Vertical datum transformation grids for Mexico

Jaime J. Carrera-Hernández

Mexico has used two vertical datums—the U.S. National Geodetic Vertical Datum of 1929 (NGVD29) and the North American Vertical Datum of 1988 (NAVD88). Because Mexico started using the NAVD88 as its vertical datum in 2015, most of Mexico's data is referenced to the NGVD29 and recent high resolution data are referenced to the NAVD88. Compounding this situation, satellite-derived Digital Elevation Models (DEMs) are referenced to the Earth Gravimetric Model 96 (EGM96), and no tools are currently available in Mexico to transform elevation data between the aforementioned vertical datums. To overcome this problem, this work presents the development of two surfaces to transform orthometric heights between the NGVD29 and NAVD88 or between the NGVD29 and EGM96 in Mexico. These surfaces can be used by any interested user to transform orthometric heights referenced to the aforementioned datums.

Background & Summary

Height is defined as the distance—measured along a perpendicular—between a point and a reference datum. According to the vertical datum of reference used, a given height can be either ellipsoidal, geodetic, or orthometric. Users of Digital Elevation Models (DEMs) should be aware of which datum their data are referenced to because differences between vertical datums can exceed tens of meters. This awareness is important due to the existing difference between local vertical datums and the satellite derived DSMs that provide global coverage and which use the Earth Gravitational Model 1996 (EGM96) geoid as reference surface, such as the Shuttle Radar Topography Mission DSM (SRTM), the Advanced Spaceborne Thermal Emission and Reflectance Radiometer DSM (ASTER) or the more recent Advanced Land Observing Satellite World 3D-30m DSM (AW3D30).

Orthometric heights \( H \) are referenced to a vertical datum of zero elevation, which has normally been considered to be the Mean Sea Level (MSL) adopted from a local tide gage—which explains why there are more than 200 vertical datums used in the world today. MSL was long considered as a reference surface; however, MSL is not an equipotential surface and other forces besides gravity—temperature, salinity, currents and wind—affect it. This situation means that the zero height determined at one sea-station will not be equal to the zero height determined at a different sea-station. This problem was addressed in North America through the development of two vertical datums: the U.S. National Geodetic Vertical Datum of 1929 (NGVD29) and the North American Datum of 1988 (NAVD88), which are the vertical datums that have been used in Mexico.

Because the concepts involved on defining the ellipsoidal, geodetic, and orthometric heights are given in different publications, only a brief summary is provided in order to show the motivation of this work. The ellipsoidal height \( h \) of a given point represents its distance from a reference ellipsoid measured along a line normal to it—which is the height provided by a Global Navigation Satellite System (GNSS) or Global Positioning System (GPS)—while the geoid height \( N \) represents the difference between an ellipsoidal height \( h \) and an orthometric height \( H \). These three heights are related to each other according to:

\[
H \approx h - N
\]

which shows that the conversion from ellipsoidal to orthometric heights can be done through the use of a geoid height model. Orthometric heights with an accuracy similar to that of leveling surveys can be obtained through the use of careful GNSS/GPS survey procedures coupled with high-resolution geoid models. This is why a new North America Vertical Datum (NAVDXX) has been proposed for 2022, which will be based on GNSS/GPS positioning and a high accuracy geoid that will cover Mexico, Canada and the Conterminous United States. Canada has already updated its vertical datum to the Canadian Geodetic Vertical Datum of 2013 (CGVD2013), replacing the geodetic levelling technique by a geoid model.
Mexico has used both the NGVD29 and the NAVD88 as vertical datums and all maps and databases developed by Mexico’s National Institute of Geography and Statistics (INEGI) before 2015—when the NAVD88 was adopted as Mexico’s current vertical datum—were referenced to the NGVD29. In fact, the elevations of Mexico’s Digital Terrain Model (CEM) created by INEGI are still referenced to the NGVD29, while the new high-resolution topography datasets developed by INEGI through either LiDAR or photogrammetry are referenced to the NAVD88. Compounding this variability, the satellite-derived Digital Surface Models SRTM, ASTER and AW3D30 use the EGM96 as vertical datum. For the Conterminous United States (CONUS), the U.S. National Geodetic Survey developed the VERTCON software to convert heights between NGVD29 and NAVD88, which have been found to range from $-40$ to $150$ cm. In Mexico there are no tools to convert orthometric heights referenced to either the NGVD29 ($H_{NGVD29}$), NAVD88 ($H_{NAVD88}$) or EGM96 ($H_{EGM96}$). To overcome this issue, this work details the generation of surfaces that can be used to transform orthometric heights between the aforementioned vertical datums.

**Methods**

Mexico, with an area of $1.9 \times 10^6$ km$^2$ is surrounded by sea on both its western and eastern sides by the Pacific Ocean and the Gulf of Mexico respectively, and has an elevation that ranges from $-10$ m a.s.l. on the Salada Lagoon to $5,636$ m a.s.l. on Pico de Orizaba—its year round snow-capped highest peak (Fig. 1). Two vertical datums have been used in Mexico to obtain orthometric heights: the United States National Geodetic Vertical Datum of 1929 (NGVD29)—and starting in 2015—the North American Vertical Datum of 1988 (NAVD88). Accordingly, the evolution of the vertical geodetic network in Mexico is closely related to the development of the vertical datums on the United States. Mexico developed its National Geodetic Network linked to the United States National Geodetic Vertical Datum of 1929 (NGVD29) through four benchmarks located on the U.S. The United States adopted the NAVD88 as its official vertical datum in the 1990s while Mexico adopted it in 2015. Although Canada participated in the development of the NAVD88, it did not adopt this vertical datum due to concerns related to an east-west systematic error: the mean sea level of the Pacific Ocean next to Vancouver was around $1.4$ m higher than the mean sea level of the Atlantic Ocean next to Halifax. Interested readers can find more information on the development of the aforementioned datums on different publications.

**Data used.** To analyze the difference between the three orthometric heights ($H_{NGVD29}$, $H_{NAVD88}$, $H_{EGM96}$) currently used in Mexico, a total of 141095 PDF files were downloaded from Mexico’s Institute of Geography and Statistics (INEGI) passive geodetic network [https://www.inegi.org.mx/app/geo2/rgnp/webpage], which are classified into horizontal or vertical geodetic networks. The horizontal geodetic network is based on static measurements taken with a dual-frequency GPS/GNSS for a minimum duration of three hours—thus providing ellipsoidal heights—and adjusted to Mexico’s Active Geodetic Network (RNGA), which started to operate in 1996. The vertical geodetic network is comprised of monumented benchmarks measured through leveling with a distance of 1 km in both coastal and urban areas, or 2 km in other locations. The basic vertical network—which is used as the basic structure of the national network—was established with a first order class II precision and was developed parallel to the main communication lines of the country. The topographic vertical network—which forms circuits that begin and end on the basic vertical network—was established with a second order class II precision except in mountainous areas, where it was developed with a third order precision, and more details on the development of Mexico’s vertical geodetic network can be found in different publications.
From the aforementioned 141095 PDF files, 59395 correspond to the vertical geodetic stations while the remainder 83100 have data for the horizontal geodetic stations—which represent GPS-derived ellipsoidal heights (h). It is worth mentioning that although INEGI’s webpage show more geodetic stations, some of them are duplicated. A section of each PDF file is shown in Fig. 2, where Fig. 2(a) shows the orthometric heights referenced to either NGVD29 or NAVD88 along with other information for each vertical benchmark such as its denomination, coordinates and condition, as well as when it was established, measured, verified and validated for each vertical benchmark. This information is also available for the horizontal benchmarks (Fig. 2(b)), which only have ellipsoidal heights. The remaining section of each file (not shown) provides a sketch in order to find the monumented datum. This information is also available for the horizontal benchmarks (Fig. 2(b)), which only have ellipsoidal heights. The remainder section of each file (not shown) provides a sketch in order to find the monumented datum. This information is also available for the horizontal benchmarks (Fig. 2(b)), which only have ellipsoidal heights.

Fig. 2 Example of PDF files downloaded from INEGI's Passive Geodetic Network for (a) vertical and (b) horizontal geodetic benchmarks. This benchmark was selected because it has orthometric heights for the three vertical datums currently used in Mexico. The difference in orthometric heights for this benchmark is 1.53 m ($H_{NGVD29} = 3115.56$ m, $H_{NAVDB8} = 3117.09$ m) while its ellipsoidal height is $h = 3110.56$ m—which has to be converted to a orthometric height. It should be noted that INEGI misnames NGVD29 on the vertical benchmarks—as it uses NAVD29 instead.

Surface transformation between $H_{NGVD29}$ and $H_{NAVDB8}$ ($\Delta H_{8829}$). As previously mentioned, the goal of this work is to obtain a transformation surface in order to vertically shift NGVD29 to NAVD88 elevations. To achieve this goal, the 31835 vertical benchmarks that have orthometric heights referenced to both the NGVD29 and the NAVD88 were selected, as shown on Fig. 5, where it can be seen that $H_{NAVDB8} - H_{NGVD29}$ for a given vertical benchmark is smaller near the coasts and larger on Mexico’s mountainous regions (Fig. 5(a,b)) and that these differences ($\Delta H_{8829} = H_{NAVDB8} - H_{NGVD29}$) are positive throughout Mexico—with maximum values of 1.5 m on heights 3000 m above the NGVD29. In comparison, the differences found in the CONUS range from −40 cm to +150 cm, with negative values on the U.S. east coast that increase westwards, reaching their maximum values.
Vertical benchmarks referenced to (a) NGVD29 and (b) NAVD88. In 1955, Mexico’s geodetic network was linked to the NGVD29 through four U.S. benchmarks: A-680 in Brownsville, TX; T-64 in Eagle Pass, TX, A-110 in El Paso, TX and K-77 in Nogales, AZ, while six mareographic stations were fixed as zero elevation in Mexico at Mazatlán, Manzanillo, Acapulco, Guaymas, Topolobampo and Tampico.

Spatial coverage of Mexico’s horizontal geodetic stations, which consist of GPS/GNSS observations (ellipsoidal heights). These heights are converted to orthometric heights ($H$) through the use of geoid heights.
on the Rockies. It should be mentioned that the differences used in this work are static—as both NGVD29 and NAVD88 are—and that the effects of seismic uplift or subsidence caused by heavy groundwater extraction in central Mexico31 are not considered.

To develop the transformation surface ($\Delta H_{8829} = H_{NAVD88} - H_{NGVD29}$), Kriging with External Drift on a local neighborhood (KEDl) was selected as the interpolation algorithm due to the fact that differences in orthometric heights vary according with $H_{NGVD29}$ (Fig. 5(b)). Kriging with External Drift (KED) is used when a secondary variable is correlated with the variable of interest32—even when these variables exhibit low correlations33—and when the value of the secondary variable is known at all data locations and at all locations being estimated34. KED was applied on a local neighbourhood (KEDl) because the mean of the variable to be estimated varies locally and because it is also more computationally efficient27. More details on semivariogram modelling and Kriging can be found in well known geostatistics books34–36.

The height differences measured at the 31835 vertical benchmarks where both orthometric heights are available (Fig. 5) were first determined and an experimental semivariogram was determined from them. A theoretical semivariogram was adjusted to the experimental semivariogram with and without using $H_{NGVD29}$ as secondary variable, and as can be seen on Fig. 5(c) the use of $H_{NGVD29}$ as secondary variable reduced the estimated semivariance. A Bessel semivariogram was automatically adjusted using weighted least squares as implemented in gstat26 using a cutoff distance of 400 km and Mexico’s Digital Elevation Model (CEM) developed by INEGI—which is referenced to the NGVD29—as secondary variable.

The Root Mean Square Error (RMSE), Mean Average Error (MAE) and the Median Absolute Deviation (MAD) of the $\Delta H_{8829}$ transformation surface were obtained through cross validation—also known as leave-one-out validation—using both gstat and hydroGOF37. The aforementioned accuracy measures are reported because they are recommended to assess the accuracy of Digital Elevation Models due to their robustness and distribution free approach to handle outliers38–40, and were determined as RMSE = 28.52 mm, MAE = 8.64 mm and MAD = 3.78 mm. The transformation surface $\Delta H_{8829}$ is shown in Fig. 6, where it can be appreciated that its lowest values appear on the Yucatán Peninsula and along Mexico’s shoreline—except on Baja California, where the difference between orthometric heights are above 1.0 m even on the shoreline.

Surface transformation between $H_{NGVD29}$ and $H_{EGM96} (\Delta H_{9629})$. In order to convert the ellipsoidal heights ($h$) measured by INEGI (Fig. 4) to orthometric heights referenced to the Earth Gravitational Model 96 ($H_{EGM96}$), the global EGM96 15’ height data ($N_{EGM96}$) distributed by the U.S. National Geospatial-Intelligence Agency was interpolated to a 1” ($\approx 30$ m) grid through bilinear interpolation as shown in Fig. 7. This surface was selected as vertical datum because current satellite-derived DEMs (ALOS AW3D30, ASTER and SRTM) are referenced to it and a 1” resolution was assumed adequate to estimate $H_{EGM96}$. The geoid heights $N_{EGM96}$ at each horizontal benchmark were estimated from the aforementioned surface using GRASS and were added to the ellipsoidal heights ($h$) measured at each horizontal benchmark in order to obtain orthometric heights ($H_{EGM96}$) according to Fig. 1. As an example, the ellipsoidal height of benchmark V150355 is $h = 3110.56$ m (Fig. 2(b)), while its EGM96 height is $N_{EGM96} = -5.705$; according to Fig. 1, its orthometric height referenced to the EGM96 is $H_{EGM96} = 3116.26$ m (with $H_{NGVD29} = 3115.56$ m and $H_{NAVD88} = 3117.09$ m).

To develop the $\Delta H_{9629}$ transformation surface, $H_{NGVD29}$ were subtracted from $H_{EGM96}$ at the 14303 benchmarks that registered both heights, with their spatial coverage shown in Fig. 8(a). These differences show a lower...
correlation with $H_{\text{NGVD29}}$ (Fig. 8(a)) than the correlation observed of $\Delta H_{8829}$ with $H_{\text{NGVD29}}$ (Fig. 5(a)), which is also evident on the adjusted semivariogram (Fig. 8(c)). Even though $\Delta H_{8829}$ exhibits a low correlation with $H_{\text{NGVD29}}$, for this case—just as for the $\Delta H_{8829}$ surface—the use of Kriging with External Drift on a local neighborhood (KEDl) yielded better accuracy measures than when no secondary variable was considered—a situation that has been reported in the case of daily precipitation\textsuperscript{33}. Through cross-validation, the accuracy measures of the $\Delta H_{9629}$ transformation surface are RMSE $= 233.5$ mm, MAE $= 107.0$ mm and MAD $= 79.3$ mm. The $\Delta H_{9629}$ transformation surface is shown on Fig. 9, where it can be seen that the datum difference is larger on the central-western region of Mexico, with smaller differences in the Yucatán Peninsula.

To assess the validity of these transformation surfaces, they were added to the original CEM$_{\text{NGVD29}}$ in order to obtain CEM$_{\text{NAVD88}}$ and CEM$_{\text{EGM96}}$ and their accuracy was assessed using the benchmarks that registered...
orthometric heights referenced to each of the three vertical datums used in Mexico. This analysis is the subject of the following section.

**Data Records**
The transformation surfaces developed in this work ($\Delta H_{8829}$ and $\Delta H_{9629}$), along with the transformed CEMs (CEM NAVD88 and CEM EGM96) are available at https://doi.org/10.6084/m9.figshare.11495055 41.

**Technical Validation**
The developed transformation surfaces were applied to Mexico’s Continuous Elevation (CEM) developed by INEGI which is referenced to the NGVD29 ($H_{\text{NGVD29}}$). To shift the CEM’s vertical datum from NGVD29 to NAVD88 the following relationship is applied:

$$\text{CEM}_\text{NAVD88} = \text{CEM}_\text{NGVD29} + \Delta H_{8829}$$  

where $\Delta H_{8829}$ represents the first transformation surface developed in this work. This datum shift is useful in Mexico in order to use—or compare—the LiDAR DEMs distributed by INEGI which are referenced to the NAVD88 with the CEM. If the CEM needs to be shifted to the EGM96 datum—for example, to compare it with the satellite-derived DEMs—then the following transformation needs to be applied:
where $\Delta H_{9629}$ represents the second transformation surface developed in this work.

In order to apply both vertical datum shifts, the generated surfaces ($\Delta H_{8829}$ and $\Delta H_{9629}$, which were developed at a 1' resolution ($\approx 1800$ m)) were interpolated to a 1" resolution ($\approx 30$ m) using bilinear interpolation and added to the CEMNGVD29—the two CEMs thus created (CEMNAVD88, CEMEGM96) are available for download at https://doi.org/10.6084/m9.figshare.11495055. The accuracy of these new CEMs was assessed using the benchmarks that registered orthometric heights referenced to each of the three vertical datums used in Mexico. For these assessments, it was assumed that differences larger than 20 m were outliers, and thus the number of benchmarks used are less than those reported in Figs. 3 and 4. Accordingly, the number of benchmarks used to validate each CEM are $n_{H_{NGVD29}} = 56961$, $n_{H_{NAVD88}} = 32950$ and $n_{H_{EGM96}} = 80584$. Of the aforementioned benchmarks, a total of 31835 have both $H_{NGVD29}$ and $H_{NAVD88}$, while 14303 have measurements for both $H_{NGVD29}$ and $H_{EGM96}$.

The results of the accuracy assessments for CEMNAVD88 (which is the one developed by INEGI), CEMNAVD88 and CEMEGM96 are shown on Fig. 10(a–c) respectively. This Figure shows that CEM EGM96 has the lowest Mean Average Error (MAE $_{EGM96} = 3.492$ m) and the lowest dispersion—estimated through the Median Absolute Deviation (MAD) with $MAD_{EGM96} = 1.683$ m. Of note is the fact that the original CEM (CEM NGVD29) has the largest MAE ($MAE_{NGVD29} = 6.035$ m, $MAE_{NAVD88} = 4.23$ m). These accuracy measures show that the transformation surfaces $\Delta H_{8829}$ and $\Delta H_{9629}$ can be used to undertake a vertical datum transformation due to the fact that the shifted CEMs have a lower Mean Average Error than the original CEM.

**Usage Notes**

The transformation surfaces developed in this work, along with the transformed CEMs (CEMNAVD88 and CEMEGM96) are distributed in GeoTIFF format. Accordingly, these files can be read with any GIS and even in R using the raster4 library.

**Code availability**

The analyses presented in this work were done with the freely available software R and the transformation surfaces developed are distributed as GeoTIFF files, which can be read in any Geographic Information System software.

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Author contributions
All the work required to develop the transformation surfaces and this manuscript was done by the author.

Competing interests
The author declares no competing interests.

Additional information
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