and biofouling can often make the notch rather difficult to see while in the water. The top vertex of the notch is the leveling point.

Figure 2.13: The photo depicts a removed parallel plate orifice that would be used with ParoScientific pressure sensor. The bottom of the upper parallel plate is the leveling point of the orifice. As can be seen, the orifices used are subject to corrosion and require inspection.

The sensor leveling point itself is treated as a TBM, including all instances described previously. It confirms the validity of the data being collected from the sensor by verifying that it is still vertically stable. **It is imperative that same point is leveled to per year in order to accurately assess sensor stability.** Failure to consistently level to that same reference point makes it impossible to assess the movement of that sensor per year. In the case of ParoScientific sensors, it is imperative that the tapedown measurement is also performed that connects the sensor leveling point to the sensor zero. The movement between the sensor leveling point and sensor zero may differ, therefore, it is necessary to perform that measurement to accurately assess the stability and movement of the sensor itself.

As a note, there have been certain configurations of ParoScientific sensors in which the orifice, sensor, and leveling point have all been attached as one assembly. This setup is not typically the case encountered, however, instances such as this may not require repeated tapedown measurements. These cases will require review by CO-OPS Engineering Division. The relationship between the orifice zero point and the leveling point is still needed for these sensors.

2.7.2 Staff

A staff is a graduated board secured to a pile, wharf, pier, etc., near the water level sensor. The staff zero is the zero of the level scale attached to the bottom of the staff. The staff stop, generally located at the top of the staff, is a convenient point installed for leveling and measurement. It is used to connect the staff to the zero point of a water level sensor. It is essentially considered the leveling point of the staff. The stop itself is a 1 1/2-in. by 1 1/2-in. by 3/8-in. (3.81 cm by 3.81 cm by 0.95 cm) brass or galvanized angle with a round head bolt (as a definite high point). The height of the reference above staff zero is measured with a steel tape, graduated in 0.01-ft. (0.3 cm) intervals, and estimated to the nearest 0.001 ft (0.03 cm). The rod stop on a portable staff is the staff stop on the support board.

A staff is used less often than in previous decades due to improvements in water level sensor technology and installation techniques. These improvements have allowed ease of access to a sensor leveling point for leveling purposes. In locations where adequate infrastructure is not available, a staff can be used to relate the sensor zero to a station bench mark network and associated local SD. This indirect method of leveling the sensor requires a series of staff to gauge comparison readings to derive the relationship between the staff and the water level sensor.

2.7.3 Electric Tape Gauge

At Great Lakes stations, the ETG is often used in lieu of a staff, where conditions make staff measurements impractical. At all permanent stations in the Great Lakes network, the ETG is used as the reference for checks of the primary and backup recording gauges. The sensor leveling point serves two purposes: to be connected to the bench mark network and serve as a point to read the tape to. The ETG is attached to a battery and voltage meter. When the bottom of the tape touches the surface of the water, current is produced. The tape is read at the leveling point and compared simultaneously with the primary sensor and/or backup sensor. In leveling to the reading mark of the ETG, a steel tape or specially designed short level rod is used. The position of the weighted end of the ETG shall be verified to ±0.001 ft (0.03 cm) and noted in the leveling record and station report. The weight should be pinned to the tape so that it cannot move in its sleeve.

Figure 2.14: On the left is an example of the typical ETG used at a Great Lakes water level station. ETGs are used at all permanent stations in the Great Lakes network as a reference to check the primary and backup water level sensors. The sensor leveling point is shown on the right.

2.7.4 Meteorological Standard Reference Marks (MET SRM)

Meteorological standard reference marks (MET SRMs) are used to define the surface or site elevation at the location where the meteorological sensors are located. Furthermore, the MET SRM is used to measure meteorological sensor elevations referenced to the MET SRM. On occasion, a MET SRM may be a permanent bench mark (that is installed up to 3 m (9.84 ft) from the meteorological sensors) as is depicted in Figure 2.15.

In most instances, however, the MET SRM is a temporary bench mark. Each station presents a unique situation for what can be defined as the MET SRM and to what datum to which it is measured. The mark itself can be a nail, bolt, spike, or other object. Figure 2.16 below presents a typical case. The main requirements for choosing a MET SRM are that it be directly below or within a reasonable distance of the meteorological sensors, and that it is on a flat surface (less than +/- 15 cm (~0.5 ft) elevation change between the tower/pole and the mark chosen (*Procedure to Establish a Meteorological Sensor Reference Mark and Measure Meteorological Sensor Heights* 2012).

Figure 2.15: An example of a MET SRM consisting of a permanent mark, not a TBM, at the base of a meteorological tower. The mark itself is a bench mark disk at 9075080 Mackinaw City, MI.

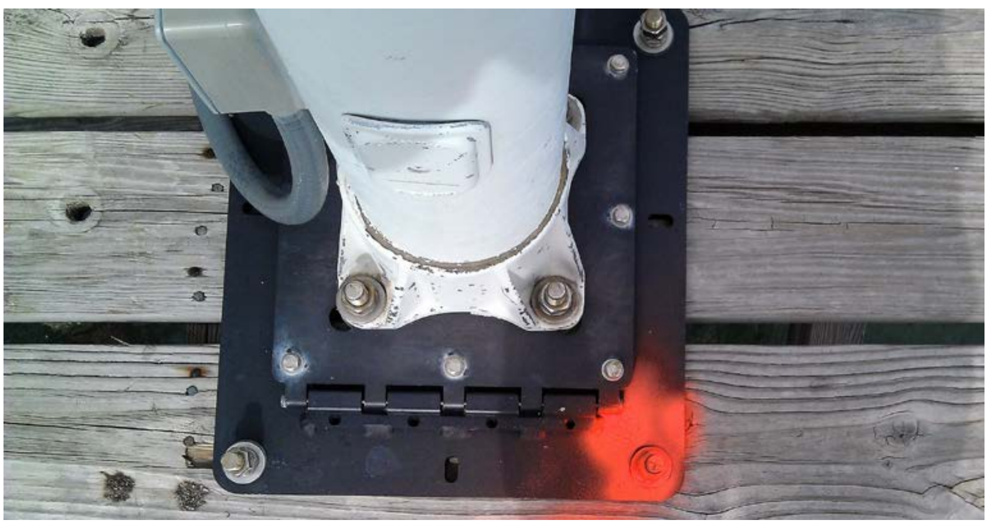


Figure 2.16: An example of a bolt (TBM) used as the MET SRM at 8723970 Vaca Key, FL. This is very common for many of CO-OPS meteorological sensors.

2.8 General Guidelines and Best Practices - Mark Placement

2.8.1 Spacing and Proximity Requirements

Bench marks should be distributed in the area around a station such that any expected localized event which might disturb a mark will not damage or destroy more than one mark in a network. Furthermore, well spaced marks ensure that vertical land motion detected is not inherent to a single structure or area. Properly spacing bench marks will allow the bench mark network to survive local or regional events such as extreme weather events, construction, or subsidence. To minimize likelihood of bench mark loss, no more than one mark should be set in a building foundation, on one owner's property, or on the same side of a street where road expansion could occur. Bench marks should be spaced at least 60 m (200 ft.) from each other, but no further than 1 km (0.6 mi.) apart. The Primary Bench Mark (PBM) shall be within 500 m (0.31 mi) of the station. To connect to the National Spatial Reference System (NSRS) via geodetic leveling, the National Geodetic Survey (NGS) requires bench mark separation of at least 500 m (0.5km). For additional information, refer to the Federal Geodetic Control Subcommittee (FGCS) specifications for geodetic leveling (*FGCS Specifications and Procedures to Incorporate Electronic Digital/Bar-Code Leveling Systems* 2004). As good practice, both the PBM and a second mark suitable as a backup PBM should be readily accessible to all marks. The PBM must be included in every level run, so this is for ease of leveling. The most stable mark in the bench mark network should be used as the PBM when possible. All bench marks should be within a radius of about 1.6 km (1 mi) from the station in order to keep leveling time to a minimum. A station location is generally determined by the positions of the primary and backup Data Collection Platform (DCP) that are installed in a tide house (gauge house).

2.8.2 Bench Marks in a Single Structure

Marks should **not** be set in the same structure whenever possible. An independent structure is a structure that is geologically independent from another structure, and one that is unlikely to be influenced by the same geologic or anthropogenic event. The main goal of this is to avoid events that would be detrimental to that single structure, which would in turn affect all marks located on that structure. For example, local construction, maintenance, or restriction of access could impact a single structure or access to that structure. This may result in the loss of any marks or the inability to access those marks located there. Additionally, events such as localized subsidence, flooding, and storm damage may result in marks located in a single structure being destroyed or too unstable for continued use. Therefore, it is generally best to space marks out when possible to mitigate bench mark network risks.

Larger piers and retaining walls are the most common examples where multiple marks have been set in the same structure. As a best practice, avoid setting multiple marks in these larger structures, even if not violating the 60 m spacing requirement. In an instance such as separate bridge abutments of a single bridge, these would likely count as separate structures (structurally) if the distance between them is sufficient. However, this introduces risks of losing both marks to the same bridge maintenance or construction.

2.9 GPS Observable Marks

One bench mark is selected per station as the GPS Bench Mark (GPSBM) and is selected based on the following criteria: (a) permanence and stability, (b) satellite visibility, (c) safety and convenience, and (d) historic GPS use. At least two marks should meet these criteria. All new marks established should be observable by GPS, whenever possible. However, one mark has been typically selected, designated, and used as a GPS bench mark in the past for repeatability and to more readily compare data sets. Marks shall be identified as suitable for GPS observations within the GPS field of the WinDesc file if meeting the aforementioned criteria. The published bench mark sheet should also state the suitability of GPS observations for each mark. When GPS observations are performed on a bench mark that mark must also be included in the leveling run performed at that station. (*User's Guide for GPS Observations at Tide and Water Level Station Bench Marks* 2013).

Marks that are to be observed by GPS should have 360 degrees of clearance around the mark at 10 degrees and greater above the horizon. This clearance is needed to maximize satellite visibility. The horizon should be clear of any obstruction including trees, structures, or large vehicles (eg. ships). Nearby obstructions may hinder satellite visibility or result in reflected signals and multipathing issues. These marks should be of Class A or Class B stability. These marks should be located in areas that are safe and secure to allow possible unattended data collection. This protects the GPS equipment from being vandalized, stolen, or interrupted during data collection sessions. Requirements for GPS observations and choosing marks are covered in greater detail in *User's Guide for GPS Observations at Tide and Water Level Station Bench Marks* (2013).

Figure 2.17: A sample GPS observation on a bench mark. Note the clear visibility and area the mark is set (away from foot traffic).

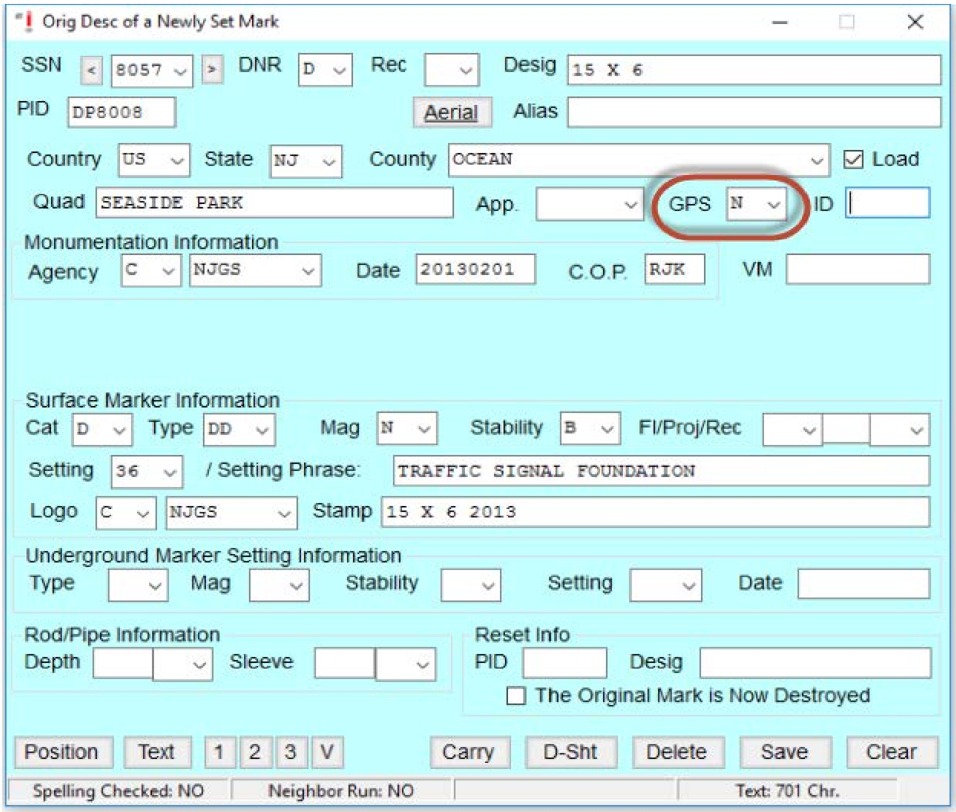


Figure 2.18: Example of a WinDesc mark description file, showing a mark that is not GPS-observable (see "N" under "GPS" attribute).

2.10 Frost Penetration

To guard against frost heave, both a pipe mark or a disk set in a concrete monument (or boulder) must be set at least 0.3 m (1.0 ft.) below the frostline. The extreme depth of frost penetration varies but, in general, it is less than 0.6 m (2.0 ft.) deep along the west coast of the contiguous United States and south of New Jersey on the east coast. The extreme depth varies from 1 m (3 ft.) in northern New Jersey to about 2 m (7 ft.) in northern Maine. On page 33 *NOAA Manual NOS NGS 1*, the extreme depth and a table to determine frost penetration is described in detail (*NOAA Manual NOS NGS 1* 1978).

2.11 Primary Bench Mark (PBM)

For every station the PBM elevation is known and is assumed to be fixed above a reference datum. For water level stations, the reference datum is designated as SD. Generally, elevations of all the bench marks in the local leveling network are referenced above the SD. The PBM should be installed or selected closer to the water level sensor because the PBM must be connected in all level runs and a shorter distance to the PBM is time efficient for level operations (see section on *2.8 Spacing of Bench Marks)*. However, the stability of the bench mark itself is considered the most important factor during selection.

Leveling between the PBM and the sensor level point enables effective monitoring of the vertical stability of the sensor relative to the PBM. The very localized relative vertical stability of the PBM is monitored, in turn, by repeated leveling to the other bench marks at the station. By monitoring the overall movement of all marks relative to the PBM, potential movement of the PBM can be identified. This comparison requires careful inspection. The PBM must be included in the level run each time the station is surveyed.

If the PBM is destroyed, shows movement in two consecutive leveling runs, or shows a clear trend of instability and movement compared to the rest of the network, then a new stable PBM must be selected from the current network of bench marks. To change a PBM, refer to the *SOP # 3.2.3.5-E16 Designating a Primary Bench Mark for New or Existing Water Level Station, and Determining Its Elevation*. As an effective practice, it is helpful to note another mark as a candidate to be a back-up PBM and include that mark in every leveling run as well. This makes it easier to potentially transfer to a new PBM should the need arise. This ensures that if the PBM is changed, all marks in the entirety of the bench mark network have sufficient leveling history.

2.12 Vertical Stability

The movement of a bench mark is defined as change in its elevation compared to that of the PBM, exceeding ±6 mm, compared to the elevation from the previous leveling run, with all elevations referenced to the same SD. The frequent leveling observation of the suspect bench mark will reveal a stability trend. Long-term stability of a bench mark can be assessed by studying its elevation relative to bench marks in the network that have a proven stability record (for a robust study, the elevation record should contain over 10 years of survey data). If the bench mark elevation trend is greater than ±9 mm over 38 years, it is deemed unstable. If more than half of the bench marks in a network reveal a trend in elevation in the same direction, the PBM should be evaluated. This is done by performing a stability analysis of the network while holding a different bench mark elevation constant. If the network does not reveal a trend similar to the first analysis, the PBM is unstable, and a new PBM should be designated. If marks are deemed unstable, see section *2.15 Unstable Marks and Removal of Bench Marks from Network.*

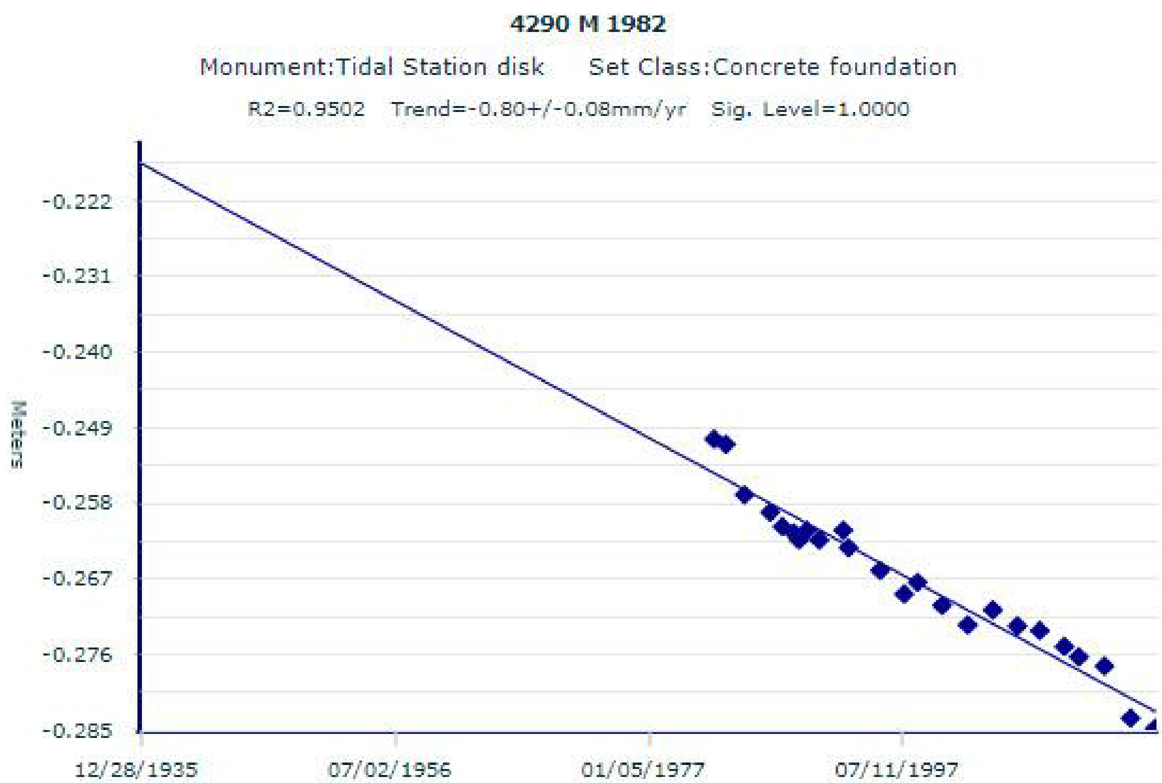


Figure 2.19: Example of a bench mark stability plot generated via the Water Level Processing Interface (WALI). WALI is a software application that allows the user to quickly perform analysis of data stored in CO-OPS database, including both bench mark and water level data.

2.13 Numbering Bench Marks

2.13.1 General Naming Conventions

To avoid confusion and ensure positive identification, new bench marks established by CO-OPS will be stamped and designated as follows:

- the last four digits of a station number (no state or lake identifiers)
- An incremental letter (different from any previous bench marks in that station's bench mark network and no usage of the letters "I" and "O")
- the current year

For example, five new bench marks set at a station such as 8594900 Washington DC, assuming there was no previous bench marks, would be stamped as follows: 4900 A YYYY, 4900 B YYYY, 4900 C YYYY, 4900 D YYYY, and 4900 E YYYY where YYYY is the current year. Station numbers are assigned by the Configuration and Operational Engineering Team (COET) of the Engineering Division of CO-OPS. The cutter system used for assigning station numbers assigns based on the stations' geographic location, first at a state and body of water level, then by lines of latitude and longitude. The first three digits of station numbers pertain to state and body of water identifiers and are **not** to be stamped on the mark. Only the last **four digits** of a station number are stamped on the mark.

The letters “I” and “O” are not to be used as they can be easily confused with numbers “1” and “0”. This is to prevent the potential misidentification and misreading of marks. In addition to this, duplicate letters of nearby bench marks that are part of the bench mark network must be avoided. A letter previously assigned to a bench mark in the local network shall not be used for a new mark in most instances, except in the specific instance where that mark is being directly replaced. New marks set should be named with the succeeding letters, alphabetically and skipping letters “I” and “O”. If a mark has a NGS Permanent Identifier (PID), efforts should be taken to continue to follow that naming convention as it was originally described.

2.13.2 Resetting Bench Marks

Resetting bench marks is generally discouraged by CO-OPS. However, certain circumstances allow for the mark to continue to be used. Generally, these cases involve situations in which damage has occurred to the mark but not in such a fashion as to cause continued instability. However, the situations that arise are entirely dependent on the type of monumentation. An example of an appropriate situation for resetting a bench mark is a bent 3D rod mark. Though the rod is bent, it can be set back into place and start a new elevation. The damage that was done to the rod dictated that the previously held reference elevation is no longer valid. For bench mark disks, if the infrastructure or surrounding area is structurally intact and in good condition, the disk can be reset in the same location. The brass disk itself should be replaced if damaged, as the high point of the disk may be compromised.

In the case of resetting a bench mark or directly replacing a previously existing mark in the same location, the bench mark shall be stamped with the existing letter that had been previously used for that mark at the station and add the word RESET (eg. 4900 A RESET 2018). For example, if mark 4900 A 2017 was to be replaced and reset, the new mark that is set would be designated as 4900 A RESET 2018 (where 2018 is the current year).

Existing bench marks that have not been stamped according to the current numbering system retain the designation stamped on the mark. This happens quite frequently due to the adoption of many bench marks monumented by organizations outside of CO-OPS

Temporary bench marks (TBM) are not stamped. However, they may typically be referred to as TBM 1, TBM 2, TBM 3, etc. Any TBMs used for leveling points for sensor or for meteorological references typically have their own naming convention and should not be included in part of the numbered TBMs used.

2.14 Bench Mark Descriptions, Recovery Notes, Photos

Bench mark descriptions, recovery notes, and “To Reach” statement shall be written in accordance with Appendix E of the *User's Guide For Electronic Levels with Translev and WinDesc* (2014) and in accordance with *User’s Guide for Writing to Reach Statements and*

Bench Mark Descriptions (2011) for bench marks that are connected using either electronic or optical levels. Bench mark descriptions, and recovery notes for Great Lakes bench marks shall be written in accordance with the NGS Bluebook, Formats and Specifications of the National Geodetic Survey Data Base http://www.ngs.noaa.gov/FGCS/BlueBook/, since those marks are not published by CO-OPS (*Input Formats and Specifications of the National Geodetic Survey Data Base* 2016).

2.14.1 "To Reach" Statement

The TO REACH statement provides easily followed directions on how to reach a CO-OPS water level or meteorological station, the sensors, and the associated bench marks. It is also used on the Published Bench Mark Sheet. These directions are written for the user who is unfamiliar with the area. Thus, the TO REACH statement should start from a readily found prominent landmark, use the mode of transportation most common to the area, and guide the user to the station via the most direct and major route. The WinDesc program does not provide the TO REACH statement that is used in the header paragraph of the tidal published bench mark sheet. Hence, the TO REACH statement to be used on the published bench mark sheet shall be provided in a separate digital file with a filename a seven digit station number and the three digit extension TOR; e.g., 9414290.TOR. This statement may also be used for each individual bench mark description in the WinDesc program, with minor editing depending on the location of the mark. See the example TO REACH statement below:

> *To reach the tidal bench marks from the U.S. Post Office on Main Street, proceed north on Main Street for 1.3 km (0.8 mi) to the intersection with Second Avenue, then west on Second Avenue for 3.2 km (2.0 mi) to its termination with Harbor Road, then SW on Harbor Road for 5.6 km (3.5 mi) to the small boat harbor and fishing pier. The bench marks are along Harbor Road and the waterfront area. The tide gauge and staff were located 4.51 m (14.8 ft) south of the offshore end of the wharf.*
> **Figure 2.20: Example TO REACH Statement**

2.14.2 Bench Mark Diagram

Bench marks incorporated into the stations network must be clearly identified on a bench mark diagram. The diagram shall be produced using a mapping tool which can label: the location of the bench marks, sensor, local landmarks, and roads used in the bench mark description, infrastructure supporting the sensor, and the body of water being observed. The diagram must also include the North arrow and CO-OPS standard title block with the station name and number, station latitude and longitude in d/m/s.x, the NOAA Chart number, unit scale, USGS Quad name, drawn by and date created.

Figure 2.21: Sample bench mark diagram from 9414290 San Francisco provided after an annual inspection to the station. All bench marks associated in the network are listed.

2.14.3 Bench Mark Recovery

Prior to the recovery of any existing marks, contact property owners and obtain permission for any marks located on private property. Take care to return the landscape to the original condition after any work performed. Notify the property owners of the work to be performed prior to arrival. Before recovery begins, check to see if any bench marks have an associated PID within the NGS Integrated Database (IDB) and review the descriptive data. NGS provides numerous tools for searches and finding a mark such as the NGS Data Explorer. When recovering bench marks, make an extensive physical search for all of the bench marks in a network. Follow the previous descriptions of bench marks and their latitude/longitude to find each bench mark during recovery. When locating each bench mark, note the previous landmark descriptions and ensure all distance measurements are still valid. Also ensure all landmark descriptions are as described. Recovery notes for each bench mark should be completed using WinDesc in accordance with the *User's Guide For Electronic Levels with Translev and WinDesc* (2014) and *Standing Project Instructions* (2017). Bench mark descriptions are covered more in depth in section *2.14.5 Bench Mark Descriptions*.

If a mark cannot be found, do not state the mark is destroyed. Bench marks should only be marked as destroyed if there is clear supporting evidence. If strong evidence suggests a mark is destroyed, clearly state the evidence (i.e. surrounding area excavated for building construction) in the recovery notes. Using photos taken of the area, CO-OPS can attempt to determine if it is destroyed and replace the mark as required. If there is physical evidence of the mark being destroyed, submit an email and photograph of the physical evidence to CO-OPS Engineering Division as well as any additional notes. Physical evidence would include examples such as finding the actual remains of a mark or finding it damaged beyond use. Evidence such as recent construction would not constitute physical evidence, even if destruction is likely implied. **A mark should not be marked as destroyed unless there is physical evidence of mark destruction**. If a mark has not been found after two consecutive attempts and evidence has mounted that the mark has been destroyed, it may be dropped from the network.

When recovering bench marks, visually inspect each bench mark for damage, weathering, and any issues. For instance, when recovering a bench mark disk, check whether the disk has moved, been physically damaged, or is loose in its setting. If these issues are substantial and it is believed the bench mark can no longer serve as an adequate bench mark for leveling, the mark should be identified as damaged in the bench mark recovery notes. If a mark is a CO-OPS owned mark, the mark is to be **removed** if possible. This is only if this is a CO-OPS owned mark. If a disk has actually been destroyed, then the recovery notes should describe the mark as destroyed, and the disk sent to NGS or CO-OPS, depending on the stamping.

Some minor issues detected can be addressed without disturbing a bench mark, **as long as it is a CO-OPS owned mark.** Any existing bench mark disk selected for use as a bench mark installed by CO-OPS should be repaired if found with edges exposed or underlying weathering of the monument. Any work done to repair a disk must be described completely in the digital recovery notes. Take extreme care not to alter the existing horizontal or vertical position of the disk. Disk longevity can be increased substantially by this maintenance. This will greatly help in preventing ice from forming under the disk or a vandal from prying the disk from its location. For all marks, perform mark additional maintenance as required **as long as it will not disturb the mark.** This includes maintenance such as replacing logo caps for deep rod marks, replacing witness posts, among other tasks. When an unusual situation arises, contact CO-OPS Engineering Division for recommendations before taking any action on the mark. If possible, send a digital photograph to CO-OPS along with the description of the situation. Notify CO-OPS of any other marks needing maintenance. Examples of mark maintenance problems include loose disks, exposed disk edges, missing logo caps, missing logo cap lids, exposed edge of concrete monuments, or imminent danger of destruction.

2.13.4 Bench Mark Photographs

Bench marks images will be stored in the CO-OPS station archives folder. Photos must be professional in nature. Digital photographs are useful for station (mark) reconnaissance, mark recovery, mark stability assessment, and quality control and as an aid during data processing and data verification. Some projects might require digital photographs during several stages.

Take sufficient photographs to describe the stamping, appearance, condition, and location of the mark and points of potential interest, including visibility obstructions, roads, runways, taxiways, or other dangers and any special setup requirements. Alter the orientation of the photographs as necessary to include this information in as few photographs as possible. Capture the tops of nearby obstructions if possible.

Photographs should be taken per the *Standing Project Instructions* (2017) for GPS observations and bench marks. When setting or recovering new marks or at the Engineering Division's request, a minimum of four photographs should be taken for each bench mark with the following views: (1) a close-up photo showing the face and stamping of the bench mark, (2) a chest or waist level photo showing the bench mark and its setting, (3) horizontal view with direction/orientation (N, NE, S, SE), (4) horizontal view with direction/orientation in different direction than previous (90^0 difference is preferred).

2.14.5 Bench Mark Descriptions

Bench mark descriptions are to be completed via WinDesc per the *User's Guide For Electronic Levels with Translev and WinDesc* (2014) and *Standing Project Instructions* (2017). When describing the benchmarks, the descriptions themselves should be in accordance with *User's Guide for Writing to Reach Statements and Bench Mark Descriptions* (2011). This document provides an in depth guide of the requirements of the description needed. In general, the bench mark description is composed of four parts, described below:

Sample sentence: From the intersection of ___(1)___, ___(2)___, ___(3)___, ___(3)___, ___(3)___, and ___(4)___.

1. General Locator Phrases that lead the user to the individual mark from a local landmark or highway intersection.
2. The marker (Monumentation) type, how it is set, a specific locator. If the mark is a primary bench mark, that should be indicated as well.

3. Taped measurements (both metric and English measurement with English measurement in parentheses) and compass directions from at least three objects in the immediate area of the bench mark, recorded in descending order of distance. Note: When referring to the cardinal compass directions (north, south, east, and west) they should be spelled out. When referring to intercardinal directions (northwest, northeast, southeast, southwest), the directions should be abbreviated (NW, NE, SE, SW)
4. Vertical reference to grade, or other appropriate reference, if the bench mark setting is not level with its immediate surroundings. This only needs to be cited if the difference between the mark and grade exceeds 0.05 m (0.2 ft). For rod marks, the vertical reference to grade and depth.

Listed below are sample bench mark descriptions for reference:

> *From the intersection of US Highway 322 and Washington Avenue in (city), proceed east on Washington Avenue for 2.4 km (1.5 mi), then go north on Christopher Columbus Avenue for 0.3 km (0.2 mi), the primary bench mark is a disk located near the front lawn of the USCG Marine Safety Office property, 45.90 m (150.6 ft) NW of the flagpole at the entrance of the main building, 24.69 m (81.0 ft) south of the light pole on the east side of Christopher Columbus Avenue, 9.20 m (30.2 ft) NNE of the north curb of Washington Avenue, 8.41 m (27.6 ft) SE of the eastern curb of Christopher Columbus Avenue, and 8.14 m (26.7 ft) east of the traffic signal post at the NE corner of Washington and Christopher Columbus Avenues. The bench mark is set 18 cm (0.6 ft) below ground, crimped to a stainless steel rod driven 11.9 m (39 ft) to refusal, and encased in a 5-inch PVC pipe with concrete kickblock.*
> **Figure 2.22: Primary Bench Mark Description - Example**

As a note, any bench mark with an associated IDB PID should be described as it is in the IDB. If there are substantial differences (eg. condition changes, different landmarks and distances) update the description. As a best practice, a bench mark recovery sheet can be submitted to NGS if changes are substantial.

2.15 Unstable Marks and Removal of Bench Marks from Network

Unstable bench marks shall only be destroyed if owned by CO-OPS and as directed in the Project Instructions. Bench mark instability is determined by CO-OPS Engineering Division after a history of repeated levels. The Engineering Division may decide other marks need to be removed from a network for other reasons as well (eg. unusable mark, lack of GPS visibility). When destroying a mark is not possible, the mark should be stamped with an “X” indicating it is no longer valid. If the unstable mark does not belong to CO-OPS, drop the mark from the local leveling network, but do not destroy it. If the bench mark has a PID, fill out a bench mark recovery sheet and submit it the National Geodetic Survey (NGS). If a mark has not been recovered successfully after two consecutive attempts at recovery, it may be dropped from the network at the discretion of the Engineering Division.

2.16 Water Level Station Types and Required Number of Bench Marks

2.16.1 Long-Term Station

A long-term station is one at which continuous observations have been made over a minimum period of 1 year. Water level observing networks such as the national network of Physical Oceanographic Real-Time Systems (PORTS®) are considered long-term stations. These stations are typically used as secondary control stations for datum calculation. The water level data collected by a secondary control station alone cannot derive the equivalent of a 19 year datum unless the simultaneous water level data compares well with that of an NWLON primary control station. NWLON stations are long-term stations that must meet additional requirements listed in the *National Water Level Observation Network Requirements* document (*National Water Level Observation Network Requirements* 2017).

At least five permanent bench marks shall be included in the leveling network at all long-term stations, other than NWLON stations. NWLON stations require ten permanent bench marks to be maintained in the network (*Standing Project Instructions For CO-OPS Observing Systems* 2017). For all long-term stations three shall be disks set in bedrock and/or deep rod marks (Class B or higher marks). The remaining bench marks shall be installed on the most suitable structures for the locality. Preference should be given to disks set in bedrock, in large man-made structures, and deep rod marks.

2.16.2 Short Term Station

A short-term station is one at which continuous observations have been made for a period of less than 1 year. The intent of these station installations is typically site specific for correlation with other measurements or for interpolation of large changes in tidal characteristics. If a minimum of 30 days of data is collected, short-term stations can function as tertiary stations for tidal datum calculations. The datum products from such installations is reduced to equivalent 19-year tidal datums through mathematical comparison of simultaneous observations from a control station or appropriate secondary station. Types of short-term stations are seasonal gauges, Vertical Datum (VDatum) projects, hydrographic survey and shoreline mapping survey support gauges, partner stations such as USACE Comprehensive Evaluation of Project Datums (CEPD) program, and special projects.

At least five bench marks shall be installed at these types of stations. One of the five shall be disks set in bedrock and/or deep rod marks (Class B or higher marks). The remaining four shall be installed on the most suitable structures for the locality and of stability Class C or higher. Preference should be given to disks set in bedrock, in large man-made structures, and deep driven rods wherever possible. It is understood that Class A/B stability bench marks will maintain a stable elevation and will most likely not be affected by surface related events that can disturb or destroy the marks increasing the likelihood of reoccupation for future projects in the area.

Chapter 3 - Leveling

Geodetic leveling procedures are used to verify the vertical stability of the water level sensor(s) and bench marks at all NOAA tide stations, both permanent and temporary. By following FGCS specifications for geodetic leveling, (Federal Geodetic Control Committee, 1984), CO-OPS maximizes the likelihood that vertical stability of the sensor is kept to within the accepted misclosure standards for Second-order Class I leveling:

$$6 \times \sqrt{D_{km}} \quad \text{where D = one-way distance}$$

Geodetic leveling typically uses high precision digital barcode leveling instruments, with matching, calibrated one-piece digital barcode invar rods. Corrections for collimation error, temperature and temperature gradients, and local gravity are applied to the data during analysis to increase the precision and accuracy of the field observations.

Situations may arise when geodetic leveling techniques may be problematic, or the required instrumentation, such as calibrated leveling rods, may not be available. CO-OPS has allowed waivers from the requirement for the Second-order leveling for select NWLON stations in Alaska, Hawaii, and Pacific Islands. Third-order or lower leveling may result in degraded precision and accuracy. Furthermore, Third-order leveling as mentioned above will not yield a valid connection/tie to the NSRS.

Field operations require a highly trained staff to ensure accurate and consistent results. Thoroughly documented field notes will ensure proper analysis of field-collected data, as well as resolving any problems or errors that may be discovered during analysis. Required leveling data include bench mark and sensor leveling points observed, date and times of leveling per sections, instrument and rod serial numbers, steel tape measurements, section distance, meteorological data, whether calibrated plugs were used, etc.

A description file will be created for each water level station using WinDesc, an NGS application, using both existing bench mark information and any new information obtained during the course of the survey. Modern digital barcode levels automatically create leveling digital files that support leveling observations. The files are populated with relevant information of either recovery or installation of bench mark metadata, then uploaded to Translev, a software for processing leveling files. Together with WinDesc, the field observations are assigned to the bench mark descriptions, and a number of output files are created, including a leveling abstract (*.abs), an HGZ file (*.hgz), a *.bok file. All of these files can be submitted to NGS for publication in the NGS Integrated Database (IDB) if the survey is conducted following Second-order, Class I (or II) FGCS specifications.

3.1 Standards and Specifications for Leveling

Leveled heights will be established following the Standards and Specifications for Geodetic Control Networks (*Standards and Specifications for Geodetic Control Networks* 1984). In the publication, detailed specifications regarding leveling procedures, instrumentation and calibration requirements are given and must be adhered to.

Second-order, Class I levels shall be used to establish high precision vertical connections among water level sensors and bench marks at all water level stations. CO-OPS has made exceptions for regions such as Alaska, Hawaii and Pacific Islands. These locations are known to provide challenges for transporting survey equipment needed to meet Second-order surveying procedures. Although third-order levels may be used at select stations, the on-site, self-checking capability inherent in Second-order levels warrants its use if at all feasible. The procedure for performing Second-order leveling using the Lecia DNA-03 along with Windesc and Translev are detailed in the *User's Guide for Electronic Leveling Using Translev and Windes 2011*. CO-OPS has approved, when a waiver request is submitted, the use of split rods and optical leveling (spirit level) for surveying in regions mentioned above because transporting one piece rods is currently not practical. Furthermore, Trigonometric leveling procedures have been approved for surveying to sensors that are mounted on elevated platforms that cannot be surveyed to using digital levels for various reasons. These techniques do not meet the minimum standards referenced in the *1984 Standards and Specifications for Geodetic Control Networks* manual therefore should be documented as no Order/Class leveling. FGCC standards specify leveling rods to be one piece.

The following standards and specifications will be followed for Second-order Class I leveling (Federal Geodetic Control Committee, 2004):

A. Calibrated geodetic leveling rods (calibration certificates on file with NGS)
B. Calibrated, one-piece invar rods (calibration certificates on file with NGS)
C. Maximum collimation error: 10 arc seconds
D. Level rod circular vial(bubble) calibrated within 10'
E. Double-run leveling procedures
F. Maximum length of sight, 60 m (197 ft) for Second-order, Class I and 90 m (295 ft) for Third-order;
    a) Maximum difference in length of forward and backward sights,
        - 5 m (16 ft) per setup (Second-order, Class I) and 10 m (33 ft) per setup (Third-order),
        - 10 m (33 ft) cumulative per section;
    b) Maximum misclosure error between forward and backward runnings are as follows (where K and M are the one-way distances in kilometers and miles, respectively);
        - (Second-order, Class I) 6 mm $\sqrt{?}$ (0.025 ft $\sqrt{?}$) per section and line
        - (Third-order) 12 mm $\sqrt{?}$ (0.050 ft $\sqrt{?}$) per section and line
    c) Minimum ground clearance of line of sight, 0.5 m (1.6 ft)
    d) Determination of temperature gradient for vertical range of line of sight at each setup, for Second-order only.

3.2 Vertical Stability Precautions

The purpose of a bench mark survey at a water level station is to detect movement (or lack thereof) between the sensor leveling point or ETG and the bench mark network. All observations require careful attention to minimize error associated with vertical position of the sensor and the bench mark network. When the change in height exceeds 6 mm (0.24 in) at a long-term coastal stations, 3 mm (0.01 feet) at Great Lakes stations, and 12 mm (0.47 in.) at short-term stations, a special check should be made for the possibility of a loose leveling point or a disturbed bench mark. Stability of the bench mark should be determined by leveling to other bench marks to check previously determined height relationships. Any findings or conclusions should be noted in the field site report and Windesc applications.

A. An organized work routine with assistants and safety observers should follow roles and responsibilities established into every procedure in every field operation. The field crew should take care and be meticulous in handling the rod(s), setting turning points, maintaining the equipment, and reporting deficiencies.
B. Collimation error can be limited using a high quality and properly maintained instrument. The level instrument angle should be measured in the field at the start of the level run. If the measurement is greater than 10 arc seconds, the level instrument will need to be serviced and its collimation adjusted. It is best not to attempt this in the field. The effect of collimation error on each observation can be reduced by limiting the sighting imbalance as much as possible.
C. To reduce error from refraction, keep sighting distances within the prescribed tolerances for the order and class of the survey and do not allow the line of sight to pass closer than 0.5 m (1.6 ft) to the ground or to an intervening object.
D. Positively identify marks. Misidentifying bench marks during a survey can cause substantial errors. The field crew should rely on the Windesc descriptions and not personal experience of the survey area to properly recover and occupy bench marks.
E. Properly occupy bench marks. The field crew should make sure to identify and occupy the marked high point of the bench mark.
F. Avoid using computer-recording devices near the source of high-energy radio-frequency emissions.

3.3 Frequency of Leveling

Leveling between the bench marks, the water level sensor, the staff (for hydrographic surveys and/or remote sensing projects), or ETG (Great Lakes stations) shall be conducted as specified in (a) the Annual Project Instructions, (b) Statement of Work for contract Tasks, (c) Agreements, (d) as directed, or (e) for emergency maintenance.

Generally the leveling between the bench marks, the water level sensor, and the staff (for hydrographic or remote sensing surveys) or ETG (Great Lakes stations) shall be conducted at all stations as specified below unless directed otherwise in the documents listed in the above paragraph.

A. At installation or removal (or upon discontinuation of data collection) of a water level station (all marks and sensor) - following Second-order, Class I procedures.
B. Two to six months interval for check levels after installation, when check levels are required or as specified in the documents listed above (PBM and four other bench marks). This is also applicable for short term stations where datums need to be made available prior to the 2nd set of leveling after the installation of the station.

C. Before and after any modification affecting the elevation of the staff, ETG, or sensor elevation change (check leveling only, PBM and two bench marks).
D. Annually, bi-annually, or any other frequency as specified in the Annual Project Instructions, agreements, or contract documents.
E. After severe storms, earthquakes, hurricanes, etc., when sensor and bench mark elevations need to be confirmed or elevation changes need to be documented (all bench marks).
F. As often as necessary to ensure minimum data loss at stations exposed to extreme environmental or geological conditions (PBM and all marks). For example this includes where significant land/water elevation changes are expected in the next half a century due to sea level rise (e.g. Florida coast), significant land subsidence (e.g. Louisiana coast) or land rise (e.g. Isostatic rebound in AK).
G. After installation of a new bench mark (PBM, new mark, and two other existing marks).

3.4 Instruments

Digital levels are the most commonly used for leveling within CO-OPS. At stations where digital leveling is not possible, CO-OPS field crew use optical compensator or spirit levels. CO-OPS currently uses the Leica DNA-03 for digital leveling and Zeiss Ni2 compensator or Wild N3 spirit level for optical leveling. If the opportunity arises to use other than listed digital level instrument, approval may be granted after instrument specifications (optic power, repeatability, etc.) are reviewed by the Engineering Division.

In differential leveling, vertical differences in elevation between bench marks are measured through a series of readings on a level rod using a digital or optical level. The accuracy of leveling, therefore, depends on both the quality of the rod and the instrument itself in combination with leveling procedures and techniques. All too often, a very high quality observing instrument is used with little attention given to the equivalent quality of the rod of which can have the same effect of reduced accuracy of the overall survey. The rod used in second-order leveling is composed of a single continuous (not collapsible or folding) Invar metal scale supported on a staff of wood or light metal (*Standards and Specifications for Geodetic Control Networks* 1984). Leveling rods are typically made of Invar (invariable metal alloy of specific iron to nickel composition). Usage of this composition of leveling rod helps to account for qualities such as thermal expansion due temperature differences. The scale is permanently attached to the foot of the staff, and is freely supported under tension by a spring-loaded clamp at the top. Thus, the staff is free to change length in response to changes in humidity and/or temperature without affecting the length of the graduated scale.

For Second-order surveys, Invar rods are to be calibrated with both index and length errors determined. This requirement may be accomplished at the time of purchase by receipt of a calibration certification from the manufacturer or by calibration and certification by an approved laboratory. Rods are to be recalibrated every 5 years. The rods should be recalibrated before reusing if the rods have been damaged, bumped or dropped (*FGCS Specifications and Procedures to Incorporate Electronic Digital/Bar-Code Leveling Systems 2004*). When using the

NGS Translev program to process digital levels, the calibration data is entered into the rods.dat file.

During a survey, it is important that the rod is held plumb for an accurate elevation to be measured. Adjustable bipod legs and a circular level bubble are used to plumb the rod and hold it steady during the reading. It is usually necessary to use a lighter and smaller rod section for the reading to the sensor leveling point and on runs that still include vertical bench marks.

In certain circumstances it is necessary to request approval to use a collapsible rod to accommodate aircraft or vessel capacities or other special conditions. For these conditions, obtain a waiver from the Engineering Division. CO-OPS has provided waivers for the use of collapsible rods and Third-order closure tolerance procedures. For Third-order leveling, rods with continuous metal scales on a wooden or fiberglass staff (calibrated in metric or English units in a block graduation pattern) are acceptable. A hand-held level bubble is used to keep the rod plumb.

Two rods should always be used. When using two rods, they must be a matched pair (rods with the same rod units, graduation pattern, index error, etc.). In addition, two-rod leveling procedures require an even number of instrument setups per section in order to cancel out any mismatch error. Index error can be eliminated by making an even number of setups for every section, thus using the same rod on every bench mark during the leveling (*NOAA Manual NOS NGS 3, Geodetic Leveling,* 1981). The rod type, rod unit, graduation pattern, and serial number must be referenced in the digital leveling files and in all field notes.

Two important characteristics of any turning point, which should always be considered when selecting the type and position, are: (a) its stability while being used (supporting the running elevation), and (b) the precision of the rod resting point. The following table lists the most common types of turning points, together with the various surfaces upon which they are used.

Table 3.1: Types of turning points.

Turning Point	Surface Type	Remarks
Steel pin with driving cap	Firm ground, dirt roads	Pin is driven vertically into ground and removed when rodman moves to the next point. Remove cap (after driving) to expose high point.
Portable turning plate (turtle) weighing at least 7 kg. (15 lb.)	Concrete pavement, hard packed gravel.	Turtle is firmly planted and removed when rodman moves to next point. Use with great caution to avoid movement.
Double headed nail in wooden stake.	Soft ground, marsh, sandy shoreline.	Stake is driven to firm bearing. Nail is driven into stake to the first bead for precise point. Elevation can be checked for a short time after run.
PK nail (Not recommended for geodetic leveling)	Asphalt road	Nail is driven into roadway. Head of nail is left exposed for point. Elevation can be checked for short time after run.

When levels are run across extremely unstable ground (marsh, swamp, shallow water bodies, etc.), conventional points may be useless and special equipment may have to be fabricated for the turning points.

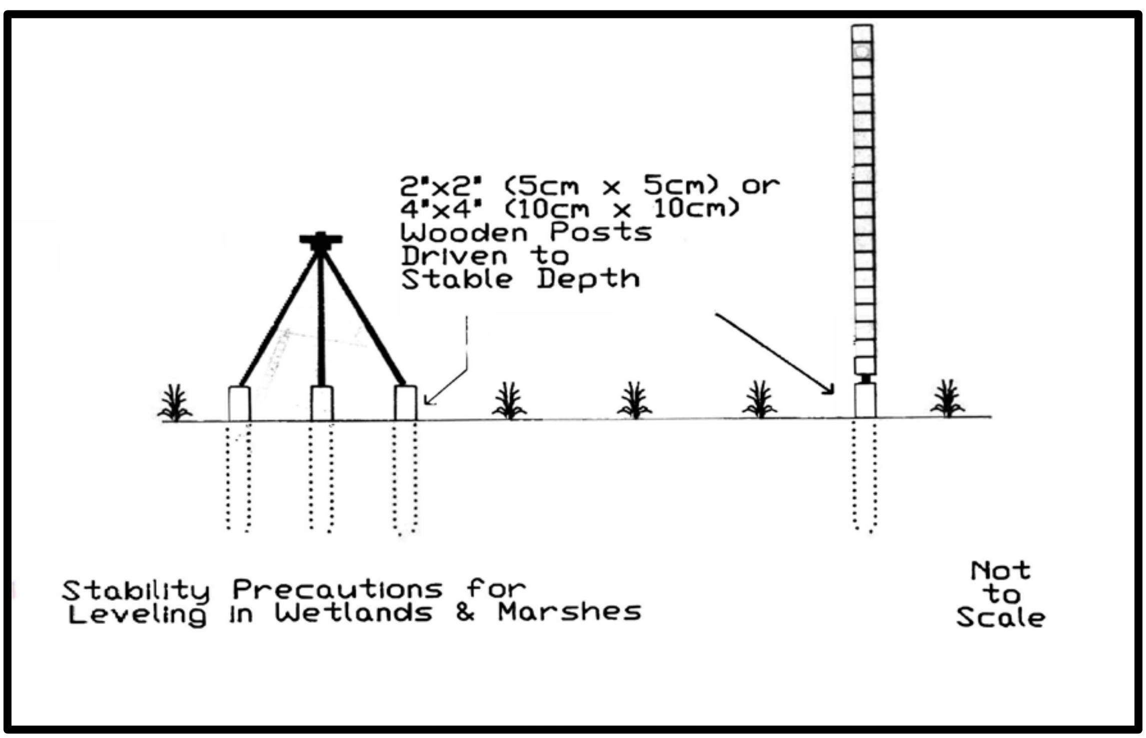


Figure 3.1: Stability precautions for leveling in wetland and marshes.

3.5 Sources of Leveling Error

Sources of error in leveling can be classified into three groups: those affecting the line of sight, those affecting the heights observed, and blunders (*NOAA Manual NOS NGS 3* 1981).

3.5.1 Curvature

The line of sight of a level instrument intersects the rod on a level plane. Since the surface of the earth is a curve, a small amount of curvature error, proportional to the square of the sighting distance, is introduced into each observation (Figure 3.2). Corrections for the curvature error are always negative (i.e., to be subtracted from the observed rod readings).

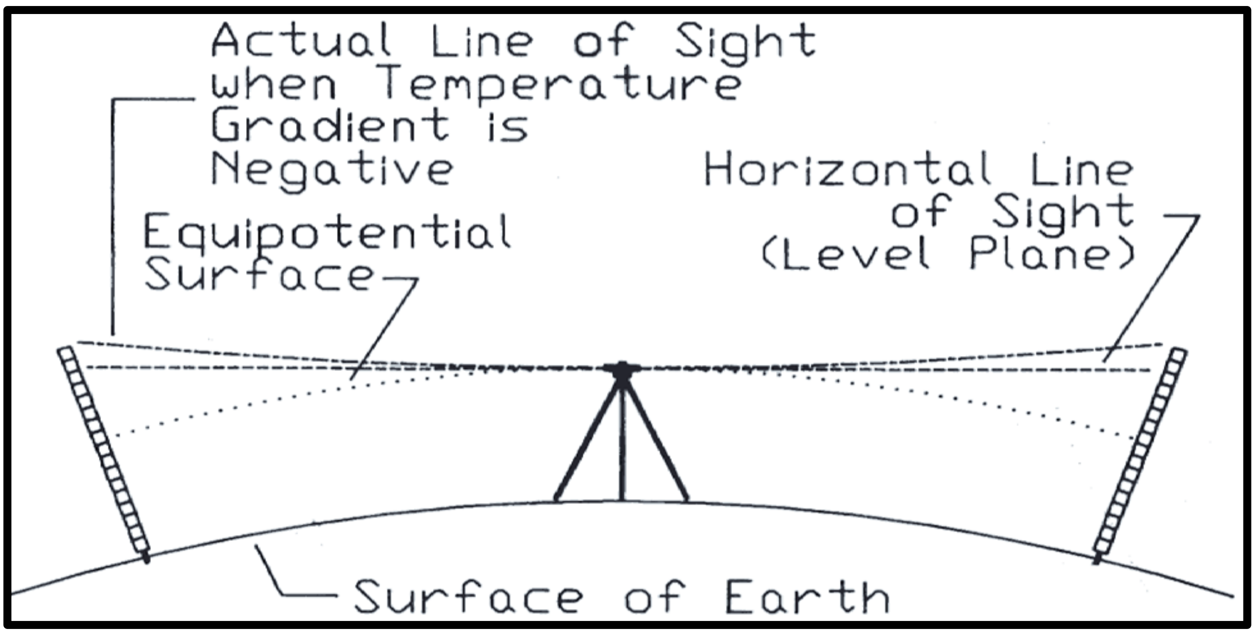


Figure 3.2: Effects of Curvature and Refraction.

The earth appears to "**fall away**" with distance. The curved shape of the earth means that the level surface through the telescope will depart from the horizontal plane through the telescope as the line of sight proceeds to the horizon. (Jamal H, January 2017)

$C= 0.0239D^2$ where D is the sight distance in thousands of feet.

Effects of Curvature are:

- Rod reading is too high
- Error increases exponentially with distance

3.5.2 Refraction

Refraction is largely a function of atmospheric pressure and temperature gradients, which may cause the bending to be up or down by extremely variable amounts. There are the three types of temperature gradients ($\Delta T/\Delta h$):

1. Absorption occurs mainly at night when the colder ground absorbs heat from the atmosphere. This causes the atmospheric temperature to increase with distance from the ground and $\Delta T/\Delta h > 0$.
2. Emission occurs mainly during the day when the warm ground emits heat into the atmosphere, resulting in a negative temperature gradient, i.e. $\Delta T/\Delta h < 0$.
3. Equilibrium occurs when no heat transfer takes place ($\Delta T/\Delta h = 0$) and occurs only briefly in the evening and morning.

The result of $\Delta T/\Delta h < 0$ is to cause the light ray to be convex to the ground rather than concave as generally shown. This effect increases the closer to the ground the light ray gets and can result in errors ~5 mm/km. The atmosphere refracts the horizontal line of sight downward, making the level rod reading smaller. The typical effect of refraction is equal to about 14% of the effect of earth curvature ("Curvature and Refraction").

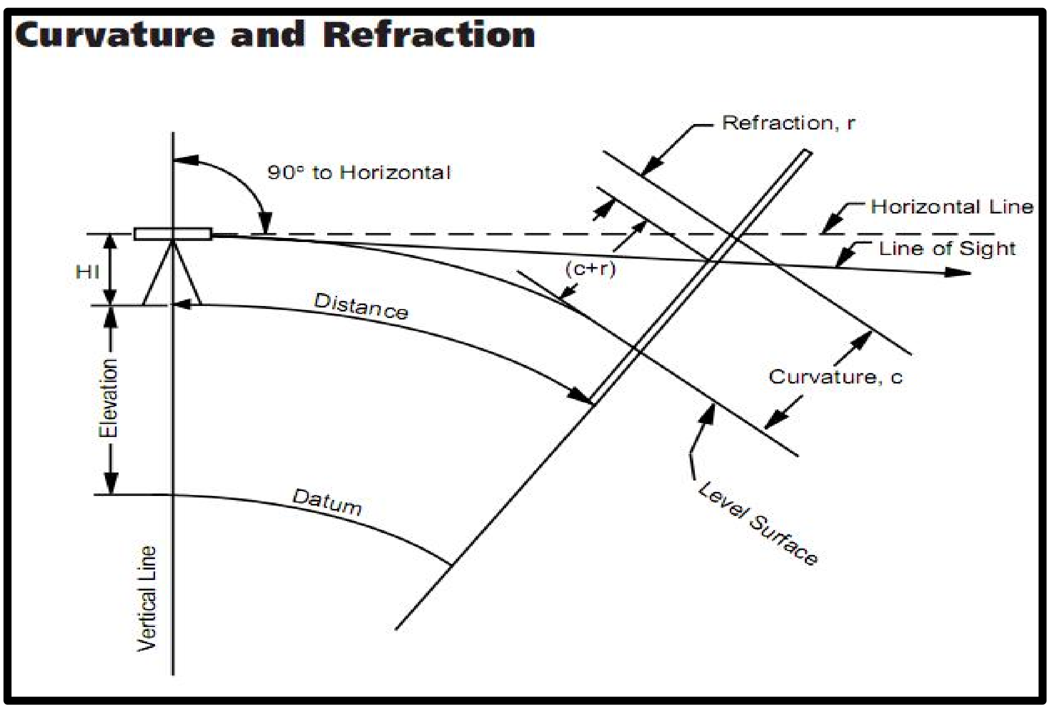


Figure 3.3: Curvature and Refraction. Source: [AboutCivil.org]

3.6 Eliminating error due to Curvature and Refraction

Following proper field procedures (taking shorter shots and balancing shots) can reduce errors. Wherever possible, rod measurements should be kept at least 0.5 m (1.64 ft.) above the ground and short observation distances of 25 m (82 ft.) should be equalized for backsight and foresight readings. The best way to reduce refraction error is to avoid the causes of refraction in the first place. This may be accomplished by:

A. increasing the height of the instrument
B. reducing the sight distance and avoiding unbalanced sights
C. taking advantage of cloudy and breezy days to run levels
D. keeping the line of sight at least 0.5 m (1.64 ft.) above the ground (or any intervening object) at all points (required)
E. avoiding positive temperature gradient conditions
(usually at night)
F. conducting observations during the time interval from 2.5 hours after sunrise to 0.5 hours before sunset.

3.7 Leveling Collimation Error

Collimation error occurs when the collimation axis is not truly horizontal when the instrument is level (adapted directly from Schomaker and Berry, 1981, pp. 3-29 through 3-36). The effect is illustrated in the sketch below, where the collimation axis is tilted with respect to the horizontal by an angle α:

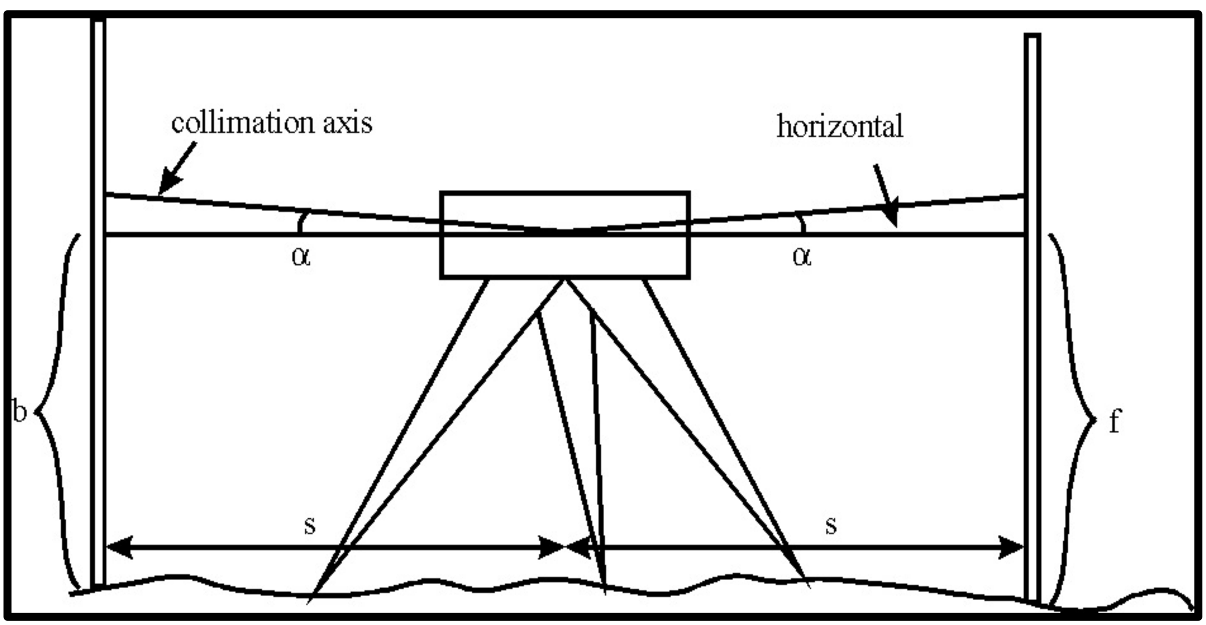


Figure 3.4: Collimation error.

3.7.1 Collimation Check

In the field, the collimation error of a leveling instrument is measured by obtaining a set of observations called the collimation check (Peg-test). Collimation error must be reduced by adjusting the instrument to within a standard accuracy. Because the necessary adjustment can change easily under field conditions (thus changing the collimation error), the collimation check should be made daily with most instruments. In addition, the check should be made any time an instrument sustains a severe shock or seems to function abnormally. The collimation check has two purposes: to determine, against a standard of accuracy, whether the instrument is properly adjusted; and to compute a factor to correct data obtained from imbalanced setups and sections. The error, CR, must be removed from each rod reading. It may be obtained in either one of two ways. The first is to look it up as a function of the sighting distance as listed in Table 3.2. The second, more precise way, is to compute it as a function of both sighting distance and a formula for temperature differential (Jordan, et al., 1956). Table 3.2 is the result of computations using the temperature differential formula and assuming average temperature gradients at a height of 1.5 m (5 ft.) under daytime conditions. Distances given are for sight lengths permitted by either Kukkamaki or 10-40 methods for collimation check.

Table 3.2: Curvature and refraction corrections for single sights.

DISTANCE		**CORRECTION TO ROD READING (CR)**	
METERS	FEET	MILLIMETERS	FEET
10	33	-0.02	-0.0001
20	66	-0.07	-0.0002
30	98	-0.15	-0.0005
40	131	-0.27	-0.0009
50	164	-0.42	-0.0014
60	197	-0.60	-0.0020
70	230	-0.81	-0.0027
80	262	-1.06	-0.0035
90	295	-1.34	-0.0044

3.7.2 Standard of accuracy for collimation error

In a properly adjusted instrument, the collimation error should be no more than ± 10.0 arc-seconds ($C < \pm 0.05$ mm/m). If an instrument exceeds this tolerance, it must be adjusted and another check made. Two methods of observation are included in the procedure for the collimation check.

3.7.3 Collimation error

During the collimation check, the angular value of the collimation error is determined. The tangent of the angular value is computed in mm/m. If the first setup is balanced and the second unbalanced (as for the Kukkamaki method given in 3.8), then:

$$C = \frac{\Delta h_1 - (\Delta h_2 - CR)}{\Delta S_2} = \frac{\Delta h_1 - \Delta h_2 + CR}{\Delta S_2}$$

where Δh_1 = difference in elevation, setup 1
Δh_2 = difference in elevation, setup 2
ΔS_2 = unbalanced distance, setup 2
CR = sum of curvature and refraction error ($-CR_b + CR_f$), the error being opposite in sign of correction in Table 3.2.

If both setups are unbalanced by the same amount, and they are leveled in opposite directions, then the corrected elevation differences are opposite in sign, and:

$$C = \frac{(\Delta h_1 - CR1) + (\Delta h_2 - CR_2)}{\Delta S_1 + \Delta S_2}$$

Since $\Delta S_1 = \Delta S_2$ and $CR_1 \cong CR_2$, the formula can be simplified to:

$$C = \frac{(\Delta h_1 + \Delta h_2) - 2CR}{2\Delta S}$$

The elevation differences, the curvature and refraction errors, and the imbalances should be measured in the same units; the resulting collimation error is a nondimensional value. For convenience, however, it is often expressed in millimeters per meter. If the collimation error is not within the tolerance for the survey, the instrument must be adjusted. When adjustment can be made in the field, the amount of error to be removed is computed from the following formula. It is referenced to the rod at the farthest sighting distance, S_F, and computed in rod units:

$$\text{error}_F = S_F + \times C_{mm/m} \times \text{conversion factor}_{\text{rod unit/mm}}$$

The error is subtracted from the last reading made on the far rod. The instrument is then adjusted in such a way that the corrected reading is observed. After performing the adjustment, the entire procedure should be repeated in order to compute and check the new collimation factor.

Note that the quantity *C*, commonly used to correct data from three-wire leveling, is not the collimation error. In the past, *C* has been defined as the product of the stadia factor and the tangent of the collimation error. This was done so that the imbalances, expressed in units of stadia interval, could be converted to units of distance at the same time that a correction for collimation error was applied to the leveling data. Modern instruments, rods, and computers make this practice unnecessary.

3.7.4 General instruction for the collimation check

Two methods sufficiently precise to satisfy the purpose of the collimation check are presented here. However, the accuracy of the result with either of these methods depends on the assumption that the error observed is entirely a function of collimation error. Other effects that alter the line of sight, such as refraction, must be controlled. To achieve this:

A. make the collimation check on uniformly flat ground, the slope of which should be less than 2%,
B. make the check only when the temperature gradient is negative (temperature decreases with height). If thermistors are not available, make the check at least 3 hours after sunrise on sunny days, or at least 5 hours after sunrise on cloudy days (this instruction may be disregarded if a damaged instrument check is conducted immediately following an accident; in this case, another check should be made as soon as the negative gradient conditions can be met),
C. allow the instrument and leveling rods to acclimatize for at least 5 minutes after removal from their cases.
D. make sure that the circular bubble levels on the instrument and rods are properly adjusted.
E. correct for curvature and refraction.

3.8 Kukkamaki method

The Kukkamaki and the Förstner and Näbauer methods are both acceptable methods for making the collimation check. This section provides detailed instructions on performing the Kukkamaki method. The procedures for performing the Förstner and Näbauer method are detailed in the *User's Guide for Electronic Levels Using Translev and Windesc*.

The Kukkamaki method for making a collimation check was developed by T.J. Kukkamaki of the Finnish Geodetic Institute (*NOAA Manual NOS NGS 3, Geodetic Leveling,* 1981). The method is especially suitable for an instrument whose collimation error changes when refocused. This change may be unacceptable with the more imbalanced setups of other methods (such as the 10-40 method). This method is currently used where optical leveling is acceptable.

The following instructions apply to any instrument-rod combination. Record data on a standard recording form.

A. On the flattest possible ground, lay out a setup with precisely 20 m (66 ft.) between the turning points (using a tape to measure this and all other distances).

Position the instrument on a line between and precisely 10 m (33 ft.) from each turning point (Figure 3.5).

B. In the Remarks column of the recording form (NOAA FORM 75-29), enter the instrument type and serial number, rod type and serial numbers, and the names of the observer, recorder, and rodman. Check all serial numbers against the equipment actually used. Label the recording form Kukkamaki Collimation Check (Figure 3.5).

C. First setup - Level the instrument. Check that the circular levels on the instrument and the rods are properly adjusted. Observe and record a set of readings by either the micrometer or three-wire procedure. Use Rod 1 as the backsight. Check that the imbalance is no more than 0.4 m (1.3 ft.).

D. Second setup - Position the instrument in line with the turning point 20 m (66 ft.) from Rod 1. With Rod 1 as the backsight, observe and record another set of readings. Check that the distances are between 19.6 m and 20.4 m (64.3 ft and 66.9 ft.). Remain in position until the collimation error has been checked.

E. Convert the elevation differences, Δh_1 and Δh_2 from rod units to millimeters. Look up the values for *CR* at the two sighting distances, 20 m and 40 m (66 ft. and 131 ft.), in Table 3.2 then compute the collimation error by:

$$C = \frac{(\Delta h_1 - \Delta h_2) - (CR_{20} - CR_{40})}{\Delta S_2}$$

F. Check *C* against the standard using:

$$C \leq \pm 0.05 \text{ mm/m}$$

If the standard is exceeded, adjust the instrument as follows:

G. Compute the error, in rod units, resulting from the collimation error in the reading made at 40 m (131 ft.) with:

$$error_{rod\ units} = 40 \text{ x } C \text{ mm/m}^{x\ conversion\ factor} \text{ rod units/mm}$$

For half-centimeter rods, the correction to the foresight readings is 8*C*. For centimeter rods, it is 4*C*. Subtract this value from the foresight reading, obtained on Rod 2 during the second setup. The result is the reading that should be obtained after adjusting the instruments. The instrument must not be moved until the adjustment is completed. Refer to the instrument manual for the mechanics of adjusting the instrument.

H. While still in position for the second setup, point the instrument toward Rod 2 and adjust the instrument until the line of sight intercepts the corrected reading.

I. Repeat the second setup (step D) and compute and check the new collimation error. The Δh_1 remains unchanged.

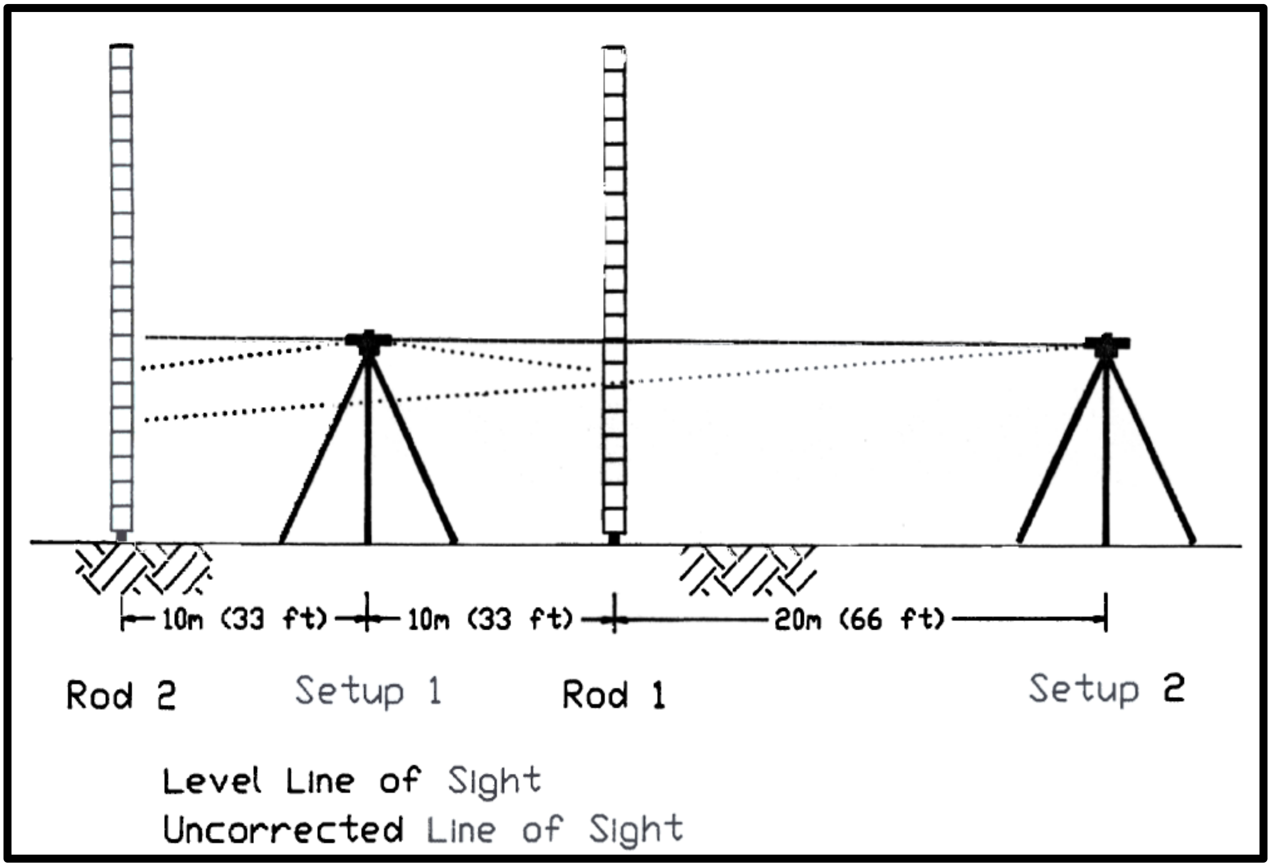
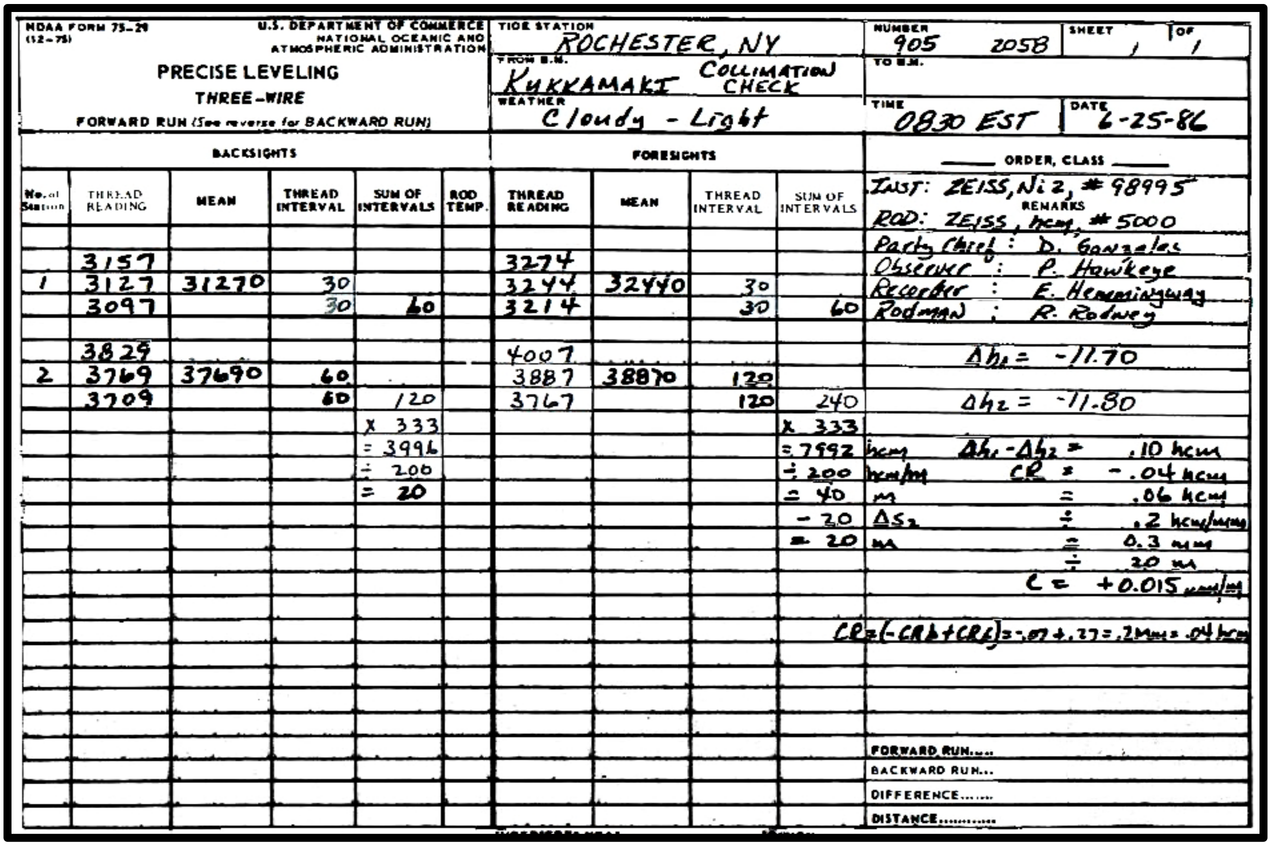


Figure 3.5: Kukkamaki Collimation Check Setup.


NOAA FORM 75-29 (12-75)
U.S. DEPARTMENT OF COMMERCE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

PRECISE LEVELING
THREE-WIRE
FORWARD RUN (See reverse for BACKWARD RUN)

TIDE STATION: ROCHESTER, NY
FROM B.M.: KUKKAMAKI COLLIMATION CHECK
WEATHER: Cloudy - Light
NUMBER: 905 2058
SHEET 1 OF 1
TO B.M.:
TIME: 0830 EST
DATE: 6-25-86

BACKSIGHTS						FORESIGHTS				
No. of Station	THREAD READING	MEAN	THREAD INTERVAL	SUM OF INTERVALS	ROD TEMP.	THREAD READING	MEAN	THREAD INTERVAL	SUM OF INTERVALS	ORDER, CLASS / REMARKS: INST: ZEISS, Ni 2, # 98995
										ROD: ZEISS, hcm, # 5000
										Party Chief : D. Gonzales
	3157					3274				Observer : P. Hawkeye
1	3127	31270	30			3244	32440	30		Recorder : E. Hemmingway
	3097		30	60		3214		30	60	Rodman : R. Rodwey
	3829					4007				$\Delta h_1 = -11.70$
2	3769	37690	60			3887	38870	120		
	3709		60	120		3767		120	240	$\Delta h_2 = -11.80$
				x 333					x 333	
				= 3996					= 7992	hcm $\Delta h_1 - \Delta h_2$ = .10 hcm
				÷ 200					÷ 200	hcm/hm CR = -.04 hcm
				= 20					= 40	m = .06 hcm
									- 20	ΔS_2 ÷ .2 hcm/mm
									= 20	m = 0.3 mm
										÷ 20 m
										C = +0.015 mm/m
										CR = (-CRb + CRf) = -.07 + .27 = .2mm = .04 hcm
										FORWARD RUN......
										BACKWARD RUN...
										DIFFERENCE.......
										DISTANCE...........

Figure 3.6: Example of Kukkamaki Collimation Check Calculations.

3.9 10-40 method

The 10-40 method for making a collimation check is so called because each setup is unbalanced, with one rod 10 m (33 ft.) and the other 40 m (131ft.) from the instrument (*NOAA Manual NOS NGS 3, Geodetic Leveling,* 1981)

The following instructions apply to any instrument-rod combination.

A. On the flattest possible ground, lay out a setup with precisely 50 m (164 ft.) between the turning points (using a tape for measurement). Position the instrument in line between the turning points, precisely 10 m (33ft.) from Rod 1. (Figure 3.7)
B. In the Remarks column of the recording form (NOAA Form 75-29), enter the instrument type and serial number, rod type and serial numbers, and the name of the observer, recorder, and rodman. Check all serial numbers against the equipment actually used. Label the form 10-40 Collimation Check.
C. First setup - Level the instrument. Check that the circular levels on the instrument and the rods are properly adjusted. Observe and record a set of readings by either the micrometer or three-wire procedure. Use Rod 1 as the backsight.
D. Second setup - Position the instrument in line between the turning points, precisely 10 m (33 ft.) from Rod 2. Observe and record another set of readings as in step C, using Rod 2 as the backsight.

E. Convert the elevation differences, Δh_1 and Δh_2, from rod units to millimeters. Look up the values for *CR* at the two sighting distances, 10 and 40 m (33 and 131 ft.).
   Compute the collimation error, in millimeters per meter, by the following formula:

$$C = \frac{(\Delta h_1 + \Delta h_2) - 2(CR_{10} - CR_{40})}{\Delta S_1 + \Delta S_2}$$

F. Check the collimation factor against the tolerance.

$$C \leq \pm 0.05 \text{ mm/m}$$

   If the tolerance is exceeded, adjust the instrument as described in steps G-I of the Kukkamaki method. Repeat the first setup.

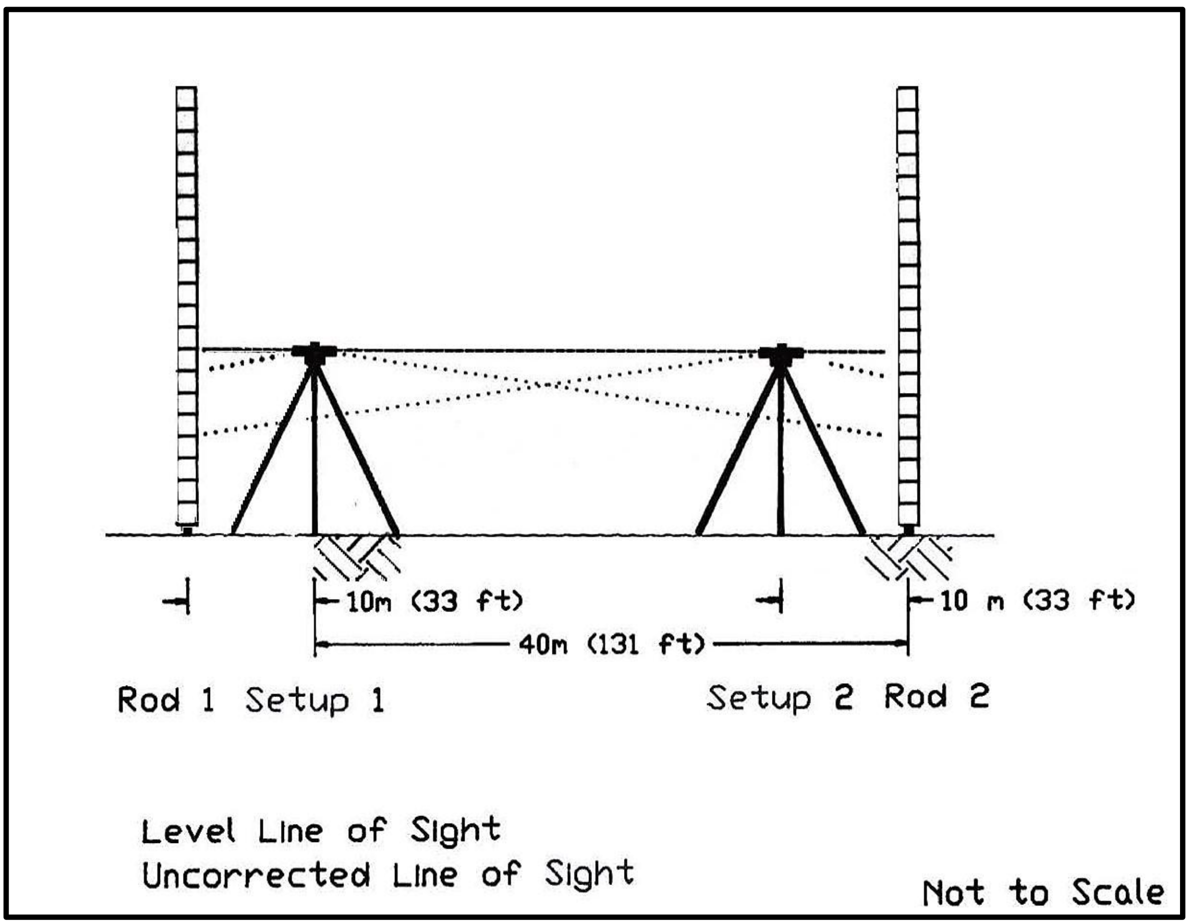
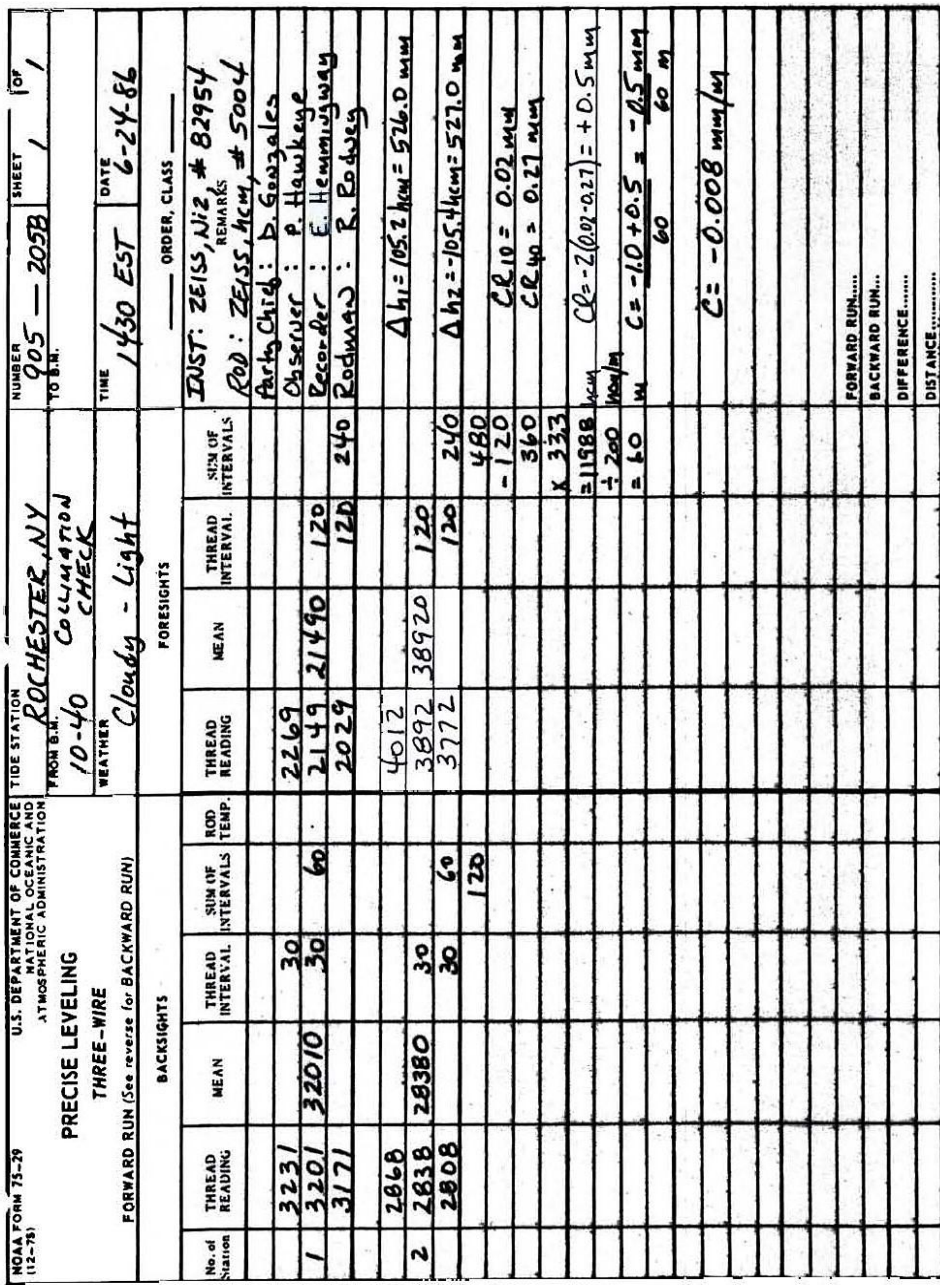


Figure 3.7: 10-40 Collimation Check Setup.



NOAA FORM 75-29 (12-75)
U.S. DEPARTMENT OF COMMERCE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
TIDE STATION ROCHESTER, NY
NUMBER 905 — 205B
SHEET 1 OF 1

PRECISE LEVELING
THREE-WIRE
FORWARD RUN (See reverse for BACKWARD RUN)

FROM B.M. 10-40 COLLIMATION CHECK
TO B.M.
WEATHER Cloudy - Light
TIME 1430 EST
DATE 6-24-86
ORDER, CLASS

No. of Station	BACKSIGHTS Thread Reading	Mean	Thread Interval	Sum of Intervals	Rod Temp.	FORESIGHTS Thread Reading	Mean	Thread Interval	Sum of Intervals	Remarks
										INST: ZEISS, Ni2 # 82954
										ROD: ZEISS, hcm, # 5004
	3231		30			2269				Party Chief: D. Gonzales
1	3201	32010	30	60		2149	21490	120		Observer: P. Hawkeye
	3171					2029		120	240	Recorder: E. Hemmingway
										Rodman: R. Rodney
	2868					4012				Δh_1 = 105.2 hcm = 526.0 mm
2	2838	28380	30			3892	38920	120		
	2808		30	60		3772		120	240	Δh_2 = -105.4 hcm = 527.0 mm
				120					480	
									-120	CR10 = 0.02 mm
									360	CR40 = 0.27 mm
									x 333	
									= 11988 hcm	CR = -2(0.02-0.27) = +0.5 mm
									÷ 200 hcm/m	
									= 60 m	C = $\frac{-1.0+0.5}{60}$ = $\frac{-0.5 \text{ mm}}{60 \text{ m}}$
										C = -0.008 mm/m

FORWARD RUN....
BACKWARD RUN...
DIFFERENCE......
DISTANCE.........

SUPERSEDES NOAA FORM 75-29, 11-72 EDITION, WHICH IS OBSOLETE

Figure 3.8: Example of 10-40 collimation check calculation.

3.10 Compensation check

When an automatic leveling instrument is approximately leveled, the compensator should be freely suspended, unaffected by its suspension and dampening mechanisms. The range of arc in which the compensator is expected to suspend freely should be somewhat greater than the arc described by a 2-mm movement of the bubble in the circular level. Thus, when the circular level is properly adjusted, the compensator should provide a line of sight having the same collimation error, within ±2 arc-seconds (±0.0097 mm/m) , no matter which direction the instrument is pointed.

A compensator, however, may hang or stick in such a way that releveling or repositioning may not remove all the error introduced. The observer should lightly tap each side of the instrument to make sure the image oscillates.

3.11 General Observing Routine

Rodman A holds the rod plumb on the starting mark (usually the staff stop or ETG reading mark). The observer sets up a maximum of 60 m (200 ft.) away for Second-order leveling or 90 m (300 ft.) for third-order. Rodman B paces the distance from A to the instrument, walks the same distance past the instrument toward the next mark, sets a turning point, and holds Rod B plumb (both rodmen must keep the bottom of the rods clean). The observer takes a backsight on Rod A [keeping the line of sight at least 0.5 m (1.64 ft.) above the ground], then a foresight on Rod B. Rodman A and the observer move to the next setup, Rod A pacing the distance as Rod B had done on the previous setup. The observer then takes a backsight on Rod B and a foresight on Rod A.

This procedure is repeated throughout the forward and backward runs of the level circuit. When a single rod is used, the time between backsight and foresight should be kept to a minimum. The instrument shall be off-leveled (physically moving the tripod) and releveled after the last foresight on the forward run, even though the instrument location does not change. This ensures that the backward and forward readings on the last mark are independent.

3.12 Parallax

The cross hairs in the level instrument must lie in the common focal plane of the objective and eyepiece lenses. This is done by focusing the instrument on a distant light-colored object (sand, sky) and then focusing the cross hairs with the eyepiece. When in focus, the observer can move his eye up and down and the cross hairs will not move with respect to the level rod.

3.13 Balanced Sights

Forward and backward sights must be nearly equal in length in order to minimize the errors due to curvature of the earth and the collimation error of the instrument. The maximum allowable difference between forward and backward sights per setup is 5 m (16 ft.) for Second-order leveling and 10 m (33 ft.) for Third-order. The maximum cumulative difference between forward and backward sights between marks is 10 m (33 ft.) for both Second and Third-order leveling. These lengths are determined by stadia readings for Second-order and pacing for Third-order. The instrument normally should not be refocused between backsights and foresights.

3.14 Sight Length

The maximum length of sight is 60 m (197 ft.) for Second-order and 90 m (295 ft.) for Third-order. Normally, the sights should be shorter due to scintillation, wind, or haze. In any instance, the sight must be short enough to eliminate uncertainty in the reading. The sighting distance (S) between the instrument and a leveling rod is observed and computed by the Stadia method:

S = [I x Stadia Factor] + Stadia Constant,

where I is the Stadia Interval such that:

I = upper rod reading - lower rod reading in rod units.

S is the Stadia Factor is a dimensionless number, usually a function of the spacing of the upper and lower stadia lines in the reticle (in most instruments it is 100:1 or 333:1), and Stadia Constant is the distance from the instrument to the point from which the Stadia Factor is used to determine sighting distance (in most instruments with internal focusing telescopes, as in the Zeiss Ni2, the stadia constant is equal to zero). The use of the above formula will result in distances in rod units. These units are to be converted to meters or feet and ultimately to kilometers or miles.

3.15 Atmospheric Conditions

During precise leveling, atmospheric conditions must be determined. The purpose is twofold; to correct for the effects of atmospheric refraction on the line of sight and to correct for effects of thermal expansion of rod scales. The three measurements to be recorded for each section of leveling are air temperature, solar radiation intensity, and wind speed (*Balazs and Young* 1982). Air temperature is measured to the nearest degree and recorded in the appropriate measurement unit at the beginning and ending of every section.

Solar radiation should be recorded as:
- Overcast - fewer than 25 percent of setups performed under sunny conditions,
- Cloudy - 25 to 75 percent of setups performed under sunny conditions, and
- Clear - more than 75 percent of setups performed under sunny conditions.

Wind speed should be estimated and recorded as:
- Light - wind speed averaged less than 10 km (6 mi.) per hour,
- Moderate - wind speed averaged 10 to 25 km (6 to 15 mi.) per hour, and
- Strong - wind speed averaged greater than 25 km (15 mi.) per hour.

3.16 Closure Tolerance

The maximum closure tolerance between the forward and backward running of a section is 6 mm√K (0.025 ft.√M) for second-order leveling and 12 mm√K (0.050 ft.√M) for Third-order, where *K* and *M* are the length of the section measured in kilometers and miles, respectively. Closure tolerances for one setup sections, two runnings of sections less than 0.10 km, and all other sections from 0.10 to 1.60 km in length are listed in Table 3.3. If the closure tolerance is greater than allowed, the section shall be rerun until independent forward and backward runs agree within the allowable limits.

Random and systematic errors usually cause some differences in closing. The allowable closure tolerance is used to eliminate blunders and systematic errors too large for the required accuracy. The prescribed procedures minimize systematic errors. Sections with excessive misclosures must be rerun until a satisfactory closure is obtained.

3.16.1 Cumulative Closure

It is possible to have individual sections that by themselves have acceptable closure tolerances, but, when combined, exceed the maximum allowable closure tolerance. The summation of the divergences must never exceed the closure tolerance for the corresponding summation of distance. This may at times require a rerun of the section or sections which individually close but, when combined, do not. For example, two 0.5-km sections, each with differences between forward and backward runs of 0.0040 m, would individually close (maximum allowable 0.0042 m) but, when combined, become a 1.0-km run with a closure of 0.0080 m exceeding the maximum allowable limit of 0.0060 m. A cumulative closure tolerance is exceeded typically when several consecutively run sections are very close to the individual closure tolerances and the divergences all have the same sign. This is particularly apt to occur when one or more very short section (typically the water level sensor or staff for hydrographic surveys, to the first bench mark) barely closes under the one setup closure tolerance as the distance is minimized and the divergence maximized.

A cumulative closure tolerance may also be exceeded by an instrument that is out of calibration. An example of one such condition is where level sections are being run on a fairly steep incline. Refraction is greatest when the top of one rod is read and then the bottom of the other. This error is magnified due to the many setups it may take to run a steep section, even though the actual distance may not be great.

Table 3.3: Maximum closure tolerance. K= Distance of run (one-way) in Kilometers.

DISTANCE (KILOMETER)	**SECOND-ORDER (6 mm √K)**	**THIRD-ORDER (12 mm √K)**
One setup section	.001 Meter	.002 Meter
Two runnings of a section less than 0.10 km in length	.0019 Meter	.0038 Meter
0.1	0.0019	0.0038
0.11	0.0020	0.0040
0.12	0.0021	0.0042
0.13	0.0022	0.0043
0.14	0.0022	0.0045
0.15	0.0023	0.0046

Use the equation as given in section 3.16 to compute the maximum closure tolerance for distances greater 0.15 km.

3.17 Leveling Procedures to the Reading Mark (RM) of the Electric Tape Gage (ETG)

When leveling to the zero of the ETG, a section of calibrated steel tape or a specially designed short rod is held at the center of the RM line. Care must be taken to ensure that the tape is held plumb and that the zero on the tape is held stationary. The tape is read in the same way as a rod. A note is made in the record indicating which of the readings were made on tape, the type of tape, and the graduation units of tape. It is preferable that the graduation interval on the tape be the same as on the rod used in the rest of the section. When the same interval is not available, all graduation conversions are to be recorded and completed on the level record form. This same procedure may be followed when leveling to vertically set marks. In those cases when a tape is read below the reading mark (or vertical mark), the observations are to be entered in proper order (top wire, middle wire, bottom wire), and entered in the proper backsight or foresight columns (but with a negative sign to reflect the down shot). The observation is then computed algebraically with the other observations. Note in Remarks on the level record form that the observation was a tape shot observed below the bench mark, i.e., "Tape down". Refer to section 2.7 of this document for further reading on Reading Marks of the ETG.

3.18 Field Records and Computations

The field notes are the only reliable record of the measurements and other pertinent information obtained. The reliability of these records are questionable unless the records have been entered in the field book at the time and place of observation. If, for clarity, an original record is copied, the original and copy are to be appropriately labeled and submitted together. The record shall always be made in ink and be as neat and clear as possible. No erasures shall be made and no correction fluid used. If an entry is found to be in error, it is crossed out neatly with a single line to retain legibility and the correction entered immediately above. All corrections are initialed by the corrector. All computations shall be checked before leaving the station.

3.19 Abstract of precise leveling

An abstract file shall be generated after completing the Translev and Windesc application with relevant leveling information. Refer to the *User's Guide for Electronic Leveling Using Translev and Windesc* for instruction on how to complete the forms within the application. The NGS applications Windesc and Translev shall be used to generate an abstract sheet for each Second-order, Class I level run. Each abstract sheet shall show the separate results of each running over each section (including rejected sections), the mean difference, the divergence, the length of the section, the designation of each section, the cumulative divergence and distance of each bench mark from the water level sensor or ETG, and the total distance (all spurs) of levels run. Rejected runs are designated by an R placed beside the rejected number.

The field elevations of each bench mark are computed above the published elevation of the PBM. To convert the starting elevation of the staff rod step or PBM from feet to meters, multiply feet by 0.3048, exactly, to obtain meters.

Sections of leveling at each station are arranged in order along the line from the PBM or ETG toward the last bench mark to be leveled. A majority of the bench marks to be leveled shall constitute the main line of leveling. Spur leveling shall be listed following the bench mark on the main line from which the spur departs. Proper notation indicating the spur leveling shall be made in the Remarks column.

The computation of a line of levels is a progressive calculation and to have all the sections in their proper order will not only facilitate the computation, but will make errors in the computed elevations much less likely to occur.

Water level or ETG reading movement in excess of .006 m (0.020 ft.), 0.003m (0.010 ft) for Great Lakes stations, relative to the PBM is indicated by comparing current levels with the preceding levels. If the history of the leveling run does not match with the current run, movement is suspected, another level run (verification run) shall be performed. It shall be performed immediately from the water level sensor or ETG reading mark to a minimum of three marks (including the PBM) in order to verify the movement.

3.20 Use of Collapsible Rods

As discussed previously, Second-order is the required geodetic leveling for all stations. CO-OPS has provided a waiver from Second-order leveling requirement for select NWLON stations in Alaska, Hawaii, and Pacific Islands - mainly because of the airline shipping restrictions for 3-meter level rods. So use of Third-order or lower leveling or optical levels is acceptable for those specific circumstances.

CO-OPS has used collapsible rods for levels in the past. NGS studies have shown that no order of leveling can be achieved with non-geodetic (collapsible) rods and NGS strongly discourages the use of collapsible rods for geodetic leveling.

The use of collapsible and non-barcoded leveling rods, can be approved for use if a waiver is submitted to Engineering Division Chief listing a justification. When approvals are granted for No-order Leveling, CO-OPS recognizes the equipment and procedures for this method are less precise than Second-order leveling. Resource managers should explore situation and specific logistics options to deliver the desired calibrated geodetic rods on site when needed at very remote locations and achieve the desired geodetic leveling results.

The waiver request must describe:

A. The uniqueness of the site
B. Logistics alternatives explored.
C. Costs prohibiting the use of approved level rods.
D. Collimation checks performed comparing level instruments and one-piece 3-meter Invar leveling rods to the selected individual collapsible level rod to be used. Follow the procedures described in the 2011 NGS report, in an environment similar to that expected during the survey trip.
E. Provide the results in an attachment to the request.

NGS reported on the testing and findings for the use of multi-piece rods, non-Invar, as required for precision surveying. This testing was performed at the NGS testing and training center in Corbin, Virginia (Steven, Edward, Kendall, Curt S, December 2011).
The report concluded:

> "*There can be no doubt that one-piece Invar level rods provide the precision demanded by geodetic leveling procedures. Repeatability in measurements throughout this test, both in the lab and in the field, as well as between the different equipment manufacturers provided the precision to meet 1st and 2nd order leveling specifications. The multi-piece leveling rods produced results that strayed from the standard of the 3-meter one piece Invar level rod by 0.5 millimeter to over 1 millimeter in scale difference determined in the lab, and by 0.5 millimeter to 7 millimeters over the course of 180 meters leveled in the field.*

Using the same equipment and following leveling specifications of always starting and ending with the same level rod on a bench mark produced close backward and forward direction leveling elevation differences. However, when observing the tops and bottoms of the leveling rods on sloping terrain, as illustrated during this test evaluation, the variation in the level rod readings does not cancel but accumulates as systematic error.

Different types of multi-piece leveling rods produced varying results based on their construction. These results may vary over time with prolonged field use. If the use of multi-piece level rods for higher order (2nd order, class II or 3rd order) geodetic leveling is considered they should be evaluated shortly before and immediately after any leveling with documented test comparisons supporting any claims of precision. Tests similar to the previously described lab and field tests could support claims that a certain level rod could provide adequate precision for some geodetic leveling over short distances and gentle terrain."

3.21 Tabulation and Computation of Third-order Levels

The equipment and procedures are less precise than for Second-Order Leveling. Only the middle (center) wire is observed and recorded, the length of the sights are balanced by pacing, the closure tolerance of $12\text{mm}\sqrt{\square}$ ($0.050\text{ ft.}\sqrt{\square}$), and non-Invar rods (metal) may be used.

Leveling Record-Tide Station (NOAA Form 76-77) is used to record all field data obtained at the station where Third-order leveling is performed. The station information required on the front of the recording book must be completed and should include: station name, station number, chief of party, observer, rodman, and the instrument and rod(s) (with type, manufacturer, serial number(s) and rod unit graduation). Page three, Description of Tide Staff, must be completed for each level run. New bench mark descriptions or recovery notes need to be recorded on pages 6-13, Description of Bench Mark, or submitted on the appropriate NOAA forms.

The levels are run from the staff or sensor leveling point to each bench mark in line and then back along the same route (if field conditions warrant, a double-run spur line is acceptable). Running loops or observing more than one backsight and one foresight from each individual setup is unacceptable.

3.22 Closure Tolerance

If all leveling errors could be eliminated, section runnings would always agree. However, since this is not possible, tolerances have been set to ensure that accepted runnings disagree by no more than an amount consistent with the precision of the prescribed leveling method. When multiple runs of a section disagree by more than the tolerance, blunders or excessive systematic errors may have occurred, and the section shall be rerun.

3.23 Closure procedure

Whenever a section is double-run, check that the difference between the two levels agree within the tolerance for the order and class of the survey.

A. Compute the difference between the two leveling runs. Because they are opposite in sign, this is the backward run plus the forward run. As a matter of convenience, the divergence is opposite in sign from the difference.
B. Compute the tolerance for the distance leveled, *K*. It is T x $\sqrt{K}$, in millimeters, where *T* is the factor for the order and class of the survey (6mm $\sqrt{K}$ for Second-order, Class I, and 12 mm $\sqrt{K}$ for Third-order), and *K* is the one-way distance (shortest if more than one) in kilometers. For example, if the distance leveled is 1.6 km, and the survey is Second-order, Class I, then: Double-run Tolerance = 6 mm x $\sqrt{1.6}$ = ±7.6 mm
C. If the divergence from step A is within the tolerance from step B, the section is closed; additional runs are not required unless water level sensor or bench mark movement is determined. If the divergence exceeds the tolerance, relevel and recheck the section to satisfy two criteria: (1) that all runs likely to contain blunders or systematic errors are rejected, and (2) that at least one forward and one backward run are acceptable. Use the rejection procedure, given below, to determine statistically unreliable runs.
D. When releveling to close the section, alternate the direction of leveling to maintain an equal number of forward and backward runs. If systematic error persists in the leveling, the mean of all the elevation differences may be biased in favor of the majority direction. Equalizing the number of runs in each direction prevents this bias.

3.24 Rejection procedure

After three or more runs of a section, check for agreement as follows:

A. Compute the mean of all runs, disregarding their signs. Do not include runs with obvious blunders.
B. Compute the difference between this mean and each run.
C. Compute the allowable difference from the mean of more than two runs. It is based on the order and class of the survey, the number of runs which were averaged, and the distance leveled. The formula is T x $\sqrt{K}$, where *T* is the approximate factor from the following table and *K* is the section length in kilometers. For a section less than 0.10 km in length, *K* = 0.10 km.

Table 3.4: Tolerance T factors for closing multiple runs.

Number of Runs	Second-order, Class I (mm)	Third-order (mm)
3	4.21	8.44
4	4.66	9.34
5	4.96	9.95
6	5.19	10.40
7	5.36	10.70
8	5.51	11.00

D. Reject any run outside the allowable difference from the mean.
E. Check the remaining runs to see if there is at least one forward and one backward. If there is, and none were rejected in step D, the section is closed. If one was rejected, compute a new mean with the remaining runs and return to step B. If only runs in one direction remain, relevel the section in the opposite direction and begin again at step A.

Notice that certain runs, rejected when the number of runs were three or four, may now be accepted when the total number increases. This is because the accuracy of the mean improves with a larger sample of data; i.e., it becomes easier to recognize when a run is different enough to be considered a blunder.

If, for any reason, a run is rejected for any cause other than excessive divergence from the indiscriminate mean of all the runs for that section, the reason for rejection shall be clearly stated in the remarks.

3.25 Special Cases: Water Crossings, Precise Reciprocal Leveling, and Unbalanced Sights

Terrain and leveling conditions often force leveling parties to use other than standard procedures to accomplish their mission. Three methods for overcoming certain obstacles are outlined in the order of quality of their results (and the magnitude of the obstacle they overcome).

3.25.1 Water Crossings

Special methods requiring reciprocal observations and special equipment have been developed for determining elevation differences for offshore station platforms and/or to extended level lines across spans where the distance exceeds the maximum tolerable sight length, for standard leveling procedures. These methods are used to increase accuracy by minimizing the error in the collimation of the instrument and refraction of the atmosphere, and by eliminating the effect of the curvature of the Earth.

The method, which is detailed in (*NOAA Manual NOS NGS 3, Geodetic Leveling, Chapter 4,* 2015) requires:

A. two observation stations
B. four level instruments (Zeiss Ni2) mounted on two specially designed tribrachs
C. four rotating optical wedges
D. two specially designed Invar rods and targets.

This system has proven itself on projects involving sights of more than 4 km (2.5 mi.) with first-order results.

3.25.2 Precise Reciprocal Leveling

Simultaneous reciprocal observations are made at each of two points. The success of this method, like all reciprocal leveling, depends on the equality of the refraction over the line in opposite directions. To secure this equality, the lines of sight at both ends should be about equal, the instrument (at both ends) should be at approximately the same height, and the lines of sight should have the highest practical clearance over land and water. For water crossings up to 600 m (1968.50 ft.), this method is designed to obtain Second-order accuracy.

Two instruments (equipment with optical micrometers) with known acceptable collimation errors and two level rods (each equipped with a target) are set up as shown in Figure 3.8. The graduation units of the plate micrometers are to be compatible with the rod unit graduations.

Each observer directs the far rodman by radio (or suitable visual means). The target is positioned in line with the center cross hair of the instrument and within the range of the micrometer such that the optical micrometer is at about one-half its vertical rotation range. The target heights are then recorded. Each observer reads the close rod (be sure to check minimum focus) and records that reading. Simultaneous readings on the far rod, using the micrometer only, are conducted every 30 seconds until ten readings have been obtained. The micrometer readings and the beginning and ending time of the readings are recorded. This completes half the observations in the set (run 1). The mean of the differences observed from each side is one observed difference between the bench marks.

The observers then change places, taking their instruments with them, but leaving the tripods and rods in place. The reading sequence is repeated in order to obtain another 10 readings (run 2). This completes one set of reciprocal observations. The final rod readings are the target heights plus the average micrometer readings. Individual differences in elevation vary considerably. This is because the readings have not been corrected for instrument error, earth's curvature, or variations of refraction. The observing program and computation procedures are so arranged, however, that these effects are minimized in the mean of the runs.

The final elevation difference for a set of observations is the mean of the two runs. The mean of a run is determined as in standard leveling procedures. The distance is determined by reading the three cross hairs directly on the far rod from one of the setups (visibility conditions may require use of the target to make these readings), or by scaling from a map. At stations where more than one set of reciprocal observations are required, the final elevation difference will be the mean of paired sets of observations retained after rejections required by the closure tolerance. Specific observation requirements will be specified in project Instructions or contract documents.

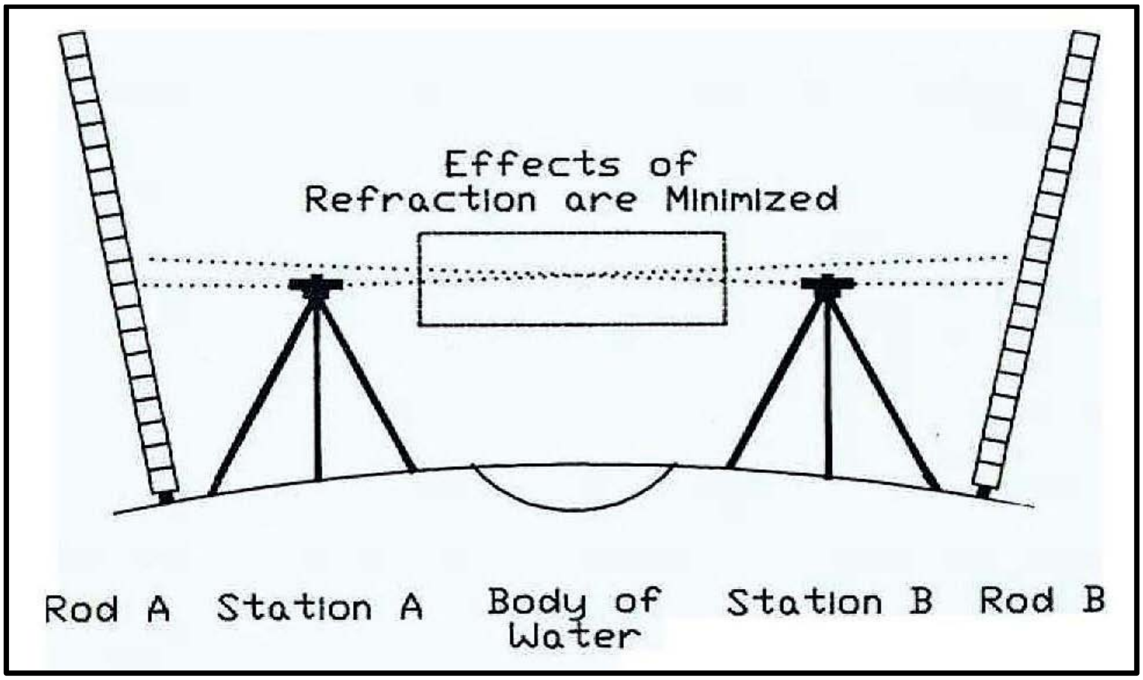


Figure 3.8: **Precise Reciprocal Leveling.**

3.25.3 Unbalanced Sights

For staffs positioned up to 150 m (500 ft.) offshore, unbalanced sights may be used. Since curvature errors do not cancel in a non-simultaneous, nonreciprocal leveling observation, the total correction to the offshore rod reading is the algebraic sum of the collimation and curvature corrections.

The collimation error in the instrument is determined by running a collimation check just before the unbalanced setup. The collimation check must be submitted with the leveling data. The correction to the offshore rod reading would be the value times the imbalance (offshore distance minus land distance). The curvature corrections are computed from the imbalance, Δs and the mean radius of the earth, r: - ($\Delta s^2/2r$), where r = 6,378,000 m. Three wires shall always be recorded (even for Third-order levels with excessive sight lengths). All attempts will be made to follow the precautions to minimize refraction. Specific observation requirements also will be specified in Project Instructions or contract documents for unbalanced sights.

3.26 Trigonometric leveling

CO-OPS has currently approved the use of Trigonometric (Trig) leveling only for determining the elevation of the air gap sensor, and the first level section from the sensor on the Single Pile Instrumentation Platform (SPIP) or an elevated platform to the nearest bench mark or TBM. As more data is collected in the future, CO-OPS will adjust these requirements as appropriate.

For primary water level sensor(s) installed on SPIP, elevated platform, or for determining the elevation of the air gap sensor, trigonometric leveling using the Total Station leveling equipment can be used to connect to the nearest land bench mark. Trigonometric leveling involves measuring a vertical angle from a known distance with a theodolite and computing the difference in elevation of each of the points from the instrument. With this method, vertical measurements can be made at the same time horizontal angles are measured for triangulation. For each section of a trigonometric survey, there is one backward run and a forward run. Both the backward and forward readings consist of a series of direct and reverse point readings. Each set of readings consisting of direct and reverse reading that is averaged, standard requirement being within 6 mm or each reading.

The procedures for Trig Leveling to the water level sensor or air gap sensor are as follows:

A. Ascertain that the total station equipment is setup to apply the combined curvature/refraction error automatically to negate the unbalanced measurement error. If this is not possible, then the error must be removed during the post processing of data.
B. Using good quality and calibrated meteorological sensors, take precise temperature/pressure/humidity readings at both end of the section (TBM to sensor). Then the mean values should be used as an input for the parts per million correction into the instrument. The level connection between TBM, PBM and all other BM in the network shall be done using the electronic levels (Second-order, Class 1).
C. For new sensors (where previous Trig leveling history is unavailable), take at least eight consistent readings of forward and backward readings using the total station, and all eight of these readings must match within 6 mm tolerance, if not, take additional readings as necessary until at least eight consistent readings are recorded for new sensors; readings not meeting the tolerance can be ignored. The mean (average) value of these eight sets of consistent readings shall be used on the level abstract to derive the elevation for the first time.
D. For sensors where we have trigonometric leveling history (i.e. 2nd year onwards), take at least eight readings of forward and backward readings using the total station, and four out of eight readings must be within 6 mm tolerance, then the other four readings can be ignored. If four readings cannot be taken within 6 mm tolerance, take additional readings as necessary until at least four consistent readings are taken. The mean value of these four sets of consistent readings shall be used on the level abstract. All measurements shall be submitted as part of the leveling metadata.

Chapter 4 - GPS

Once the leveled heights (with respect to Station Datum) are obtained via double-run, Second-order, Class I geodetic leveling according to FCGS standards and specifications, all marks will in the future be connected to the NSRS via GPS observations, following NGS' "Leveling with GPS" procedures (in prep.). This will allow all bench marks, including the PBM, to have heights in the NGS Integrated Data Base (IDB) with respect to the National Vertical Datum, published in NGS Datasheets to the nearest cm. The NGS IDB will maintain the original high precision heights with respect to Station Datum, for comparison to routine check leveling.

Refer to Chapter 2 of this document to properly select a GPSBM and to the SOP *User's guide for GPS observations at tide and water level station bench marks Updated March 2013.* The guide was developed in a coordinated efforts with National Ocean Service (NOS), National Geodetic Survey (NGS), to obtain relative accuracy in connecting water level stations to the International Terrestrial Reference Frame (ITRF) and the North American Datum of 1983 (NAD 83) coordinate systems. This guide documents requirements to perform a GPS occupation session on a selected GPS bench mark as well as retrieving the required solutions and datasheet from the Online Positioning User Service (OPUS). CO-OPS' requirement is to occupy a bench mark (preferably the PBM) for a 4-hour session then retrieve the OPUS datasheet that contains the Ellipsoid and the Orthometric height. The GPS bench mark must be included in the geodetic survey before or after the GPS session, but during the same station visit. The current GPS requirement is to repeat the GPS occupation on the bench mark every 5 years with the exception of the Gulf and Alaska regions because of the sea level change in those areas. The GPS frequency requirement for select stations in the Gulf and Alaska region is once every year in coordination with the annual inspection and the annual survey of the bench mark network. In the near future, the portion of the guide referring to the 4-hour GPS occupation on a single bench mark may be updated to require simultaneous 24-hour GPS occupation on two bench marks that are 0.5km (0.31 mi.) apart. Longer GPS observation on two bench marks that are well spaced out increase the accuracy of the tie to National Spatial Reference System (NSRS) via the Orthometric height.

There are ongoing efforts as this document is written to use cGPS technology to monitor vertical land motion. CO-OPS has begun work that will study cGPS technology and has already deployed working groups within CO-OPS coordinated with NGS guidance. In the coming years, CO-OPS will develop an operational plan to utilize cGPS technology to supplement geodetic leveling. This document will then need to be updated to reflect the new and approved methodologies for cGPS usage.

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