

Procedures for Connecting SET Bench Marks to the NSRS

Establishing GNSS-derived ellipsoid/orthometric heights
on Surface Elevation Table Bench Marks

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PURPOSE AND SCOPE OF DOCUMENT

These guidelines were developed in response to a growing interest in accurately measuring local sea level rise in relation to coastal land elevation. Central to this task is obtaining accurate and precise connections between wetland surface elevation and local water levels. For over a decade, Surface Elevation Tables (SETs) have been used to measure and monitor coastal wetland surface elevation with respect to an in situ vertical bench mark. However, these bench marks, often located in remote coastal settings, have traditionally been isolated from consistent spatial reference. These guidelines were developed to provide the necessary information to bring ellipsoidal heights to SET bench marks via Global Navigation Satellite System (GNSS) technology. Once vertical control has been established in a coastal wetland setting, other coastal observing systems can likewise be connected, such as local water level recorders, permanent vegetation monitoring plots, etc. Furthermore, by connecting SET bench marks to a consistent vertical framework, the vertical velocity of the bench mark can be measured over time, providing information on local rates of deep subsidence.

Bringing accurate and precise elevations to remote coastal wetland settings is fraught with difficulties and logistical constraints. Surveying has traditionally avoided the typically unstable, unconsolidated, and very dynamic wetland soils. Survey methods have to be adapted to this environment, also taking into consideration minimizing impacts to the sediment surface which is being measured. This document draws on extensive field trials conducted at SET sites distributed across southeastern Louisiana, in collaboration with the University of New Orleans, the US Geological Survey, and the Louisiana Department of Natural Resources.

The main body of this manual provides the user with basic information on how to conduct a GNSS campaign in coastal wetland settings. The document is designed to help the user decide where and when to use static GNSS observations on SET foundations, and when to use Real-Time Kinematic GNSS (RTK) techniques. Guidelines are given for conducting both types of campaigns. The guidelines cover procedures from designing to the execution of a GNSS campaign, and the subsequent data processing and submission. A detailed glossary is given, including the acronyms used throughout the text. The main body of the guidelines concludes with a list of references. In one of several attachments, the guidelines provide several examples of static and RTK campaigns that were conducted in southeast Louisiana. Another attachment provides detailed information on how to establish a vertical point of reference on a SET bench mark. The third and fourth attachments describe the use of two different custom-made GNSS antenna adapters for SET foundations. Finally, the fifth attachment provides guidelines on how to transfer the elevation of a SET foundation to the height of the SET measuring instrument when it is deployed on the foundation. This allows individual observations of wetland surface elevation to be expressed in relation to a vertical geodetic datum.

INTRODUCTION

Connecting SET Control Monuments to the NSRS

Traditional leveling and GNSS survey procedures are not necessarily well suited for work in flooded, unstable, and often very remote coastal wetland sites. In addition, SET bench marks were not originally designed to accept a GNSS antenna. For these reasons, the NOAA National Geodetic Survey tested new methodologies and techniques specifically adapted to bring accurate vertical control to SET foundations. As a result of extensive field tests, NGS is able to provide guidelines for ensuring successful GNSS-derived ellipsoid/orthometric heights on Surface Elevation Table bench marks (SET BMs) relative to the National Spatial Reference System (NSRS). The term “bench mark” to the geodetic community, is an object, commonly a disk or rod with a well-defined marked point (hereafter referred to as a Vertical Point of Reference, or VPR) whose height is referenced to the NSRS (NGS 2001). The SET community uses the term “SET bench mark” to describe any rod or pipe that supports a SET measuring instrument. With the release of these guidelines, it is hoped that all SET BMs eventually will fit the definition of a geodetic bench mark. In that spirit, these guidelines will refer to a SET pipe or rod as a BM or SET BM. The procedures described herein were field tested and verified in a cooperative pilot project in southeastern Louisiana.

The SET is a leveling device designed to sit on a permanent bench mark pipe or rod and measure changes in elevations in inter-tidal and sub-tidal wetlands (Boumans and Day 1993, Cahoon et al. 1995). Once installed on the bench mark, the SET establishes a constant reference plane with respect to the bench mark, allowing for repeated measurements of the sediment surface with a high level of accuracy (Cahoon et al. 2002).

Surface Elevation Table (SET)

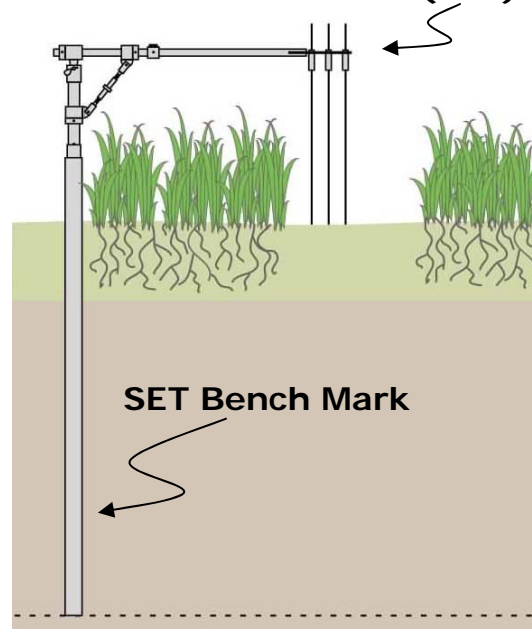


Figure 1 A reference plane, parallel to the equipotential surface, is established when the Surface Elevation Table (SET) instrument is deployed atop the bench. Drawing courtesy of Don Cahoon, USGS

The vertical constancy of the reference plane within the NSRS, however, has been only as reliable as the vertical stability of the BM that supports the SET. A major function of the NGS and its predecessors has been to develop and utilize guidelines for establishing BMs of the highest quality and stability, which includes a standard for rods driven to refusal (Floyd 1978). In lower Louisiana, even deep-set steel rods that were driven to the NGS's refusal standard have shown a significant amount of vertical displacement attributed to land subsidence. For example, three NGS BMs used in this pilot project were found to have vertical velocities ranging from -5.37 mm/yr to -12.68 mm/yr (Shinkle and Dokka 2004). By knowing the height of a SET BM in relation to the NSRS, it is possible to establish and accurately monitor changes in vertical elevation change of the marsh surface relative to the NSRS without regard to the immediate stability of the SET BM.

The NGS defines the NSRS as the official system of the federal government which allows a user to determine geodetic latitude, longitude and height, plus orthometric height, geopotential, acceleration of gravity and deflection of the vertical at any point within the United States or its territories. Furthermore, the NSRS encompasses the official national shoreline of the United States. The NSRS contains information about its orientation and scale relative to international reference frames, as well as the precise orbits of all satellites used to define, realize or access the NSRS. Lastly, the NSRS also contains all necessary information to describe how all of these quantities change over time (NGS 2007).

Connecting SET BMs to the NSRS creates a relationship with two important national vertical datums. Currently, the federal government officially recognizes the North American Datum of 1983 (NAD 83), which uses the Geodetic Reference System of 1980 (GRS 80) ellipsoid as the reference surface for three-dimensional positions, e.g. XYZ Cartesian coordinates, geographic coordinates and ellipsoidal heights, etc. This is the ellipsoid and datum for all NGS published positions and ellipsoidal heights. Ellipsoidal height refers to the height of the BM in relation to the surface of the NAD 83 ellipsoid; positive (+) above the surface and negative (-) below the ellipsoidal surface.

The other important datum is the North American Vertical Datum of 1988 (NAVD 88), which allows direct leveling observations on the earth's topography to be referenced to a common surface. The most common types of heights referenced to the NAVD 88 are known as Helmert orthometric heights (an approximation of true orthometric heights), often informally referred to simply as "elevations".

The accuracy of GNSS-derived NAVD88 orthometric heights is largely dependent on the precision of the modeled difference between NAD 83 ellipsoidal heights and NAVD 88 orthometric heights. These differences are used by NGS in transforming a purely gravimetric geoid model into a "hybrid geoid model". Hybrid geoid models have been created at NGS since 1996 (Smith and Milbert, 1999), and are built explicitly to transform from the official ellipsoid height system (e.g. NAD 83) to the official orthometric height system (e.g. NAVD 88) for a region. The most accurate hybrid geoid model for the conterminous USA is Geoid03 (Roman et al, 2004). It should be noted that the precision of GEOID03 varies across CONUS based on the quality and availability of gravity, GPS, leveling and digital elevation models. After the accuracy of the observations, the geoid model is the most important factor in determining the accuracy of GNSS-derived orthometric heights. For this reason, it is best to use ellipsoidal heights when comparing changes over time.

Establishing the relationship between the SET BM and the vertical datums provides local vertical control within often isolated coastal environments where vital research and monitoring programs are already in place. Specifically, connecting SET BM's to the NSRS enables the following three operations:

- 1) Generating a baseline vertical height on the SET BM from which to measure BM stability over time
- 2) Enabling the transfer of NSRS elevations to SET datasets through the measurement of the vertical offset between the SET BM and the equipotential plane of reference of the deployed SET instrument (Attachment E)
- 3) Providing local vertical control to obtain NSRS connections to local wetland surface elevations (e.g. permanent vegetation transects) and water level recorders

SET Bench mark stability is always assumed, but it can now be measured over time through GNSS-based observations as described in this manual. The relationship between vertical datums provides a mechanism for determination of actual height change at the marsh surface. Prior to connecting SET BM's to NSRS, SET could only be used to monitor relative elevation change over time. When SET BM's are connected to NSRS, and the vertical offset between the BM and the deployed SET is known, SET datasets can actually record absolute change in heights with respect to geodetic datums. When national water level datum information is incorporated, sea level change experienced at the marsh surface can also be determined.

GNSS Technology

Two variations of the GNSS will be described in these guidelines. Both incorporate survey-grade instruments with differential GNSS technology and methodology for the highest possible accuracy. It should be noted upfront that even with advances in GNSS technology, it has its limitations. For the purposes covered in these guidelines, GNSS measures accurately in centimeters, not millimeters.

The more precise and versatile of the two techniques is referred to as "static" GNSS surveying. Receivers are set up on a station and allowed to collect satellite data over a period of time. The greater the distances involved between stations, the more observation time is needed. Static GNSS methodologies were refined (Zilkoski et al. 1997; Zilkoski et al. 2008) to meet 2-cm (or 5-cm) vertical accuracy. Those methods have been adapted here to meet the unique conditions of a marsh environment. Zilkoski (1997) demonstrates how static GNSS can be employed to make accurate connections to the NSRS over long distances. This is especially important in remote, tectonically volatile areas where the most accurate and reliable measurements available are needed.

For connecting large numbers of SET BMs, a less costly GNSS technology known as real-time kinematic (RTK) uses one or more static primary control points ("base stations") and secondary control points ("rover" stations), where the rover is set up for seconds or minutes over a point to be surveyed. The accuracy of the measurements comes from removing common-mode errors between the rover and base(s). This technique may be employed to monitor established SET heights or when accurate heights are not as critical. As the name implies, the system delivers positions and heights on site almost instantaneously. While RTK GNSS is fast and is an excellent choice for occupying many stations in a small area, it has its drawbacks. One major consideration for choosing the appropriate technology is

cost-effectiveness. Due to the limited range of radio signals used in an RTK survey, it is likely an RTK SET projects will still need static surveying to establish a network of strategically spaced stations. This means an unavoidable upfront investment (purchase or rental) in static GNSS receivers and training. In many cases, static GNSS receivers can later double as RTK receivers, but still would require software upgrades, additional equipment and training. Depending on the size of the project and density of the SET sites within areas of the project, users could forego RTK and use only static GNSS to meet the project's specific goals with highly satisfactory results.

SET Bench Marks

A SET device is situated atop of and engaged with shallow-set or deep-set BMs prior to taking measurements. The depth to which BMs are driven is determined by the soil horizons and underlying strata that are integrated into the measurements of change observed at a particular site.

Over time improvements have been made to the original SET BM to enhance precision. This evolution has resulted in a variety of BM types with three distinct differences in the top section to which a SET is engaged. The highest point atop these three top section types is considered hereafter the "Vertical Point of Reference" (VPR) (See figures 2.1, 2.2, and 2.3).



Figure 2.1. Surface Elevation Table (SET) bench mark (BM) top type #1 (of 3): A 2-inch diameter aluminum pipe with four predetermined positions (notches) for the SET. Shown is an RTK GNSS survey underway. A dimple marks the Vertical Point of Reference (VPR), the highest point on the BM.



Figure 2.2. SET BM top type #2 (of 3): A 9/16-inch stainless steel rod w/eight-hole collar for orienting the SET. A leveling staff is being backsighted in the determination of the height of a GNSS antenna (or SET) above the BM.



Figure 2.3. BM top type #3 (of 3): Stainless steel receiver with 1"-8 thread stainless steel pipe coupled to a deep-driven, 9/16-inch diameter, stainless steel rod with concrete protecting the coupling from tampering.

To access SET BMs without disturbing the sediment surface, the SET community routinely establishes either permanent or temporary boardwalks (figure 3). Boardwalks are generally two 2" x 8" x 10' boards laid parallel on either side of the BM and elevated atop four supports (stools, crates, saw horses, or permanent piers), one at each end of the two boards. A third board is laid perpendicular across the two near the location of the SET BM providing access for the observer.

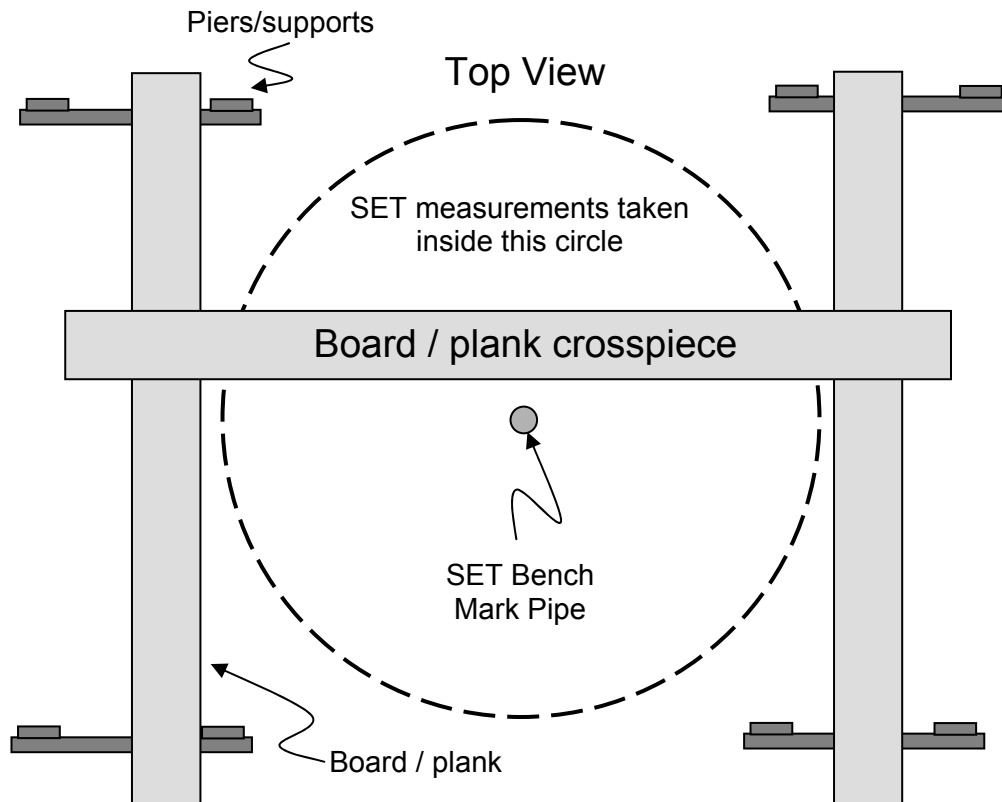


Figure 3. Overhead view of elevated boardwalk permits access to the SET BM without disturbing the marsh surface around the BM.

ESTABLISHING GNSS-DERIVED HEIGHTS ON SET BENCH MARKS

The planning and execution of a GNSS height project is well documented in two NGS publications (Zilkoski et al. 1997 and 2008). This section will address idiosyncrasies specific to SET height projects that are not covered in the aforementioned publications. All publications including this document assume near ideal conditions. Certain situations may require the collection of more data, which might mean extending the observation period or reoccupying a particular point or set of points.

For the purpose of monitoring the vertical movement of the SET stations, **it is strongly recommended that ellipsoidal heights be used**. The ellipsoid is the surface on which GNSS data reductions are made. The 3-D coordinates (XYZ or latitude, longitude and ellipsoid height) produced through GNSS technology are not influenced by local uncertainties of a geoid model, making changes in the height component more reliable for future comparisons.

Planning

In planning a GNSS campaign to connect SET BMs to the NSRS, the first decision to make is the degree to which static observations will be used. This decision is heavily influenced by the geographic distribution of SET BMs and the available survey equipment. For the purposes of these guidelines, a SET “field” refers to a local network of SET BM’s located within a limited geographic area and geomorphic setting, for example, within the same wetland complex (figure 4). If only few SET BM’s are to be connected to the NSRS, one might opt for a static-only campaign, as static observations will give the highest accuracy positions. In addition, the cost of renting or purchasing a few static antennas and receivers is generally moderate compared to that of RTK equipment. If the SET BM’s within a SET field are very close to each other, then one may opt to establish several primary control points via static GNSS observations, and then transfer NSRS elevations to the remaining SET BMs via leveling, as the sight distances of the leveling runs will be short. Here too, the cost of establishing a couple primary control points via static GNSS observations is generally moderate. Alternatively, if there are numerous SET BMs within a field, or the BMs are separated geographically, then a mixture of static GNSS observations and RTK observations may be the best and most efficient option.

If a static-only campaign is employed, then one can skip to “Choosing NSRS stations to control the project” (see below). If a subset of SET BMs is chosen for static observations, the following guidelines should be used to help identify the most suitable candidates for static GNSS observations (primary control points).

Choosing Base Stations within a SET Field

Regardless of the technique used to transfer elevations from primary to secondary control points (i.e. leveling or RTK), at least two primary control points should be established within a field of SETs. Multiple primary control ensures that 1) the relative stability of the control points can be assessed by comparing their relative elevations, 2) the elevations obtained from each primary control can be checked for coherence, and 3) if one primary control point is damaged, another one remains to serve as local vertical control.

Leveling in the wetland environment is fraught with difficulties and risks. The unstable nature of the soils and the presence of water increase the risk of dropping and damaging sensitive and costly leveling equipment in transit or during deployment. The unstable soils also cause difficulties in obtaining an accurate reading of the leveling rod. The need to make short level runs increases the number of observations that have to be made, thereby increasing the introduction of errors under these unstable conditions. However, if there are few SET BMs within a SET field, and they are grouped close together, leveling will provide the greatest within-network precision in transferring NSRS elevations from the primary to the secondary control points.

In the case of optical and laser leveling, the primary control points need to be chosen such that all secondary control points lie within line-of-sight of the primary control points, and within the specified maximum distances allowed for the stated precision of the instrument (refer to instrument manual and specs). Since one will have to check the relative elevations between the two or more primary control points, they must also be within that maximum distance, unless local, temporary turning points are deployed on the marsh surface (which also increase the probability of errors). Attachment C, "Kendapter-based Instrumentation and Methodologies for a GNSS antenna on a SET bench mark," provides guidance on optical barcode and laser level techniques specifically adapted to the wetland environment.

If an RTK campaign is chosen, the location of the primary control points ("base stations") within a SET field is determined by the broadcast range of each secondary control point ("rover station") as explained in Henning (2008). Each rover station must be able to connect to two different base stations so that there can be a check of the accuracy of the RTK solutions. That means that two base stations must be within broadcast range of each rover station, conservatively about a 5-km radius.

The accuracy of RTK observations may be affected by the distance separating the base stations (Henning 2008). Any atmospheric variation and/or local distortion in the ground network between stations become more apparent as distance between the base stations increases. Because of this, base stations should be spaced apart from each other to encompass the overall level of accuracy being obtained at rover stations. An RTK solution from one base station corroborating the solution from a more distant base station yields a high degree of confidence in the values being generated. Also, during the selection process it is important to bear in mind that each base station will need to be visited a minimum of three times. Typically, base stations should be as far apart as possible, but with the following considerations:

- Will the RTK radio signal reach the farthest rover stations?
- Is route and travel time between base stations reasonable?
- Is the base station accessible at low tide?
- How far from the debarkation point will equipment have to be carried?
- Does the site have permanent platforms (an advantage)?
- Is the site prone to flooding at high tide?
- Is the site relatively secure (not likely to attract unwarranted attention)?
- Is it a deep-set BM (higher potential for vertical stability)?

With mapping software, site selection based on a 5-km radio signal range can be easily discerned. Project planning should start by plotting the sites based on their coordinates on mapping software. Assuming an elongated field, a 5-km radius buffer is placed around the farthest-most site on one end. The same is done to the farthest-most site on the opposite end of the field. All sites should fall within one of the two buffer regions. Any sites within the area where the two buffers overlap are suitable base stations, based on radio range. On larger fields, a third site may need to be buffered if a pair of suitable sites is not found in the overlap of two buffers. Sites pairs within the overlap of any two (or three) buffers are eligible for use as base stations for all the remainder of the sites the within the two (or three) buffers. It is important to remember, sites need to be selected from buffer overlaps in pairs, but as far apart as possible. It is quite possible if three buffers are needed, a total of four base stations (two site pairs) will be required.

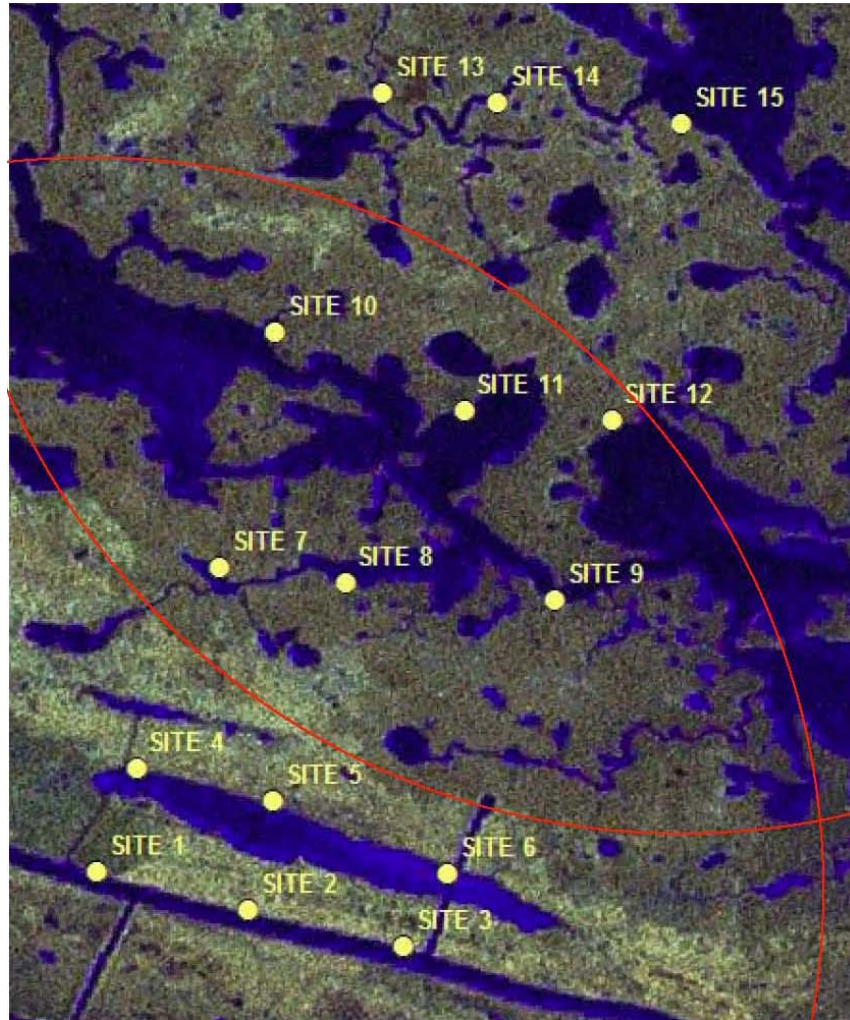


Figure 4. Example SET field. Note 5-km buffer around Sites 1 and 15.

Figure 4 shows a SET field consisting of 15 sites. The graphic was created in ArcGIS using SET site coordinates layered on a Landsat imagery background. The farthest extents of the field are about 7 km between sites 1 and 15. A 5-km-radius buffer was placed around each of them. Potential base stations for an RTK survey include sites 7 – 12. All other sites are within 5 km of these two.

It is important to remember that RTK cannot operate outside the range of its radio signal, making this limitation the most important overall factor in selecting base stations (Henning 2008). However, this distance limitation does not apply when using cellular modems to relay correctors. Users should be aware of distance-based uncertainties in differential GNSS that can impact accuracy. Spatial decorrelation occurs when satellite signals travel to the base and rover receivers through significantly different atmospheric conditions. However small, uncertainty regarding the magnitude of this error increases with the distance between the receivers. To monitor this phenomenon, base station pairs should be spaced as far apart as practical.

To keep separation at a maximum in the above example, two potential pairs would be sites 7 and 12, and sites 9 and 10. According to the LandSat image the route between sites 9 and 10 is much more appealing than the route between sites 7 and 12. Field reconnaissance should confirm this, as well as suitability based on the remaining criteria (low tide accessibility, platforms, etc.).

Choosing NSRS stations to control the project

Once the primary control points have been chosen, existing stations must be selected to provide ties to the NSRS. Eligibility requirements for NSRS stations can be found in the publications Zilkoski et al. (1997 and 2008).

After determining which types of NSRS stations will be needed, a search can be conducted at the NGS datasheet retrieval website (<http://www.ngs.noaa.gov/>), click on "datasheets", to provide a list of NSRS stations within a radius of up to 48 km of a geodetic coordinate (position of a primary control point). Usually only the most centrally located primary control point in a SET field needs to be used as the starting coordinates for the database search.

1. Enter coordinates
2. Input a radius of 30 miles (48 km)
3. Select "Vertical Precise GPS or better" under Data Type Desired
4. Submit. Once the new page is displayed, select "Re-sort" by "Dist" (distance) as shown in Figure 5.

Any of the following stations types may be used in the project to control both position and ellipsoidal heights (3-D NSRS station). Move down the list and select the following stations types (ctrl + click for multiples):

|H V|Vert. Source | H = Horizontal Order (A,B,1,2,3) ;

V = Vertical Order (1,2,3,m,p)

|0 V|88/ADJUSTED| where V = 1, 2 or 3 (first, second, or third order vertical);

88/ADJUSTED = North American Vertical Datum of 1988 network (NAVD88), after completion of the NAVD88 General Adjustment of 1991

|H h|88/GPS OBS. | where H = 0 or 1 (no or first order horizontal);

88/GPS = GPS Height Modernization Elevation, most probable accuracy = $\pm 2-5$ cm

Note: When H = 0, the station will have Accuracy Estimates for northing, easting and ellipsoid heights on its data sheet. Try to avoid using stations with estimates greater than 2 cm.

Station List Results for: N295604-W0900713-30

Help

Re-Sort-By Dist Pid H V Vert_Source Lat_approx Lon_approx Stab Designation

11.3 AU2141 . m 88/ADJUSTED N294743 W0900113 A... D 367
11.3 AU0748 . 1 29/ADJUSTED N295533 W0901833 C... E 166
11.3 BJ3526 . 1 88/ADJUSTED N300234 W0901545 C... JPE 2 C
11.3 BJ3872 . 1 88/ADJUSTED N300147 W0901624 C... JPE 4 C
11.3 BJ3873 . 1 88/ADJUSTED N300126 W0901645 C... JPE 9 C
11.3 AU0744 . 1 29/ADJUSTED N295535 W0901829 C... X 8
11.4 AF9544 A h 88/GPS OBS. N295244 W0895630 ... ENGLISH TURN 1 CORS ARP
11.4 AB6385 A h 88/GPS OBS. N295244 W0895630 ... ENGLISH TURN 1 CORS L1 PHASE CENTER
11.4 AF9593 A h 88/GPS OBS. N295245 W0895631 ... ENGLISH TURN 2 CORS ARP
11.4 AB3307 0 1 88/ADJUSTED N295244 W0895631 A... ENGLISH TURN
11.4 AT1436 0 1 88/ADJUSTED N295244 W0895631 C... ROWL
11.4 BH1700 . 1 29/ADJUSTED N300107 W0895725 C... 233 R LAGS
11.4 AU0341 . m 88/ADJUSTED N295621 W0901835 B... A 319
11.4 AT0307 . 1 29/ADJUSTED N295548 W0895551 C... E 3134 LAGS
11.4 BJ1465 . m 88/ADJUSTED N300003 W0901737 R... K 276
11.4 BH1824 . 1 88/ADJUSTED N300257 W0895902 A... K 374

Warning - To avoid TimeOut, select only the stations you need.

Select All

Get Datasheets (for the stations I've selected above)

Move (the above station list to a File->Print Window)

Reset

Continuously Operating Reference Stations

NSRS station types

Figure 5: Station list results from NGS's datasheet retrieval website

For orthometric height projects where the previous station types are greater than about 10 km away from a SET monument, adding a nearby first-order vertical control station to the observing scheme will increase compatibility with other vertical stations in the immediate area. Using stable, first-order vertical control whenever possible reduces uncertainties and complications later. Look for the following annotations for 1st- 2nd- and 3rd-order vertical control in the retrieval listing:

```
|x 1|88/ADJUSTED|
|x 2|88/ADJUSTED|
|x 3|88/ADJUSTED|
```

The project must be tied to at least the two closest Continuously Operating Reference Stations (CORS). Looking through the list of NSRS stations, the names of the CORS will end in "CORS ARP," such as ENGLISH TURN 1 CORS ARP (figure 5).

5. Select "Get Datasheets." The datasheets can be sent to a printer or saved as a file in the different formats supported by your browser.

Another retrieval option on the NGS datasheet webpage allows NSRS station data to be exported to an ESRI shapefile format that can be used in any compatible software.

Plot all NSRS stations by coordinates, along with all SETs primary control points from the project using the mapping software. Begin final selection by eliminating unsuitable stations, making sure the location and spacing of remaining stations meet or **exceed** minimum requirements (Zilkoski et al. 1997). To complete the observing sketch, the dots must be connected (e.g. figure 6). All stations, both new and existent, need to be connected with lines (representing measured baselines) in a series to form closed loops with a high strength of figure (avoid acute angles). Each station will have at least two connections to adjacent stations. Any connection longer than about 40 km will have to be broken down by adding stations in between (either new or existent) until the 40 km limit is satisfied. Refer to Zilkoski et al. (1997) if the 40-km limit is geographically impossible or impractical.

All stations will need to be visited in advance of the field observations. If the project is to be submitted to the NGS (see section on DATA SUBMISSION for benefits), notes for updating station descriptions are taken at this time. The NGS website has detailed instructions for writing and formatting descriptions to be included in the NGS integrated database (NGSIDB; http://www.ngs.noaa.gov/PC_PROD/DDPROC4.XX/dformat.documentation.html).

Planning static GNSS observation sessions

One of the most important variables to consider when planning a static GNSS campaign is the length of the observation sessions. Longer static GNSS observation sessions will yield more accurate results. NGS recommends at least 4 hours of data to be submitted to its On Line Positioning User Service (OPUS) for GNSS vertical height solutions. Furthermore, multiple observation sessions offset in time across several days lead to higher confidence results, as the solutions rely on different satellite geometries. As an example, height modernization surveys, which routinely achieve 1 cm ellipsoidal height accuracy, require three or more sessions, each at least 5.5 hours long, on two or more days, where two of the observation time spans are offset to sample different satellite geometries (from the NGS OPUS web page, http://www.ngs.noaa.gov/OPUS/Using_OPUS.html).

In deciding session lengths for static GNSS observations, the user should consider the long-term use of the positioning data, as well as the logistics of the field campaign. A single, long observation session on one day will give a good estimate of ellipsoid height, but it will cause estimation problems if the vertical bench mark velocity is to be calculated at a subsequent observation session (regression analysis requires multiple observations at each time interval, e.g. Year 0 and Year n). Therefore, multiple observation sessions across several days are recommended in this guidelines document. Due to the remoteness of many SET sites, it may be inefficient to deploy and recover GNSS antennas and receivers each day of a multi-day campaign. Therefore, these guidelines provide a methodology to deploy receivers in the field and leave them to run for several consecutive days.

GNSS receivers are deployed and left to run over four days (deployed on one day and retrieved four days later), collecting about 72 hours of total data per baseline. To facilitate data management, GNSS receivers should be programmed to store data in 24-hr data sets beginning and ending on the same day-of-year based on Greenwich Mean Time. Each day is one session.

A minimum of three receivers is highly recommended. Two can be used, but the third receiver effectively cuts the duration of the project in half.

The operational status of a CORS should be checked prior to incorporating it in an observing session.

The duration of field observations is primarily dependent on the number of receivers available for the campaign and the number of receivers that can be deployed on a given day. The number of receivers that can be deployed per day, in turn, is dependent on logistics, such as available personnel, available transportation (including watercraft and tow vehicles), travel time, site accessibility, etc.

Due to the unknowns associated with different SET height campaigns, it would be impossible here to address every possible scenario. One possibility includes two personnel, one water craft and a tow vehicle with room for GNSS equipment, and three GNSS receivers w/accessories. When scheduling receiver deployment, it is recommended to start at a loop near one end of the observing sketch and work toward the opposite end.

This scenario would involve one crew deploying three receivers one day and then moving two of them on the fourth day, seventh day, tenth day, etc. in a leapfrog fashion, until all baselines have been measured. This method is the simplest to plan and execute. Expect to exchange the batteries on all three receivers with freshly charged ones at each movement day over the course of the project. An example campaign of 9-stations (includes two CORS) and 10 baselines would span 10 days using this method, but would require only four days of field work.

The example SET height project in Figure 6 meets all current requirements. All baselines are about 40 km or shorter, and two CORS and three 3-D NSRS stations are included in the scheme. See Attachment A for an example schedule for incorporating a two-person crew and three GNSS receivers.

More receivers and/or personnel would increase productivity, but will make planning much more complex, unless it was simply a matter of multiples. By doubling the personnel, watercraft, vehicles and equipment, two crews could be sent out at the same time, potentially increasing productivity by about 250% (e.g. while three receivers can measure two vectors at a time, six receivers can measure five vectors or 2.5 times more production than three receivers alone).

Another viable possibility includes using six GNSS receivers with a two-person crew. On the same 9-station project, a two-person crew would be busy deploying and/or moving just two receivers per day, but everyday for six working days. As many as four receivers might need to be retrieved on the sixth and last day. Overall duration of field observation time is cut nearly in half.

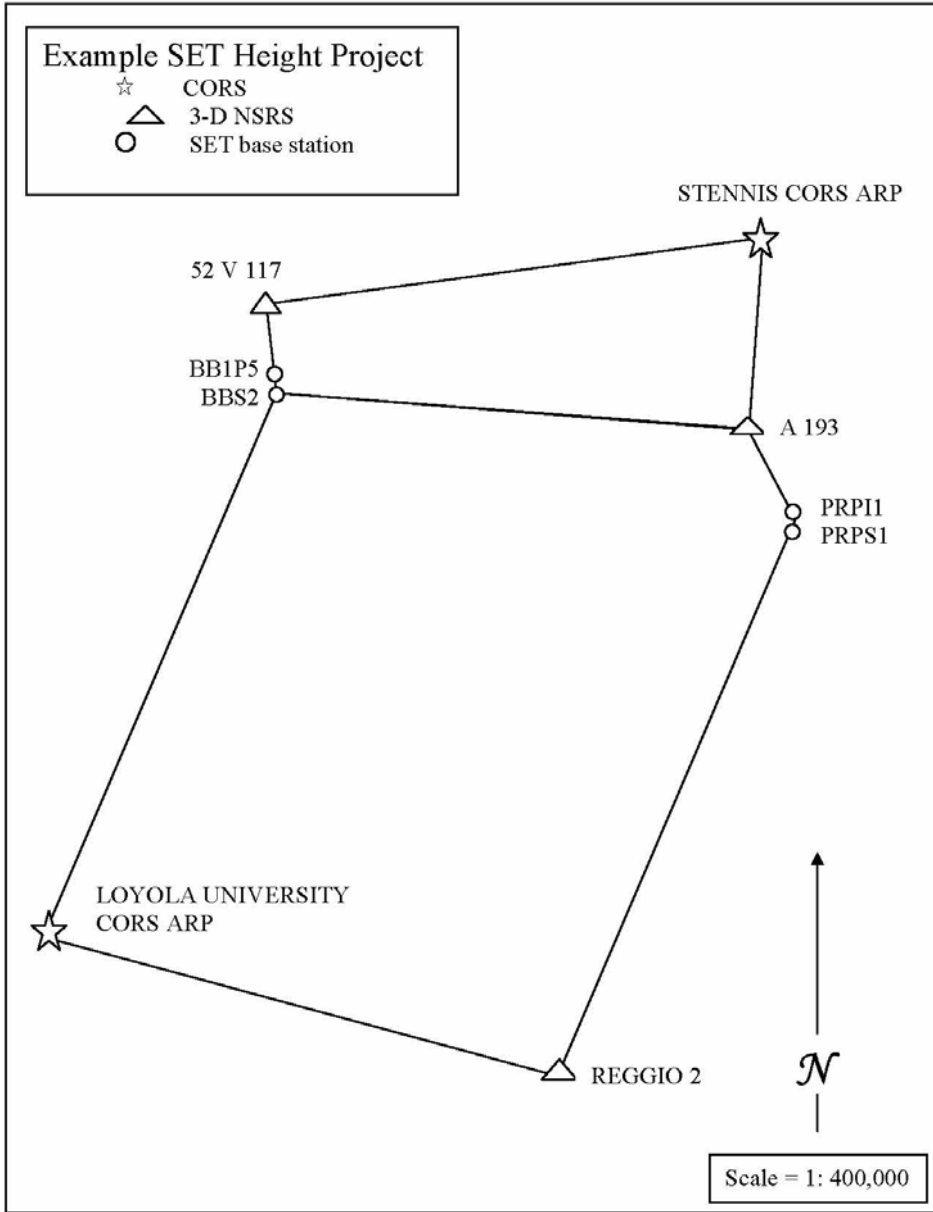


Figure 6. Nine-station GNSS-derived height project for two SET fields. Actually scale is 1: 500,000.

Special Equipment

Current conventions for static GNSS stations call for the use of a 2-meter, fixed-height tripod (Zilkoski et al. 1997, Zilkoski et al. 2008). The tip of the tripod’s center staff rests on a conventional control monument’s VPR while three legs swing out from the top and set firmly in the ground to provide stability and support. While a SET BM would have no problem accommodating the tripod, it would be nearly impossible to use it without disturbing the surrounding marsh surface being monitored.

To access SET BMs without disturbing the sediment surface, the SET community routinely establishes either permanent or temporary boardwalks on site. Unfortunately, these boardwalks do not provide sufficient stability for the conventional tripod setup.

In response to these limitations, GNSS antenna adapters for SET BM's have been developed by NGS and the US Geological Survey (Figure 7). The descriptions of the adapters and the techniques for using them are outlined in Attachments C and D. The essence of each adapter is to securely place a GNSS antenna (with any required antenna extensions) plumb to the equipotential surface above the SET BM. Four different methodologies are hereby proposed for determining the precise height of the GNSS antenna above the SET BM in the field. The first three methods involve the use of a tribrach atop a SET BM adapter (collectively called the "Kendapter," Attachment). Since leveling the tribrach will alter the height of the antenna above the SET BM, the vertical offset between the SET BM VPR and the antenna needs to be measured in the field. The methods relying on the Kendapter are given in the chronological order of their development. The first method uses a highly sensitive digital bar-code level. Although the results can be excellent, the method requires much care, as the instrument is sensitive to even the slightest movement of the substrate, transmitted through the tripod. To overcome this limitation, a second method is proposed, which uses a relatively inexpensive remotely-operated laser level. The operator does not have to be next to the tripod, eliminating much of the vibration that would otherwise interfere with the digital bar code level. The third method involves using a tiltmeter and calipers to measure the tilt of the SET BM and the vertical separation between the top and bottom planes of the tribrach, respectively. Finally, the fourth method relies on the use of a tiltmeter and a fixed-dimension GNSS antenna adapter, rather than the Kendapter-tribrach combination. Since the leveling the top plane a fixed-dimension adapter does not change the dimensions of the adapter, the only measurement needed in the field is an estimate of the tilt in the SET BM. An inexpensive tiltmeter can be used for this purpose. Each method has its strengths and weaknesses, and these guidelines provide the user with information to help decide which methodology is best suited for the GNSS campaign.

Batteries need to be able to power a GNSS receiver for at least 72 hours on a single charge. On the marsh where vandalism is not an overriding issue, three 18-Ah, "gel cell" batteries (lead-acid batteries with a gel used in place of a liquid electrolyte) can be wired in parallel and placed in an inexpensive plastic container large enough to also accommodate the GNSS receiver. The container need not be waterproof, but should be tightly covered. The buckets NGS used were purchased directly from a container manufacturer, but are the same as used by some cat litter manufacturers (Figures 8.1, 8.2 and 8.3)

The GNSS-in-a-bucket (Figures 8.1, 8.2 and 8.3) must be elevated and secured on a platform high enough to avoid any chance of water infiltration from rising tides or potential storm surge. Retrieve or delay deploying equipment if weather forecasts predict a significant storm. For receivers deployed at SET base stations, a separate spare bucket with batteries would facilitate the battery exchange operation on every fourth day. The GNSS receiver can simply be switched over to a new bucket with fresh batteries.

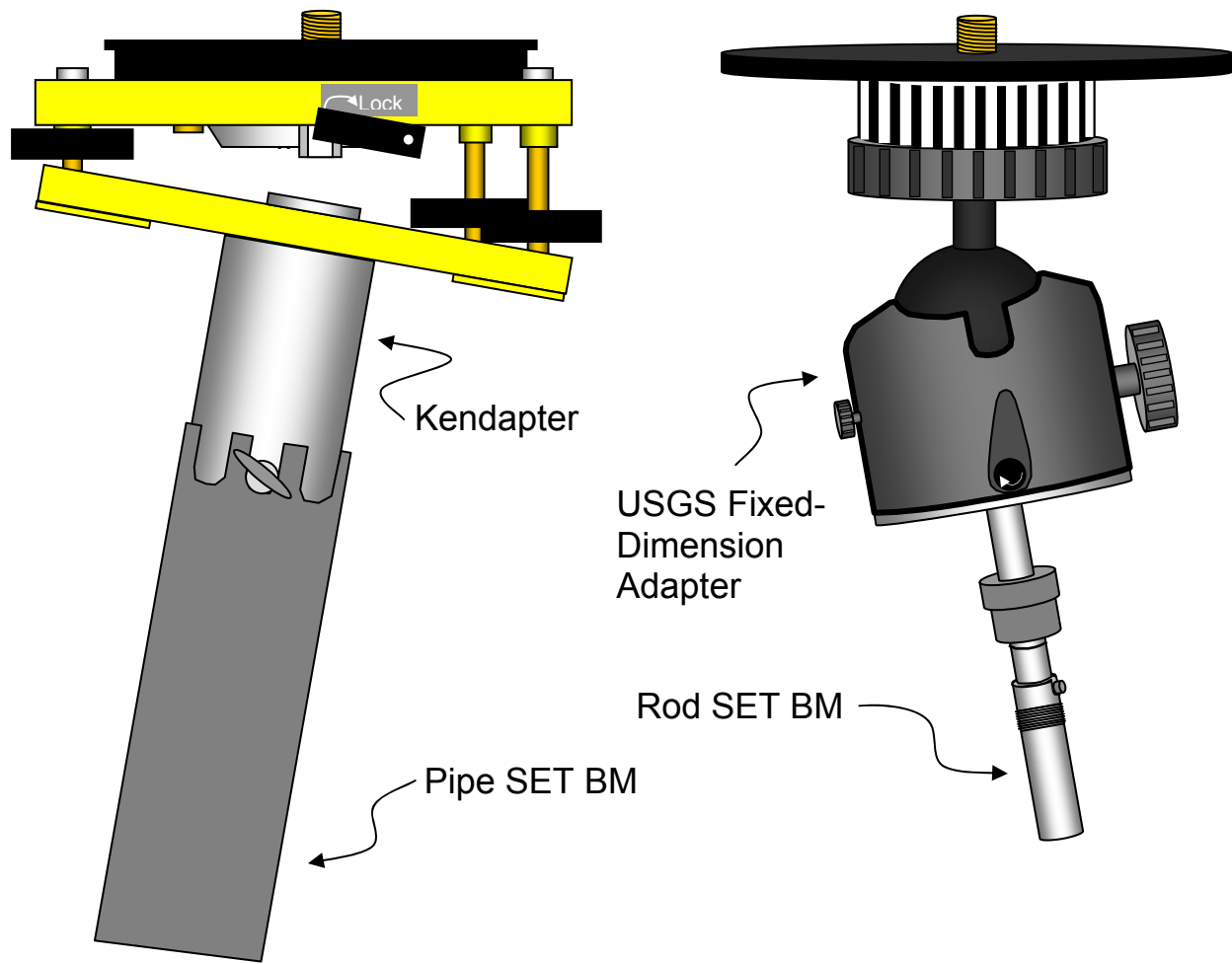


Figure 7. Examples of two GNSS antenna adapters for Surface Elevation Table (SET) bench marks (BM). Kendapter + tribrach shown on left; USGS Fixed-Dimension adapter on the right.



Figure 8.1 GNSS-in-a-bucket (lid open), cost-effective method to keep receiver high and dry.



Figure 8.2. Notch cut in top edge of bucket to allow for GNSS antenna cable.



Figure 8.3. Three 18-Ah “gel cell” batteries taped together and wired in a parallel circuit fit nicely in the bottom of the bucket. Three-prong connectors were used to prevent damage to GNSS receiver by accidentally reversing the polarity when connecting the batteries.

Logistics

Many factors are taken into consideration when planning logistics for a SET survey; however the observing sketch and schedule dictate which stations need to be occupied at any given time. Travel times and personnel accommodations are important and should be considered and weighted appropriately during project planning. Equipment must be equally available to all who have a need for it. Staging the entire campaign from a central location, in many cases, might be preferable to relocating nearer the day’s activities. This also alleviates the inconvenience of moving equipment and personal affects between accommodations.

Observing Methodology

SET BMs slated to be occupied in a GNSS height project generally fall into the category of primary or secondary base stations. This is mostly due to the fact that SET fields are fairly sparse. Where a large number of SET fields are found in a relatively small area, i.e. fields spaced 10 km or less apart, some advantages might be found in establishing a secondary base network as described in Zilkoski et al. (1997 and 2008).

Due to the remoteness and difficulty in reaching the sites, the vast majority of the time SET base stations should usually be treated as primary base stations. The GNSS receivers are set up and left to store data in 24-hr data sets. Receivers can be preprogrammed to automatically end one data file at 23:59:59 UTC and start writing data to a new file. Once the GNSS receiver is properly set up and turned on, it will continue to collect data unattended until the batteries rundown. To ensure enough good data is gathered to avoid the need for re-observations, receivers should be set up and left to run uninterrupted over two UTC days. This will yield approximately 72 hours of data.

Before the GNSS antenna can be set up on a SET base station, a VPR will need to be located and marked on the SET BM (Attachment B). The height of the antenna above the VPR will also need to be measured or calculated according to one of the methodologies explained in Attachments C and D.

To avoid attracting undesired attention, the GNSS-in-a-bucket can be hidden from view with a camouflage covering. The antenna is a different matter because covering it could interfere with satellite reception. However, a double thickness of mosquito netting helped to conceal the antenna (Figure 9). Tests at NGS showed the material had no significant affects on antenna calibration values.



Figure 9. GNSS antenna deployed atop a Surface Elevation Table (SET) bench mark, covered with a double layer of mosquito netting for camouflage.

Execution

It is important to note that to solve a vector between adjacent stations on the observing sketch, GNSS receivers must be collecting data simultaneously. Following a well-planned schedule based on a properly drawn observing sketch is crucial.

Caution: Field observers should understand how to check the receiver memory prior to deployment to assure adequate space remains. At the same time, no data should be deleted from the receiver unless the observer can verify it has been backed up in at least two separate places. Batteries should also be fully charged and replaced as needed.

Data Management

Data should be downloaded and backed up on a portable device each time a GNSS receiver is retrieved. The memory in most modern GNSS receivers has space for all the data it will be expected to collect in the project, even for a major campaign. It is advisable to leave the data intact on the receiver memory after the download to a portable device is complete. Downloaded data should be transmitted to the data manager as soon as possible for safekeeping. If a station's collected data is lost or misplaced, not only will that station need to be reoccupied, stations adjacent to it on the observing sketch will need to be reoccupied, too. Accurate GNSS solutions require receivers to work in tandem.

Post-Processing and Adjustment of Data

All major manufacturers of survey-grade GNSS equipment have post-processing software available. If the project is to be submitted for NGS to store and maintain, the software should have routines that will export the data in a "Blue Book" format according to *Input Formats and Specifications of the National Geodetic Survey Data Base*. The publication is found at <http://www.ngs.noaa.gov/FGCS/BlueBook/>. Alternatively, a new service called "OPUS-DB" is offered which will process, store and disseminate individual GNSS stations. This service may be found at <http://www.ngs.noaa.gov/OPUS>.

Each manufacturer's post-processing software is different. If users intend to post-process using proprietary software, they should participate in vendor-provided training, usually worked into the cost of the software and/or equipment or provided at additional cost.

NGS provides no-cost post-processing (PAGES-NT) and least-squares adjustment software (ADJUST) with documentation and instructions. They can be found at <ftp://ftp.ngs.noaa.gov/pub/pnt6> and http://www.ngs.noaa.gov/PC_PROD/ADJUST/, respectively.

An interactive Internet project management program called OPUS Projects has been developed and, with enough user interest, will be finalized and released to the public. The system allows collected data to be transferred from local storage to servers at the NGS via the Internet. OPUS Projects will post-process data and e-mail a report to the user. The data submitted is compiled in Blue Book format as a G-file.

A client/server system called Pocket GNSS Manager (PGM), which works independent of OPUS-Projects, is also available. PGM client can be loaded onto a mobile device and used to

record pertinent field metadata during deployment and retrieval of GNSS receivers. The metadata, necessary for the project to be submitted to NGS and included in the NGSIDB, is transferred to the server where it is compiled in Blue Book format as a B-file.

B- and G-files can be used in the NGS least-squares adjustment program ADJUST to further analyze and determine final positions and heights for the stations in the project.

Training for NGS programs and software is currently available at no cost. Contact NGS for more information at www.ngs.gov.

Data Submission

While it is not necessary to submit a SET height project to NGS, there are many advantages to doing so. NGS will work with the SET community to ensure the entire campaign, from planning to final quality checks meets the highest standards for accuracy. Once the data resides in an NGS database, it can be kept current as the latest developments arise. All data associated with a station are archived for future use in a historical context, whether or not they may have been superseded by more accurate values along the way. Stations retrieved from an NGS database (as in "datasheets") have a plethora of information regarding the station that is of interest to the scientific community. For example, horizontal velocities are currently available that are caused by tectonic plate movement. As more data become available, vertical velocities will also be associated with control stations.

To preserve and protect sensitive sites, NGS has worked with research partners in the past to restrict public access to SET station datasheets. Contacting the NGS and making this request in the early stages of the project is a good idea.

ESTABLISHING RTK GNSS-DERIVED HEIGHTS ON SET ROVER STATIONS

Real-time kinematic (RTK) GNSS technology should provide two-centimeter to three-centimeter relative accuracy in positioning and height determination, often within a few minute's time per station (Henning 2008). As with any measurement instrumentation, RTK is not foolproof; errors can be made without due diligence. The basic methodology is described in Henning 2008, and is adapted here to the particular situation of remote fields of wetland SET bench marks. The guidelines described below will help to reduce error from common sources. In this section heights are emphasized, but positional errors should never be ignored.

To avoid blunders and ensure the RTK GNSS system is functioning properly, base station positions and heights should be determined ahead of the RTK survey. This allows the user to set up on the base station and use the RTK rover unit on the other base station(s) for a check. A difference between the RTK-generated values and the known values from the static GNSS survey indicates the level of accuracy that can be achieved before continuing with the occupation of the SET rover stations.

Another major key to ensuring quality is to occupy each rover station twice, once with the RTK base receiver set up on one base station, followed later by a second occupation with the base set up on another other base station. Again, a comparison of the results will indicate the level of accuracy being achieved.

While most major brands of RTK hardware and software will yield similar results, each has its own sequence of steps to arrive at that point. It is highly recommended that users get some training through the respective dealerships for the specific brand of RTK they will be using. These guidelines will address the similarities of all RTK systems and special circumstances specific to a wetlands survey that would not necessarily be addressed in training workshops.

Planning

The achievable accuracies are limited to the manufacturer's stated accuracy of the equipment. GNSS planning software should be used to determine the Vertical Dilution of Precision (VDOP) values, a unitless number that reflects the quality of satellite geometry for GNSS-derived heights. Include the desired observation times and project area. Observations should be avoided during intervals of time when VDOP values are four or greater. Planning software is available online from various manufacturers and normally included in the software packages supplied with RTK GNSS equipment.

Observing Methodology

Base Setup and Check

As per manufacturer's instructions, the user should import or manually enter the known positions and heights of the base stations into the data collector. These values enable critical error checks of the RTK system in the field and allow immediate determination of rover station positions and heights.

Users should refer to the specific GNSS receiver's operator's manual for field setup of the RTK base station receiver. The antenna setup and antenna height calculation are identical to the static antenna setup using any of the methods outlined in Attachments C and D. If the user has chosen to determine the height of the GNSS antenna above the SET BM by using a geodetic level with the tribrach-based adapter (Attachment C), then a temporary bench mark (TBM) should be established and a height computed from the base station VPR (height difference added to known height of base station). The TBM need only be stable enough hold the height with the added weight of the rover pole for a few minutes. Before leaving the site, perform a check to ensure the RTK system is working and data has been entered correctly.

The RTK rover antenna is set up as described by the manufacturer's operator manual on a rover pole. With the base receiver on one base station, the rover pole should next be placed on the other base station's VPR (an adapter is not necessary – the tip of the rover pole or a "topo shoe" can rest on the top-most surface of the bench mark). The stakeout feature is used to check the observed height against the known height and should compare to within ± 3.0 cm. Expect to see horizontal error from the base station check of about 2.5 cm, in addition to one or two centimeters of error normally present in the system. The 2.5 cm is due to the fact that the HPR and VPR are not the same point on SET BM tops. Save this check if your software has that provision. This checking procedure should be performed each time the base station is setup and should be done at the start of the observations. An

observation check not meeting the ± 3.0 cm height tolerance must be resolved before RTK control monuments can be determined.

Possible causes of a >3.0 -cm check include but are not limited to:

- Bad observing window used (high VDOP)
- Incorrect values entered for known points
- Base antenna set up incorrectly
- Satellites have been set to unhealthy and are unavailable for use due to maintenance, repositioning or other issues (www.navcen.uscg.gov)
- Wrong antenna height or type entered during setup
- Bubble levels out of alignment
- Rover pole or base antenna extension pole is bent
- Monument has been disturbed or otherwise has moved since the original static survey
- Heavy solar activity (not common) (www.sec.noaa.gov)

Rover Station Observations

To ensure that the desired accuracy is met, **independent observations should be made to each rover station from two base stations previously connected to the NSRS.**

The two new observations should compare to within ± 3.0 cm. Observations not meeting the ± 3.0 cm height tolerance must be resolved, normally by observing the points again at a different time (different SV constellation or better VDOP). The final value of the occupations will be a mean of the two solutions.

At each RTK rover station:

1. Determine the VPR as described in Attachment B. The point will serve as both the HPR and VPR for the rover station. The point will be occupied directly with the rover pole (a GNSS antenna adapter is not used).
2. Set and plumb the rover pole on the VPR. Bi-pod legs are recommended to steady the antenna pole. If a pointed tip is used, it must contact the exact point marked as the VPR. If a topo shoe is used, the foot must rest on the top-most surface of the SET BM. The rover pole may be rotated about its length to ensure that this point is occupied. To avoid disturbing the marsh surface, the legs should be kept on the center board of the boardwalk. To plumb the antenna and maintain plumb requires that the observer stand as still as possible.
3. Start the data collection as specified in the operator's manual, waiting until the data collector indicates optimal quality has been achieved before storing the values. (Information about quality indicators for the various brands of data collectors and their associated software would unnecessarily burden these guidelines. Details can be found in the operator's manual.) Alternatively, different filter settings can be applied to most RTK data collector programs that either prevent the user from storing positions and heights before criteria has been met, or automatically saves the values when a condition has been achieved.
4. After occupying all rover stations, move the base receiver to another base station following RTK base station setup and check as described earlier.
5. Occupy all rover stations a second time (Steps 2 and 3).

A comparison of the two heights of each rover station should be made in the field to satisfy the ± 3.0 cm height tolerance. The final value of the occupations will be a mean of the two independent occupations. Each GNSS manufacturer has its own scheme for comparing and then averaging the two independent occupations.

Some software packages do not allow two different occupations of the same point to have the exact same station name or do not allow a direct comparison of the heights. If the software does not have the provision to name the same station and compare the observations to meet the ± 3.0 cm height tolerance directly, the stakeout feature can be used to compare a previously determined value with your second value.

DATA MANAGEMENT

There are many different schemes for data management peculiar to the different brands of RTK GNSS packages. Independent observations from two known base stations produce a single averaged position and height for each rover station.

All software packages have backup routines. It is strongly recommended to download data from the data collector daily and to backup the survey jobs often. Observers should transmit backed up data to the data manager as often as possible and keep a copy in their possession for safe storage.

GLOSSARY

CORS: a network of continuously operating reference stations (CORS). Each CORS site provides Global Navigation Satellite System (GNSS - GPS and GLONASS) carrier phase and code range measurements in support of 3-dimensional positioning activities throughout the United States and its territories.

Ellipsoidal height: The vertical distance from a point on the earth's surface to the ellipsoid, a geometric approximation of the earth's surface. These are the heights obtained by processing Global Navigation Satellite System (GNSS) signals.

Equipotential plane: a surface of constant gravity. The plane is at all points normal to the gravity field. Points along an equipotential plane have the same pull of gravity.

Geoid: The equipotential surface which would coincide exactly with the mean ocean surface of the Earth, if the oceans were in equilibrium, at rest, and extended through the continents. The geoid is essentially a gravitational model of the earth.

GNSS: Global Navigation Satellite System, a network of orbiting satellites that provide autonomous geo-spatial positioning on the earth's surface. This term refers to the satellites launched by both the United States (NAVSTAR GPS) and Russia (GLONASS).

Height modernization: a program within NOAA's National Geodetic Survey (NGS) that provides accurate height information by integrating Global Positioning System (GNSS) technology with existing survey techniques. Two NGS publications (Zilkoski et al. 1997 and

2008) provide excellent guidelines as to how height modernization may be achieved. (<http://www.ngs.noaa.gov/heightmod/definition.shtml>)

Kendapter: A custom-made GNSS antenna adapter designed to fit atop all known versions of Surface Elevation Table (SET) foundations. The term can also refer to the adapter fitted to a Wild-type survey tribrach, allowing a GNSS antenna to be plumb.

NGS: National Geodetic Survey, a line office of the National Ocean Service, under the National Oceanic and Atmospheric Administration whose mission is to define and manages the national coordinate system. This network, the National Spatial Reference System (NSRS), provides the foundation for transportation and communication; mapping and charting; and a multitude of scientific and engineering applications.

NSRS: The National Spatial Reference System, a consistent coordinate system that defines latitude, longitude, height, scale, gravity, and orientation throughout the United States. NSRS comprises a consistent, accurate, and up-to-date national shoreline; a network of continuously operating reference stations (CORS) which supports 3-dimensional positioning activities; a network of permanently marked points; and a set of accurate models describing dynamic, geophysical processes that affect spatial measurements.

Orthometric heights: The height of the earth's surface normal to the geoid at that location (see Geoid).

RTK: Real Time Kinematic (GNSS): the term refers to the equipment and procedures based on the use of carrier phase measurements of the Global Navigation Satellite System (GNSS) signals where a single reference (base) station provides real-time corrections to a mobile (rover) station. Through these corrections, centimeter accuracy positions can be obtained at rover stations.

SET (Sediment Erosion Table or Surface Elevation Table): a device used for measuring changes in elevations in inter-tidal and sub-tidal wetlands based on a constant reference plane established by the SET (Boumans and Day 1993). Furthermore, the SET is designed to sit on a permanent bench mark pipe or rod [SET BM] that is driven into the marsh surface until refusal. (Cahoon et al. 1995).

SET base station: a SET BM connected to the NSRS during a modified GNSS height modernization project wherein its relative position and height are established. At least two SET base station are established per SET field.

SET field: two or more SET sites within a defined area. A SET field is usually identified by a descriptive name taken from a local geographic or geological feature.

SET bench mark: a base structure substantial enough to support a surface elevation table while sedimentation measurements are being taken. Common types of BMs include aluminum pipe or stainless steel rod driven into the soil to varying depths. When a SET BM is included in a GNSS height modernization project, it is identified as a SET base station or SET rover station.

SET rover station: a SET BM connected to the NSRS using real-time kinematic GNSS techniques that determine its position and height relative to at least two SET base stations.

SET site: the area immediately surrounding and including a single SET BM.

VPR: Vertical Point of Reference: this is the marked, upper-most point on a bench mark, to which an elevation (height) is referenced.

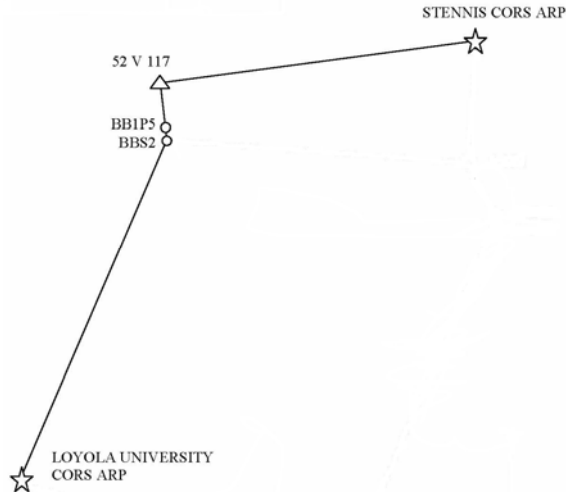
A complete list of geodetic terms and definitions can be found at the NGS website at http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml

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Attachment A:

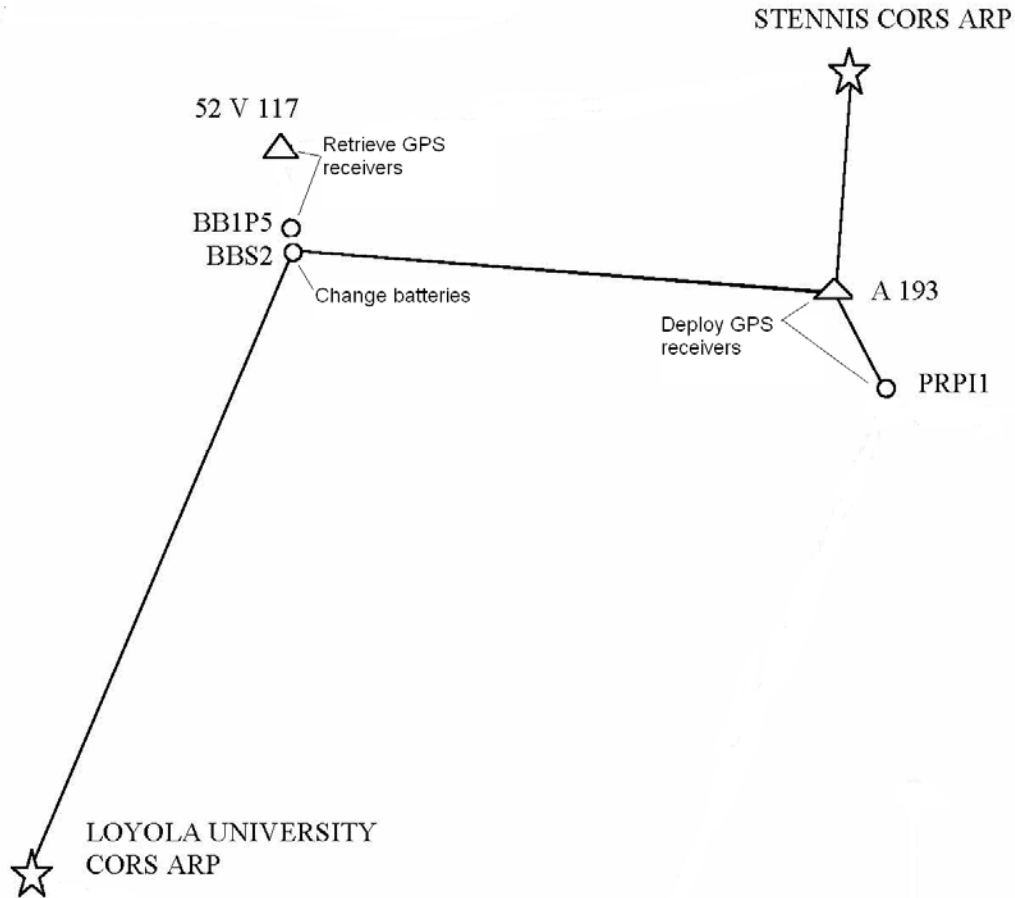
Typical schedule for a two-person crew and three GNSS receivers



Day 1				Day-of-year 007	
				Monday, 7-Jan-08	
Session 007 A				Start (UTC): 18:00	Start (Loc): 12:00
				Stop (UTC): 23:59	Stop (Loc): 17:59
Observer	Vehicle	Recvr	4CID	Station Name	Comments
			NDBC	STENNIS CORS ARP	CORS
AMC/CAW		1001	52V1	52 v 117	NSRS station - deploy
AMC/CAW		1002	BB1P	BB1P5	SET base station - deploy
AMC/CAW		1003	BBS2	BBS2	SET base station - deploy
			NOLA	LOYOLA UNIVERSITY CORS ARP	CORS

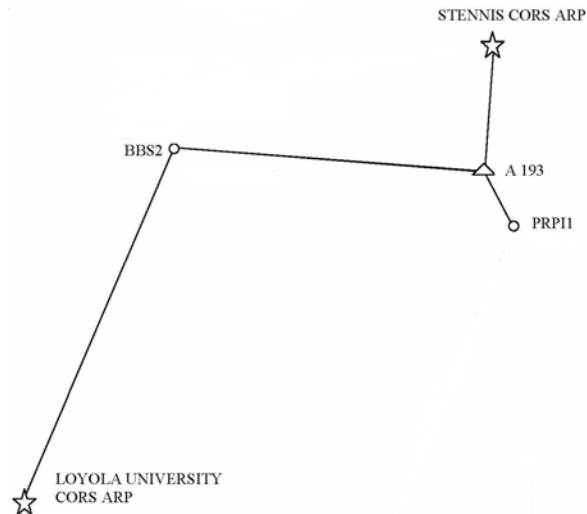
Day 2				Day-of-year 008	
				Tuesday, 8-Jan-08	
Session 008 A				Start (UTC): 0:00	Start (Loc): 18:00
				Stop (UTC): 23:59	Stop (Loc): 17:59
Observer	Vehicle	Recvr	4CID	Station Name	Comments
			NDBC	STENNIS CORS ARP	CORS
		1001	52V1	52 v 117	NSRS station
		1002	BB1P	BB1P5	SET base station
		1003	BBS2	BBS2	SET base station
			NOLA	LOYOLA UNIVERSITY CORS ARP	CORS

Day 3				Day-of-year 009	
				Wednesday, 9-Jan-08	
Session 009 A				Start (UTC): 0:00	Start (Loc): 18:00
				Stop (UTC): 23:59	Stop (Loc): 17:59
Observer	Vehicle	Recvr	4CID	Station Name	Comments
			NDBC	STENNIS CORS ARP	CORS
		1001	52V1	52 v 117	NSRS station
		1002	BB1P	BB1P5	SET base station
		1003	BBS2	BBS2	SET base station
			NOLA	LOYOLA UNIVERSITY CORS ARP	CORS



Day 4				Day-of-year	010		
					Thursday,	10-Jan-08	
Session	010	A		Start (UTC):	0:00	Start (Loc):	18:00
				Stop (UTC):	16:00	Stop (Loc):	10:00
Observer	Vehicle	Recvr	4CID	Station Name		Comments	
			NDBC	STENNIS CORS ARP		CORS	
AMC/CAW		1001	52V1	52 v 117		NSRS station - retrieve	
AMC/CAW		1002	BB1P	BB1P5		SET base station - retrieve	
AMC/CAW		1003	BBS2	BBS2		SET base station - replace batteries	
			NOLA	LOYOLA UNIVERSITY CORS ARP		CORS	

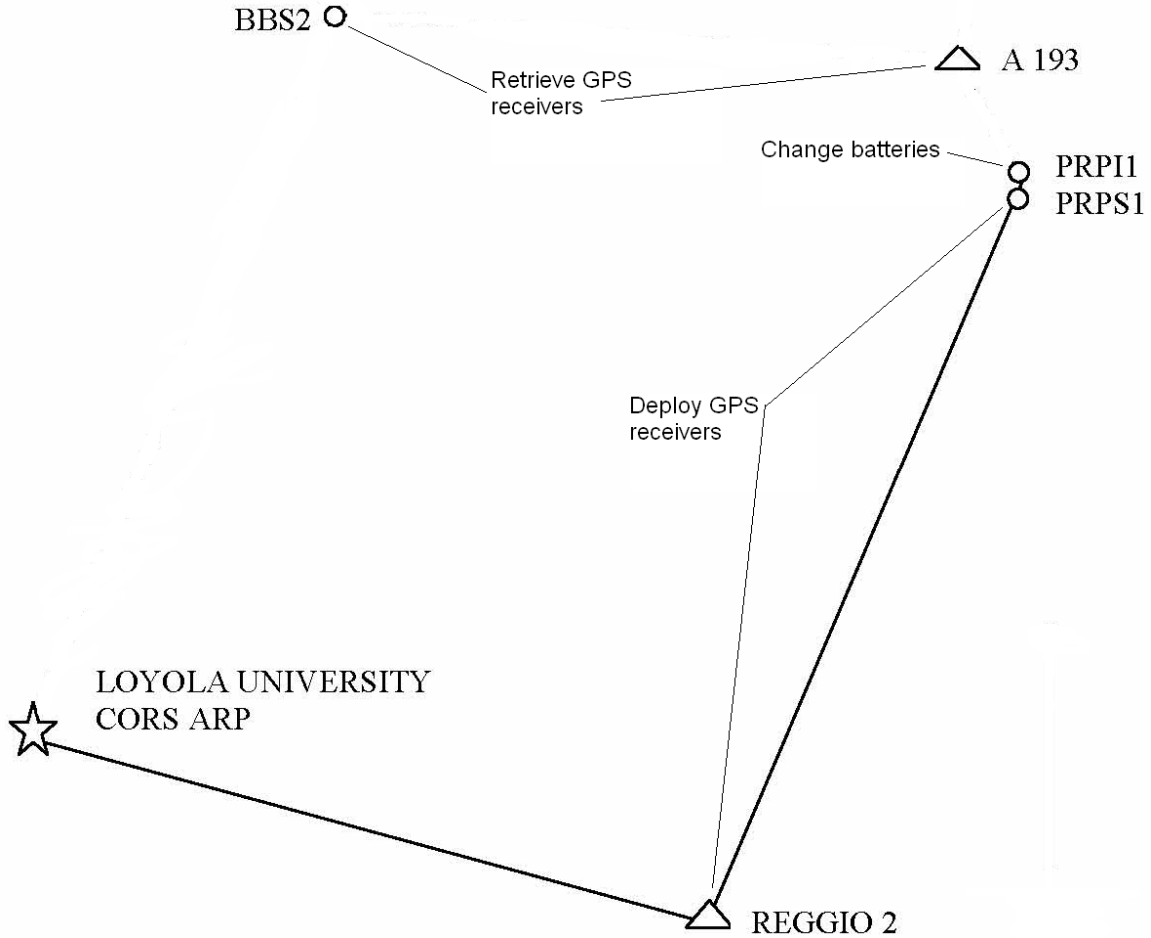
Day 4				Day-of-year	010		
					Thursday,	10-Jan-08	
Session	010	B		Start (UTC):	18:00	Start (Loc):	12:00
				Stop (UTC):	23:59	Stop (Loc):	17:59
Observer	Vehicle	Recvr	4CID	Station Name		Comments	
			NOLA	LOYOLA UNIVERSITY CORS ARP		CORS	
		1003	BBS2	BBS2		SET base station	
AMC/CAW		1001	A193	A 193		NSRS station - deploy	
AMC/CAW		1002	PRPS	PRPS1		SET base station - deploy	
			NDBC	STENNIS CORS ARP		CORS	



Day 5				Day-of-year 011	
				Friday, 11-Jan-08	
Session		011	A	Start (UTC): 0:00	Start (Loc): 18:00
				Stop (UTC): 23:59	Stop (Loc): 17:59
Observer	Vehicle	Recvr	4CID	Station Name	Comments
			NOLA	LOYOLA UNIVERSITY CORS ARP	CORS
		1003	BBS2	BBS2	SET base station
		1001	A193	A 193	NSRS station
		1002	PRPS	PRPS1	SET base station
			NDBC	STENNIS CORS ARP	CORS

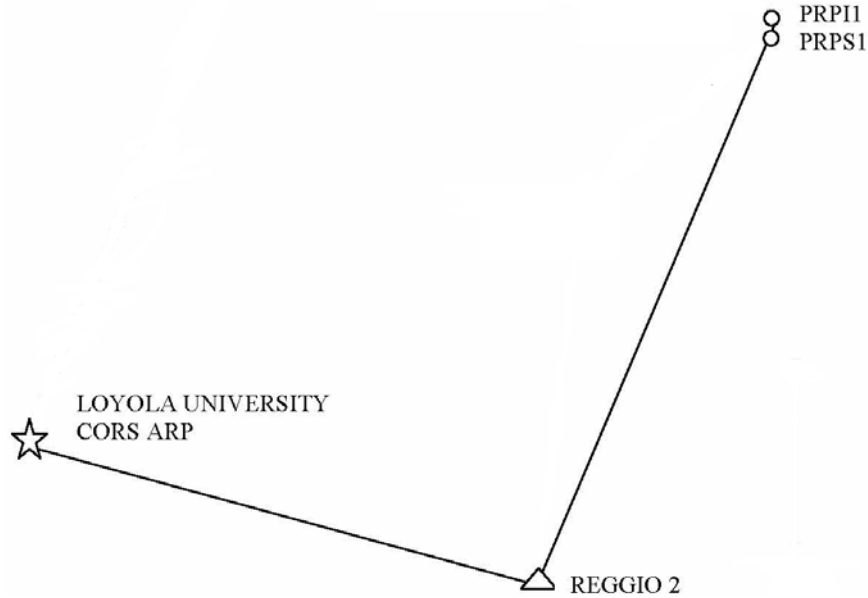
Day 6				Day-of-year 012	
				Saturday, 12-Jan-08	
Session		012	A	Start (UTC): 0:00	Start (Loc): 18:00
				Stop (UTC): 23:59	Stop (Loc): 17:59
Observer	Vehicle	Recvr	4CID	Station Name	Comments
			NOLA	LOYOLA UNIVERSITY CORS ARP	CORS
		1003	BBS2	BBS2	SET base station
		1001	A193	A 193	NSRS station
		1002	PRPS	PRPS1	SET base station
			NDBC	STENNIS CORS ARP	CORS

Day 7				Day-of-year 013	
				Sunday, 13-Jan-08	
Session		013	A	Start (UTC): 0:00	Start (Loc): 18:00
				Stop (UTC): 23:59	Stop (Loc): 17:59
Observer	Vehicle	Recvr	4CID	Station Name	Comments
			NOLA	LOYOLA UNIVERSITY CORS ARP	CORS
		1003	BBS2	BBS2	SET base station
		1001	A193	A 193	NSRS station
		1002	PRPS	PRPS1	SET base station
			NDBC	STENNIS CORS ARP	CORS



Day 8				Day-of-year	014	
					Monday, 14-Jan-08	
Session	014	A		Start (UTC):	0:00	Start (Loc): 18:00
				Stop (UTC):	16:00	Stop (Loc): 10:00
Observer	Vehicle	Recvr	4CID	Station Name		Comments
			NOLA	LOYOLA UNIVERSITY CORS ARP		CORS
AMC/CAW		1003	BBS2	BBS2		SET base station - retrieve
AMC/CAW		1001	A193	A 193		NSRS station - retrieve
AMC/CAW		1002	PRPS	PRPS1		SET base station - replace batteries
			NDBC	STENNIS CORS ARP		CORS

Day 8				Day-of-year	014	
					Monday, 14-Jan-08	
Session	014	B		Start (UTC):	18:00	Start (Loc): 12:00
				Stop (UTC):	23:59	Stop (Loc): 17:59
Observer	Vehicle	Recvr	4CID	Station Name		Comments
		1002	PRPS	PRPS1		SET base station
AMC/CAW		1003	PRPI	PRPI1		SET base station - deploy
AMC/CAW		1001	REGG	REGGIO 2		NSRS station - deploy
			NOLA	LOYOLA UNIVERSITY CORS ARP		CORS



Day 9		Day-of-year	015		
		Tuesday,	15-Jan-08		
Session	015 A	Start (UTC):	0:00	Start (Loc):	18:00
		Stop (UTC):	23:59	Stop (Loc):	17:59
Observer	Vehicle	Recvr	4CID	Station Name	Comments
		1002	PRPS	PRPS1	SET base station
		1003	PRPI	PRPI1	SET base station
		1001	REGG	REGGIO 2	NSRS station
			NOLA	LOYOLA UNIVERSITY CORS ARP	CORS

Day 10		Day-of-year	016		
		Wednesday,	16-Jan-08		
Session	016 A	Start (UTC):	0:00	Start (Loc):	18:00
		Stop (UTC):	23:59	Stop (Loc):	17:59
Observer	Vehicle	Recvr	4CID	Station Name	Comments
		1002	PRPS	PRPS1	SET base station
		1003	PRPI	PRPI1	SET base station
		1001	REGG	REGGIO 2	NSRS station
			NOLA	LOYOLA UNIVERSITY CORS ARP	CORS

Day 11		Day-of-year	017		
		Thursday,	17-Jan-08		
Session	017 A	Start (UTC):	0:00	Start (Loc):	18:00
		Stop (UTC):	18:00	Stop (Loc):	12:00
Observer	Vehicle	Recvr	4CID	Station Name	Comments
AMC/CAW		1002	PRPS	PRPS1	SET base station - retrieve
AMC/CAW		1003	PRPI	PRPI1	SET base station - retrieve
AMC/CAW		1001	REGG	REGGIO 2	NSRS station - retrieve
			NOLA	LOYOLA UNIVERSITY CORS ARP	CORS

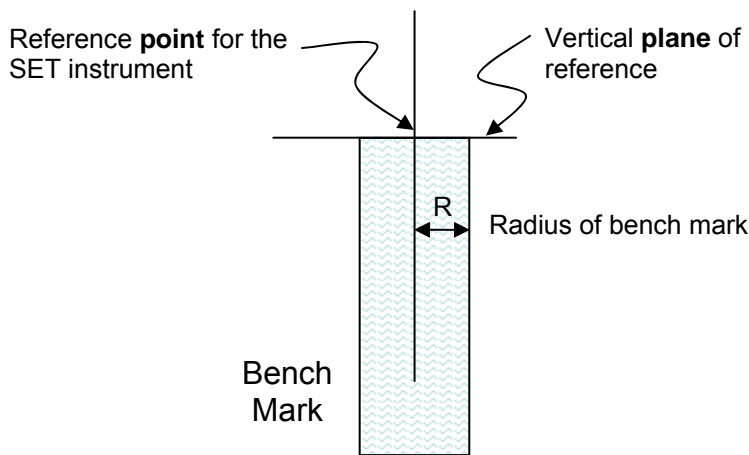
Attachment B:

Determining the Vertical Point of Reference
on a Surface Elevation Table (SET) Bench Mark



According to standard leveling practices, the top-most surface of a vertical bench mark is the vertical point of reference (VPR), whether it is a brass disk or deep rod (Schomaker and Berry 1981). For brass disks or deep rods, the highest point on the mark is easily defined; for a typical SET bench mark, however, the location of the top depends on the precise orientation of the bench mark with respect to the vertical. Note that when in operation, the position of the SET instrument itself is relative to the top center of the bench mark, which is a void into which the base of the instrument is placed. If the bench mark is perfectly plumb, the reference point of the SET is the same as the top surface of the mark (figure B.1a). If the bench mark is tilted, however, then there is a systematic error between the highest point on the mark and the top center (figure B.1b). The magnitude of the systematic error depends on both the type of SET bench mark, as well as the angle of tilt (Table B.1). The small diameter of the Rod SET (16mm) results in much smaller systematic error than in the larger pipe-based SET (30.2 mm; Figure B.2).

A. Bench mark plumb



B. Bench mark tilted

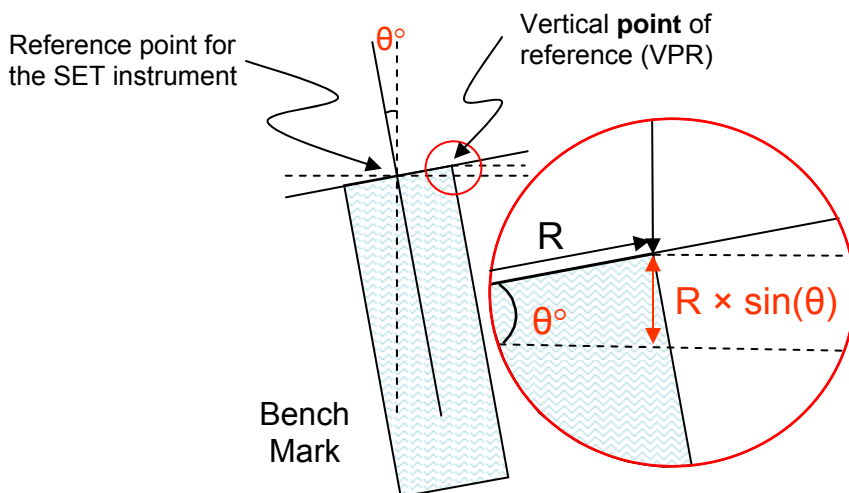


Figure B.1. Sketch showing relationship between the top of the bench mark and the top center of the bench mark, as the mark is tilted away from the vertical.

Table B.1. Systematic error between the center of the Surface Elevation Table (SET) bench mark and the top side of the bench mark, over different tilt angles of the mark.

Tilt Angle (θ°)	Systematic Error (mm)	
	Trad. Pipe SET	Deep Rod SET
1	0.5	0.2
2	1.1	0.3
3	1.6	0.5
4	2.1	0.6
5	2.6	0.8
6	3.2	1.0
7	3.7	1.1
8	4.2	1.3
9	4.7	1.4
10	5.2	1.6

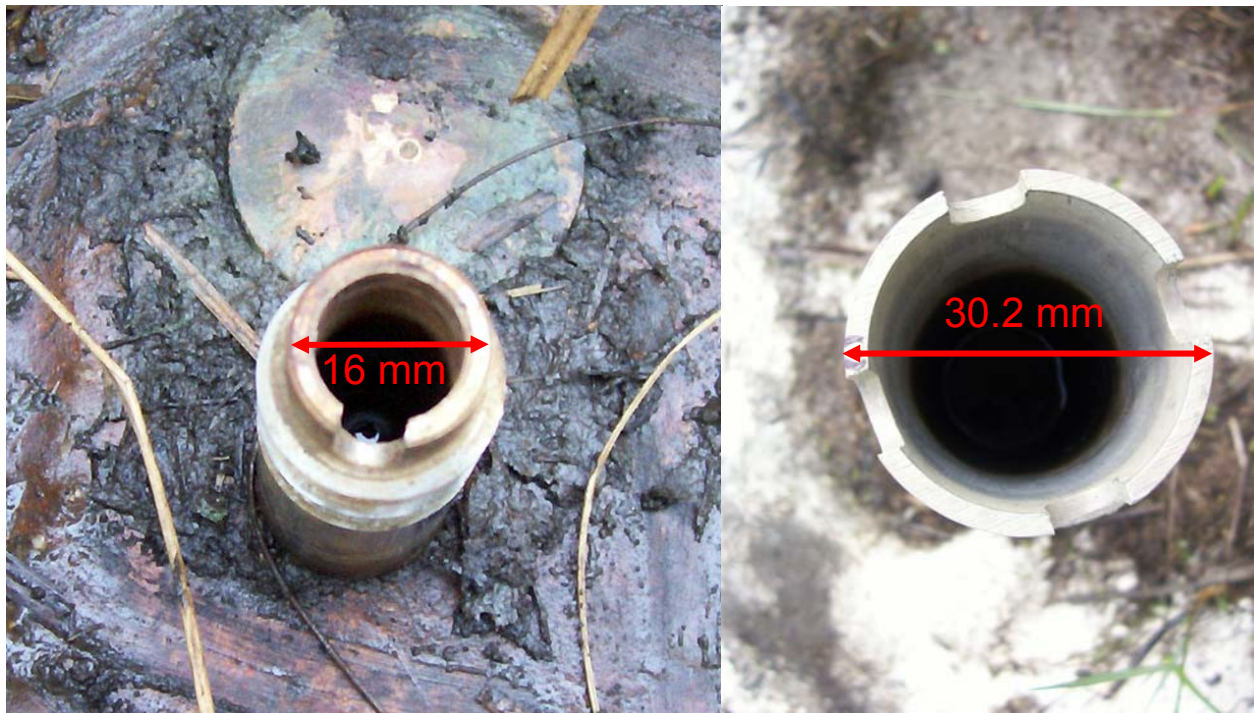


Figure B.2. Diameters of Surface Elevation Table (SET) bench marks. Left: deep rod SET; right: traditional/older pipe-based SET.

The surveyor needs to take care in being consistent in the designation of the VPR, especially when using the traditional pipe-based SET. Following standard practices, it is recommended to use the highest point on the bench mark as the VPR. The location of the top most point on a SET bench mark can be facilitated by using a tiltmeter or leveling vial. During field trials, a standard rod level (40' vial) was aligned to the exterior surface of the SET BM and rotated around the mark. The deviation of the bubble away from the center was noted as the level was turned around the mark. The section of the mark closest to the bubble when the bubble is farthest away from the bench mark corresponds to the highest point on the mark (figure B.3). This point should be stamped and labeled to ensure repeatability of measurements.

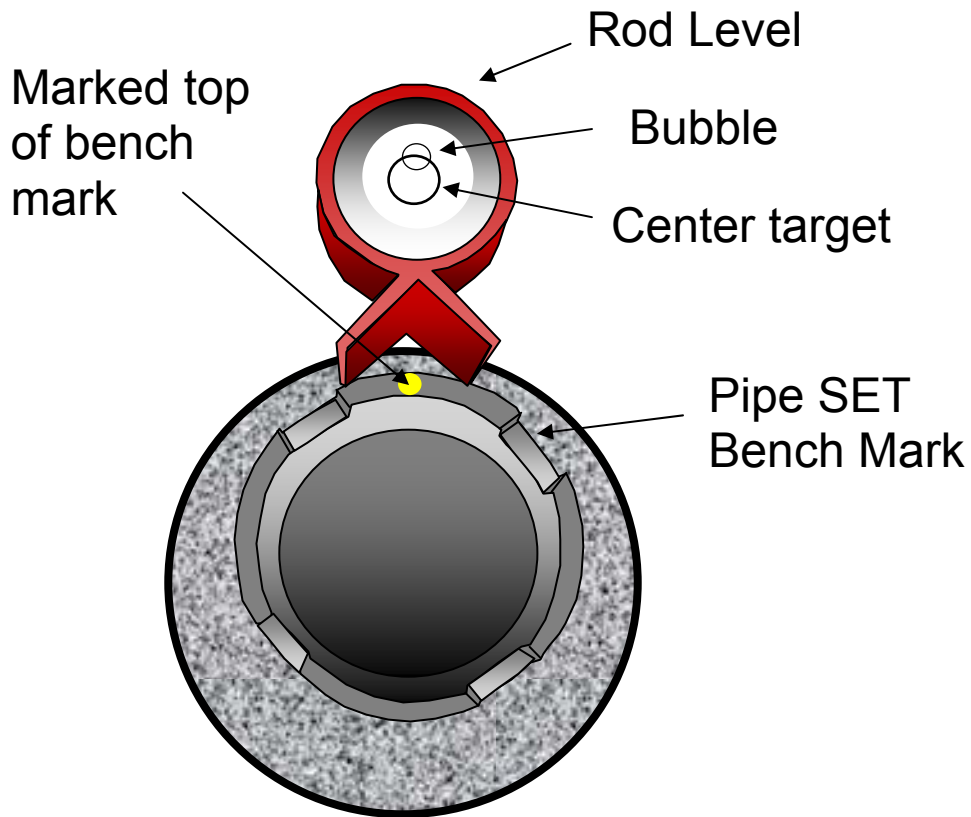


Figure B.3. Sketch showing how a rod level can be used to determine the top of a SET bench mark is the mark is tilted away from the vertical.

References

Schomaker, M.C. and R.M. Berry. 1981. Geodetic Leveling. NOAA Manual NOS NGS 3, NOAA Rockville, MD. 224 pp.

Attachment C :

**Kendapter-based Instrumentation and Methodologies
for a GNSS Antenna on a SET Bench Mark**



Part I: The Kendapter

A novel GNSS antenna adapter has been engineered and developed by NGS's Instrumentation & Methodologies Branch (I&M) that eliminates the need for a tripod-mounted GNSS antenna. The device, called a Kendapter (Figures C.1, C.2, and C.3), mounts solidly to any of the three SET BM designs currently in use. It consists of four parts; a custom built SET adapter that attaches to a rod, pipe or receiver, a standard Wild-type surveying tribrach, a rotating tribrach adapter, and a Zeiss-type plug with 5/8"-11 threads (sometimes called a "gidney"). Once secure and leveled, it allows a survey-grade GNSS antenna to be plumbed and centered over the horizontal point of reference (HPR, effectively the vertical center of rotation of a SET BM top). It might be necessary to use a 0.5-meter extension to raise the GNSS antenna above surrounding vegetation, allowing a clear view of the sky. An engineering sketch of the custom-built SET adapter with dimensions is given in figure C.4.

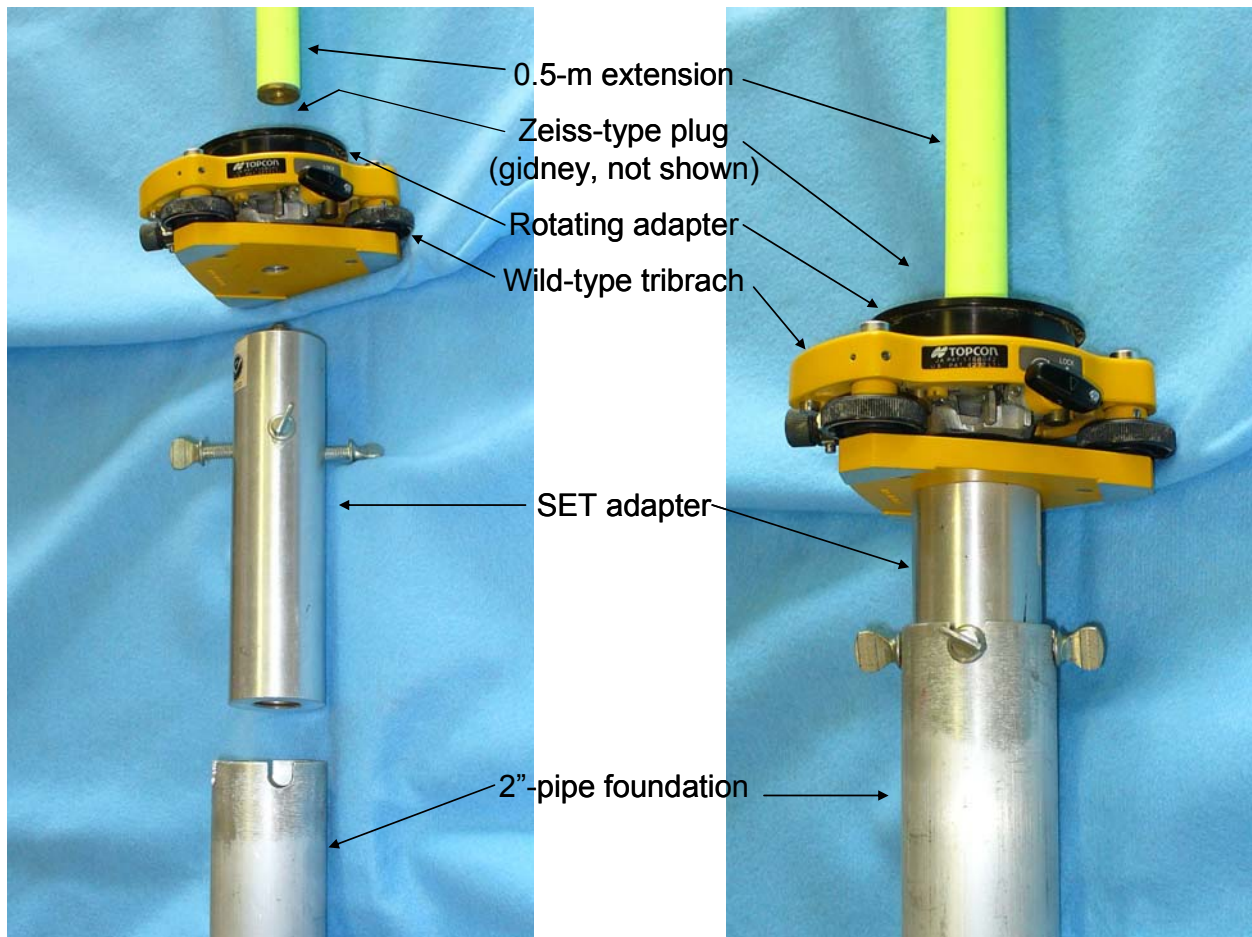


Fig. C.1 Kendapter on a 2" pipe Surface Elevation Table (SET) bench mark (BM)

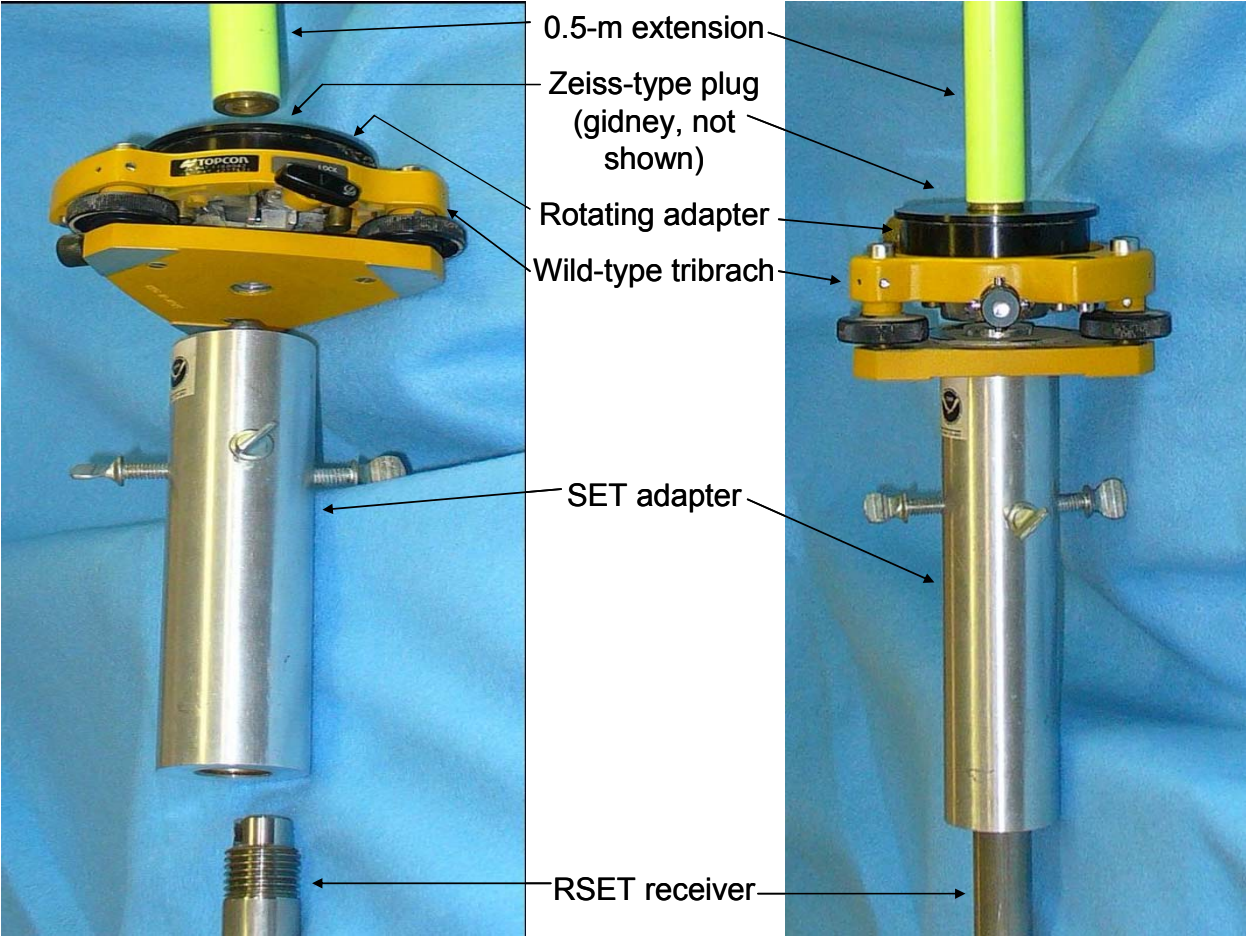


Fig. C.2. Kendapter on a Deep Rod SET receiver BM

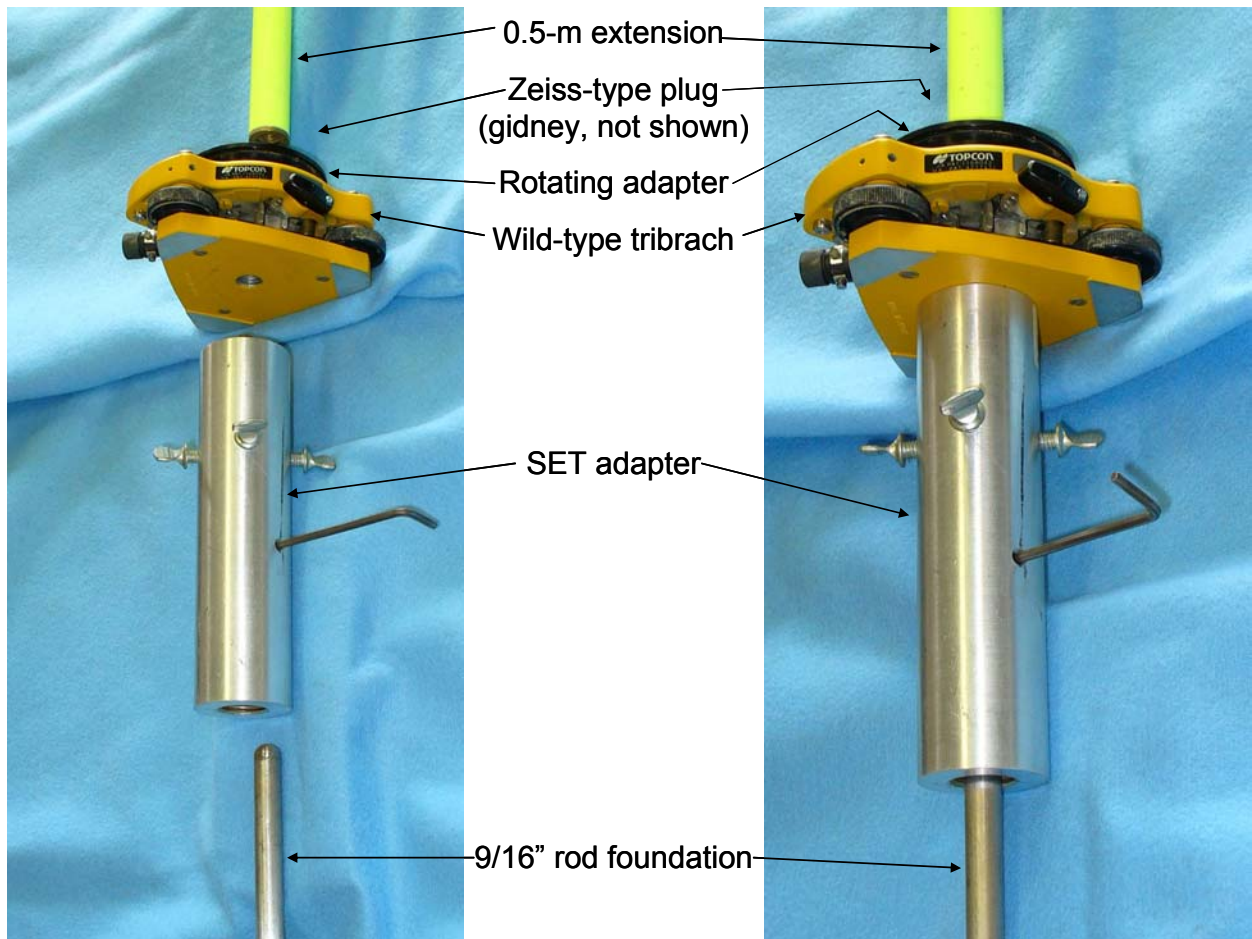


Fig. C.3. Exploded view, Kendapter on a 9/16" SS rod. An allen wrench and a set screw (pictured) are used to secure the Kendapter to the rod. One of the four thumbscrews may also be moved down and used in place of the set screw, eliminating the need for an allen wrench.

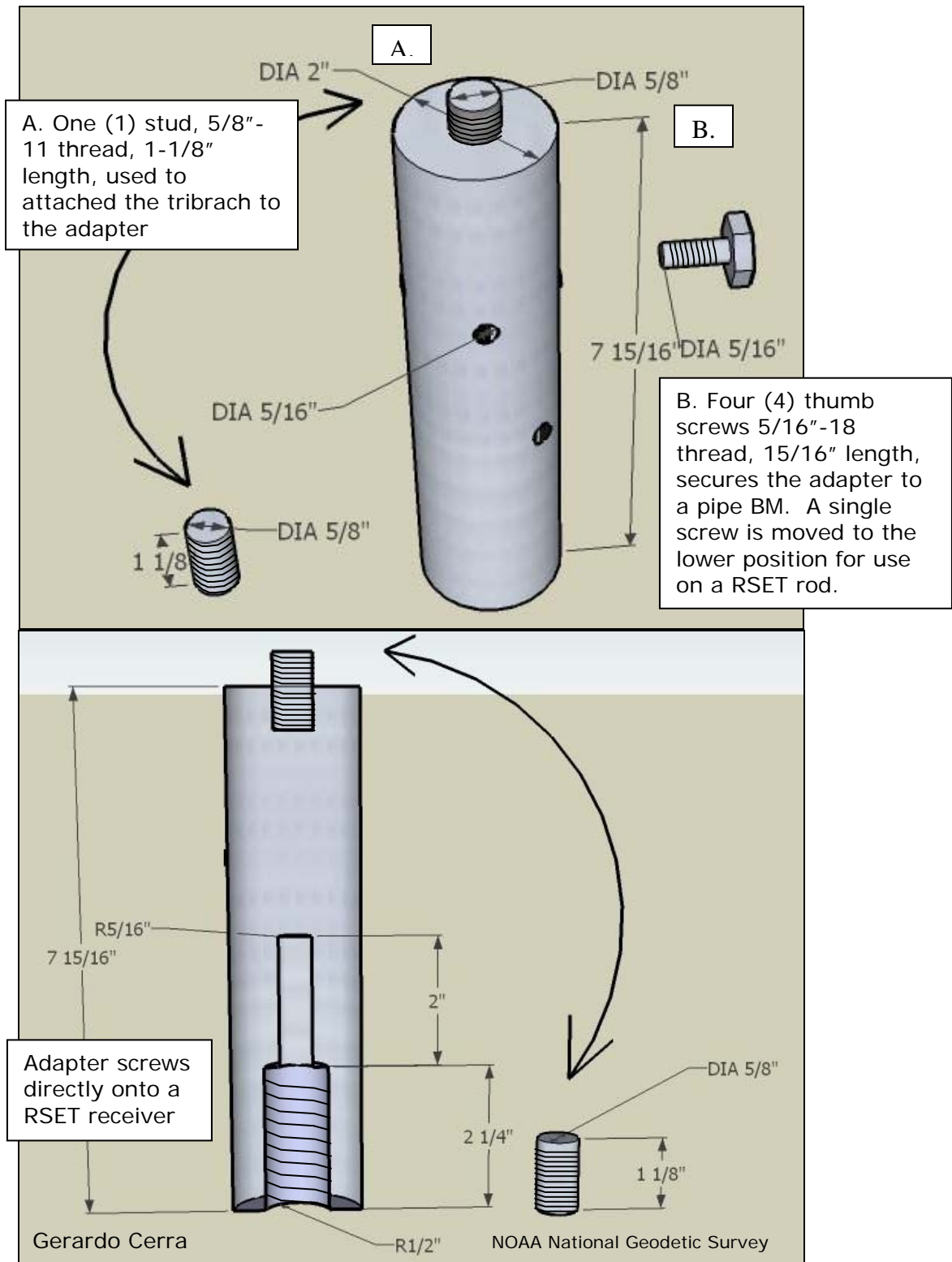


Fig. C.4: Engineering sketch of the bottom portion of the Kendapter, which is designed to connect to any of the three known versions of SET bench marks. The upper stud connects to a Wild-type tribrach.

Part II. Methodologies for Calculating GNSS Antenna Heights using the Kendapter

Leveling the tribrach portion of the Kendapter results in a change in the height of the GNSS antenna above the SET BM VPR. The user must therefore measure the realized height in the field after the plumb has been set. A problem posed by the Kendapter is that it obstructs access to the VPR, making it impossible to directly measure the height measurement of the GNSS antenna above the VPR. However, three different methodologies for indirectly obtaining this height above the VPR evolved over the course developing these guidelines and are covered in detail below.

Part II.1. Standard Differential Leveling Procedures

A survey-grade level can be used to obtain accurate and precise GNSS antenna heights in the field using standard differential leveling procedures (figure C5; [Schomaker and Berry 1981](#)). Special considerations for leveling on unconsolidated sediments in the wetland environment are given below.

In conducting differential leveling with a standard survey-grade level, a tripod holding the level is deployed on the marsh surface, at a short distance from the SET bench mark (e.g. 10 m) with the legs pushed into the substrate far enough to ensure sufficient stability. The operator should strive to insert the tripod legs into vegetated substrate, as it is generally much more cohesive than unvegetated surfaces. Alternatively, flat, tethered weights (e.g. barbells) can be placed on the marsh surface under the tripod legs to provide the needed stability.

The greatest of care must be taken to avoid disturbing the unstable sediments closest to the SET bench mark. The SET instrument measures surface elevation dynamics within a radius of approximately one to one and a half meters from the bench mark. This constitutes a no-walk area. Many SET plots have permanent platforms and boardwalks to avoid stepping anywhere near the mark. Unfortunately, using a tripod requires the surveyor to step on the marsh surface. For this reason, care must be taken to place the tripod far enough away from the mark so as to minimize site disturbance near the area of measurement.

High end digital barcode levels will be sensitive to the slightest instability in the marsh surface, so the operator must take great care not to move when the level is reading. The level may also be sensitive to hydrological movements, such as those caused by winds, waves, and tides, resulting in vibrations of the marsh surface.

Assuming the level has been set up and calibrated according to manufacture specifications, a back sight is taken to the SET BM VPR (figure C.5, left panel). The Kendapter is mounted on the SET BM, and the tribrach is leveled. A foresight is then taken to the leveled surface of the tribrach (figure C.5, right panel). The difference between the two observations is the height of the Kendapter above the VPR. Any antenna extensions required for the deployment of a GNSS antenna need to be carefully installed atop the tribrach, taking care not to take the tribrach out of plumb. Any antenna extensions that are used must be factored in the calculated antenna height above the SET BM VPR.

At the conclusion of the GNSS antenna deployment, the GNSS antenna and any antenna extensions are carefully removed, taking care not to disturb the tribrach. A new fore sight is taken as above, on the top of the tribrach plate. The Kendapter is then removed from the SET bench mark, and a back sight is recorded. As before, any antenna extensions between the top plate of the tribrach and the GNSS antenna need to be factored in the antenna height calculations. The initial and final calculated antenna heights are compared, and any significant height discrepancies need to be resolved.

Although this method can provide very good results, the sensitivity of the level to any slight movement of the unstable marsh surface may result in many failed observations. Additionally, the high cost and lack of environmental sealing of most levels render their use in wetland environments somewhat risky. For these reasons, an alternative method for obtaining GNSS antenna heights was developed (Part II.B).

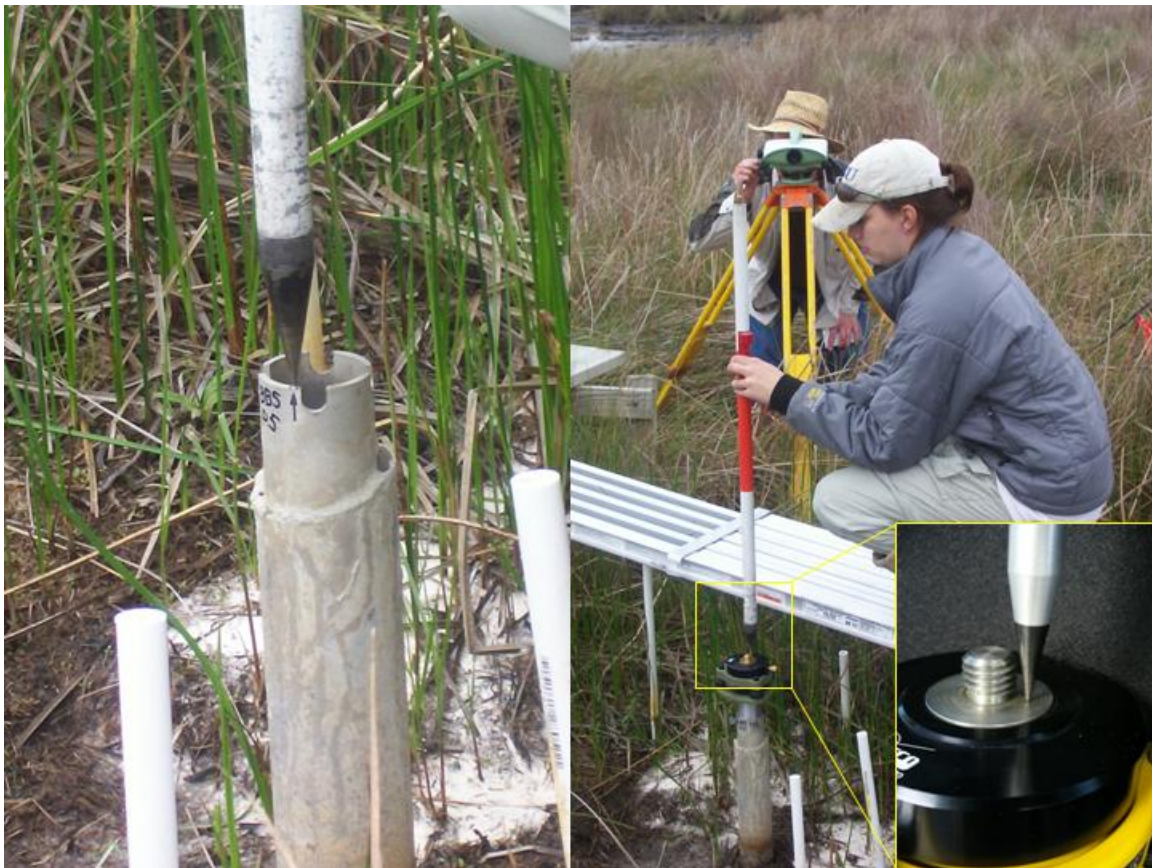


Figure C.5. Leveling techniques can be used to determine GNSS antenna heights using a Kendapter in the field. Left panel: a backsight is taken on the Vertical Point of Reference of the SET bench mark. Right panel: a foresight is taken on top of the tribrach once the tribrach has been leveled. Inset: proper placement of a level rod on a tribrach.

Part II.2. The RoboLaser™ Technique

Disclaimer: RoboToolz® Robolaser™ was the first instrument found that claimed to meet NGS's criteria for a remote-controlled, 360° rotatable, self-leveling laser with a precision of +/- 6 mm at 30 m and a beam bright enough for use in sunlight conditions. Other comparable laser levels may be available.



Figure C.6. The RoboLaser™ technique in operation in a tidal freshwater wetland. The remotely operated, self-leveling level is shown in the foreground. The operator, on the left, is holding the remote control used to direct the laser beam horizontally. A customized level rod slider is used to help keep the level rod plumb while adjusting the level and reading the height off the rod.

The Robolaser™ technique was developed as a response to two considerations that arose with the use of a digital barcode level in the wetland environment: 1) the lack of stability of the level tripod due to the weight of the operator, and 2) the high cost and lack of environmental sealing of the barcode level. To accurately and cost-effectively obtain GNSS antenna heights, the traditional level instrument was replaced with a remote-controlled, automatic laser level instrument (hereafter RoboLaser™), purchased for under \$300. After NGS's initial testing and system development, UNO field tests and onsite refinements produced instrument heights with a consistent precision of ± 3 mm or better.

As with the traditional leveling described above, care must be taken to avoid disturbing the sediment near the SET bench mark. However, the tripod should be placed as close as is practical to the mark to ensure the highest accurate readings (e.g. 5-10 m). As above, flat weights can be placed on the sediment surface under the tripod legs to help stabilize the tripod. The tripod height should be adjusted so that the beam is about one to one and a half meters above the bench mark, so that the beam is easily seen by a person taking the height reading at the bench mark (figure C.7). The laser is self-leveling within a given range of tilt: care must be taken to ensure that the top surface of the tripod is close enough to the horizontal plane to ensure that the laser can be self-leveled (if the unit is not leveled, the laser beam will be in flash mode). Once the laser is set up according to specifications and aimed in the general direction of the SET bench mark, no one should approach the level.

A level rod is then set plumb above the VPR and, using the remote control, the sideways motion of the RoboLaser® is adjusted until the laser beam intersects the rod (figure C.7). The remote has two sets of positioning buttons: the fast speed buttons (left and right) are best used to get the laser beam within the vicinity of the level rod; once the beam is close, the final adjustment is made with the slow speed buttons. The height at which the laser intersects the rod is recorded. This is the back sight reading.

At the conclusion of the GNSS antenna deployment, the antenna and any extensions are carefully removed, taking care not to disturb the tribrach. A new fore sight is taken as above, on the top of the tribrach plate. The Kendapter is then removed, and a new back sight is taken to the SET BM VPR. As before, any antenna extensions between the top plate of the tribrach and the GNSS antenna need to be factored in the antenna height calculations. The initial and final calculated antenna heights are compared, and any significant height discrepancies need to be resolved. Note that the RoboLaser® technique has an empirically determined accuracy of three millimeters using the custom slider described below.

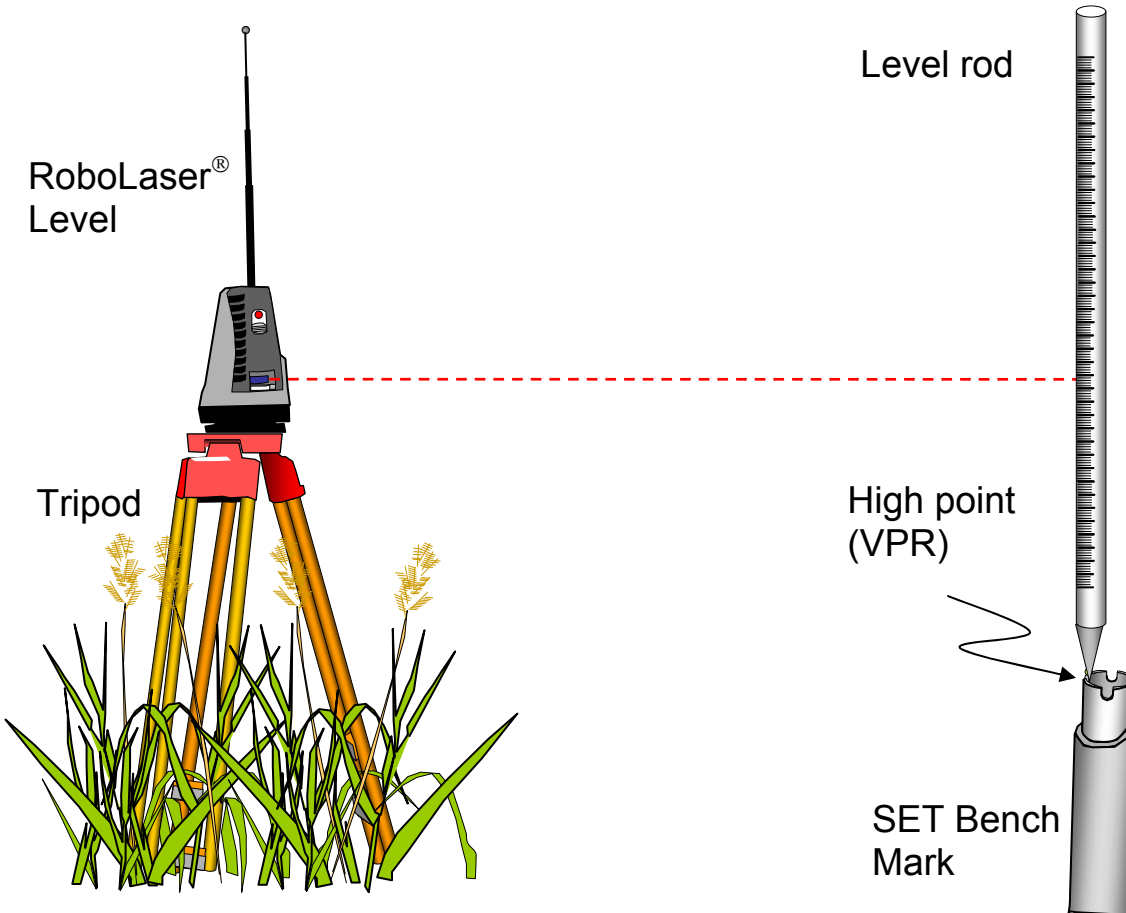


Figure C.7. Taking a back sight level shot on a Surface Elevation Table (SET) bench mark using the RoboLaser[®] level. The level and tripod assembly are placed so that the laser beam is easily read by an operator with a level rod. Note that the level rod must be plumb above the Vertical Point of Reference (VPR) on the SET bench mark.

A customized rod level slider was designed to facilitate the three synchronous tasks of plumbing the level rod, adjusting the position of the laser beam, and reading the level rod itself (figure C.8). The slider is constructed of an acrylic block, to which is affixed a 40-minute rod level (figure C.9). A horizontal line is etched in the acrylic to assist the operator in reading the height of the laser beam along the level rod. A thumb screw is used to tighten the slider against the level rod once the laser beam is split equally on both sides of the etched line. Care must be taken to align the etched line at eye level, so the proper height measurement can be made (figure C.10). Using the slider enables the highest accuracy to be maintained using this RoboLaser[®] technique (± 3 mm). However, one must acquire skill to conduct these three simultaneous tasks successfully. Of the three tasks, positioning the slider vertically is the most crucial, as a slight deviation of the level rod from plumb will affect the final height measurement much less than a similar error in placing the slider (the former acting through the cosine of the resulting angle, and the latter directly affecting the height).

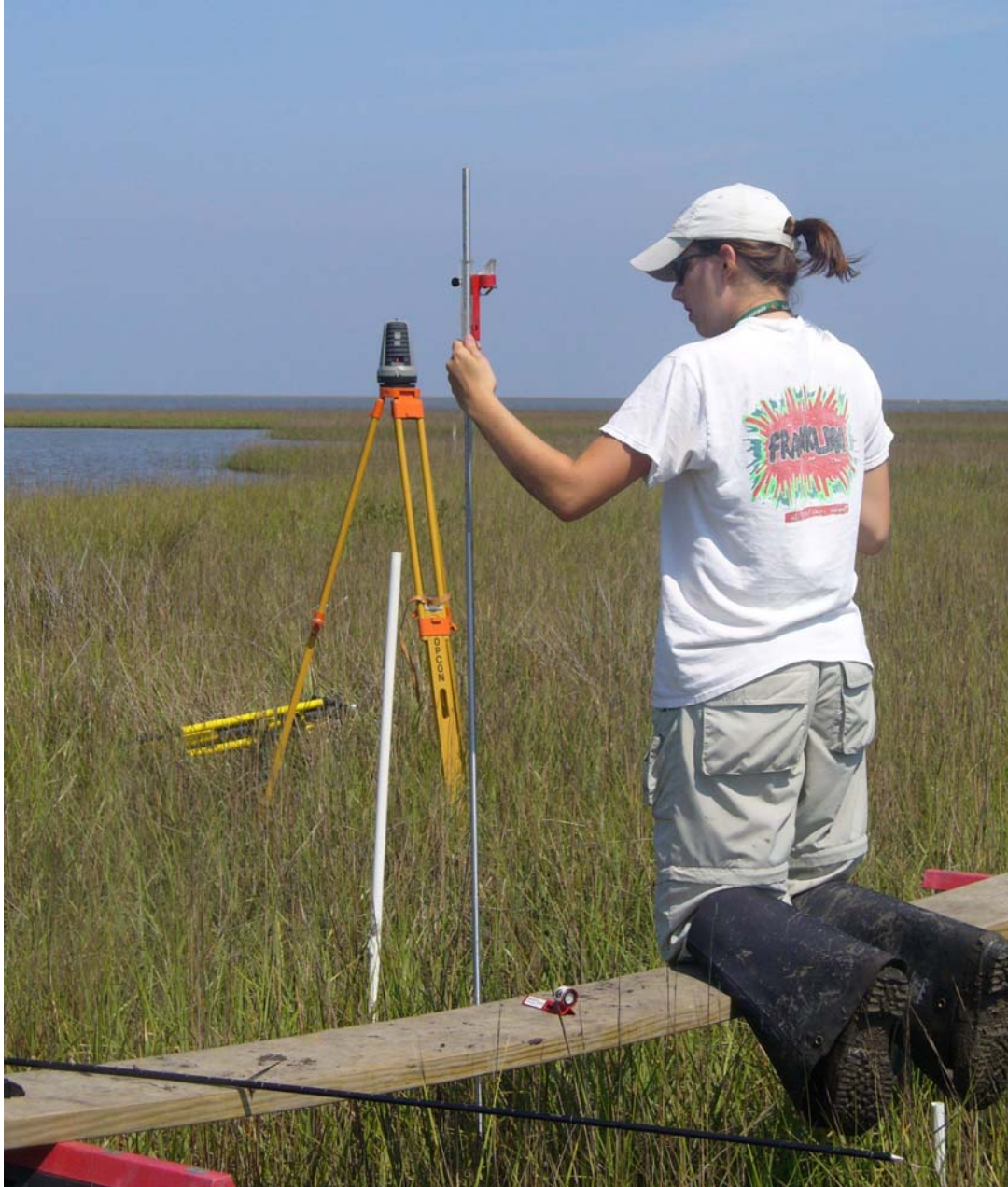


Figure C.8. Photograph of RoboLaser® technique being used to measure a Global Navigation Satellite System (GNSS) antenna height above a Surface Elevation Table (SET) bench mark in southeastern Louisiana. A customized level rod slider is seen in use to facilitate the synchronous tasks of plumbing the level rod, moving the laser level, and reading the height on the rod.

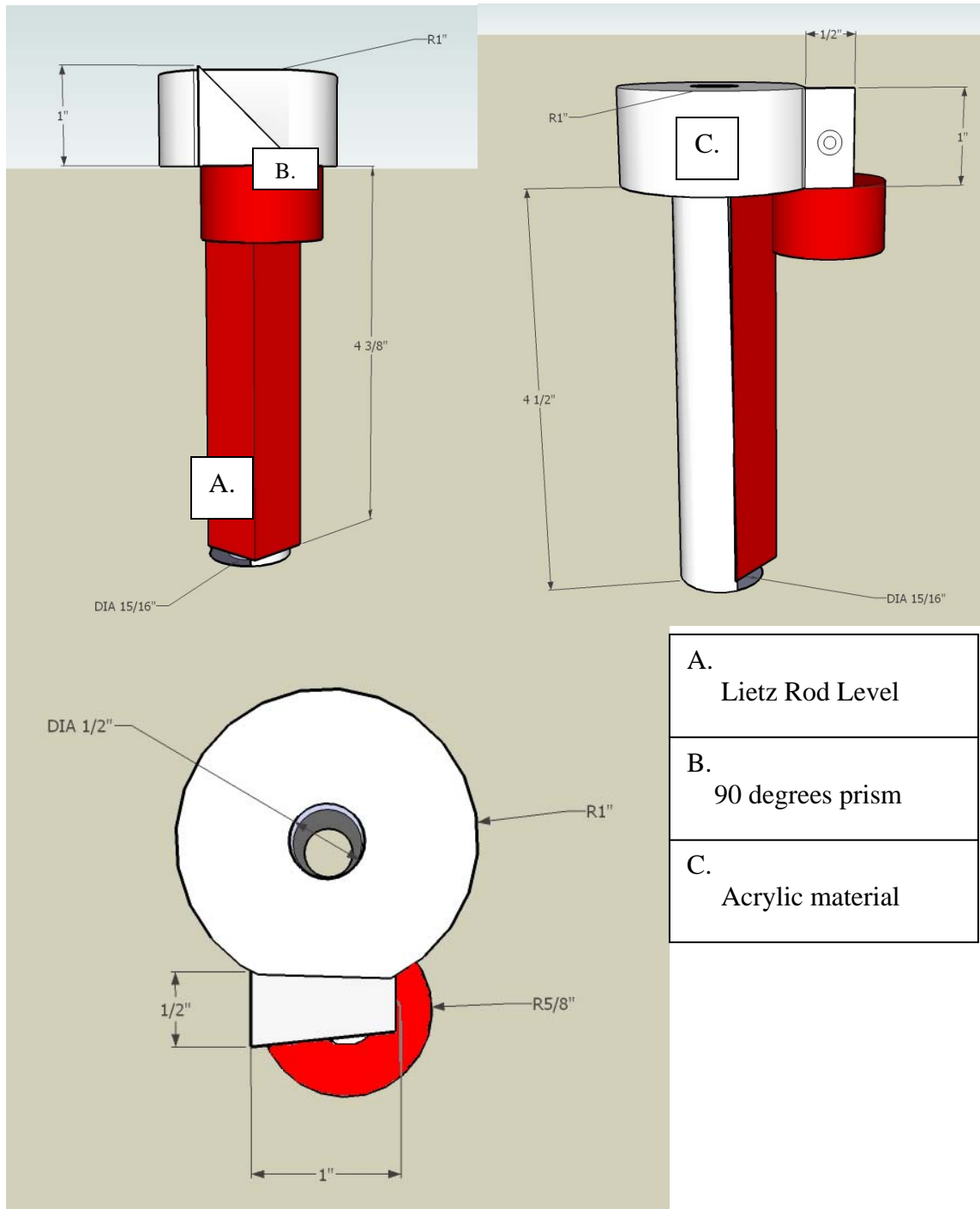


Figure C.9. Engineering sketch of custom level rod slider for the RoboLaser® level technique of determining Global Navigation Satellite System (GNSS) antenna heights on Surface Elevation Table (SET) bench marks.

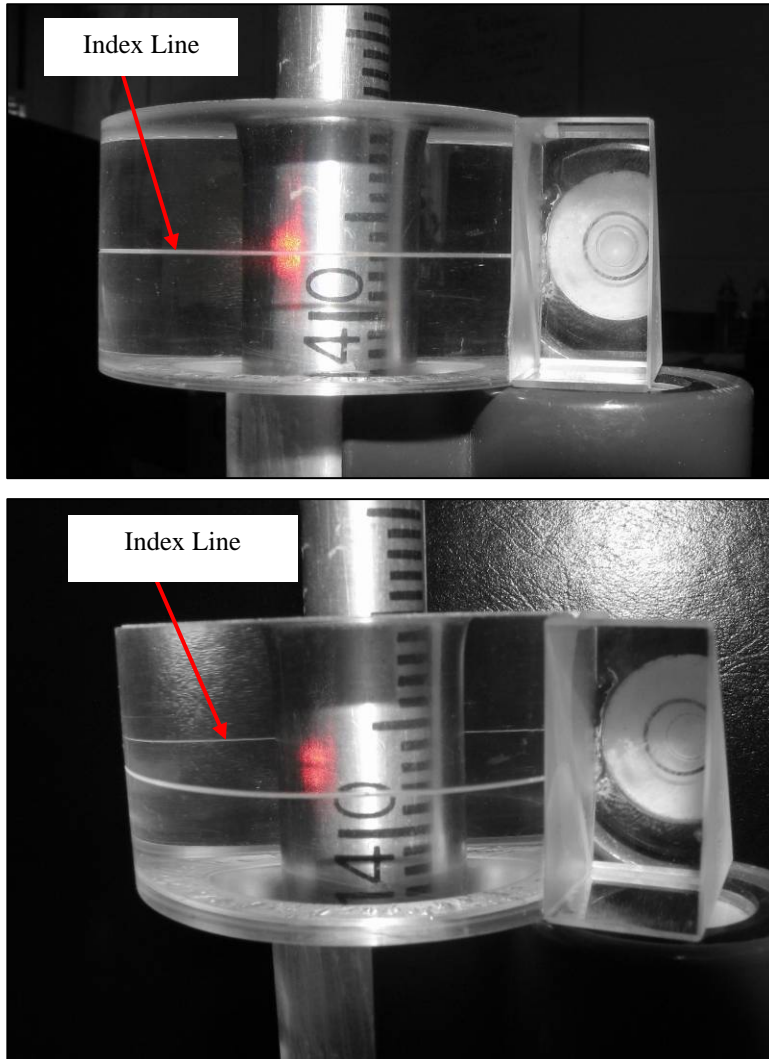


Figure C.10. Top panel: Customized acrylic slider used to accurately measure the intersection of a laser level beam with a level rod. The rod is kept plumb by referencing the rod level, as seen through the 90° prism (to the right). The slider is adjusted vertically until the laser beam is bisected by the etched index line (read here as 40.3 cm). Note that the index line is aligned with the viewer's eyes. Bottom panel: If the viewer's eyes are not lined up with the etched index line, an erroneous height measurement may result (read here as 40.2 cm).

Part II.3. The Caliper/Tiltmeter method

This technique evolved in response to the difficulties and logistics involved with leveling in the field. If the dimensions of the leveled tribrach and the tilt of a SET BM can be accurately measured, then the vertical height of the tribrach atop the SET BM can be calculated, based on trigonometric principles. An electronic tiltmeter (about \$45) and a set of vernier calipers were used in the development of this technique (see attachment D for tiltmeter performance evaluation).

Once the Kendapter is placed on the SET BM, the tribrach is attached and the top plate is leveled (Figure C.11). There are several dimensions in this arrangement that need to be measured (Figure C.12). In this configuration, it will be necessary to determine the vertical separation between the VPR and the top plane of the tribrach in order to reference the GNSS antenna to the VPR of the SET. This separation between the VPR and the tribrach is called "L" and shown in purple in figure C.12.

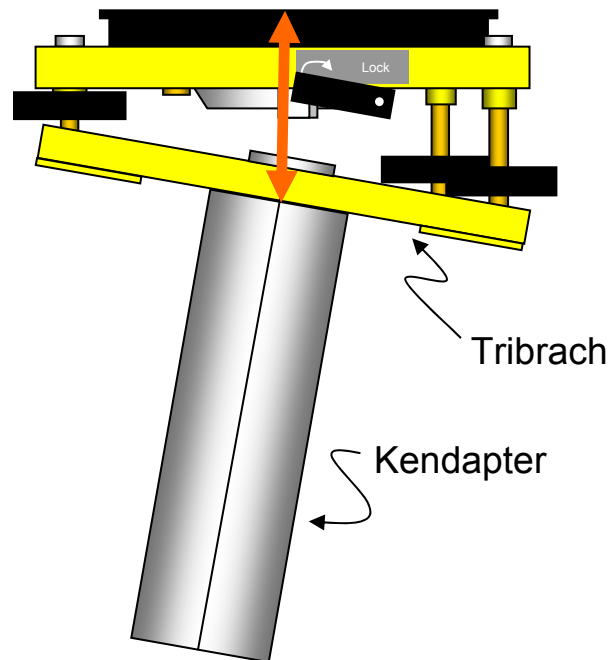


Figure C.11. Side view of Kendapter and tribrach. Orange arrow shows height of top place of tribrach above center of Kendapter

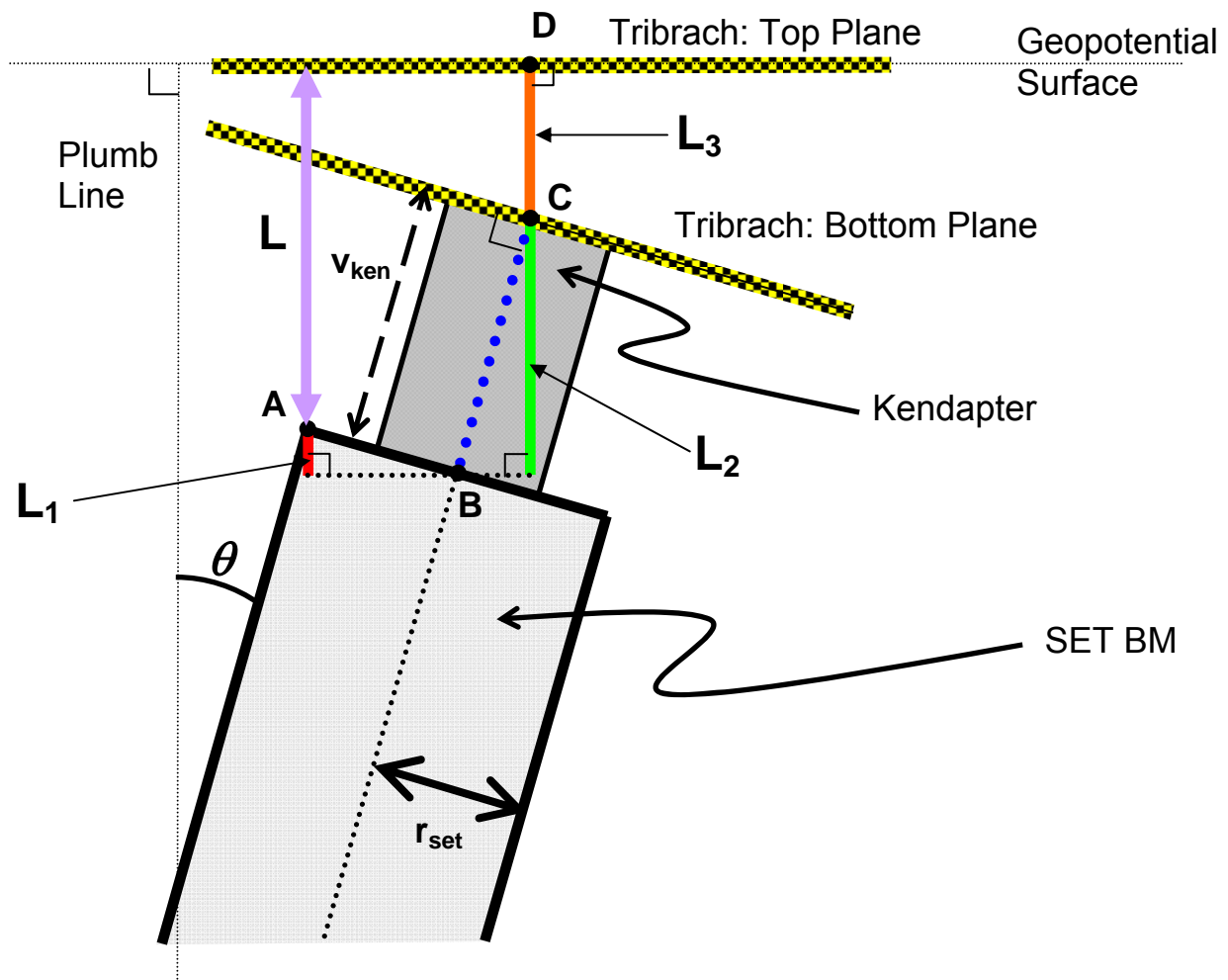


Figure C.12. Sketch of the custom "Kendapter" GNSS antenna adapter and tribrach atop a pipe Surface Elevation Table bench mark. The sketch shows the different dimensions that need to be known (r_{set} , v_{ken}) and/or measured (θ , L_3) to resolve the height of the tribrach top plane above the SET bench mark vertical point of reference (A)

In that figure, the SET bench mark is assumed to have a tilt of θ degrees relative to plumb. When the Kendapter is in place it may be difficult or impossible to directly measure L . However, L can be derived as follows. First, note that the following equation C.1 holds (refer to figure C.12):

$$L = L_2 + L_3 - L_1 \quad (\text{Eq. C.1})$$

Where L_1 (red), L_2 (green) and L_3 (orange) are all vertical lines in the local system of the SET BM. The procedures for determining each of these 3 lengths follows:

- L₁: Separation between VPR and center-of-top of SET BM

First, measure the tilt of the SET BM (θ) using a tiltmeter. This is best accomplished by placing a tiltmeter flat against the side of the bench mark, and rotating the instrument about the mark while noting how the readings change. The maximum number will correspond to the tilt of the mark. As a check, a rod level vial can be used to determine the direction of the tilt (see Attachment B) and a tiltmeter measurement taken at that location.

Once the tilt angle has been measured, use a set of calipers to determine the radius of the SET BM (r_{set}). Table C.1 gives the radii of two typical SET BMs. The geometry of figure C.12 can be used to derive the following relationship:

$$L_1 = r_{SET} \sin \theta \quad (\text{Eq. C.2})$$

Table C.1. Measured radii of two widely-used Surface Elevation Table (SET) bench mark receivers.

SET Bench Mark	Radius (mm)
Pipe SET	30.3
Deep Rod SET	10.0

- L₂: Separation between center-of-top of SET BM and center-of-bottom of tribrach

This distance L_2 depends on the angle of inclination (θ) and the vertical height of the Kendapter (v_{ken}). The Kendapter is a tool developed by NGS (standardized in size and built to fit the three most common SET Bench Marks). Each type of SET BM will interface differently with the adapter, so the particular dimension needed will have to be measured. Table C.2 gives the corresponding measurements of v_{ken} from an adapter that was used in the test procedures. The geometry of figure C.12 can be used to derive this relationship:

$$L_2 = v_{ken} \cos \theta \quad (\text{Eq. C.3})$$

Table C.2. Measured height of a Kendapter atop three different Surface Elevation table (SET) bench marks (v_{ken} ; refer to text).

SET Bench Mark	v_{ken} (mm)
Pipe SET	54.5
Deep Rod SET (rod)	91.6
Deep Rod SET (receiver)	163

- L₃: Separation between center-of-bottom of tribrach and center-of-top of tribrach

The distance along the very center of the tribrach between the bottom and top planes can be determined through some quick measurements and the application of planar geometry. Using the calipers, measure the distance between the outer edge of the top and bottom planes of the tribrach at three points that must be radially symmetric around the tribrach (that is, separated by 120 degrees) and equidistant from the central (z) axis of the tribrach. For simplicity and ease of measurement, it is recommended that these separations be done at the midpoints between the legs (Figures C.13 and C14).

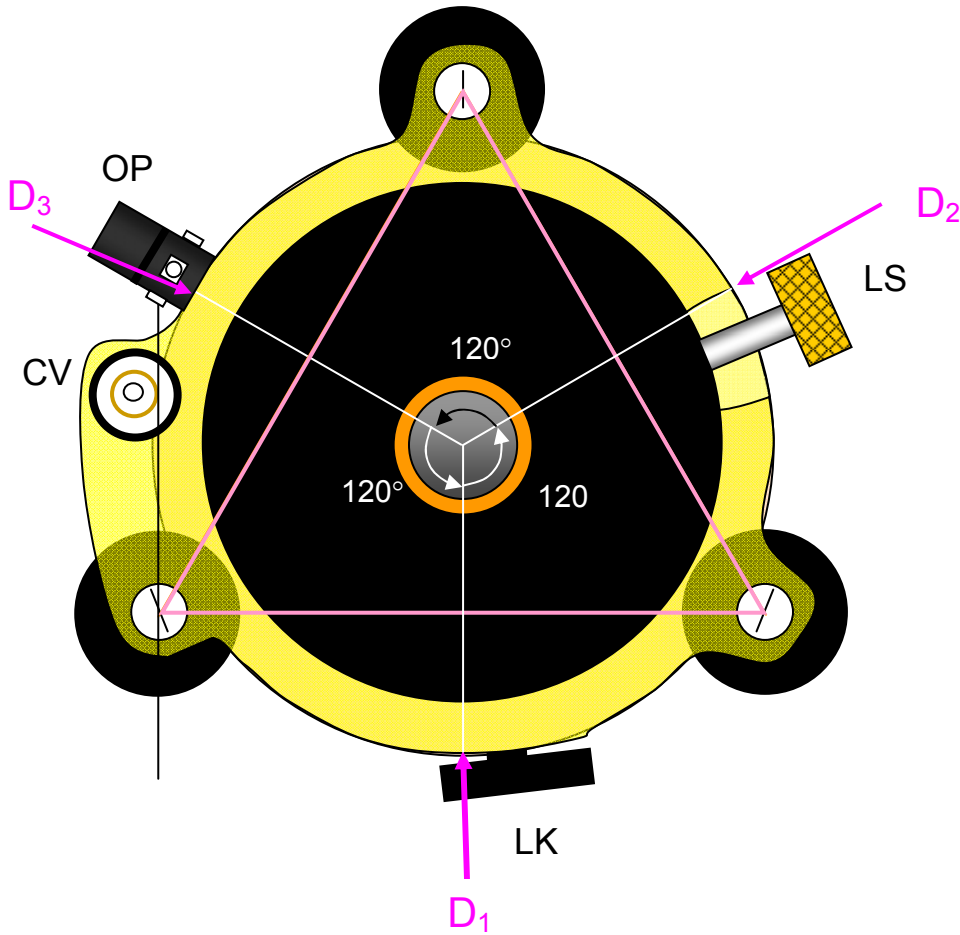


Figure C.13. Top view of Wild-type tribrach used with the Kendapter GNSS antenna adapter. CV = circular vial; OP = optical plummet; LK = tribrach lock knob ; LS = center locking screw; three points where the measurements D₁, D₂ and D₃ are taken are labeled

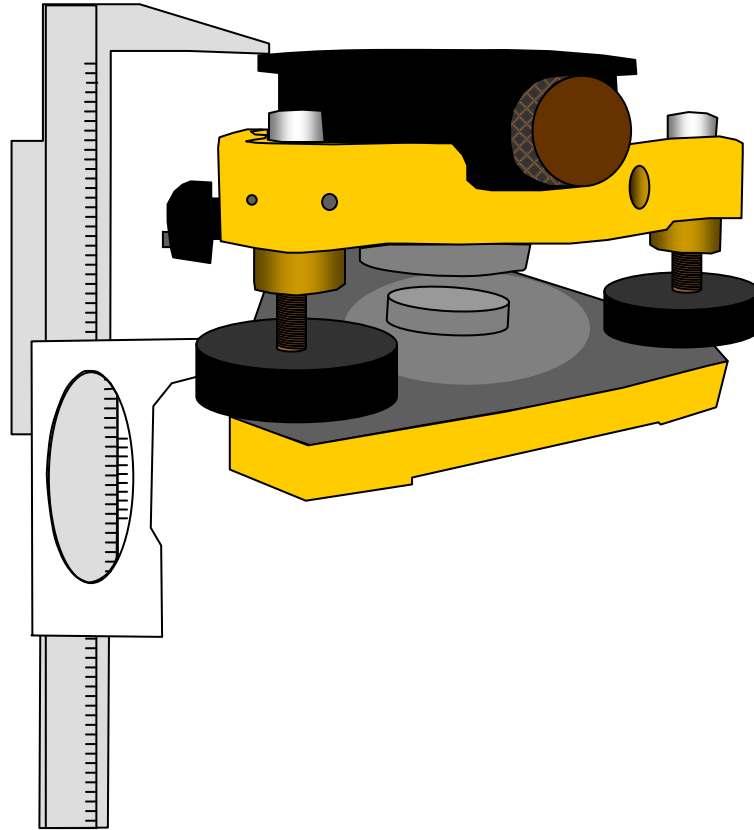


Figure C14. Sketch showing use of vernier calipers in measuring the distance between the top and bottom plates of a Wild-type tribrach

Let these three measurements be called D_1 , D_2 and D_3 . Then, through planar geometry laws, the value for L_3 will always be:

$$L_3 = \frac{D_1 + D_2 + D_3}{3} \quad (\text{Eq. C.4})$$

This will hold as long as the measurements of D_1 , D_2 and D_3 are separated by 120 degrees from one another, around the tribrach and at points equidistant from the central (z) axis of the tribrach. A derivation of this formula is found below.

Once L_1 , L_2 and L_3 are determined, the value "L" can be seen from equation C.1.

In summary, the height of a GNSS antenna above a VPR on a SET BM can be obtained using a Kendapter + tribrach assembly by measuring the tilt of the BM and the separation of the tribrach plates at three radially symmetric points about the tribrach.

- Error Analysis

The vertical offset height between the center of the top plate of a tribrach and the VPR on a SET bench mark can be resolved to within ± 0.5 mm through the use of precision calipers and an accurate tiltmeter/inclinometer. As shown in the earlier sections, the calculation of overall height is based on several measurements:

- 1) radius of the top of the bench mark
- 2) tilt of the bench mark
- 3) offset induced by Kendapter
- 4) separation of the two plates of the tribrach

The overall measurement error will depend on the instrumentation available to measure both distance and angles, as well as the degree of bench mark tilt. For the purposes of this analysis, a student-grade vernier caliper was used to measure distances to ± 0.1 mm. A precision tiltmeter resolved degrees to within 0.1° .

Based on the stated precision of the vernier calipers and digital tiltmeter, maximum and minimum deviations of L1 were calculated according to equation C.2 (Table C.3). Several measurements may be needed to calculate the length of the Kendapter, depending on the type of bench mark used, resulting in an augmentation of error. The overall error of this measurement (v_{ken}) was calculated at 0.3 mm (Table C.2). The measurement of the separation between the two plates of a tribrach will yield error due to both instrument error, but also measurement error related to the placement of the calipers. To estimate the potential error of this technique, four volunteers were assigned the task of taking the three height measurements shown in equation C.4 when the tribrach was plumbed at ten degrees of bench mark tilt (one set of measurements per person). The resulting estimate of L3 had a standard error of ± 0.1 mm. Putting all these measurements together, one can assume that the error in the vertical distance from the SET BM VPR and the horizontal top plate of the tribrach will be no more than 0.5 mm at ten degrees of tilt (Table C.3).

Table C.3. Error components for measurements of the height of the top plate of a tribrach atop a Surface Elevation table (SET) bench mark using a custom adapter ("Kendapter"), at a bench mark tilt of ten degrees. Error estimates are based on stated precision of vernier calipers (0. and a digital tiltmeter

<u>Component</u>	<u>Standard Error (\pm mm)</u>
L1	0.03
L2	0.33
L3	0.10
Total	0.46

- Derivation of Equation C.4

In equation C.4, it is stated that any three vertical measurements between the top and bottom planes of a tribrach, if the measurements are separated by 120 degrees around the z axis and equidistant from the central (z) axis of the tribrach, will average to the actual separation between the two center points of the top and bottom tribrach planes. This derivation will make use of the rules of planar geometry.

In general, when given three points in space which have the coordinates (x_1, y_1, z_1) , (x_2, y_2, z_2) and (x_3, y_3, z_3) respectively these three points define a unique plane, which satisfies the following equation:

$$\begin{vmatrix} x & y & z & 1 \\ x_1 & y_1 & z_1 & 1 \\ x_2 & y_2 & z_2 & 1 \\ x_3 & y_3 & z_3 & 1 \end{vmatrix} = 0 \quad (\text{Eq. C.5})$$

For the sake of convenience, presume that the top plane of the tribrach is co-incident with the xy plane (thus $z=0$ for all points on the top plane). The bottom plane of the tribrach will assume to be tilted, relative to the top plane. (Curiously, it will be shown that no information whatsoever about the actual orientation of the bottom plane's tilt is needed to derive equation C.4.)

Presume also that the centers of the two tribrach planes will lie along the Z axis. Therefore the coordinate of the top plane's center point is $(0,0,0)$. The coordinate of the bottom plane's center point is $(0,0,-L_3)$.

The three caliper-measured points are assumed to lie 120 degrees relative to one another, around the z axis, and equidistant from the z axis. That is, there will be three pairs of x,y coordinates at which the vertical separation is taken (D_1, D_2 and D_3) between the two planes. It is further assumed that these points are all the same distance, s , from the center of the tribrach's central (z) axis. The actual value of s is immaterial, as long as it is constant for the three points. A general equation for the first x,y pair can be written as;

$$\begin{aligned} x_1 &= s \sin(\alpha) \\ y_1 &= s \cos(\alpha) \end{aligned} \quad (\text{Eq. C.6})$$

Where α is the azimuth, from the local x axis, around the z axis for the first pair of points (top plane / bottom plane) where D_1 will be measured. Like most other values, it will ultimately shown to be irrelevant.

The x/y sets for the D_2 and D_3 measurements must therefore be:

$$\begin{aligned}
x_2 &= s \sin(\alpha + 120^\circ) \\
y_2 &= s \cos(\alpha + 120^\circ) \\
x_3 &= s \sin(\alpha + 240^\circ) \\
y_3 &= s \cos(\alpha + 240^\circ)
\end{aligned}
\tag{Eq. C.7}$$

Plugging the values for $x_1, y_1, x_2, y_2, x_3, y_3$ into equation C.5 and simplifying, one arrives at the following:

$$\begin{aligned}
&-\frac{s}{2} \left[s\sqrt{3}(3z - z_1 - z_2 - z_3) \right. \\
&+ \left(3x\{z_3 - z_2\} + y\sqrt{3}\{z_2 + z_3 - 2z_1\} \right) \cos(\alpha) \\
&\left. + \left(3y\{z_2 - z_3\} + x\sqrt{3}\{z_2 + z_3 - 2z_1\} \right) \sin(\alpha) \right] = 0
\end{aligned}
\tag{Eq. C.8}$$

Where z_1, z_2 and z_3 are the z coordinates of the three measurements points on the lower tribrach plane. Since it was assumed that the top tribrach plane had $z=0$ at all points, then it can be written:

$$\begin{aligned}
z_1 &= -D_1 \\
z_2 &= -D_2 \\
z_3 &= -D_3
\end{aligned}
\tag{Eq. C.9}$$

Each D_i represents one of the three caliper-measured distances between the top and bottom planes of the tribrach. Equation C.8 is the equation for the lower tribrach plane in the local xyz system. It was already presumed that the central point of the lower plane had coordinates ($x=0, y=0, z=-L_3$). As such, if $x=0$ and $y=0$ and $z=-L_3$ (as well as the relationships in equation C.9) are plugged into equation C.8 then equation C.8 simplifies to:

$$-\frac{s^2\sqrt{3}}{2} [3(-L_3) + D_1 + D_2 + D_3] = 0
\tag{Eq. C.10}$$

Solving this equation for L_3 yields:

$$L_3 = \frac{D_1 + D_2 + D_3}{3}
\tag{Eq. C.11}$$

QED

References

Schomaker, M.C. and R.M. Berry. 1981. Geodetic Leveling. NOAA Manual NOS NGS 3, NOAA Rockville, MD. 224 pp.

Attachment D :

USGS Fixed-Dimension GNSS Antenna Adapter

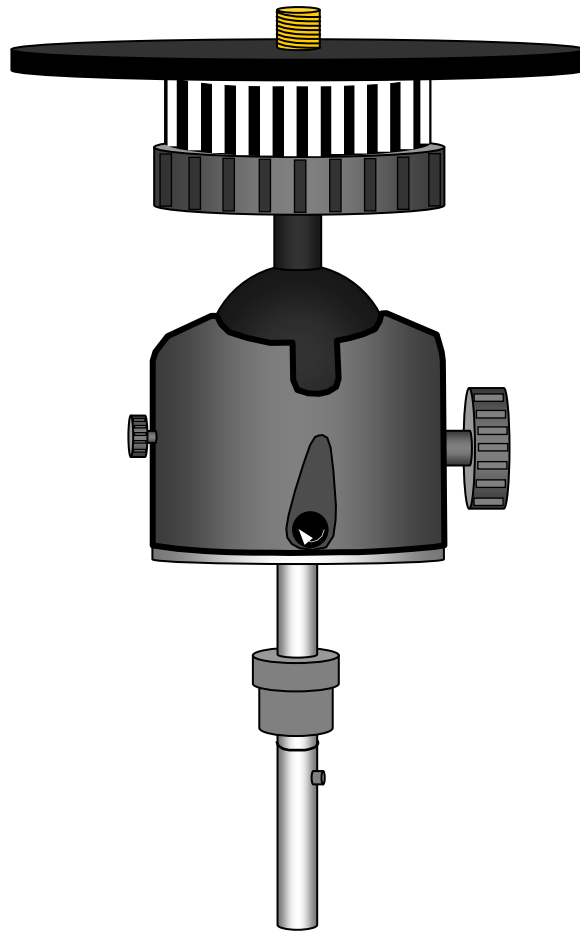


Figure D.1. The U.S. Geological Survey's fixed-dimension Global Navigation Satellite System (GNSS) antenna adapter for deep rod Surface Elevation Table (SET) bench marks.

Introduction

A fixed-dimension Global Navigation Satellite System (GNSS) antenna adapter was designed by the US Geological Survey to fit atop deep rod Surface Elevation Table (SET) bench marks (Figure D.1). The development of this tool was in response to several problems related to the need to measure the antenna height above the vertical point of reference (VPR) using a Kendapter in the field. The Kendapter, a very useful and practical adapter which is made to fit all known versions of SET bench marks, relies on a Wild-type tribrach to create a level surface atop of which to place a GNSS antenna. The problem the tribrach is that it is not fixed-dimension: the vertical offset of the top plate from the point of attachment on the Kendapter will change depending on exactly how many revolutions of each of the three adjustment screws are completed until the top plate is level. Prior to developing the caliper/tiltmeter method (Appendix C, Part II.3) for getting around this problem, and in light of some of the problems of taking and using leveling equipment into a SET field, the "fixed dimension" adapter was developed.

The concept of a fixed-dimension adapter arose as an alternative to leveling altogether on the marsh surface. In the fixed-dimension adapter, the mechanism to plumb the antenna will not cause a change in the dimensions of the adapter. Since the dimensions remain fixed, any vertical offset due to the tilt of the bench mark should be able to be resolved through angle-based computations, assuming the tilt of the bench mark is known.

The US Geological Survey (USGS) developed a fixed-dimension GNSS antenna adapter that is based on an off-the-shelf ball and socket camera mount with adapter plate which can take a GNSS antenna or antenna extensions (figure D.1). Component parts are given below:

- 1) Ball Head - Manfrotto Maxi Ball Head (#490)
- 2) 5/8" Adapter plate - Manfrotto 5/8" Survey Adapter (#3428 or #324)
- 3) Deep Rod SET adapter Plate - Custom built unit

The camera mount and adapter plate cost around \$250 (2007), and the custom base, meant to mate the camera mount to a rod SET receiver, cost another \$150 to build.

There are two components of vertical error that interact when this fixed-dimension GNSS adapter is used on a bench mark that is not plumb (Figure D.2). As the bench mark tilts, the antenna height will be reduced by the cosine of the angle (seen in the difference between A and A'). The vertical distance A' is equal to $A \cos(\theta)$. This vertical error due to the adapter itself is generally very small over the range of tilt angles 0 - 10° (Table D.1). A second component of vertical error is the difference in height between the top center of the bench mark (the point of reference for the GNSS adapter), and the Vertical Point of Reference as defined in this document (top side; see Attachment B). This error, termed systematic error, is very small for the Rod SET, but much larger for the traditional pipe-based SET. This second component of error is also easily predicted (table D.1). The vertical error and systematic error add together, resulting in shorter antenna heights than would be expected if the bench mark were plumb (Table D.1). The actual antenna height above the VPR would be reduced by close to 4 mm in the case of the Rod SET.

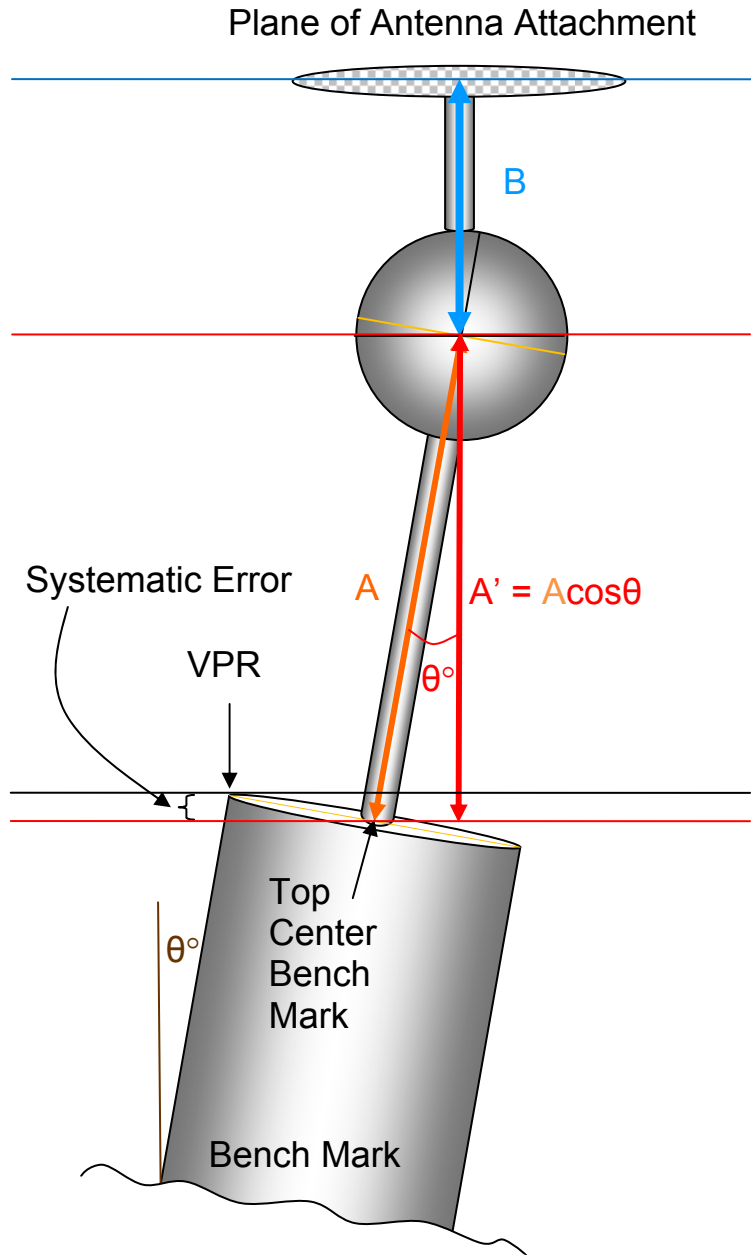


Figure D.2. Two components of vertical error occur with the tilting of a Surface Elevation Table (SET) bench mark when using a fixed-dimension Global navigation Satellite System (GNSS) antenna adapter. Vertical error with respect to the top center of the bench mark is given as $A' = A \cos(\theta)$. Systematic error also occurs, as the difference in height between the top center of the bench mark, and the top side of the bench mark (called the Vertical Point of Reference, or VPR).

Table D.1. Expected components of vertical error in calculated Global Navigation Satellite System (GNSS) antenna heights using the US Geological Survey's fixed-dimension GNSS antenna adapter on a Surface Elevation Table (SET) bench mark over a range of bench mark tilt angles. Total error is a combination of vertical error from the adapter, and systematic error due to a height difference between the top center and top side of the bench mark, over the range of tilt angles.

Tilt °	Vertical Error (mm)	Systematic Error (mm)		Total Error (mm)	
		Rod SET	Pipe SET	Rod SET	Pipe SET
0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.1	0.5	0.2	0.6
2	0.1	0.3	1.1	0.4	1.2
3	0.2	0.4	1.6	0.6	1.8
4	0.4	0.6	2.1	1.0	2.5
5	0.6	0.7	2.6	1.3	3.3
6	0.9	0.8	3.2	1.7	4.1
7	1.2	1.0	3.7	2.2	4.9
8	1.6	1.1	4.2	2.7	5.8
9	2.0	1.3	4.7	3.3	6.8
10	2.5	1.4	5.2	3.9	7.7

Laboratory Test Results

The USGS fixed-dimension GNSS antenna adapter was thoroughly tested on a Rod SET bench mark under laboratory conditions to determine how well actual antenna heights compared to theoretical calculations based on tilt angles. The differences between the two were within two tenths of a millimeter (Figure D.4). This figure shows that, as long as tilt angles are known, theoretical calculations can model actual antenna heights very well, to within a fraction of a millimeter.

A comparison of Figure D.4 with Table D.1 underscores the importance of measuring bench mark tilt angles in the field. This is especially true in the case of the traditional pipe-based SET, where the systematic error is very important. Note that as of this writing, the fixed-dimension adapter has yet to be engineered to fit the pipe-based SET bench mark.

**Changes in Instrument Height due to bench mark tilt:
USGS Fixed-Dimension GNSS Antenna Mount (camera ball-mount type)**

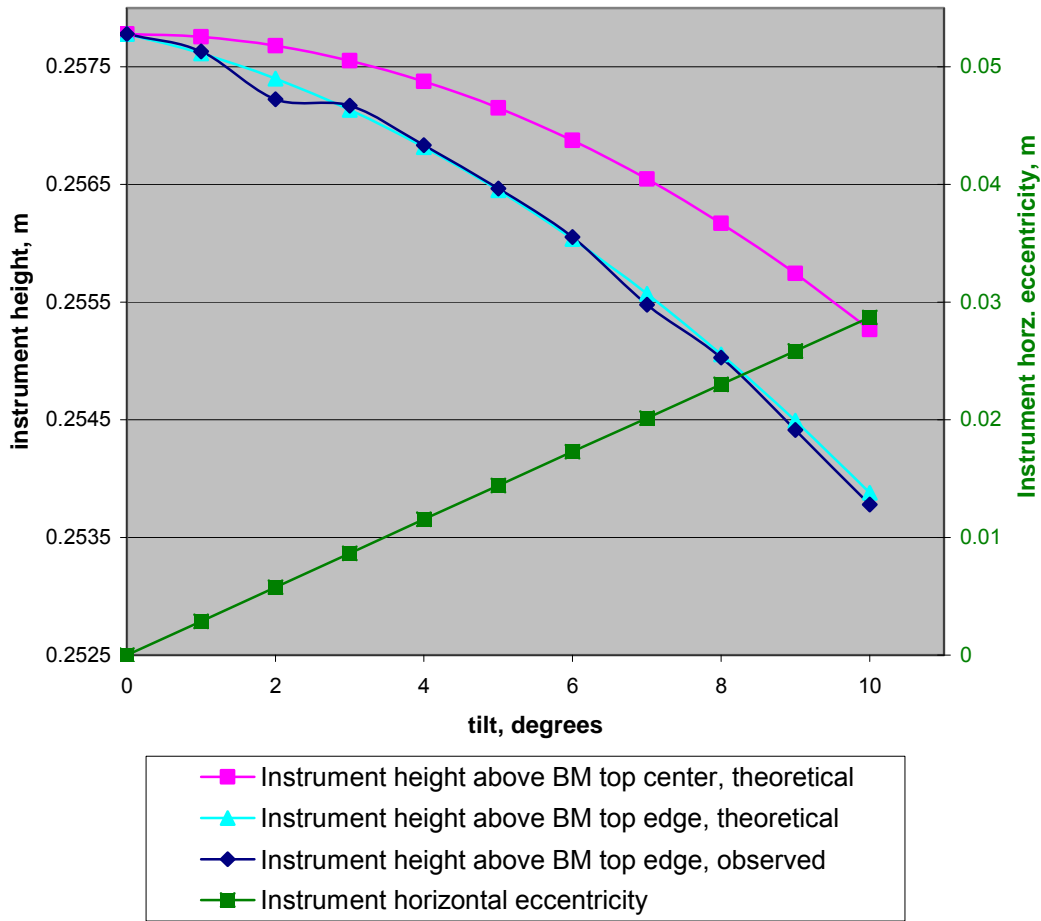


Figure D.4. Laboratory testing results from the US Geological Survey’s fixed-dimension Deep Rod Surface Elevation Table (SET) bench mark Global Navigation Satellite System (GNSS) antenna adapter.

Field Test Results

The USGS fixed-dimension GNSS antenna adapter was tested under field conditions to see if it remained plumb while supporting a heavy GNSS antenna. A Trimble GNSS antenna and a 0.5 m antenna extension were attached to the upper mount. The adapter was found to maintain plumb using the digital tiltmeter after three days in the field (Table D.5). These results agreed with visual estimates of tilt using a 40-minute rod level, which gave a maximum vertical error of 0.01 mm.

Table D.5. Field test results using the the US Geological Survey's fixed-dimension Deep Rod Surface Elevation Table (SET) bench mark Global Navigation Satellite System (GNSS) antenna adapter.

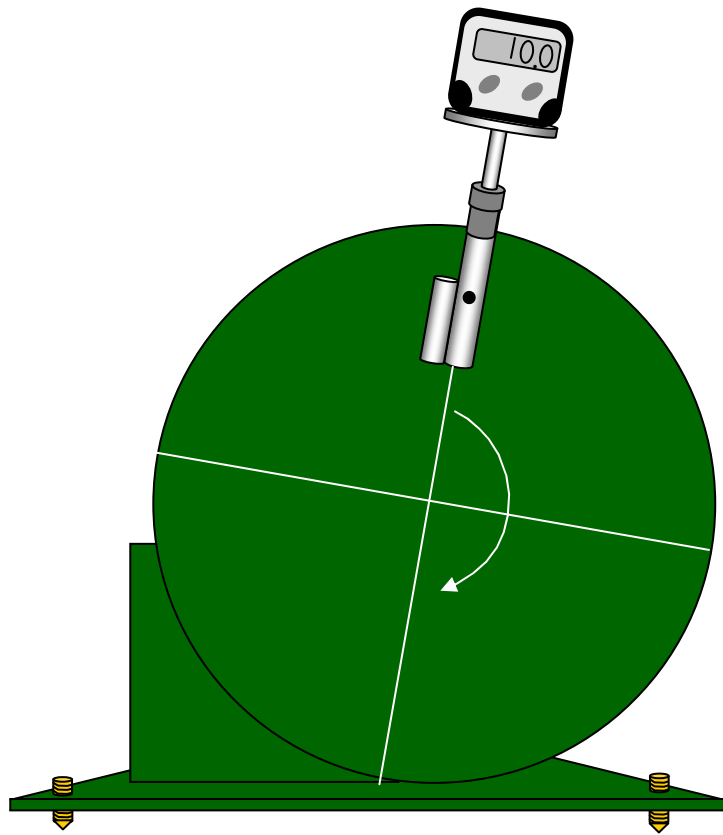
Direction	Tilt (degrees)*		Antenna Height (m)		Error (m)
	Initial	Final	Initial	Final	
A	0	0.3	0.767	0.766992	-0.000008
B	0	0.1	0.767	0.766999	-0.000001
C	0.1	0.4	0.766999	0.766986	-0.000014
D	0.3	0	0.766992	0.767	0.000008

*Tilt degrees measured with digital tiltmeter

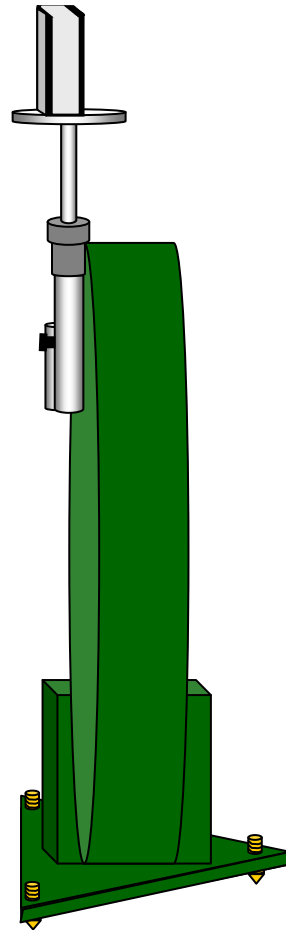
In summary, the USGS fixed-dimension GNSS antenna adapter for the Deep Rod SET proved to have very consistent and repeatable characteristics, could hold a GNSS antenna plumb over a multiple-day deployment, and could allow the user to calculate GNSS antenna heights using an inexpensive digital tiltmeter. Due to the fixed-dimension characteristic, no leveling is required to obtain antenna heights. Future refinement of this adapter would include retrofitting it to adapt to the traditional pipe-based SET bench marks.

Portable Electronic Tiltmeter

A portable electronic tiltmeter (\$45) was tested under laboratory conditions (Figure D. 5) and found to give excellent results for measurement of tilt angles on a Rod SET bench mark (Table D.2). The particular tiltmeter tested needed to be calibrated before each use; it is recommended to bring a calibration tool in the field, since it is very easy to accidentally re-zero the particular tiltmeter tested.



Front View



Side View

Figure D.5. Laboratory set-up for testing digital tiltmeter on a machinist's wheel. Machinist's wheel was tilted $\pm 10^\circ$ with respect to the vertical.

Table D.2. Laboratory test results comparing a portable, digital tiltmeter to angles set by a machinist's wheel. Note that the tiltmeter's stated accuracy is 0.1 degrees.

Statistic	Value
Average (degrees)	0.03
Standard Error (degrees)	0.02
N	54
Minimum (degrees)	-0.1
Maximum (degrees)	0.5

Attachment E :

Measuring Vertical Offset Heights of the SET Instrument



Introduction

Until recently, SET technology could only be used to monitor relative surface elevation change – relative to the first baseline observation. SET datasets could be used to monitor the elevation gain or elevation loss of coastal wetlands, providing indications of their sustainability in face of current and projected sea level rise. Although trajectories of elevation change have proven very useful in coastal science and management (e.g. Cahoon et al. 2006), much more utility could be gained by knowing the precise relationships between coastal/wetland surface development and local mean water levels. Such a relationship would allow researchers and managers to know with greater accuracy and precision how a coastal wetland responds to changing local water levels, and when in the future a wetland surface would be in jeopardy of wetland loss. Connecting SET datasets to the National Spatial Reference System would enable comparisons among surface elevation trajectories over a wider geographic region. Finally, such connections would also allow the elevation change data to be corrected for any future bench mark instability. This document provides information on how geodetic datums can be transferred from the SET bench mark to the equipotential reference surface of the deployed SET, and thereby to the individual pin observations themselves (Figure E.1).

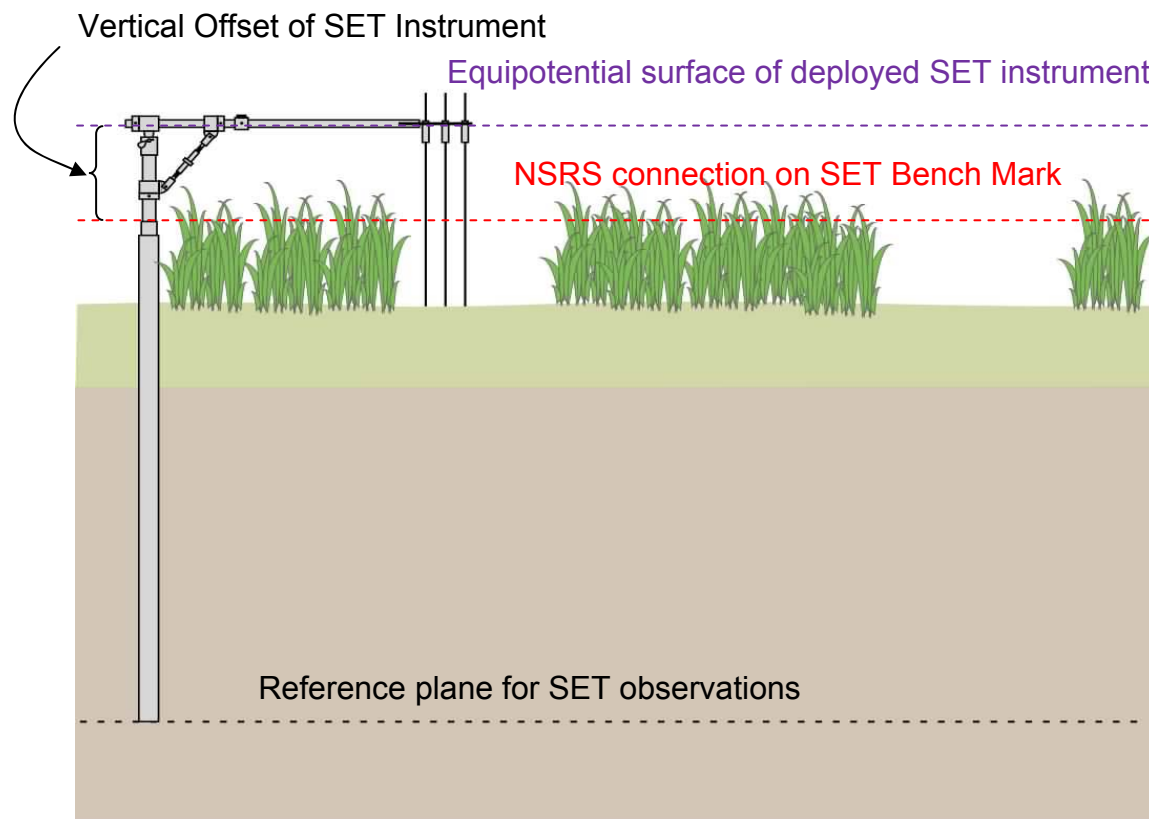


Figure E.1. Diagram showing the relationship between the reference plane for the Surface Elevation Table (SET) bench mark (the bottom of the mark), the equipotential reference surface generated by the deployed SET instrument atop the SET bench mark, and the top of the SET bench mark which has a geodetic connection to the National Spatial Reference System (NSRS). Diagram courtesy of Don Cahoon, USGS.

If SET bench marks were guaranteed to be perfectly vertical, then a constant vertical offset could be calculated under controlled conditions. However, such a guarantee is unrealistic for SET bench marks in the field, even if they were plumb at the time of installation (due to land motion, ice scour, etc.). The vertical offset is expected to be reduced as the bench mark deviates from plumb (Figure E.2): the greater the tilt, the lower the offset height. Therefore, the vertical offset is expected to differ among bench marks in the field according to their different tilt angles.

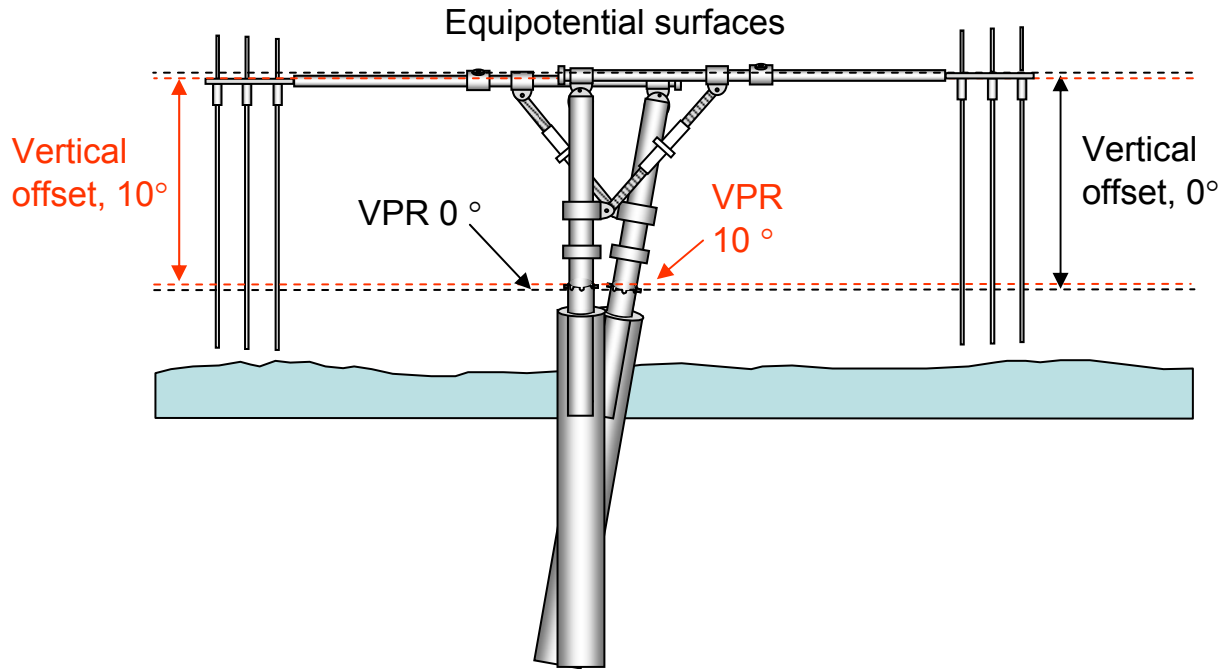


Figure E.2. Expected relationship between the vertical point of reference (VPR) and the equipotential surface of a Surface Elevation Table (SET) deployed atop a SET bench mark as the bench mark deviates from plumb (0°).

A question arises as to whether a given SET bench mark in the field will exhibit a fixed or variable vertical offset height across the different positions which the SET instrument occupies during its deployment over the surface of the plot. If the axis of pivot in the SET instrument is perfectly in line with the center of the bench mark, then one could expect a constant offset for a given bench mark (Figure E.3). However, it is unclear whether this relationship holds up in the field.

The vertical offset between the VPR and the equipotential surface of the SET can be reliably measured using high accuracy leveling techniques, as outlined in Schomaker and Berry (1981) and discussed in Attachment C of this document. Main highlights regarding the general leveling procedure in the marsh are indicated below.

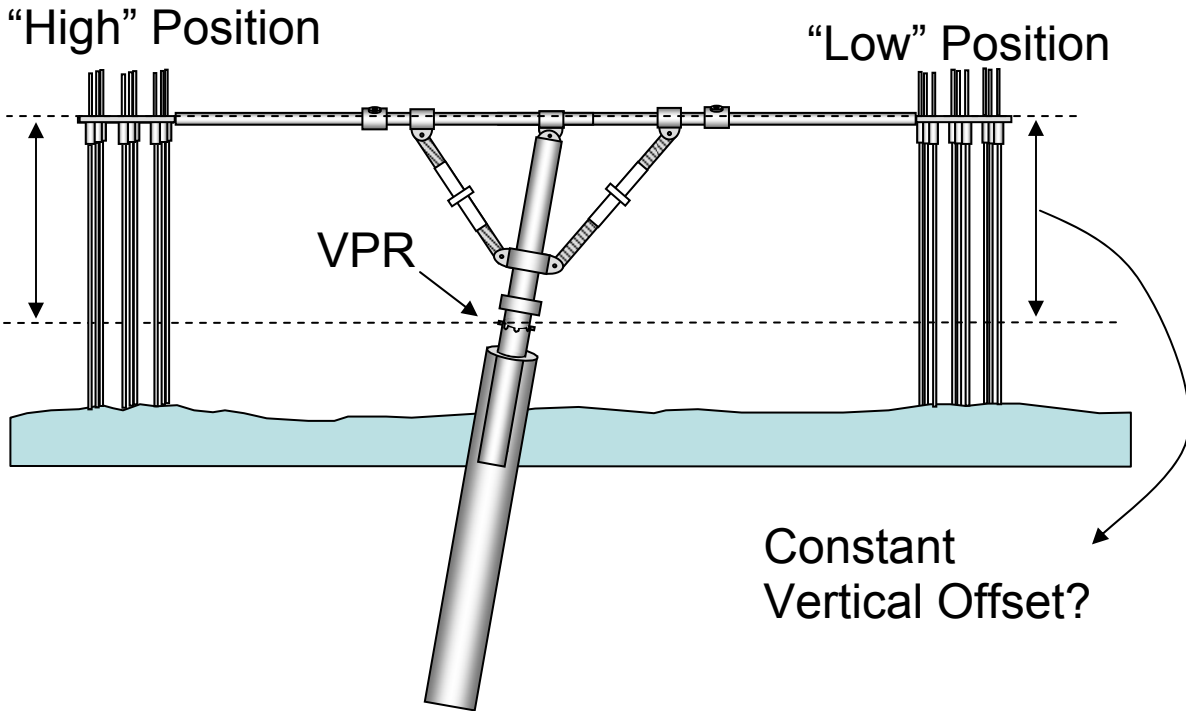


Figure E.3. The vertical offset between the deployed arm of the Surface Elevation Table (SET) and the vertical point of reference on the SET bench mark (VPR) should be constant regardless of the position assumed by the SET instrument.

Standard Leveling

The tripod holding the level is placed on the marsh surface, at a short distance from the SET bench mark (e.g. 10 m) with the legs pushed into the substrate far enough to ensure sufficient stability. The tripod legs should be placed into cohesive sediments if possible. Barbells can be placed on the marsh surface under the tripod legs to provide the needed stability. Care must be taken not to encroach on the sediment surface where actual SET measurements are taken. Digital barcode levels will be sensitive to the slightest instability in the marsh surface, so the operator must take great care not to move when the level is reading.

A backsight is taken to the SET BM VPR. The SET instrument is then deployed atop the bench mark in a chosen measurement position. The instrument is then adjusted to attain the equipotential surface. A lightweight, hand-held digital bar code rod is gently placed on the surface (i.e. the table in the traditional SET, or the bar in the Rod SET), and the foresight is measured. Care must be taken not to put pressure on the arm of the SET, which could lead to a negative bias. The difference between the backsight and the foresight is the vertical height offset between the VPR and the equipotential surface. The SET is then removed, and a second backsight is obtained on the VPR, and checked for consistency.

RoboLaser® Technique

The RoboLaser® technique has also proven reliable for measuring vertical offsets of the SET in the field. The tripod holding the laser should be placed as close as is practical to the mark to ensure the highest accurate readings (e.g. 5-10 m). As above, flat weights can be placed on the sediment surface under the tripod legs to help stabilize the tripod. Ideally, the tripod is positioned so that the beam is about one to one and a half meters above the bench mark. The top surface of the tripod should be as horizontal as possible, so that the laser will easily self-level. Once the laser is set up according to specifications and aimed in the general direction of the SET bench mark, no one should approach the level.

A level rod is then set plumb above the VPR and, using the remote control, the sideways motion of the RoboLaser® is adjusted until the laser beam intersects the rod. The custom slider described in Attachment C can facilitate the tasks of plumbing the rod while marking the height of the laser beam.

The SET instrument is then deployed atop the bench mark in a chosen measurement position, and adjusted to attain the equipotential surface. The level rod is placed on the surface (i.e. the table in the traditional SET, or the bar in the Rod SET), and the foresight is measured. Care must be taken not to put pressure on the arm of the SET, which could lead to a negative offset bias. The difference between the backsight and the foresight is the vertical height offset between the VPR and the equipotential surface. The SET is then removed, and a second backsight is obtained on the VPR, and checked for consistency.

Analysis and Conclusions

Figure E.4 provides a graphic summary of vertical offsets for two different Deep Rod SET (RSET) instruments as measured atop bench marks in the field. One RSET instrument is represented by the 7A and 7D sites; another is given in the FM sites. The offsets for sites 7A and 7D were obtained using a digital barcode level for all four positions occupied by the SET instrument about the bench mark; the offsets for the FM sites used the RoboLaser® technique, corresponding to the highest and lowest sides of the bench mark.

The results show variability both among and within RSET bench marks. Variability within the 7A and 7D bench marks is high enough to result in non-significant differences among bench marks ($F_{3,11} = 2.12$, $P = 0.16$). It is unclear if the variability within bench marks can be explained a consistent trend in heights around the marks: only two of the four plots support this concept (7D1 and 7D2). This suggests that the variability in vertical offset heights at a given bench mark may be also related to both machine and human error.

The results of the Robolaser® data are consistent with those of the barcode level, however the data show significant offset heights among the three measured bench marks ($F_{2,3} = 30.5$, $P = 0.01$), suggesting possible effects of bench mark tilt. No tilt angle data were available.

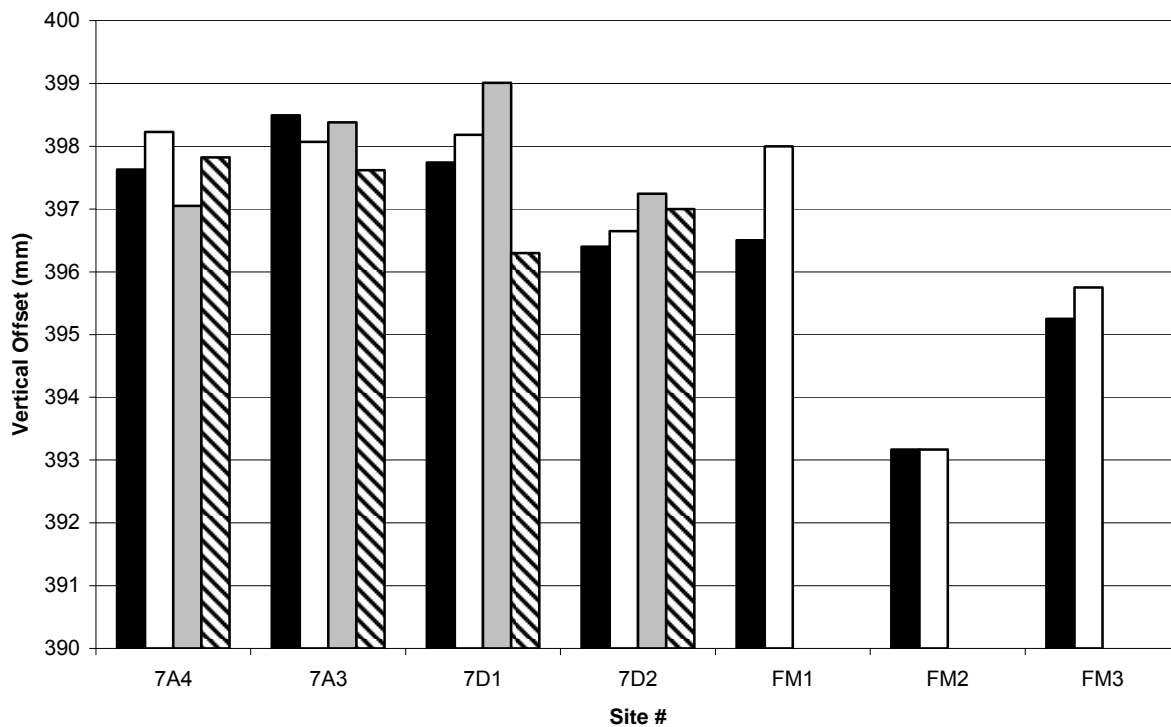


Figure E.4. Vertical offset heights between the top side of a Deep Rod Surface Elevation Table (RSET) bench mark (also called the vertical point of reference, or VPR) and the equipotential surface of the outstretched bar of the RSET. Sites 7A – 7D were measured with a digital barcode level; sites FM were measured with the RoboLaser® technique (see Attachment C document for reference)

Measurements of offset heights for the traditional pipe-based SET generally show more variability –both among and within bench marks -than was seen in the RSET data (Figure E.5). Measurements taken by digital barcode leveling show relatively consistent offsets among the four bench marks tested (Sites A31; $F_{3,12} = 0.44$; $P = 0.73$). Three of the four show trends support the idea that a tilt in the bench mark may cause a consistent change in the offset height about a mark (A31_2-A31_4). The BL sites show significant differences in offset heights across the thirteen different bench marks ($F_{11,20} = 4.82$; $P = 0.0012$). Where all four positions were measured by the RoboLaser® technique, all sites also suggest uniform patterns that may be related to bench mark tilt (BL7, BL13, BL15).

In summary, the available data suggest that vertical offsets vary both among and within bench marks. The behavior of vertical offsets needs to be empirically verified in the field. Further research is needed to test whether it may be possible to successfully model the offset based on measured tilt angles in the field.

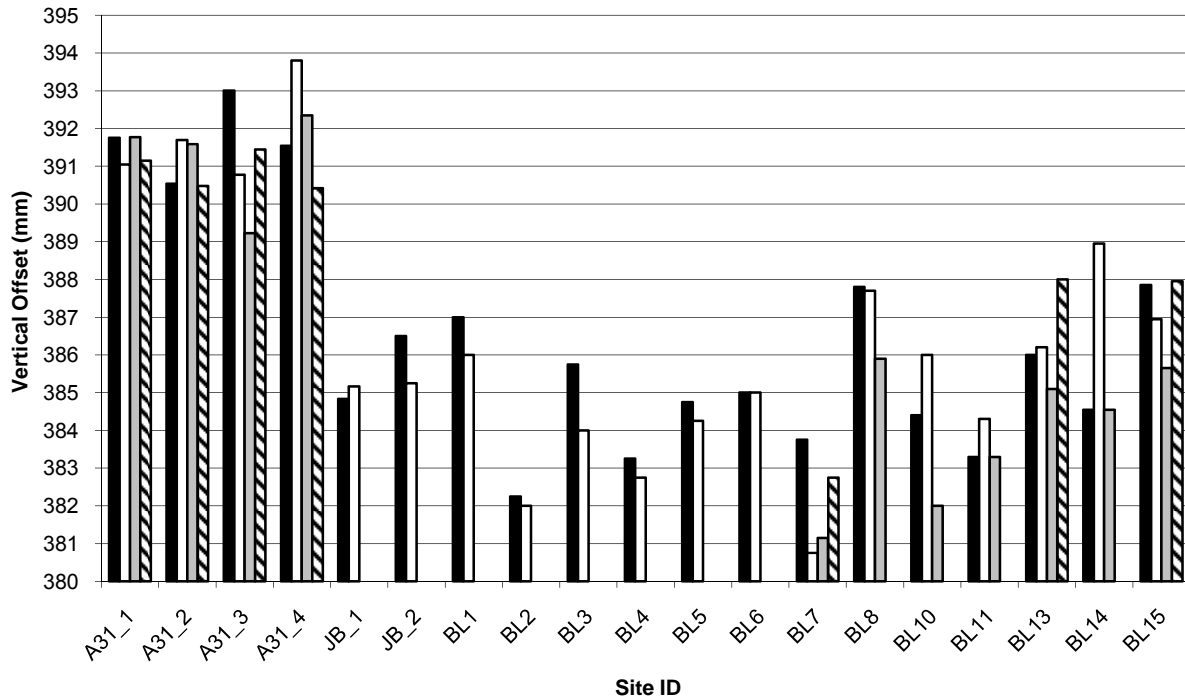


Figure E.5. Vertical offset heights between the top side of a traditional pipe Surface Elevation Table (SET) bench mark (also called the vertical point of reference, or VPR) and the equipotential surface of the outstretched arm of the SET. Data are relative to three different SET instruments: A31, JB, and BL. Sites A31 were measured with a digital barcode level; sites JB and BL were measured with the RoboLaser® technique (see Attachment C document for reference)

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