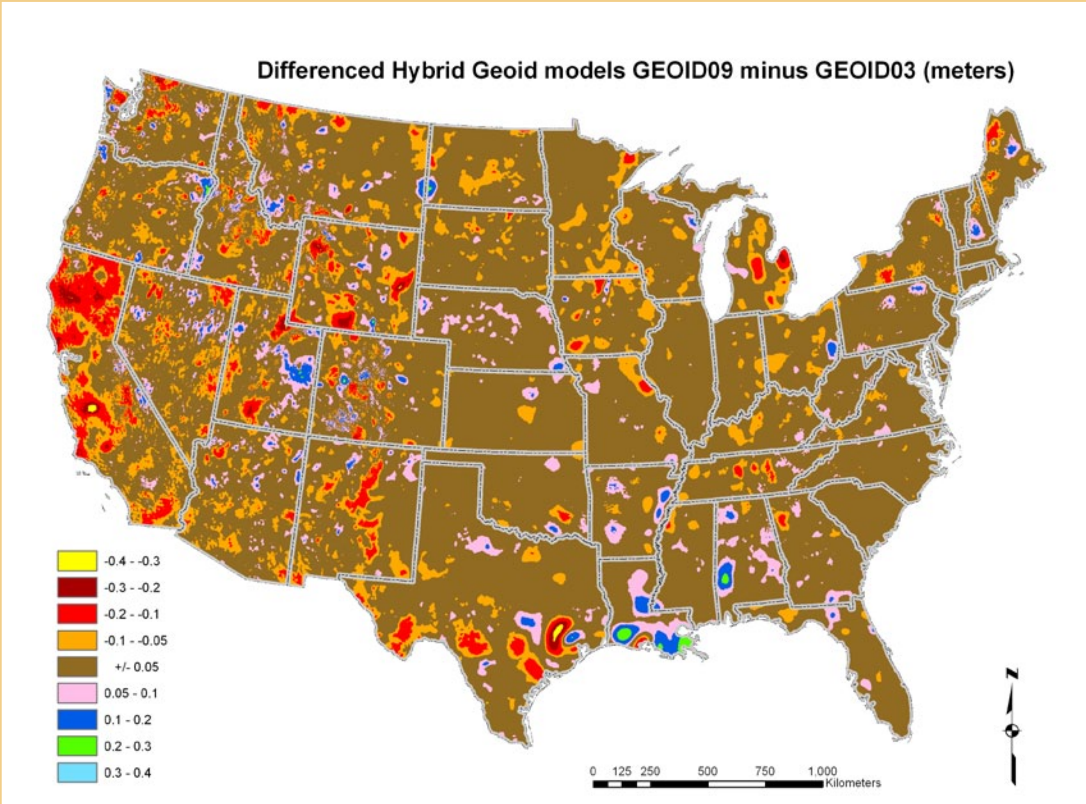

Figure 7. Difference between hybrid geoid models (GEOID09 minus GEOID03).

Frames for the Future

New Datum Definitions for Modernization of the U.S. National Spatial Reference System

Replacing NAVD 88—Challenges and Benefits (Part 3 of 4)

Hybrid Geoid Models–Applications and Consequences

A transformation tool will be developed by NGS to convert between National Vertical Datum (NVD) and NAVD 88 heights. This tool will be based on the national data set of GPSBMs at the time NVD is released. Continuing to determine accurate and current NAD 83 ellipsoid heights on leveled NAVD 88 bench marks up through the release of NVD will result in a more accurate transformation. This, of course, assumes the bench marks used are still consistent with the overall NAVD 88 network (i.e., the marks have not physically changed in height due to subsidence, uplift, etc.).

As a related note to GEOID09 and future hybrid geoid models, there is significant difference in many parts of the U.S. between GEOID09 and earlier geoid models (see national geoid difference plot in **Figure 7**). For many areas of the U.S., such as the mountainous western states, it is recommended that previous GNSS surveys performed to establish NAVD 88 orthometric control that utilized GEOID03 or earlier hybrid models be evaluated for possible adjustment with GEOID09 (or future hybrid models). In addition to the change in geoid models, NAD 83 (NSRS2007) ellipsoid heights determined in the national readjustment of 2007 also affect GNSS-derived NAVD 88 orthometric heights. GEOID09 is based on the

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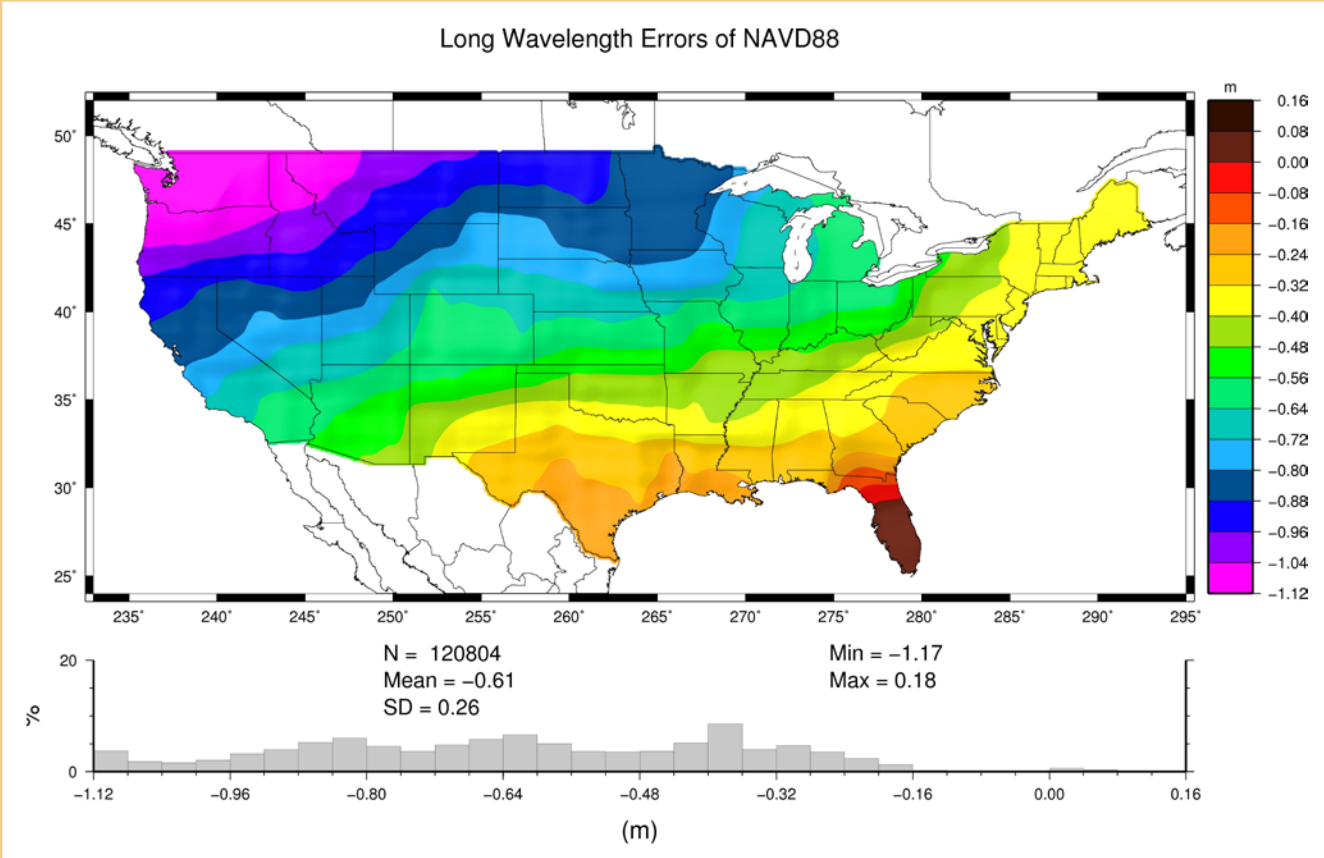

Figure 8. "Slope" of the NAVD 88 datum with respect to the gravimetric geoid as defined by GRACE satellite gravity data (from Roman, et al., 2010b).

NSRS2007 ellipsoid heights, whereas previous geoid models are based on earlier, more locally determined ellipsoid heights. Recall only NAD 83 (1986) and NAD 83 (NSRS2007) are national realizations; all others were regional realizations. Hence, hybrid geoid models based on regional NAD 83 realizations may have biases due to the local nature of those realizations.

Surveys published by NGS that report GNSS-derived orthometric heights to the nearest centimeter are referred to as "Height Modernization" (HM) surveys. The intent of a Height Modernization survey is to determine NAVD 88 orthometric heights consistent with the local NAVD 88 network, at accuracies of 2 cm or 5 cm (depending on the procedures used, as detailed in Zilkoski et al., 1997 and 2008), without incurring the significantly higher costs of geodetic leveling. HM surveys determine NAVD 88 orthometric heights on stations by using GNSS observations, a hybrid geoid model, and leveled NAVD 88 orthometric heights on existing bench marks. Observations are performed both on existing NAVD 88 bench marks in addition to new passive stations. In the least-squares vertical adjustment of the survey, constrained ties to existing NAVD 88 control are used to determine NAVD 88 heights on the new stations. As one would expect, if there are significant changes to the hybrid geoid model used in adjusting a HM survey, one might not be able to use control determined in a previous HM survey as constraints in a new HM survey if the surveys used different hybrid models in the vertical adjustments.

As an experiment, four HM surveys previously conducted in Arizona were adjusted with both GEOID03 and GEOID09 and the differences evaluated. In an area of significant difference between the geoid models, using GEOID03-based surveys could not be used as constrained control in surveys performed later and adjusted with GEOID09.

Based on the results of the experiment, the Arizona Height Modernization Program (AZHMP) performed a vertical adjustment of all HM surveys (and other NGS surveys performed to establish precise ellipsoid heights, such as Federal Base Network surveys) with GEOID09. To accomplish this adjustment, 44 surveys (1655 stations) were combined into a single observation file (i.e., a single 1655-station survey spanning from 1996 to 2010 was created). Results from the combined vertical adjustment shows changes in GNSS-determined orthometric heights ranging from −19 cm to +22 cm. In addition, 18 NAVD 88 leveled bench marks that previously could not be constrained could be used as constraints (presumably because GEOID09 better represents the NAVD 88 datum surface than earlier hybrid models).

In areas similar to Arizona (i.e., where there are significant differences between GEOID03 and GEOID09 as shown in **Figure 7**), it is likely that HM surveys performed using prior geoid models will not "fit" with later surveys using GEOID09 and NAD 83(NSRS2007) ellipsoid heights, and consequently they will not fit well with the NAVD 88 / NVD transformation tool. However, before undertaking an extensive effort to readjust HM surveys in an area to a new hybrid geoid model, some test cases in the area should be investigated. In addition, NGS is in the process of evaluating whether to perform a nationwide vertical adjustment of all appropriate existing

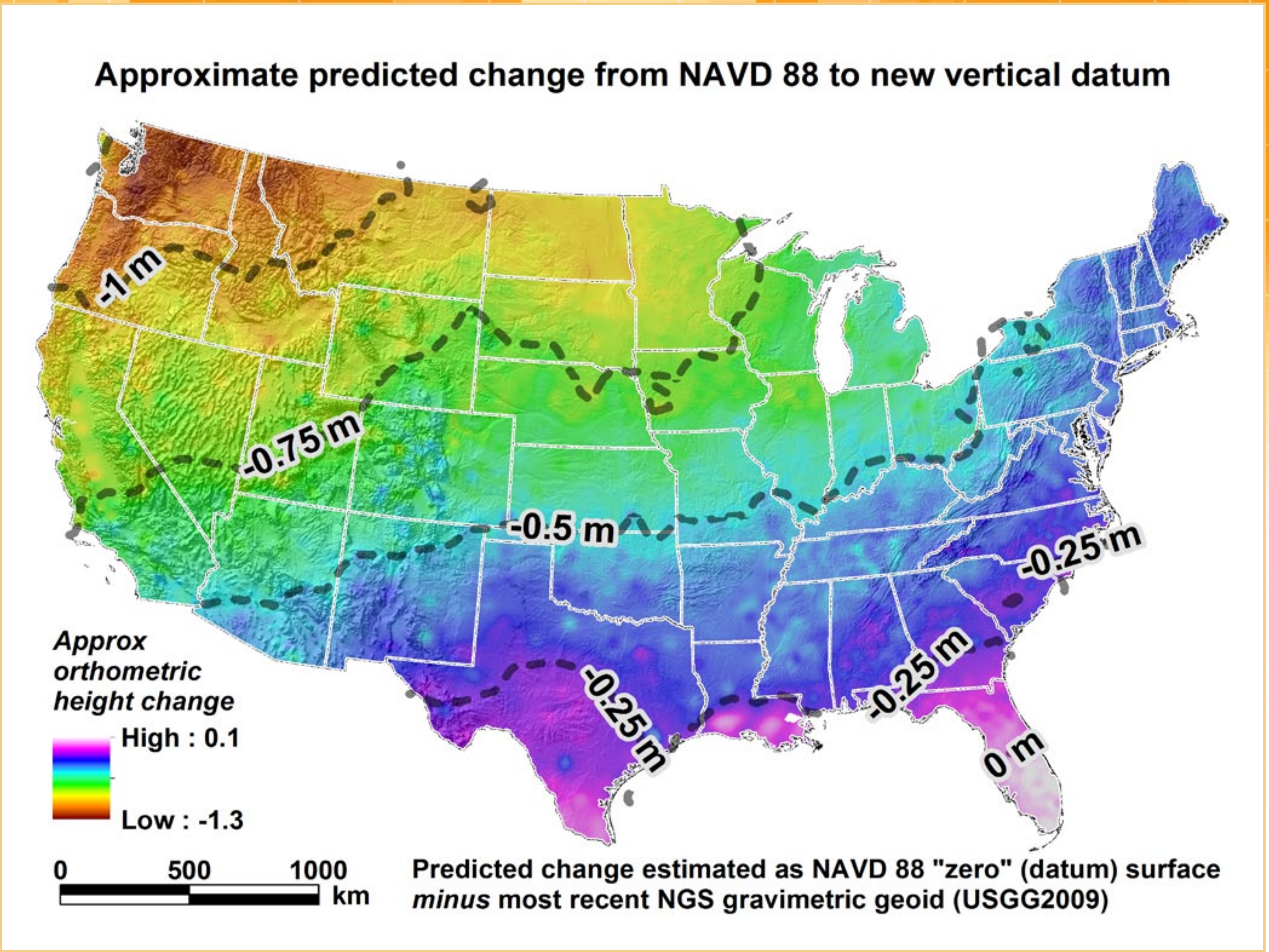

Figure 9. Estimated change in orthometric heights from NAVD 88 to NVD. These changes are based on the assumption that the geoid model used for NVD will be based on essentially the same reference geopotential value as USGG2009.

GNSS surveys in the NGS database using the latest available hybrid geoid model. Because of this, consultation with NGS is encouraged before undertaking an adjustment of existing HM surveys.

Since NVD is still under development, and NGS is in discussions with Canada and Mexico regarding the new datum, the exact relationship of NVD to NAVD 88 is currently unknown. However, it is a certainty that there will be a significant difference, relative to NAVD 88, in some portions of this country. This is due to the known slope of the NAVD 88 surface compared to the very best continental scale geoid models currently available, which are those from the GRACE (Gravity Recovery and Climate Experiment) satellite mission. As shown in **Figure 8**, the NAVD 88 datum surface slopes from approximately -1.12 m (below) in the northwest to +0.16 m (above) in the southeast, when compared to GRACE gravity field data. Additional information about GRACE is available at grace.jpl.nasa.gov.

Since the orthometric heights of NVD will be determined by a gravimetric geoid model, likely with satellite missions such as GRACE as its foundation, the range of orthometric height differences depicted in the figure will, at a minimum, be seen when NVD heights are compared to NAVD 88 heights. The final height difference at any given location will be determined by what geopotential value is defined as the "zero" surface for the NVD geoid model, as well as any vertical motion at an individual bench mark occurring between the time of its NAVD 88 observations and the release of NVD. **Figure 9** shows an estimate of the change in orthometric heights from NAVD 88 to NVD. These changes are based on the assumption that the NVD geoid model will use essentially the same reference geopotential as USGG2009. At this time it appears that assumption is likely correct (Roman, 2011), and so **Figure 9** should provide a reasonably good estimate of the change in orthometric heights to within about a decimeter.

Benefits of NVD

In addition to allowing better usage of GNSS technology, both current and future, a vertical datum referenced to a geopotential surface is needed due to the comparatively high cost of maintaining a national vertical datum based on precise leveling. Not only is a leveling-based vertical datum considerably more expensive (between $200 M and $2 B to re-level the U.S., as estimated by the NGS), it is a waste of funds when compared to the cost, accuracy, and ease of maintenance of a national vertical datum defined using ellipsoid heights (based on a new geocentric geometric datum) and a purely gravimetric geoid model.

This high cost of re-leveling the entire U.S. has prevented NGS from fully maintaining the portion of the NSRS comprised of leveled bench marks. While in most areas of the U.S. the bench mark network is still quite reliable, there are significant portions of the U.S. where the bench mark network is no longer reliable (e.g., due to subsidence caused by fluid withdrawal and the accompanying consolidation of sediments). Analysis of a portion of a 1st Order level line south of Phoenix, AZ, shows subsidence up to 2.069 m (6.788 ft) from the period 1967 to 1992. One particular bench mark pair, approximately 1.2 km (0.75 mile) apart, subsided 0.702 m (2.302 ft) and 0. 695 m (2.282 ft) from their previous heights from 1967 to 1980. Note that the two marks subsided within 0.006 m (0.020 ft) of each other. If a prudent surveyor, in the course of establishing heights (elevations) for a client, were to check their work by starting on one of these marks and closing on the other they could check at 0.02 ft. Furthermore, note that if the subsidence continued at the same rate, the marks would now be more than 4.5 ft (1.37 m) below their published heights, since those heights were last determined in 1980. This illustration from Arizona is not an isolated occurrence; significant subsidence is occurring in parts of California, Nevada, Texas, Louisiana and other Gulf Coast states. Uplift is also causing bench mark height change, most notably in the Great Lakes region due to Glacial Isostatic Adjustment (GIA).

Since NVD will define height values within a national, mathematical, and geophysical model–rather than through heights assigned to individual survey marks within a network of passive marks–maintenance will only be required in areas where the geoid is expected to change (rather than where the height of monuments is expected to change). Some causes for the geoid changing in a location would be significant regional changes to mass, such as GIA. In these areas, a program of geoid monitoring (using geophysical models, repeat gravity observations, CORS data, etc) will be operated to provide the temporal component of the vertical datum. While small changes (mm/year) may be tracked for scientific use, it seems likely that only when the geoid has changed by 1 cm or more will these "updates" will be incorporated into the national model. Since NVD orthometric heights will be subject to change from either an updated geoid model or a change in NGD ellipsoid height(s) at the active control stations, the NVD orthometric heights must have epoch dates (realizations) similar to those of NAD 83, e.g. NVD (epoch 2025.00). Note that users of the new datums will undoubtedly see ellipsoid height changes occurring more rapidly than geoid height changes, due to the different rates of change between crustal motion and actual geoid change. Therefore, observed orthometric height changes will more likely be due to actual crustal motion than as (detectable) geoid height change.

> **"No longer will an expensive leveling project be required to re-establish passive control with acceptable orthometric heights."**

While a model-based height system may seem more complex, an obvious advantage is that loss of marks (due to construction, development, etc.) will not have a major impact on the datum accessibility (though there is an obvious inconvenience caused to local surveyors). The loss of a mark, or a series of marks, will not incur significant expense to re-establish the national orthometric height datum in that area. No longer will an expensive leveling project be required to re-establish passive control with acceptable orthometric heights. Instead, a cost-effective GNSS survey will provide needed vertical control. Additionally, the NVD does not require transfer of heights from level lines, sometimes over long distances, as vertical control can be easily established in the "coverage area" of the NGD-tied active stations (i.e., CORS) Furthermore, this system will provide heights that are accurate to a few centimeters, on a national basis, and can more easily be updated to account for change due to subsidence, uplift, and sea level change.

It is expected that there will continue to be a need/requirement for precise leveling. However, that requirement will be primarily for the determination of precise height differences on projects in local areas, rather than the establishment, or transfer, of the vertical datum across the Nation or a large geographic area. With the implementation of NVD, the Federal Geographic Data Committee's (and relevant subcommittees) standards and specifications for geodetic leveling will require revision. It will not be reasonable to expect precise leveling (e.g. 1st Order, Class II) to close between stations with NVD orthometric heights determined from GNSS observations unless the station separation is quite large; hence, new specifications and methodologies will be necessary.

Invitation for Comment or Inquiry:

Readers who wish to comment on the definition and implementation of NVD are invited to send their comments, or questions, to: Mark.Eckl@noaa.gov. You are also invited to contact your nearest NGS Geodetic Advisor (www.ngs.noaa.gov/ADVISORS/AdvisorsIndex.shtml) for more information or to comment on the new datum.

References for this four-part series are available in the Exclusive Online-only Content area of amerisurv.com

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