NAVD 88 AND NGS' RESPONSIBILITY TO THE SURVEYING AND MAPPING COMMUNITY

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BIOGRAPHICAL SKETCH

David B. Zilkoski received a B.S. degree in Forest Engineering from the College of Environmental Science and Forestry, Syracuse, New York, in 1974, and an M.S. degree in Geodetic Science from the Ohio State University in 1979. He has been employed by the National Geodetic Survey (NGS) since 1974. From 1974 to 1981, as a member of the Horizontal Network Branch, he participated in the new adjustment of the North American Datum of 1983. In 1981, he transferred to the Vertical Network Branch and served as Chief, Vertical Analysis Section, until 1986. His present position is Geodesist, Vertical Network Branch, and Project Manager, New Adjustment of the North American Vertical Datum.

Mr. Zilkoski is a member of the American Congress on Surveying and Mapping (ACSM) and is an instructor for the NGS Vertical Control Workshop and ACSM-NGS Surveying Instrumentation and Coordinate Computation Workshops. He is also a member of the American Geophysical Union and President of International Association of Geodesy Special Study Group 1.102, "Vertical Reference Systems."

ABSTRACT

The differences between the new North American Vertical Datum of 1988 (NAVD 88) and the present National Geodetic Vertical Datum of 1929 (NGVD 29) will be the result of many factors. It is difficult to separate the overall change in bench mark heights into individual components such as the effects of systematic error, crustal movement, and datum distortion. In most "stable" areas, relative height changes between adjacent bench marks should be less than 1 cm.' Analyses indicate that some absolute height values will change much more. Preliminary results indicate that many bench mark height values will change from 50 to 75 cm, with some changing as much as 150 cm. In many stable areas a single bias factor, describing the difference between NGVD 29 and NAVD 88, can be estimated and used for most mapping applications.

The National Geodetic Survey recognizes that NAVD 88 is not complete even after new adjusted heights have been computed and distributed. A preliminary list of NGS' responsibilities is provided for review and comment.

The Federal Geodetic Control Committee (FGCC) and the American Congress on Surveying and Mapping (ACSM) have established committees to investigate the impact of NAVD 88 on their members' activities and the activities of others in the user community. Members of both committees have been briefed on the results of the datum definition study and were requested to document their products and services that will be affected by the readjustment.

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These two committees have drafted recommendations for NAVD 88. The most significant recommendations were to (1) perform a minimum-constraint, least squares adjustment of the data for NAVD 88, (2) shift the datum vertically to minimize ecompilation of national mapping products, (3) develop computer transformation software to convert between NGVD 29 and NAVD 88, and (4) develop national and/or regional geoid models to ensure Global Positioning System (GPS) height differences that meet at least second-order, class II Federal Geodetic Control Committee (FGCC) precise geodetic leveling standards.

NGS realizes it may be necessary to provide two vertical datums, an international NAVD 88 and a national NGVD 29, in order to meet different users' technical and economic requirements.

INTRODUCTION

The new adjustment of the U.S. vertical control network received approval and funding in fiscal year 1978. In 1982, the National Oceanic and Atmospheric Administration (NOAA) and Canada signed a Memorandum of Understanding (MOU) regarding the adoption of a common, international vertical control network called the North American Vertical Datum of 1988 (NAVD 88).

Bench marks included in the NAVD 88 Helmert blocking phase (approximately 65-70 percent) will have final adjusted heights available in December 1990. Some bench marks in "stable" areas were removed from the adjustment (denoted as "POSTed") because older data did not fit with the latest data. These will be incorporated into NAVD 88 after the final adjustment. There are also some bench marks in vertical crustal motion areas that will receive additional analysis before being adjusted into NAVD 88.

In most "stable" areas, relative height changes between adjacent bench marks should be less than 1 cm. Analyses indicate that some absolute height values will change much more. Many bench mark height values will change from 50 to 75 cm, with some changing as much as 150 cm. The differences between NAVD 88 and the present National Geodetic Vertical Datum of 1929 (NGVD 29) are caused by many factors. It is difficult to separate the overall change in bench mark heights into individual components such as the effects of systematic error, crustal movement, datum distortion, and datum definition.

In areas of vertical crustal motion, relative height changes will depend on the magnitude of the actual physical movement of the bench marks. In many stable areas a single bias factor, describing the difference between NGVD 29 and NAVD 88, can be estimated and used for most mapping applications.

The National Geodetic Survey recognizes that NAVD 88 is not complete even after new adjusted heights have been computed and distributed. The development and maintenance of a nationwide vertical reference system should be viewed as an ongoing effort that includes responsibilities assumed by NGS and the users. A preliminary list of NGS' responsibilities is provided for review and comment.

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DISTORTIONS IN NGVD 29

An investigation of NGVD 29 general adjustment results indicates that large adjustment corrections (residuals) were distributed in some areas of the country during that adjustment. For example, the accumulated 1929 adjustment correction along a 3,000 km east-west leveling route from Crookston, Minnesota, to Seattle, Washington, was 89 cm.

Some users indicate that NGVD 29 is currently meeting their needs.
They question the need for NGS to readjust the National Geodetic Vertical Control Network. NGS currently has approximately 40,000 km of new leveling data that have not been incorporated into NGVD 29.
Incorporating new data into NGVD 29 consumes large amounts of NGS' resources because existing inconsistencies in NGVD 29 require major area readjustments. An example of one inconsistency in NGVD 29 is near Oak Hill, Florida. Here, between bench marks D 227 and JLR 370, which are only 0.85 km apart, a 10-centimeter difference exists between published NGVD 29 height differences and adjusted height differences computed in a special minimally constrained test adjustment of the Florida primary leveling network. (See table 1.)

Table 1. An example of inconsistency in NGVD 29 (Florida).

Bench Mark	Special Adjusted Height (m)	Published NGVD 29 Height (m)	Difference Between Special Adj. and Published Height (cm)	Second Difference (cm)
D 227	3.624	3.624	0.0	
JLR 370	3.296	3.192	10.4	-10.4
J 211	3.502	3.405	9.7	0.7
JLR 371	3.358	3.263	9.5	0.2
HALE RM 2	2.882	2.884	-0.2	9.7

It is not known exactly how many large inconsistencies exist in the present NGVD 29 published height values. Some detected in recent years during analyses performed in support of special adjustments include a 13-c'entimeter inconsistency located in Milton, Florida; a 14-centimeter inconsistency in the Hampton Roads, Virginia, area; a 5-centimeter inconsistency at Colonial Beach, Virginia; a 3-centimeter inconsistency in Cole Point, Virginia; and a 4-centimeter inconsistency at Indian Head, Maryland. NAVD 88 analysis is certain to uncover more of these inconsistencies.

Users are usually not aware of these inconsistencies because NGS has periodically readjusted large portions of the vertical network, distributing the inconsistencies over large areas. NGS does not have the resources to continue to maintain NGVD 29 as in the past. If the National Geodetic Vertical Network is not totally readjusted, as will be accomplished by NAVD 88, these inconsistencies will become more pronounced. Eventually there would be a large number of areas in which surveyors would not be able to check their work using the present NGVD 29. NAVD 88 is specifically designed to remove the inconsistencies and distortions in the present NGVD 29.

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ANALYSES OF NAVD 88 PRIMARY VERTICAL NETWORK

NGS' Vertical Network Branch has undertaken a special study to compile a primary vertical network spanning the conterminous United States (a subset of the entire National Geodetic Vertical Network) using the latest leveling data available. Analyses of this network were helpful in determining the effects of various datum constraints and the magnitudes of height changes to be expected between NGVD 29 and a new adjustment. The results are documented in detail in a report by Zilkoski et al. (1989).

This primary network consists of 200 loops containing 909 junction bench marks. The network connects to 57 U.S. primary tidal stations which are part of the National Primary Tidal Network and 55 international water-level stations along the Great Lakes. In addition, 28 border connections were made to the Canadian vertical control network and 13 to the Mexican vertical control network.

Minimum-Constraint Adjustment Results

The first adjustment performed was a minimum-constraint least squares adjustment holding fixed the height of the primary tidal bench mark at Key West, Florida, referenced to the 1960-78 local mean sea level tidal epoch. This tide station was arbitrarily selected as the constraint; any station could have been used. The height was referenced to the 1960-78 tidal epoch so all other adjusted heights of tidal bench marks could be compared with their corresponding local mean sea level values.

Figure 1, a "rough" contour map, depicts the differences between heights estimated from the minimum-constraint least squares adjustment and presently published NGVD 29 heights at the junction bench marks.
Referring to figure 1, an east-to-west systematic difference between the minimum-constraint adjusted heights and the published NGVD 29 heights seems to exist. This accumulates to a significant difference of about 160 cm from Maine to Washington.

DIFFERENT NAVD 88 DATUM DEFINITION SCENARIOS

To assist in the NAVD 88 datum definition decision, several adjustments were performed using different constraints. In addition to the minimum-constraint least squares adjustment discussed previously, four other adjustments using the same data but different constraints were performed:

(1) the 1960-78 tidal heights of primary bench marks at Key West, Florida, and Portland, Maine, were held fixed;

(2) the 1960-78 tidal heights of primary bench marks at Key West, Florida, Portland, Maine, Neah Bay, Washington, and San Diego,California, were held fixed;

(3) the 1960-78 tidal height of Key West, Florida, was held fixed and an observation of 70 gal-cm (standard error equal to 0.1 gal-cm) between the Duck, North Carolina, tidal station and the Crescent City, California, tidal station was added to the data; and

(4) the 1960-78 tidal height of Key West, Florida, was held fixed and an observation of 70 gal-cm (standard error equal to 10 gal-cm) between the Duck, North Carolina, tidal station and the

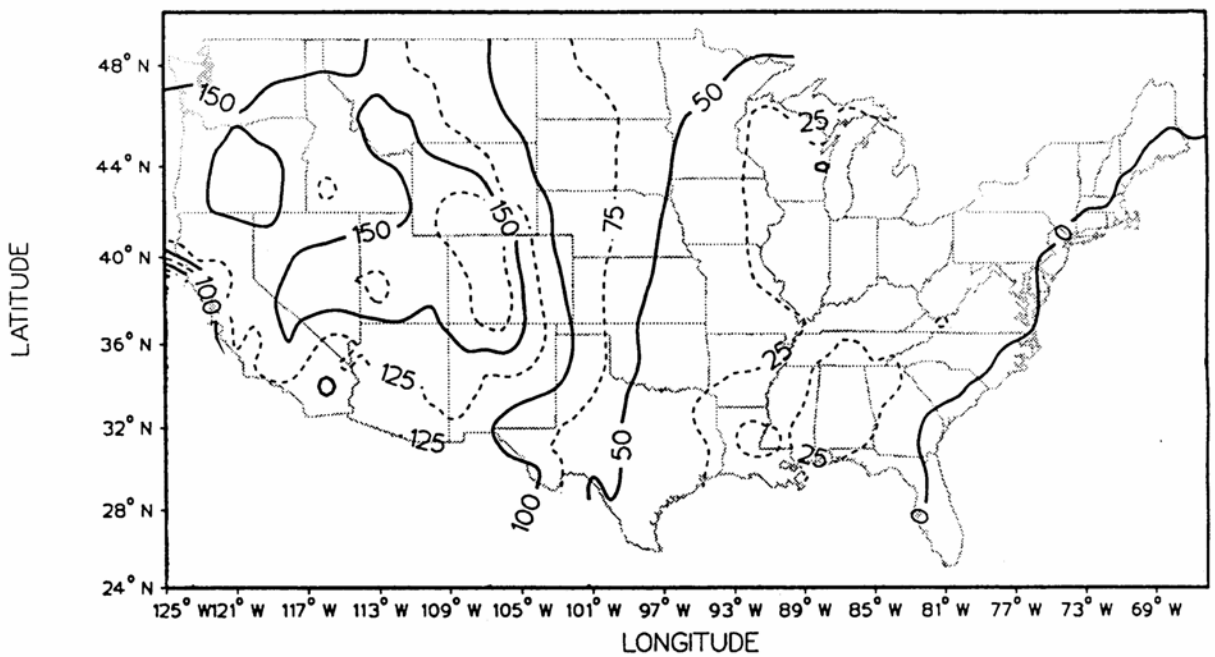

Figure 1. Contour map depicting height differences between a minimum-constraint adjustment (one proposal for NAVD 88) and published NGVD 29. Minimum constraint for the adjustment was the height of the primary tidal bench mark at Key West, Florida, referenced to the 1960-78 local mean sea level tidal epoch (units = cm).

Crescent City, California,- tidal station was added to the data.

The results obtained from these adjustments indicate that no matter which datura definition scenario is chosen for NAVD 88, including a minimum-constraint solution, changes in absolute heights of as much as 75 to 100 cm will exist between NGVD 29 and NAVD 88 (Zilkoski et al. 1989). Even constraining the heights of two tidal bench marks on each coast produced large (25 cm) differences between the special NAVD 88 primary vertical control network adjusted heights and published 1960-78 tidal heights.

SELECTION OF A DATUM

An obvious choice for the common, international NAVD 88 datum is a variation of adjustment number 4 discussed in the previous section, i.e, holding the height of one tidal bench mark referenced to the 1960-78 tidal epoch fixed (or minimizing the differences between specific tidal height values and NAVD 88 heights), and adding observations between appropriate tidal stations with their appropriate standard errors.

The selection of a datum with the heights of four bench marks held fixed would minimize the differences between NGVD 29 and NAVD 88 in the locations of the constraints, but would add large distortions to the data. Differences would still approach 1 meter in the Rocky Mountains.
This type of datum would not be as useful to people estimating precise GPS-derived orthometric heights.

It has been generally understood that two vertical datums would be required for a certain time period following completion of NAVD 88 to meet users needs: (1) a datum defined by holding one height fixed, i.e., minimum-constraint, for surveyors and scientists who require very accurate height difference relationships and (2) a second vertical datum for mappers and others who require less accurate height difference relationships, i.e., one similar to NGVD 29, but not maintained to its current high accuracy standards. This is not the most desirable situation, but may be necessary due to current budgetary constraints of users.

As a matter of fact, the second datum could be a general readjustment of NGVD 29, where presently published NGVD 29 heights of several (perhaps 25) bench marks strategically located across the United States were held fixed. These bench marks could be selected in such a manner that the adjustment distribution correction would be less than 1 mm per kilometer. The local surveyor performing leveling in support of mapping projects would not detect the remaining distortions. The absolute height differences between the readjusted NGVD 29 and the published NGVD 29 would be less than 30 cm (1 ft), and relative height differences would be less than 1 cm. The large local distortions and inconsistences due to piecemeal adjustment constraints imposed in previous years would, for the most part, be removed in the readjusted NGVD 29. However, users would still have to convert old NGVD 29 published values not included in the general readjustment, i.e., published third-order U. S. Geological Survey (USGS) and U.S. Army

Corps of Engineers (COE) bench marks, to the new readjusted NGVD 29 to have a consistent set of heights.

NGS realizes that it nay be necessary to provide and support two vertical datums: (1) a new international NAVD 88 and (2) the existing NGVD 29 or a readjusted national NGVD 29, in order to meet different users' technical and economic requirements. The two committees discussed in the next section are considering the implications of maintaining two vertical daturas.

DISCUSSION OF DATUM DEFINITION SELECTION

As implied above, regardless of datum definition, large differences will exist between the international NAVD 88 and the national NGVD 29 heights. It should be noted that the NAVD 88 heights are better estimates of orthometric heights than the NGVD 29 heights. Better estimates of orthometric heights will become more critical in the future as surveying techniques continue to become more sophisticated and more accurate. The improved accuracy of geoid height determinations using GPS data requires the best estimate of "true" orthometric heights. Many cartographers want heights on their maps based on the best estimate of "true" orthometric heights.

Most surveying applications should not be significantly affected because the changes in relative height between adjacent bench marks should be less than 1 cm. The absolute height values will change much more, but this should not be the surveyor's biggest concern. The biggest problem the surveyor will have is ensuring that all height values of bench marks in the project are referenced to the same vertical datum, preferably NAVD 88. The leveling data associated with 500,000 bench marks established by USGS have not been placed in computer-readable form and will not have NAVD 88 heights. In addition, COE has established hundreds of thousands of bench marks across the nation which will not have NAVD 88 heights. This will still be a problem even if a major readjustment of NGVD 29 is performed to remove inconsistencies in NGVD 29 due to previous adjustment constraints.

The Federal Geodetic Control Committee (FGCC) and the American Congress on Surveying and Mapping (ACSM) have established committees to investigate the impact of NAVD 88 on their members' activities and the activities of others in the user community. Members of both committees have been briefed on the results of the datum definition study (Zilkoski et al. 1989) and were requested to document their products and services that will be affected by the readjustment.

The FGCC Subcommittee members have been asked to identify specific examples describing the real impact of NAVD 88 on their products and the effect it will have on their users. These examples will be included in the final FGCC report to document the impact NAVD 88 will have on Federal agencies. The ACSM committee is performing similar analysis to document the impact NAVD 88 will have on state, local, and private organizations.

Both committees have drafted significant recommendations for NAVD 88 (ACSM 1990 and FGCC 1990) specifying that NGS should: (1) perform a minimum-constraint, least squares adjustment of the data for NAVD 88, (2) shift the datum vertically to minimize recompilation of national mapping products, (3) develop computer transformation software to convert between NGVD 29 and NAVD 88, and (4) develop national and/or regional geoid models to ensure GPS height differences meet at least second-order, class II FGCC precise geodetic leveling standards.

NGS' RESPONSIBILITY TO THE SURVEYING AND MAPPING COMMUNITY

To assist users, NGS will compare published NGVD 29 heights with NAVD 88 heights to estimate a single bias factor describing the difference between NGVD 29 and NAVD 88 for small areas, e.g., for a 7.5-minute quad. These bias factors could be published in tables or loaded onto magnetic media and distributed to users. Computer programs using appropriately designed and validated data files will be developed which estimate a bias factor on a point-by-point basis. The accuracy of the bias shift will depend on the number of valid bench marks within the area of interest. Heights of some bench marks may have changed due to crustal movement; obviously, these bench marks should not be used to estimate the bias factor. Preliminary analyses of contour plots based on the special primary network adjustment results indicate that in most small areas, e.g., 15 minute by 15 minute, the difference in bias factors between the extremes of the boundary would be less than 10 cm. (See figs. 2 and 3.) However, due to local distortions, like the inconsistency in NGVD 29 shown in table 1, larger differences in bias factors may occur.

The National Geodetic Survey recognizes that NAVD 88 is not complete even after the final set of adjusted heights have been computed and distributed. The development and maintenance of a nationwide vertical reference system should be viewed as an ongoing effort that includes responsibilities of NGS and the users. A preliminary list of NGS' responsibilities is given below. This list is not meant to be complete. NGS would appreciate comments and suggestions from all users.

NGS' Responsibilities

- Establish and implement procedures to officially replace NGVD 29 with NAVD 88

- Provide documentation and publication of NAVD 88 final results .

- Provide documentation of datum definition study

- Develop contour maps depicting NGVD 29 - NAVD 88 height differences

- Prepare and publish NAVD 88 data sheets

o In cooperation with professional organizations and societies, educate NAVD 88 users

  - Prepare publications for "non-surveyors"

  - Present seminars and workshops about NAVD 88

o Compile documentation to brief Congress, state officials, and the private sector on the impact of NAVD 88 and benefits in order to minimize problems with uninformed users

o Compute bias shifts between NGVD 29 and NAVD 88

  - Verify and load all NGVD 29 heights into NGS integrated data base

  - Estimate bias factors with standard errors

  - Design and validate data files to be used in estimating bias factors

  - Compile table of shifts for 7.5-minute quad series

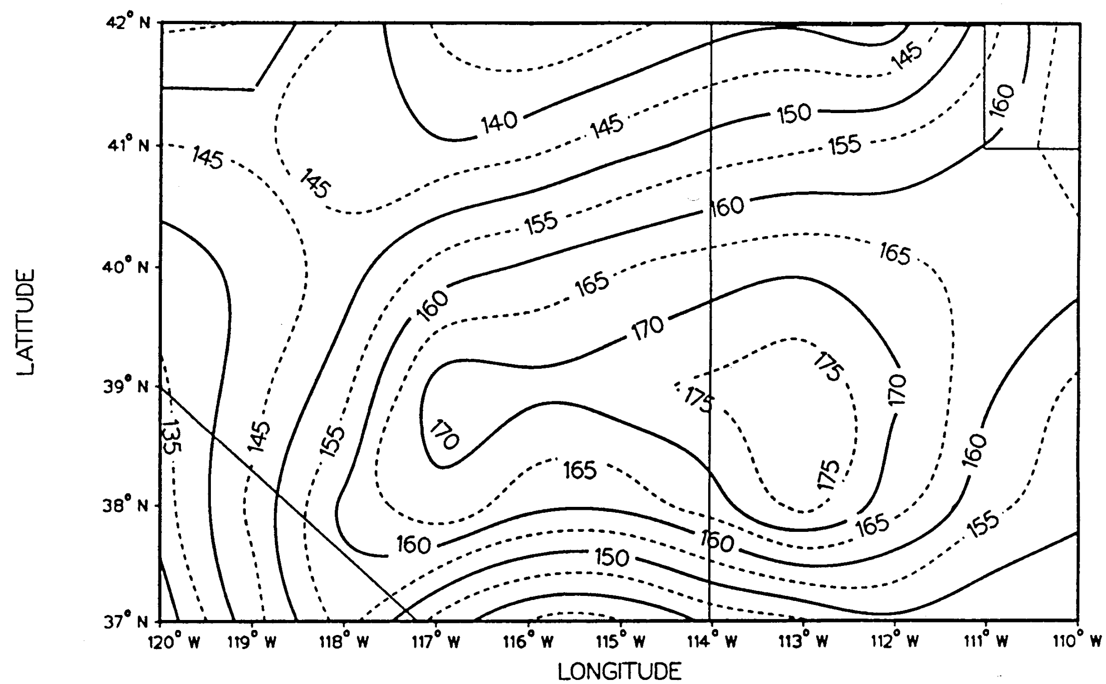

Figure 2. Contour map depicting height differences between a minimum-constraint adjustment (one proposal for NAVD 88) and published NGVD 29 between latitudes 37° and 42° and longitudes 110° and 120°. Minimum constraint for the adjustment was the height of the primary tidal bench mark at Key West, Florida, referenced to the 1960-78 local mean sea level tidal epoch (units = cm).

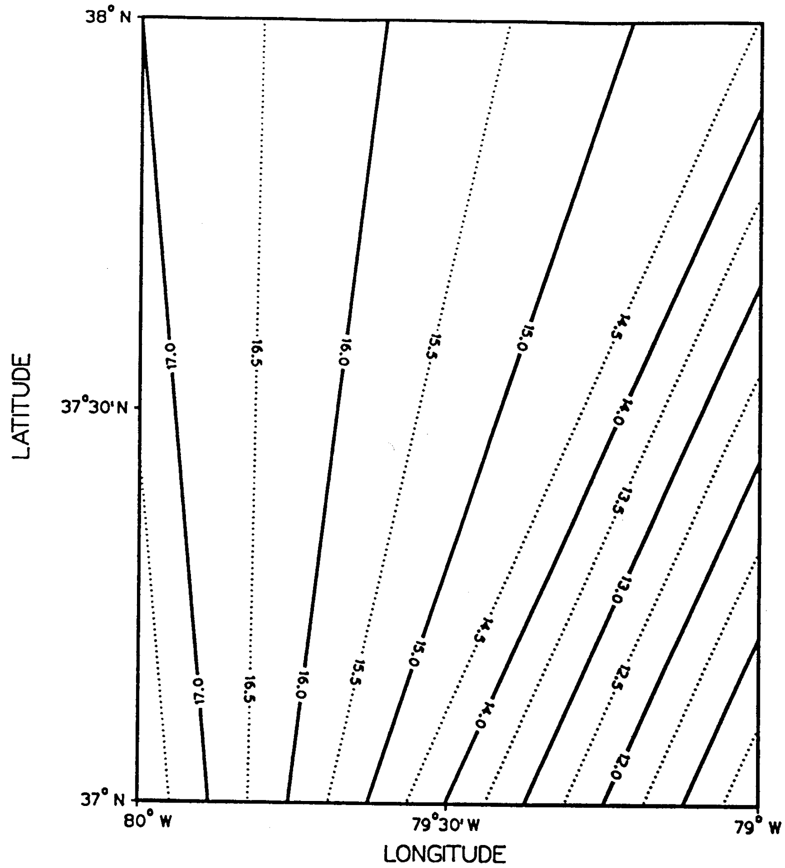

Figure 3. -- Contour map depicting height differences between a minimum-constraint adjustment (one proposal for NAVD 88) and published NGVD 29 between latitudes 37° and 38° and longitudes 79° and 80°. Minimum constraint for the adjustment was the height of the primary tidal bench mark at Key West, Florida, referenced to the 1960-78 local mean sea level tidal epoch (Units = cm).

  - Prepare routines which estimate bias factor and its standard error for a given area (min./max. latitude and longitude)
  - Prepare routines which estimate bias factor and its standard error for a given point (latitude and longitude)

- o Analyze bias shift computations to determine where other data, e.g., COE and/or USGS data, may be required (in computer-readable form) to improve the estimate of the bias factor

- o Analyze vertical control network to separate bias shift into components: changes due to datum definition, crustal movement, improved corrections applied to leveling data to account for systematic errors, and removal of adjustment distortions in NGVD 29

- o Incorporate other data, e.g., COE and/or USGS data, into NAVD 88 (data must be in computer-readable form)

- o Evaluate the practicality of two vertical datums

  - Maintain the present National Geodetic Vertical Datum of 1929 to the 10-30 cm accuracy level for the next 5-7 years

  - During that period, determine if two datums, i.e., NAVD 88 and a readjusted NGVD 29, should be maintained indefinitely due to technical and/or economic considerations

- o Integrate GPS-derived orthometric heights into NAVD 88

NAVD 88 FINAL ADJUSTMENT COMPLETION DATE OF DECEMBER 1990: WHAT DOES THIS REALLY MEAN?

The final general adjustment of NAVD 88 is scheduled for completion in December 1990. This means that bench marks included in the NAVD 88 Helmert blocking phase (approximately 65-70 percent of the total) will have final adjusted heights available in December 1990. These bench mark height values will be in the NGS Integrated Data Base (IDB) and available for immediate retrieval. They will also be published on NAVD 88 height listing sheets during fiscal years 1991-92.

Bench marks in "stable" areas which were removed from the adjustment (denoted as "POSTed") because older data did not fit with the latest data will be incorporated into NAVD 88 after the final adjustment is completed. This task is scheduled to be performed during fiscal years 1991-92.

Bench marks "POSTed" in large crustal movement areas, e.g., southern California, Phoenix, Arizona, Houston, Texas, and southern Louisiana will be published as special reports after the final adjustment is completed. This will be an on-going, long-term task which is scheduled to start in January 1991. It is important to note that some bench marks in crustal movement areas, i.e., bench marks which were included in the NAVD 88 Helmert blocking phase, will be available immediately after the final adjustment. The heights of these bench marks will be based on the latest available data, but still may be influenced by crustal movement effects.

CONCLUSION

Analyses indicate that large differences of as much as 50-75 cm will exist between NAVD 88 and NGVD 29 heights no matter which datum definition scenario is chosen for NAVD 88. These differences are due to factors such as large distribution corrections (residuals) from the NGVD 29 adjustment, better estimates of corrections applied to account for systematic errors, and estimating geopotential differences using actual gravity values instead of normal orthometric height differences. This new set of NAVD 88 heights will be a better estimate of orthometric height than the presently published NGVD 29 heights.

Users of orthometric heights require the best estimate of bench mark heights referenced to the geoid. This will become more critical in the future as surveying techniques continue to become more sophisticated and more accurate. The improved accuracy of geoid height determinations using GPS data requires the best estimate of "true" orthometric heights.

As implied above, undistorted heights will be beneficial to GPS users who are estimating GPS-derived orthometric heights. The largest error in estimating GPS-derived orthometric heights is the uncertainty in estimating geoid heights. The new NAVD 88 adjustment should provide estimates of "true" orthometric height differences which will support the typical user when estimating and verifying relative GPS-derived orthometric heights. It should be possible to estimate relative GPS-derived orthometric heights to a sufficient accuracy to meet the requirements of most engineering projects. This should decrease the cost of establishing elevation control in most engineering and mapping projects.

Two national surveying and mapping committees have drafted recommendations for NAVD 88. The most significant recommendations are: (1) perform a minimum-constraint, least squares adjustment of the data for NAVD 88, (2) shift the datum vertically to minimize recompilation of national mapping products, (3) develop computer transformation software to convert between NGVD 29 and NAVD 88, and (4) develop national and/or regional geoid models to ensure GPS height differences meet at least second-order, class II FGCC precise geodetic leveling standards.

It may be necessary to provide two vertical daturas to meet different users' technical and economic requirements. The international NAVD 88 datum will provide a consistent, very accurate set of height values for mappers, surveyors, scientists, and other users while NGS would maintain a readjusted national NGVD 29 datum with a consistent, less accurate set of height differences for those mappers and others who are unable to use NAVD 88 at this time.

REFERENCES

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