North American Vertical Datum and International Great Lakes Datum: They Are Now One and the Same

David B. Zilkoski

NAVD 88 Project Manager
Vertical Network Branch
National Geodetic Survey, NOAA
Rockville, Maryland 20852
(301) 443-8567

ABSTRACT

For the general adjustment of the North American Vertical Datum of 1988 (NAVD 88) and the International Great Lakes Datum of 1985 (IGLD 85), a minimum-constraint adjustment of Canadian-Mexican-U.S. leveling observations was performed holding fixed the height of the primary tidal bench mark, referred to the new IGLD 85 local mean sea level height value, at Father Point/Rimouski, Quebec, Canada. Therefore, IGLD 85 and NAVD 88 are one and the same. Father Point/Rimouski is an IGLD iwater^level) station located at the mouth of the St. Lawrence River and is the reference station used for IGLD 85. This constraint satisfies the requirements of shifting the datum vertically to minimize the impact of NAVD 88 on U.S. Geological Survey (USGS) mapping products, as well as provides the datum point desired by the IGLD Coordinating Committee for IGLD 85. The only difference between IGLD 85 and NAVD 88 is that IGLD 85 bench mark values are given in dynamic height units and NAVD 88 values are given in Helmert orthometric height units. The geopotential numbers of bench marks are the same in both systems.

Preliminary analyses indicate that the overall differences for the conterminous U.S. between orthometric heights referred to NAVD 88 and to the National Geodetic Vertical Datum of 1929 (NGVD 29) range from approximately -40 to +150 cm. However, in most "stable" areas, relative height changes between adjacent bench marks appear to be less than 1 cm. In many areas a single bias factor, describing the difference between NGVD 29 and NAVD 88, can be estimated and used for most mapping applications. The overall differences between dynamic heights referred to IGLD 85 and to International Great Lakes Datum of 1955 (IGLD 55) will range from approximately 1 to 40 cm.

INTRODUCTION

For the general adjustment of the North American Vertical Datum of 1988 (NAVD 88) and the International Great Lakes Datum of 1985 (IGLD 85), a minimum-constraint adjustment of Canadian-Mexican-U.S. leveling observations was performed. The height of the primary tidal bench mark at Father Point/Rimouski, Quebec, Canada, was held fixed as the constraint.

Therefore, IGLD 85 and NAVD 88 are one and the same. Father Point/Rimouski is an IGLD water-level station located at the mouth of the St. Lawrence River and is the reference station used for IGLD 85. This constraint satisfies the requirements of shitting datum vertically to minimize the impact of NAVD 88 U.S. Geological Survey (USGS) mapping products, as well as provides the datum point desired by the IG Coordinating Committee for IGLD 85. The only difference between IGLD 85 and NAVD 88 is that IGL bench mark values are given in dynamic height unit and NAVD 88 values are given in Helmert orthometric height units. Geopotential numbers for individual bench marks are the same in both systems.

Analyses indicate that the overall difference; for the conterminous U.S. between orthometric heights referred to NAVD 88 and to the National Geodetic Vertical Datum of 1929 (NGVD 29) range from approximately -40 to +150 cm. (See figure 1.) However, in most "stable" areas, relative height changes between adjacent bench marks appear to be] than 1 cm. In many areas a single bias factor, describing the difference between NGVD 29 and NAVD can be estimated and used for most mapping applications. The overall differences between dynamic heights referred to IGLD 85 and to the Internationional Great Lakes Datum of 1955 (IGLD 55) will range from approximately 1 to 40 cm. (See figure 2.)
Table 1 lists some reasons why people should convert to NAVD 88 and IGLD 85.

HISTORY OF U. S. NATIONAL GEODETIC VERTICAL DATUMS

The first leveling route in the United States considered to be of geodetic quality was established in 1856-57 under the direction of G. B. Vose of the U.S. Coast Survey (predecessor of the Coast and Geodetic Survey and, later, the National Ocean Service). The leveling survey was required to support current and tide studies in the New York Bay and Hudson River areas. The first leveling line officially designated as "geodesic leveling" by the Coast and Geodetic Survey followed an arc of triangulation along the 39th parallel. This 1887 survey began at bench mark A in Hagerstown, Marylan

By 1900, the vertical control network had grown to 21,095 km of geodetic leveling. A reference surface

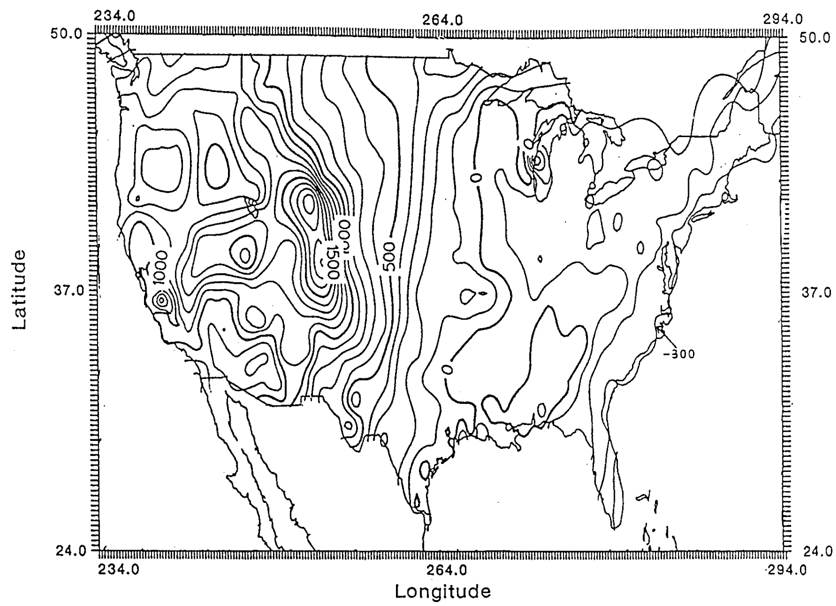

Figure 1.--Contour map depicting height differences between NAVD 88 and NGVD 29 (units = mm).

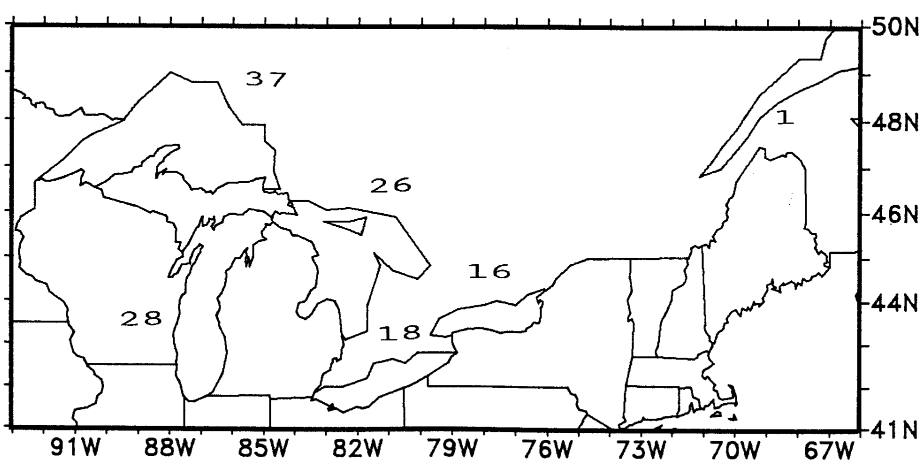

Figure 2.--Average height differences between IGLD 85 and IGLD 55 (units = cm).

Table 1.--Reasons to convert products to NAVD 88 and IGLD 85.
Surveys between bench marks will often close better
NAVD 88 will provide a better reference to estimate GPS-derived orthometric heights
IGLD 85 will provide a better reference to estimate heights of water-level surfaces on the Great Lakes
Data and adjusted height values will be readily available and accessible in convenient form from NGS' Integrated Data Base
Federal surveying and mapping agencies will stop publishing on NGVD 29 and IGLD 55, and will publish only on NAVD 88 and IGLD 85
Surveys performed for the Federal government will require use of NAVD 88 and IGLD 85
The American Congress on Surveying and Mapping and Federal Geodetic Control Subcommittee recommend using the new datum

was determined in 1900 by holding elevations referenced to local mean sea level fixed at five tide stations. Data from two other tide stations indirectly influenced the determination of the reference surface. Subsequent readjustments of the leveling network were performed by the Coast and Geodetic Survey in 1903, 1907, and 1912 (Berry 1976). The next general adjustment of the vertical control network was accomplished in 1929. By then the international nature of geodetic networks was well understood and Canada provided data for its firstorder vertical network to combine with the U.S. net. The two networks were connected at 24 locations through vertical control points (bench marks) from Maine/New Brunswick to Washington/British Columbia. Although Canada did not adopt the "Sea Level Datum of 1929" determined by the United States, Canadian-U.S. cooperation in the general adjustment greatly strengthened the 1929 network. Table 2 lists the kilometers of leveling involved in the readjustments and the number of tide stations used to establish the datums.

HISTORY OF GREAT LAKES VERTICAL CONTROL NETWORKS

A detailed report on the history of the vertical control networks used in the Great Lakes region can be found in a report by Lippincott (1985). The following is a summary from Lippincott's 1985 report.

Levels of 1877

In 1841, the U.S. Congress appropriated funds to survey the northern and northwestern lakes of the United States. The U.S. Army Corps of Engineers (COE) established the U.S. Lake Survey (USLS) to perform the surveys. By 1860, leveling surveys were underway and some water-level data were already being used to determine relative changes on each lake. By 1875, sufficient leveling observations existed to connect Oswego Harbor on Lake Ontario to local mean sea level in New York City, Lake Ontario to Lake Erie. and Lake Erie to Lake Huron. In 1876, leveling was performed between Escanaba on Lake Michigan and Marquette on Lake Superior.

In 1877, the leveling and water-level data were used to establish the vertical datum on each of the Great Lakes. This adjustment was called the "Levels of 1877."

Water-Level Transfers

The water-level transfer procedure has been used to establish vertical datums on the Great Lakes since 1875. The procedure assumes that the mean water surface estimated at one location on a lake is equal (during a certain period of time) to another location on the same lake. Fig. 3 depicts the water-level transfer concept. Leveling data are used to estimate the height difference between the "zero" mark on the staff and a reference bench mark. Mean water-level gauge readings are used to determine the elevation of the lake level at a particular site as referenced to the zero mark on a particular staff. This is performed at two or more gauge sites on the same lake it is then assumed that the two mean water surfaces represent the same geopotential surface. Therefore, an observation of zero geopotential difference can be made.

U.S. Lake Survey 1903 Datum

By 1902, USLS releveled all its Great Lakes lines. In 1903, the U.S. Coast and Geodetic Survey (now called the National Ocean Service) performed a network adjustment which included the USLS leveling lines and several water-level transfers. The 1903 network adjustment results were adopted by USLS. Using additional leveling data and water-level transfers, the remaining bench marks on the Great Lakes network were incorporated into a new network which was called the "U.S. Lake Survey 1903 Datum" or the "1903 Datum."

Adjustment of 1935

By 1933, almost every U.S. harbor on the Great Lakes had a water-level gauge. An adjustment using the

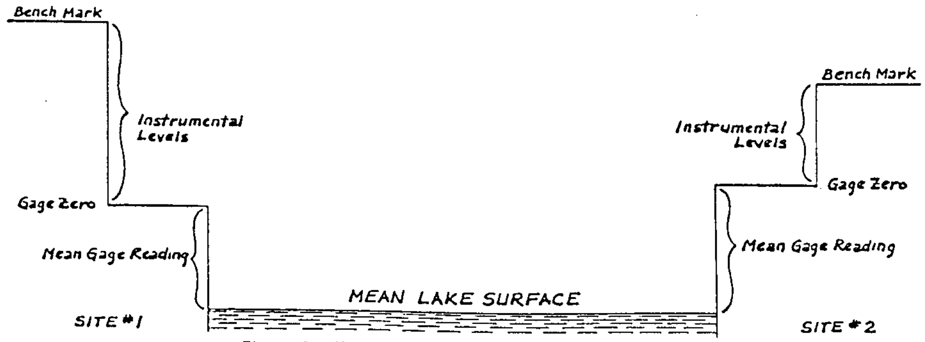

Figure 3.--Water-Level transfer (Lippincott 1985).

Table 2.--Amount of leveling and number of tide stations involved in previous readjustments.

Year of Adjustment	Kilometers of Leveling	Number of Tide Stations
1900	21,095	5
1903	31,789	8
1907	38,359	8
1912	46,468	9
1929	75,159 (U.S.) 31,565 (Canada)	21 (U.S.) 5 (Canada)

the latest leveling and water-level transfer data was performed in 1936. This adjustment was called the "Adjustment of 1935" or the "1935 Datum."

A new mean sea level connection was not established in 1935; therefore, USLS held a few adjusted heights from the 1903 adjustment, i.e., one adjusted height on Lake Ontario (Oswego), one on Lake Erie (Cleveland), and one on Lake Huron (Harbor Beach). New elevations on Lake Superior were determined using a water-level transfer from Harbor Beach to DeTour and leveling from DeTour to Point Iroquois.

International Great Lakes Datum of 1955

In 1953, USLS and its Canadian counterpart initiated a program of coordinating basic hydraulic and hydrologic data in the Great Lakes area. The Canadian agencies used heights referenced to the 1903 Datum, while the U.S. used heights referenced to the 1935 Datum. These differences were small, but did cause some confusion. The International Coordinating Committee decided that a joint international Great Lakes Datum should be established. This led to the International Great Lakes Datum of 1955 (IGLD 55).

IGLD 55 used water-level transfer data from the period 1952-58. A first-order leveling line was performed along the St. Lawrence River from Point-au-Pere (Father's Point), Quebec, to Kingston, Ontario. The United States leveled along the U.S. side of the river and made several ties along the border. Once again, leveling observations were performed between lakes and water-level transfer observations were made between stations on each lake.

The datum for IGLD 55 was determined by holding the elevation of local mean water level fixed at Point-au-Pere. Normal dynamic elevations, i.e., dynamic elevations using normal gravity values, were adopted as the elevations to be used and published for IGLD 55. According to Lippincott (1985), the primary reason for adopting dynamic elevations for the new datum was to provide a means for the more accurate measurement of geopotential hydraulic head between points.

NEW ADJUSTMENT OF THE NORTH AMERICAN VERTICAL DATUM OF 1988

Approximately 625,000 km of leveling have been added to the National Geodetic Reference System (NGRS) since the 1929 general adjustment that created NGVD 29. In the intervening years, numerous discussions were held to determine the proper time for the inevitable new general adjustment. In the early 1970's, NGS conducted an extensive inventory of the vertical control network. The search identified thousands of bench marks that had been destroyed, due primarily to post-World War II highway construction, as well as other causes. Many existing bench marks were affected by crustal motion associated with earthquake activity, post-glacial rebound (uplift), and subsidence resulting from the withdrawal of underground liquids. Other problems (distortions in the network) were caused by forcing the 625,000 km of leveling to fit previously determined NGVD 29 height values. Some observed changes, amounting to as much as 9 m, are discussed in previous reports (Zilkoski, Balazs, and Bengston 1989; Zilkoski 1986; Zilkoski and Young 1985).

In order to perform the new general adjustment, NGS prepared a budget initiative for fiscal year 1977 to finance this project, a revision of which was later approved, and the adjustment project, called the North American Vertical Datum of 1988 (NAVD 88), formally began in October 1977. The NAVD 88 project has dominated NGS' Vertical Network Branch (VNB) activities since approval and funding in 1977. Major NAVD 88 tasks are described in detail in previous reports (Zilkoski 1986, Zilkoski and Young 1985).

An important feature of the NAVD 88 program was the releveling of much of the first-order NGS vertical control network in the United States. The dynamic nature of the network requires a framework of newly observed height differences to obtain realistic, contemporary height values from the readjustment. To accomplish this, NGS identified 81,500 km (50,600 miles) for releveling. Replacement of disturbed and destroyed monuments preceded the actual leveling. This effort also included the establishment of stable "deep-rod" bench marks, which will provide reference points for future "traditional" and "satellite" leveling systems. Field leveling of the 81,500 km network was accomplished to Federal Geodetic Control Committee (FGCC) first-order, class II specifications, using the "double-simultaneous" method (Whalen and Balazs 1976).

Helmert blocking consisted of the partitioning of 875,000 unknowns (approximately 500,000 permanently monumented bench marks and 375,000 temporary bench marks) and associated observations into manageable blocks and performing the equivalent of a simultaneous least squares adjustment of the entire data set. Helmert blocking began in a production mode in October 1989, with the new general final adjustment completed in June 1991.

NAVD 88 GENERAL ADJUSTMENT COMPLETED IN JUNE 1991: WHAT DOES THIS REALLY MEAN?

The general adjustment of NAVD 88 was completed in June 1991. This means that bench marks included in the NAVD 88 Helmert blocking phase (approximately 80 percent of the total) have final NAVD 88 and IGLD 85 adjusted heights available. This should include most recoverable, published IGLD 55 bench marks in the United States.

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 during fiscal years 1992-93,

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 1992. It is important to note that some bench marks in crusfcal movement areas, i.e., bench marks which were included in the NAVD 88 Helmerfc 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.

HEIGHT SYSTEMS RELEVANT TO IGLD 85

There are several different height systems used by the surveying and mapping community. Two of these height systems are relevant to IGLD 85: orthometric heights and dynamic heights. Geopotential numbers relate these two systems to each other.

The geopotential number (C) of a bench mark is the difference in potential measured from the reference geopotential surface to the equipotential surface passing through the survey mark. It is the amount of work required to raise a unit mass of 1 kg against gravity through the orthometric height to the mark. Geopotential differences are differences in potential which indicate hydraulic head.

The orthometric height of a mark is the distance from the reference surface to the mark, measured along the line perpendicular to every equipofcential surface in between. A series of equipotential surfaces can be used to represent the gravity field. One of these surfaces is specified as the reference system from which orthometric heights are measured. These surfaces defined by the gravity field are not parallel because of the rotation of the Earth and gravity anomalies in the gravity field. Two points, therefore, could have the same potential but may have two different orfchometric heights. The value of the orthometric height at a point depends on all the equipotenfcial surfaces beneath that point.

The orthometric height (H) and the geopotential number (C) are related through the following equation:

$$C = G * H,$$

where G is the gravity value estimated for a particular system. Height systems are called different names depending on the G selected. When G is computed using the Helmert height reduction formula (Helmert 1890), which is what was used for NAVD 88, the heights are called Helmert orthometric heights; when G is computed using the International formula for normal gravity, the heights are called normal orthometric heights; and when G is equal to normal gravity at 45 degrees latitude, the heights are called normal dynamic heights.

It should be noted that dynamic heights are just geopotential numbers scaled by a constant, using normal gravity at 45 degrees latitude equal to 980.6199 gals. Therefore dynamic heights are also an estimate of hydraulic head. In other words, points that have the same geopotential number will have the same dynamic height.

IGLD 55 is a normal dynamic height system which uses a computed value of gravity based on the International formula for normal gravity. Today, there is sufficient observed gravity available to estimate "true" geopotential differences instead of "normal" geopotential differences. The "true" geopotential differences, which were used in IGLD 85 and NAVD 88, will more accurately estimate hydraulic head.

ANALYSES OF IGLD 85 PRIMARY VERTICAL CONTROL NETWORK

To assist in identifying and documenting the impact of IGLD 85, NGS compiled a primary vertical control network using the latest U.S. and Canadian data available. The control network started at the mouth of the St. Lawrence and included leveling lines which surrounded the Great Lakes. Analyses of this network were helpful in determining the effects of the datum constraint, magnitudes of height changes from the present International Great Lakes Datum of 1955, deficiencies in network design, selection of water-level station pairs to be used to generate zero geopotential difference observations, and additional releveling requirements. The results of this special project were documented in a report by Zilkoski and Balazs (1989).

Analyses of the latest available leveling data indicate that each lake represents an equipotential surface to some degree. On each lake there are some water-level stations which appear to be too high or too low relative to the rest of the stations on that lake. For example, mean water levels estimated at Thunder Bay (station 10050) and Grand Marais (station 9090) differ by only 0.6 kgal-cm (0.02 ft), but the west and east ends of Lake Superior differ by 17.4 kgal-cm (0.57 ft), with the west end higher than the east end.

The analyses provided the information needed to select water-level station pairs to be used to generate zero geopotential difference observations. These observations were included in the NAVD 88 network.

NAVD 88 AND IGLD 85

As stated in the beginning, for the general adjustment of NAVD 88 and IGLD 85, a minimum-constraint adjustment of Canadian-Mexican-U.S. leveling observations was performed. The height of the primary tidal bench mark at Father Point/Rimouski, Quebec, Canada, was held fixed as the constraint. Therefore, IGLD 85 and NAVD 88 are one and the same. This should help to eliminate confusion between the two datums. The only difference between IGLD 85 and NAVD 88 is that IGLD 85 bench mark values are given in dynamic height units and NAVD 88 values are given in Helmert orthometric height units. Geopotential numbers for individual bench marks are the same in both systems.

This network will provide the best estimate of geopotential numbers for vertical control in the Great Lakes region.

CONCLUSION

This paper described the history of vertical datums used in the Great Lakes region and gave the progress by the National Ocean Service in support of the new adjustment of the International Great Lakes Datum of 1985.

Analyses of a primary vertical control networkwere performed to select appropriate water-level station pairs to be used to generate zero geopotential difference observations. These observations were included in the NAVD 88 network. Geopotential numbers from the general adjustment of NAVD 88 were used to compute IGLD 85 dynamic heights. They will provide the best estimate of hydraulic head.

If secondary gauge data are placed in computer-readable form, they will also be incorporated into NAVD 88 and IGLD 85. NGS will publish NAVD 88 heights and provide, upon special request, geopotential numbers for all bench marks included in NAVD 88. NGS personnel have been working with IGLD representatives to develop an IGLD 85 implementation plan.

The use of GPS data and a high-resolution geoid model to estimate accurate GPS-derived orthometric heights will be a continuing part of the implementation of NAVD 88 and IGLD 85. It is important that users initiate a project to convert their products to NAVD 88 and IGLD 85. The conversion process is not a difficult task, but will require time and resources.

REFERENCES

Berry, R. M., 1976: "History of Geodetic Leveling in the United States," Surveying and Mapping, 36(2), pp. 137-153.

Federal Geodetic Control Committee (FGCC), 1984; Standards and Specifications for Geodetic Control Networks. National Geodetic Information Center, NOAA, Rockville, MD 20852, 33 pp.

Helmert, F. R., 1890: Die Schwerkraftim Hochgebirge, Insbesondere in den Tyroler Alpen. Veroff. Konigl. Preuss., Geod. Inst., No. 1.

Lippincott, H. A., 1985: Great Lakes Vertical Datums. Proceedings of the Third International Symposium on the North American Vertical Datum. Rockville, MD, April 21-26, National Geodetic Information Center, NOAA, Rockville, MD 20852.

Whalen, C. T. and Balazs, E. I., 1976: Test Results of First-Order Class III Leveling. NOAA Technical Report NOS 68, National Geodetic Information Center, NOAA, Rockville, MD 20852.

Zilkoski, D. B., 1986: The North American Vertical Datum of 1988 (NAVD 88) - Tasks, Impacts, and Benefits. Proceedings of the Symposium on Height Determination and Recent Vertical Crusfcal Movements in Western Europe. September 15-19, Hannover, FRG.

Zilkoski, D. B. and Young, G. M., 1985: North American Vertical Datum (NAVD) Update. Proceedings of the U.S. Army Corps of Engineers 1985 Survey Conference. Jacksonville, Florida, February 4-8, U.S. Army Corps of Engineers, Vicksburg, MS.

Zilkoski. D. B., Balazs, E. I., and Bengston, J. M., 1989: "NAVD 88 Datum Definition Study." Unpublished NGS Technical Report, September 1989.

Zilkoski, D. B., and Balazs, E. I., 1989: "Analyses Performed by the National Geodetic Survey in Support of the Readjustment of the International Great Lakes Datum." Unpublished NGS Technical Report, October 1989.