NOAA Technical Report NOS 139

NOAA Guidance Document for Determination of Vertical Land Motion at Water Level Stations Using GPS Technology

Silver Spring, Maryland
August 2015

noaa National Oceanic and Atmospheric Administration

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

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NOTICE

Table of Contents

1.0 Introduction

1.1 Purpose

This document provides general guidance for the determination of vertical land motion at long-term continuously operating water level stations, for the purpose of separating this signal from relative water level change as measured at the water level station and the subsequent determination of absolute water level change. While there are several ways to determine absolute vertical land motion (within the context of a global terrestrial reference frame) that affect a water level station, the most accurate methods or approaches all require the use of Global Navigation Satellite System (GNSS) technology in some fashion. GNSS is a constellation of satellites that are used to precisely determine the geographic location of a user's receiver anywhere in the world. The GNSS includes satellite systems such as GPS, GLONASS (Russian), Galileo (European), and others. Continuously operating long-term GPS systems that use GNSS technology are generically referred to as cGPS or CORS stations.

This guidance is based on experiences and standard operating procedures of the NOAA NGS-managed network of Continuously Operating Reference Stations (CORS) and NOAA CO-OPS-managed National Water Level Observation Network (NWLON) and is targeted toward a general audience. This guidance could also apply to any group wanting to establish a long-term water level gauge and monitor the vertical land motion which affects it.

Water level stations provide information on long-term sea level variations *relative* to the local land (specifically the motion of land upon which the water level station and local benchmarks rest). For many coastal applications, knowledge of relative sea level change is of primary importance to understand how the sea is changing relative to the land for coastal inundation and maritime charting and mapping purposes, among others.

GPS measurements (either through a permanent, continuously operating long-term GPS reference station (cGPS), or through episodic GPS static re-surveys of the same point) provide information on long–term variations in vertical and horizontal land movement. For applications pertaining to global sea level studies, it is necessary to ensure the two long-term measurements have a common vertical survey tie so they have a common reference. The rates of relative sea-level change can then be directly related to the vertical velocities of the local land. After careful adjustment of the sea level data for vertical land motion over time, an absolute rate of sea-level change (though still geographically dependent on the location of the water-level station) can be determined and the sea level data becomes more useful for understanding regional and global sea-level change and has been applied to various global sea level reconstructions (Ray and Douglas, 2011; Jevrajeva, 2014).

1.2 Background

To estimate *absolute* sea-level variability from water level station records, both the sea level variations and the vertical land motion must be analyzed in the same geocentric reference frame (*Plag et al.*, 2013, *Bevis et al*, 2002). Long-term water level station records do not directly provide this information because tide gauge records measure relative sea-level variations that include contributions from vertical land motion, among others. CO-OPS recently published a technical report on estimating vertical land motion from long-term tide station records (*Zervas, et al.*, 2013). This indirect estimation provides information at locations at which CORS stations have not yet been established nor survey connections made. The methodology is operationally being used in sea-level change calculators (USCGRP, 2013) while awaiting the co-located GPS connection discussed in this report. Other technologies being used to estimate vertical land motion include use of InSAR space geodesy technology (*Brooks et al*, 2007). However InSAR does not automatically provide geocentric height variations unless it is merged with cGPS stations (see, e.g. Hammond et al., 2011).

Precise determination of vertical land motion at water level stations continues to be a priority area of investigation for NOAA for a variety of applications. The application of the information is directly related to the work of other agencies being supported by NOAA, such as DoD (including the USACE (USACE, 2013)), in assessing risk to their infrastructure and future designs from sea level rise.

There are only a few standard methods for directly determining absolute vertical land motion at a water-level station. They are:

1) Physically mounting a continuous GNSS antenna (at a CORS or cGPS location) on the water-level gauge structure in a way that ensures its motion will exactly match the motion of the water level sensor itself.
2) Performing a geodetic leveling survey between the water-level sensor and the Antenna Reference Point (ARP) or ARP companion reference mark of a "nearby" or co-located continuously operating cGPS station on an episodic basis (annually or more frequently).
3) Performing a geodetic leveling survey between the water-level sensor and a "nearby" passive geodetic control mark and also performing a static GNSS survey on that mark which ties in to a global network of continuously operating cGPS stations. Both the leveling and GNSS surveys are done episodically (annually or more frequently).
4) Presuming that a continuous cGPS station "near" (<1.0 km) a water-level station moves at the same vertical rate as the water-level station, without a direct surveying tie.

Method 4 requires the least amount of additional work (with NWLON and CORS stations already built, this method simply requires an assumption of what "near" is defined to be). It is the least scientifically sound and requires corroborating information. This is because vertical land motion can be localized, and presumptions about long term equal motion between two points cannot easily be proven. In some areas, 1 km would be too far away. In others, even up to 10 km may be possible.

Methods 2 and 3 are essentially variations of one another, where the land motion is viewed episodically, rather than continually, through repeat GNSS surveys tied to the global reference frame. Method 3 provides a history of geodetic relationships over time which can be analyzed for trends assuming a frequent history of GPS static occupations over several years. Survey standards for static GPS surveys on bench marks are found in CO-OPSb (2013) and accuracies have been assessed by NGS (T. Soler et al, 2006). Standards call for a static GPS occupation on a bench mark for a minimum of four (4) hours which should be repeated on the same bench mark each year. Repeat short-term surveys have not been proven to provide information as accurate as continuous measurements however. Method 2 is preferred as long as physically touching the operational cGPS antenna is not required. (This may require establishment of a companion reference point next to the cGPS with a measured elevation difference to the ARP at the time of cGPS installation, or possibly the use of indirect surveying methods, such as sighting the ARP directly from a geodetic level, or performing non-reciprocal trigonometric leveling without the use of a reflector target).

Method 1 is the only method above which shows a direct, continual tracking of land motion at the water-level gauge if it is assumed the water level gauge is moving with the local land. Whether or not this continual tracking is significantly advantageous over the episodic tracking of Methods 2 and 3 remains to be seen. The cost in equipment, installation, maintenance, data transfers to gain continual vertical land motion must be weighed against the lack of continual tracking at the cost of more field time, but less equipment and maintenance costs. The use of "preferred" depends on what is trying to be accomplished. Methods 1 or 2 are preferred for satellite altimeter calibration, but for establishing ground motion for a long-term sea level record, Method 2 or 3 may be the best choice if a tide gauge bench mark is the control point.

Despite the unresolved question of the best tradeoff between Methods 2/3 and Method 4, above, the international community (IOC, 2006 and IOC 2012) has recommended that all long-term tide gauges be equipped with co-located permanent continuous receivers (cGPS). Previously, NOAA has investigated use of GPS data from NGS CORS located nearby tide stations (Method 4) to estimate absolute sea level change (Snay *et al*. 2007). Using funding provided by NOAA Office of Climate Observations, new CORS continue to be established at NWLON stations that are part of the Global Sea Level Observing System (GLOSS) network as budgets allow. Several CORS have also relatively recently been established at Great Lakes NWLON stations to monitor the effects of continuing Glacial Isostatic Adjustment (GIA) on hydraulic flows of the Great Lakes (Gill, 2014). Other non-federal and academic organizations are also establishing cGPS systems at NOAA tide stations for various programmatic and research purposes (Texas A&M/ CBI, USM and ODU).

CO-OPS maintains an annual field survey schedule where geodetic leveling is performed between the water level gauge reference point and nearby passive geodetic control marks, which are in turn routinely occupied with GNSS (Method 3) every year or every five (5)years depending upon location. A comprehensive financial/scientific trade off study between Method 2 and Method 3 could therefore be performed, but has not yet been undertaken.

2.0 Water Level Stations

NOAA operates a National Water Level Observation Network (NWLON) of 210 long-term continuously operating water level stations along the coasts, including the Great Lakes. NWLON stations provide long-term data sets necessary for the tidal datum reference systems for the US and the International Great Lakes Datum for the Great Lakes. NWLON stations provide the high quality long-term data series to establish relative sea-level trends and lake-level trajectories. Twenty-nine (29) NWLON stations are part the US contribution to IOC Global Sea Level Observing System (GLOSS). Other partners include academic institutions such as the University of Hawaii Sea Level Center (UHSLC) which operates 53 long-term stations that contribute to GLOSS. Other government agencies and non-government institutions also operate long-term water level stations for their own research and program goals (TCOON, NERRS, USACE and USGS).

Water level stations provide water level information relative to the local land near the water level gauge. This is accomplished though repeat surveys from the water level sensor points to local networks of bench marks. Elevation differences between the water level gauge and the bench marks are monitored over time to assure vertical stability of the bench marks themselves. This is done through geodetic leveling, which by itself only checks local stability and does not yield absolute vertical land motion of the bench marks.

Unstable bench marks are replaced over time. The repeat ties to the sensor references also assure vertical stability of the sensor platforms, often located on piers, docks and offshore structures. In addition to local stability, the absolute vertical motion of the bench marks is checked through a temporary GNSS survey on those marks, tied to a global reference frame. Vertical movement of the sensors can be accounted for in the long-term record by continuously monitoring and tracking relative movement over time. It typically takes several years of record to establish unwanted movement. When found, adjustments are made to historical data and new sea level trends and datums are re-calculated.

Tying the water level gauge to the bench marks also allows for the station reference datum to be recovered in the case of catastrophic loss of the sensor due to storms or tsunamis. Physical sensor reference points are established at the sensor assembly mount for acoustic sensors, leveling collars are used for Microwave Water Level Sensors (MWWL), and precise steel tape measurements are made to the underwater brass orifices for air-driven bubbler pressure gauges (see appendix for examples of leveling connections to sensors). The primary bench mark elevations form the foundational station datum. All measurements over time are related to the common station datum established when the station was first installed (CO-OPS 2013). The water level gauges must be placed such that they are able to measure expected maximum and minimum water levels.

3.0 The NGS CORS Network

The NGS CORS network is a US managed network of cGPS systems and is a multi-purpose cooperative endeavor involving government, academic, and private organizations. The sites are independently owned and operated. Each agency shares their data with NGS, and NGS in turn analyzes and distributes the data free of charge. As of July 2015, the CORS network contains more than 2,000 stations, contributed by over 240 different organizations, and the network continues to expand.

CORS provide GNSS data consisting of carrier phase and code range measurements in support of three-dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States, its territories, and a few foreign countries. Each CORS contains a continuously operating GNSS geodetic quality receiver. Surveyors, GIS users, engineers, scientists, and the public at large that collect GPS data can use CORS data to improve the precision of their positions. NGS CORS enhanced post-processed coordinate accuracy approaches a few centimeters relative to the US National Spatial Reference System, both horizontally and vertically.

NGS has established specifications for establishing a national CORS (NGS 2014). Not all cGPS systems automatically become part of the national NGS CORS network. The design of CORS incorporates aspects of security and accuracy. The configurations include a choke ring antenna (to help mitigate multipath effects) as well as an antenna mount and radome developed for GPS reference stations. In addition, for CORS requirements, adequate horizon and elevation must be established to minimize multipath GPS measurement errors. In the absence of substantial infrastructure to provide vertical stability and mount the GPS antenna, CORS specifications include a poured concrete monument to provide mechanical stability. A typical concrete monument has a 2-ft diameter below-ground base to a depth of 12 feet and a 12-inch diameter above-ground pillar to a height of 5 feet. A 2-inch diameter stainless steel antenna mast is placed into the top of the concrete monument.

Each CORS has an Antenna Reference Point (ARP) that is the point on the exterior of the antenna to which the antenna phase center positions are referenced. Each CORS should also have a unique and permanent companion point on or near the CORS monument to which the ARP is measured. This mark must remain invariant with respect to the monument.

4.0 Co-location

4.1 Criteria

The term "co-location" will be used in this document to mean any configuration of cGPS and water level station which support methods identified in section 1.2. As such, co-location requires the GPS antenna and water level gauges be located "near" each other such that:

- The cGPS system and water level sensor reference points can be accurately surveyed together and/or directly measured in relationship to each other.
- The systems must be located close enough together to ensure ease of performing routine surveys (if method 1 is not used).
- The systems must be located on stable infrastructure and in an environment conducive to long-term sustainability of measurement, including a review of the environmental risks affecting such measurement sustainability, such as those from storm surge, inundation, and damage from wind and waves.
- There is not an unknown differential in long-term vertical land movement between the cGPS system and the tide gauge.

If the CORS ARP is not at the water level station, or if it is there but not physically mounted in a way that ensures a perfect match between its vertical motion and that of the water level reference point, then a survey that establishes and monitors elevation differences of the tide gauge station datum and the CORS Antenna Reference Point (ARP) should be performed routinely over time to monitor for vertical stability. For this process to be successful, it is important that the surveys do not require physically disturbing either the CORS antenna reference system or the water level sensor system. Survey connections are to be made between passive bench marks and reference marks without a need to touch the sensors and antennas. GPS elevations on CORS reference marks and water level elevations on water level station bench marks are determined and monitored through their normal operations. Other important criteria include: 1) sky view or GPS horizon, 2) staying away from confounding reflectors (nearby metal roofs, ships that are moored near the tide gauge), and 3) the long-term prospects that the station will not be relocated due to pier construction, coastal projects, etc. Because of these issues, co-location at the tide gauge is often not the best option.

4.2 Configuration Options

As exemplified above, co-location may have several configurations and there is not currently any configuration standard. The configurations could range from the cGPS and water level sensor located on the same structure to a physical separation of the two systems by up to a kilometer. The international community is obtaining experience with various configurations (Bevis *et al.*, 2002 and IOC, 2006). If the application is satellite altimeter calibration, one may choose to measure VLM directly at the tide gauge (i.e collocated GPS with the sensor) thus reducing the error in VLM introduced by the level ties between the tide gauge and the TGBM.

In some direct co-location (Method 1) configurations, the cGPS antenna could be installed on the same sensor infrastructure component (piling, platform, instrument shelter, etc.) as the water level gauge, thus requiring only a local steel tape measurement for instance, to establish and monitor the elevation difference of the reference points of each sensor. In fact, if the mounting of cGPS antenna and water level gauge reference point is on the same physical structure, and that structure has no known structural compressibility, then the actual distance between the two sensors need not be known, as the movement of the cGPS antenna can be related directly to that of the water level sensor. NOAA has had some success in establishing CORS on the infrastructure of Great Lakes water level stations because the instrument shelters are built atop substantial concrete sumps that reach generally over 10 feet into the ground and do not suffer from frost heave. Other institutions such as UHSLC (10 stations) have co-located tide gauges and cGPS. Plag (2013) is partnering with NOAA/NOS to establish direct co-location cGPS configurations at NWLON stations in southern Chesapeake Bay.

For configurations for which the two systems are not co-located on the same structure (are located a certain distance apart) then a level connection must be periodically made between reference points for the two systems to establish them in the same reference frame and to monitor for any differential vertical motion between them (Methods 2 or 3). In general, if a CORS system and water level station are located within 1.0 km of each other, then an accurate direct leveling connection can be made between the CORS reference bench marks and the water level station bench marks. The bench mark network standards established for NOAA water level stations calls for all bench marks to be within 1.6 km of the tide gauge to facilitate leveling and establishment of elevations of the local land relative to local mean sea level (NOS 1987). NGS CORS co-located with NWLON stations in this configuration can be connected during annual NOS field visits to NWLON stations. Frequent leveling is recommended (annually if possible) over a long period of time (10-20 years) (Wöppelmann et al, 2007). The leveling error can potentially become a significant part of the total error budget at longer distances thus stations more than 1.0 km away should not be considered as "co-located" in the practical sense, though they may still be of interest for certain applications. This leveling would have two purposes; to establish the elevation difference between the sea level reference datum and the CORS system reference datum, and to monitor that elevation difference over time to detect any trends. Second Order, Class I levels will typically be run between the CORS system reference marks and tidal bench marks, except at some ocean islands where Third Order leveling equipment can only be used due to transportation/shipping limitations.

5.0 Error Analysis

Relative sea-level trends derived from long-term tide station records generally range from -20 to + 20 mm/yr depending upon the amount of vertical land motion. The present estimated *absolute* global rate from altimeter data (1993- present) is approximately 3.0 mm/yr with climate models projecting increasing global rates of 11 to 17 mm/yr by 2100 (IPCC 2014). Given the mm/yr level of accuracy desired to understand global sea level change, the vertical velocities due to land motion should also be at a commensurate accuracy level.

The error budget for accurate estimation of a global rate of sea level change at a tide station by correcting the tide station relative sea level trend with a vertical velocity from a CORS has three main sources.

a. The error in the determination of the sea level trend from the tide station record.
b. The error in the level connection between the tide station and the CORS
c. The error in the determination of vertical velocity from the CORS record.

The complete removal of the second error source is an advantage of the direct mounting of CORS at the water level station (Method 1) over other methods of co-location. These considerations apply for global sea level reconstructions based on tide gauges. Of equal importance is the use of cGPS corrected tide gauges for satellite altimeter calibration. Error reduction is obtained by looking at altimeter-tide gauge comparisons over a network of stations, so you don't need 30-60 years of data to get reliable estimates of the altimeter drift.

5.1 Sea Level Trend Computation Error Contribution

In general, the longer the tide station record, the lower the error in the derived sea level trend. Figure 1 shows this relationship. In light of this knowledge, NOAA/CO-OPS does not publish sea level trends for tide stations with less than 30 years of data. NOAA always presents and disseminates trends and their standard errors so they can be applied in the right context with full awareness of uncertainty. Many research scientists recommend only using data records from tide stations with greater than 60 years for estimating global sea level change (Douglas, 2001). For meaningful application, the error in the trends should only be a small proportion of the numerical magnitude of the trend itself.

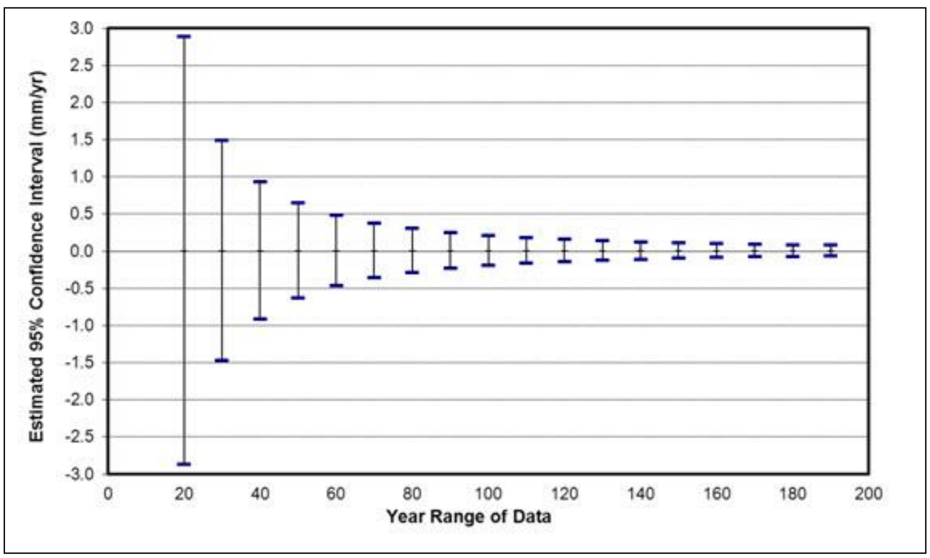

Figure 1. Variations in uncertainties of sea level trends with length of data series (from Zervas (2009))

5.2 Leveling Error Contribution

The shorter the distance between the water level station and the CORS, the lower the error will be in the leveling connection. Figure 2 illustrates this relationship of leveling closure tolerances to distance leveled taken from CO-OPS leveling manuals (CO-OPS, 1987). Second Order, Class I levels have a section closure tolerance of 6 mm per square root of the distance (km). Section closure errors are only blunder checks and not total error, but the relationship to leveling distance is clear and underscores the need to have the shortest distance possible between the two systems. The actual predicted error build up in an adjusted leveling survey of Second Order, Class I is 1.0 mm per square root of kilometers leveled (FGCC, 1984). Keeping the leveling to 1.0 km or less will restrict the error to 1.0 mm at any given annual survey. The leveling error translates into an elevation uncertainty in knowing the differential elevations between the tide gauge and the CORS over time and will propagate into an uncertainty in any trend which exists in the elevation differences that would affect the global sea level rate estimation. It is estimated that establishing co-located systems within 1.0 km constrains the leveling error contribution between any two years to approximately 1.4 mm/yr and if repeated over a seven (7) year period it would drop the leveling error component to approximately 0.2 mm/yr, which is the same order of magnitude of the errors in the tide gauge sea level trends and the CORS vertical velocities. Figure 3 shows the relationship of the relative accuracy of leveling between two points with distance using Second Order, Class I levels. Longer distances (>1.0 km) between CORS and tide gauges also heightens the risk of actual (and unwanted) differential vertical land motion due to variations in local underlying geology.

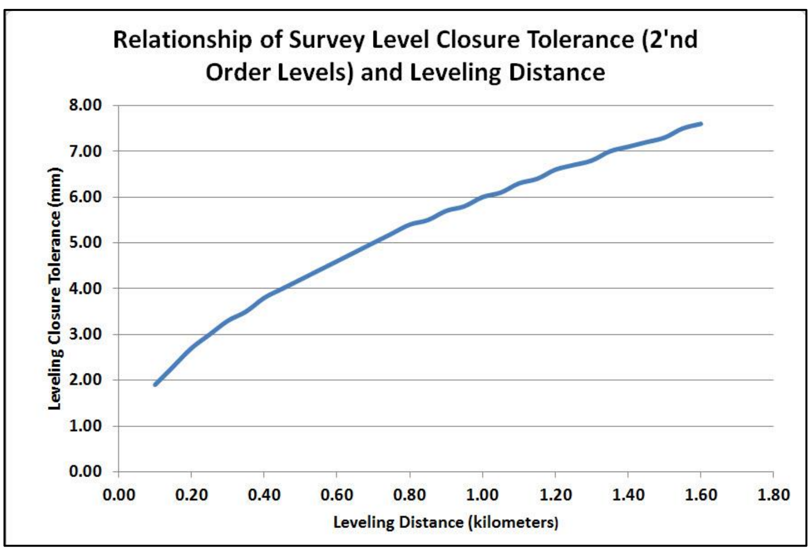

Figure 2. Leveling closure tolerances for Second Order, Class I Levels.

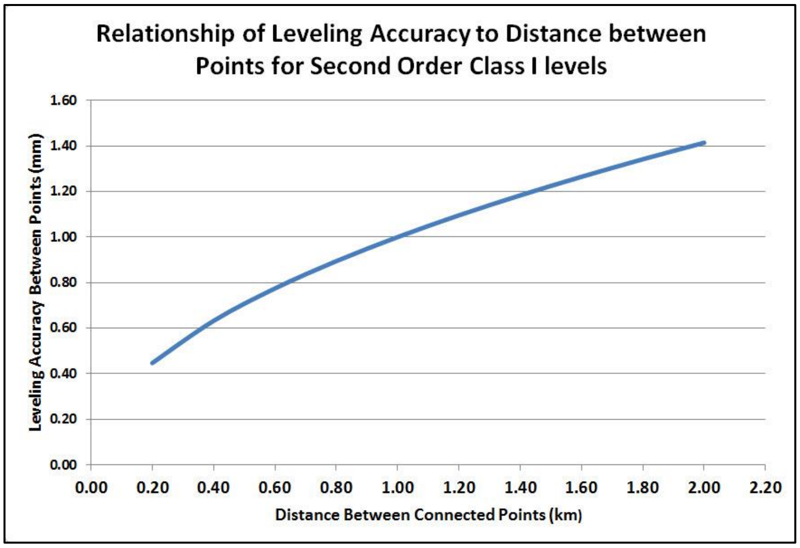

Figure 3. Leveling accuracy changes with distance

5.3 CORS Vertical Velocity Error Contribution

The longer the cGPS data record, the lower the error in determination of vertical velocity of land movement. Figure 4 taken from Snay et al, (2000) illustrates this relationship where reasonable errors (for global sea level application) in determination of vertical velocities from cGPS data are not obtained until a minimum of 10 years of data are obtained. Other more recent studies have shown that cGPS records of 4.5 years can give reasonable trend estimates (Blewitt et al., 2010).

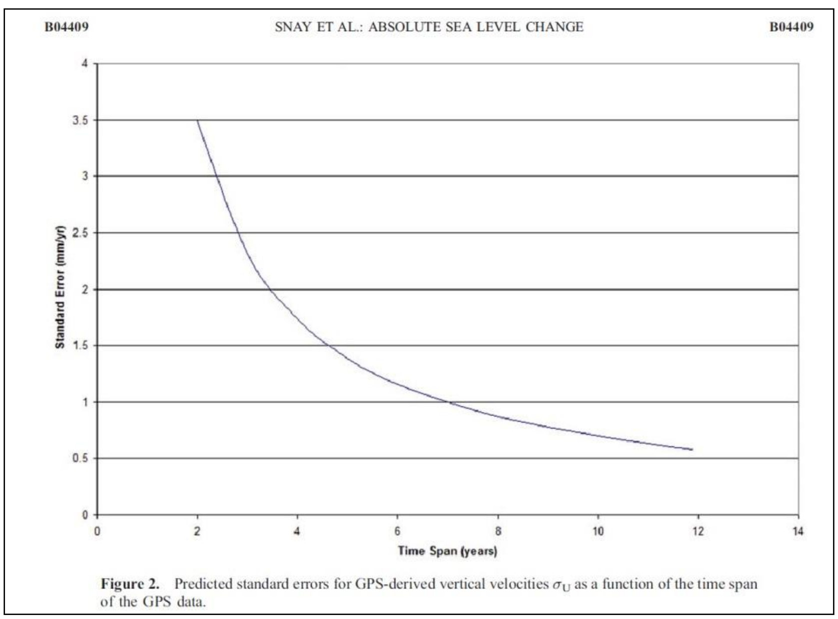

Figure 4. Relationship of standard error of cGPS vertical velocities with time span

5.4 Error Budget Estimation

Estimation of error in estimation of trend in global mean sea level from a tide Station co-located with a CORS is provided for a few examples below. Assuming error source independence, the total error can be estimated as the combination of three independent error sources and thus can be estimated as the square root of the sum of the squares of each error source:

$GSL_{absolute}$ Trend Error =

SQRT $((RSLTG)^2 + (LCT)^2 + (CORSST)^2)$)

Where RSLTG = standard deviation in the relative sea level trend determined from a tide gauge record (Figure 1); LCT = error contribution to the trend from the geodetic leveling connection between the tide gauge and the CORS: CORSST = standard deviation in determination of the vertical velocity trend from a CORS (Figure 2). Note that in all three errors, data collected over longer spans of time will always lower the size of errors in the trend. These examples assume a level connection is made between systems once per year for a minimum of seven (7) years.

Example 1:

Newport RI:

- Tide gauge series length: 76 years
  - Standard Deviation of Relative Sea level Trend: +/- 0.09 mm/yr
- Distance between CORS and tide gauge: 0.54 km;
  - Potential estimated error contribution from annual leveling: +/- 0.20 mm/yr
- CORS series length: 8.1 years
  - Standard deviation of CORS vertical velocity: +/- 0.90 mm/yr

Estimated Absolute Sea-Level Trend Error = SQRT $((0.09)^2 + (0.20)^2 + (0.90)^2)$
= +/- 0.93 mm/yr.

If the two systems were on the same structure requiring no leveling, then the estimated error becomes +/- 0.90 mm/yr.

Example 2:

La Jolla, CA

- Tide gauge series length: 89 years
  - Standard deviation of Sea level Trend: +/- 0.15
- Distance between CORS and tide gauge: 0.75 km;
  - Estimated error contribution from annual leveling: +/- 0.20 mm/yr
- CORS series length: 18.2 years
  - Standard deviation of CORS vertical velocity: +/- 0.20 mm/yr

Estimated Absolute Sea-Level Trend Error = SQRT $((0.13)^2 + (0.20)^2 + (0.20)^2)$
= +/- 0.32 mm/yr.

If the two systems were on the same structure requiring no leveling, then the estimated error becomes +/- 0.25 mm/yr.

Error Analysis Limitations:

The error analysis makes the basic assumption that there is a linear trend in RSL and vertical land motion. The assumption that there is a continuing linear trend in sea surface height is increasingly challenged by non-linear changes in ocean heat content and in mass exchange with the cryosphere and land water storage. For many coastal locations, the assumption that there is a linear trend in vertical land motion is not valid. At locations close to changing ice loads, significant non-linear contributions are present. Similarly, in areas with changing sedimentation, water, oil or gas extraction, and other anthropogenic changes, vertical land motion has significant non-linear contributions. Extrapolation of vertical land motion measured over a decade or so into the past must be used only as a first-order estimate with the realization that the assumptions of linearity may not be true. Other models can be used for sea level and land motion changes besides a simple linear trend.

6.0 Summary

This document provides operational guidance for determining rates of vertical land motion at the location of water level stations and specifically for co-location of a CORS and long-term water level stations for that purpose. Co-location requires putting long-term water level data and the cGPS data in the same local vertical reference frame accomplished using direct measurement and leveling surveys. NOAA NGS and NOAA CO-OPS have very specific standards for establishing the national CORS network and the NWLON to meet NOAA mission responsibilities. These standards are provided to the general public and in collaborations with other agencies and academic groups. To meet the goals of monitoring global sea level rise, very accurate rates of sea-level change and vertical velocities of land motion must be obtained from long-term data sets. To reach this goal, co-located water level stations and cGPS systems must be established and maintained to ensure long-term vertical stability and sustainability.

Acknowledgements

The authors gratefully acknowledge the comments and technical advice provided by Prof. Hans-Peter Plag (ODU) and Prof. Mark Merrifield (UHSLC).

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Appendix

1.0 Examples of leveling connections to water level sensors.

1.1 Acoustic sensor leveling point

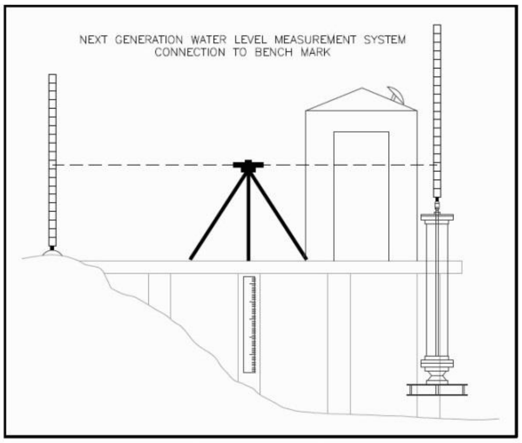


Figure 4-3
Leveling Fixture In Use

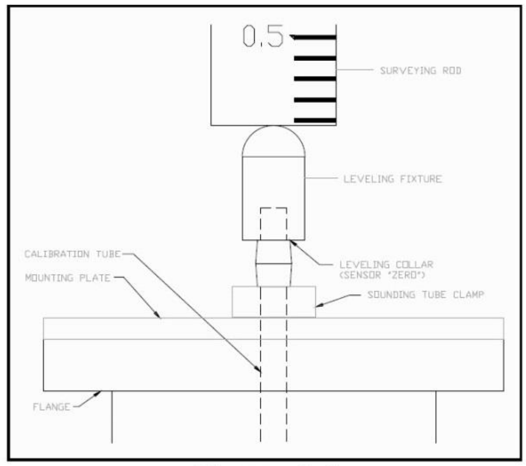
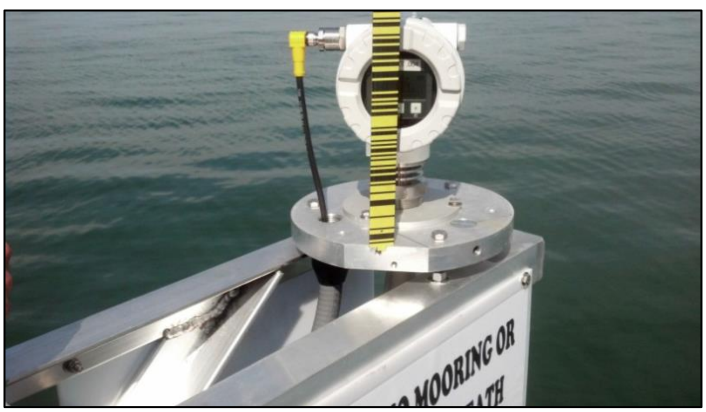


Figure 4-4
Leveling Fixture Close Up

1.2 Barcode leveling scale on microwave sensor leveling point



Close-up of leveling point and barcode rod

Leveling backsight to leveling point and barcode rod

2.0 Example of CORS monument reference mark

Close-up of GPS CORS monument reference mark

CORS GPS tri-pod mount configuration

3.0 Example of Co-location of tide gauge and CORS GPS

Co-located tide gauge and CORS GPS at Crescent City, CA