GEOID99 and G99SSS: 1-arc-minute geoid models for the United States

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Abstract. Two new geoid models have been computed for the United States and its territories. The first model is the purely gravimetric G99SSS model, approximating the geopotential surface \( W_0 = 62636856.88 \text{ m}^2/\text{s}^2 \) and referenced to the geocentric GRS-80 ellipsoid whose origin coincides with the ITRF96(1997.0) origin. The other model is the hybrid GEOID99 model, which encompasses all gravimetric information of G99SSS as well as the vertical datum information of 6169 GPS-derived NAD 83 (North American Datum 1983) ellipsoid heights co-located with spirit-leveled NAVD 88 (North American Vertical Datum 1988) Helmert orthometric heights. The coverage of both models in the conterminous United States (CONUS) is from 24°N to 58°N latitude and 230°E to 300°E longitude. Long-wavelength geoid structure was controlled by the EGM96 model coefficients, medium-scale information by 2.6 million gravity measurements, and local features through the use of 30-arc-second and (recently created) 3-arc-second digital elevation models. In addition to new elevation data, there were corrected errors in the old elevation data, better satellite altimetry data, and ellipsoidal corrections in G99SSS and GEOID99 that were not applied in G96SSS and GEOID96. The GEOID99 model replaces the GEOID96 model as the primary conversion surface between NAD 83 ellipsoid heights and NAVD 88 Helmert orthometric heights. While GEOID96 had the ability to convert absolute heights (of the 1996 GPS-on-bench-mark data set, or GPSBM) at the \( \pm 5.3\)-cm level, GEOID99 works with the latest GPSBM at the \( \pm 4.6\)-cm level. The improvement from 5.5 to 4.6 cm in RMS further translates into about 2 cm of additional accuracy in single-tie differential GPS-based leveling over most short baselines. Of this 4.6 cm, some 2.0 to 2.5 cm is attributed to correlated errors in the gravimetric geoid and local GPS errors, decorrelating around 40 km. The GPS-derived ellipsoid heights in CONUS have changed since 1996 due to an increased number of observations and new adjustments of previously observed areas. This new GPS data is reflected in GEOID99, but not GEOID96, which effectively renders GEOID96 out of date (in an absolute sense), so that the absolute agreement between GEOID96 and the 1999 set of GPSBM is only at the \( \pm 6.5\)-cm level. In addition to the geoid models in CONUS, gravimetric geoid models were produced in Alaska, Hawaii, and Puerto Rico and the American Virgin Islands. Surface deflection of the vertical models were also computed and show agreement with astro-geodetically determined deflections below the 1-arc-second level.

Key words: Geoid – GPS – Datums – Reference systems – Gravity – Deflections of the Vertical

1 Introduction

The demand for a highly accurate geoid model in the United States (US) has grown substantially in the last decade (Parks and Milbert 1995; Henning et al. 1998). In fact, with the success of GEOID96 (Smith and Milbert 1999), the demand became even greater for a similar geoid, but with increased accuracy. In order to move towards this goal, two new high-resolution geoid undulation models have been computed by the National Geodetic Survey (NGS) for the USA, G99SSS and GEOID99. The G99SSS model is a gravimetric, geocentric geoid undulation model, approximating the geopotential surface \( W_0 = 62636856.88 \text{ m}^2/\text{s}^2 \). This value of \( W_0 \) was chosen to comply with the work of Burša (1995). GEOID99 is a hybrid model, meaning that it incorporates both the gravimetric information of G99SSS as well as information obtained through GPS measurements on spirit-leveled bench marks. Like GEOID96 (Burša 1995), the GEOID99 model was built to support the direct conversion of NAD 83 (Schwarz 1989) ellipsoid heights into NAVD 88 (Zilkoski et al. 1992) Helmert orthometric heights.

In addition to customer demand for a better geoid model, there were substantial scientific reasons to compute a new model. Among these were the following: the creation of NGSDEM99, a new 1-arc-second digital...
elevation model (DEM) for the northwest US (Smith and Roman in press); the completion of the high-accuracy reference networks, HARNs (Bodnar 1990; Doyle 1993; Flynn 1998; Strange and Love 1991) and first re-observations of the Federal base network vertical component, FBNVC (Frakes 1999); the acquisition of significant new gravity data; the correction of a 15 x 15-arc-second mis-registration error in the TOPO30 DEM (Row and Kozleski 1991); and a new method of computing the ellipsoidal corrections for Stokes’ formula (Fei and Sideris 2000).

2 New data and theory

Improvements between the 1996 and 1999 NGS geoid models are primarily based on improved data sets with some new theory involved. New data sets include an updated 1-arc-second DEM for the northwest USA, a complete set of NAD 83 GPS height data on NAVD 88 leveled bench marks for all 48 conterminous United States (CONUS), and recently acquired gravity data sets (terrestrial, altimetric, and airborne).

Improvements to geoid computation theory and methodology include the use of multiple bands to minimize the convergence of the meridian error inherent in using a 2-D FFT (fast Fourier transform) for computing terrain corrections (TCs). (See also Kirby and Featherstone 1999.) Also, an improved method of computing the ellipsoidal corrections for Stokes’ formula (Fei and Sideris 2000) was incorporated to more accurately solve the geodetic boundary-value problem in computing G99SSS.

2.1 New digital elevation model

DEMts are used to generate a grid of terrain corrections for the computation of Faye anomalies (see e.g. Smith and Milbert 1999). In GEOID96, a 30-arc-second interval grid, TOPO30 (Row and Kozleski 1991), was selected for the entire CONUS region. For GEOID99, a new 1-arc-second DEM, NGSDEM99 (Smith and Roman in press), was available. The NGSDEM99 model was built from 7.5-arc-minute quadrangles of the United States Geological Survey (USGS) and ‘level 1’ digital terrain elevation data (DTED) of the National Imagery and Mapping Agency (NIMA). It covers the northwest USA (39°-49°N, 234°-256°E). Further information is also available at http://www.ngs.noaa.gov/DEM.

Finally, a mis-registration of TOPO30, placing nearly all data southwest by 15 x 15 arc seconds, was found by the NGS in 1997. This was mostly correctable by shifting all data northeast by 15 x 15 arc seconds, creating a modified TOPO30 file for use in GEOID99. Unfortunately the error was not 100% consistent, making the use of the modified TOPO30 file acceptable, but still possibly containing some erroneously registered height values.

2.2 New GPS on leveled bench marks

In 1998, the NGS completed the HARN adjustments of the 48 CONUS. The completion of this network was a landmark achievement for the NGS, adding thousands of new GPS heights on leveled bench marks (GPSBMts) (Milbert 1998) to the 2951 used in the production of GEOID96 (Smith and Milbert 1999). The completion of the HARNs in 1998 was an opportunity to update the geoid model and use real data, not extrapolation (Smith and Milbert 1999), to model the local trends in the disagreement between the geoid and GPSBMts.

However, almost as soon as the HARN ended, the FBNVC began; first in Wisconsin, and then moving to Washington and Oregon. This effort is primarily a revisiting of each of the 48 states to re-observe the old HARNs and to add some new survey points, but most especially to observe with such accuracy as to achieve \( \pm 1 \, \text{cm} \) (1-\( \sigma \)) GPS-derived ellipsoid heights (Frakes submitted). However, only Wisconsin was observed, adjusted and formally part of the NGS integrated database (NGSDB) by the deadline for inclusion in GEOID99. The Washington and Oregon data were observed and preliminarily adjusted and were used in GEOID99 before final adjustment and loading of the GPS data into the NGSDB. Researchers at the NGS were confident that no significant difference between the preliminary and final adjustments of Washington and Oregon would be seen (Milbert and Pursell (NGS) personal communication). On 26 August 1999 the final GPSBM data set was chosen for use in GEOID99, containing 6169 GPSBMts. These points are plotted in Fig. 1.

The final criteria for selection of the 6169 points are described in an online NGS document (Smith and Roman 1999). Briefly, the criteria are as follows.

1. A, B or first-order GPS data were used to determine the ellipsoid height.
2. Leveling (of various orders and classes) was performed according to Federal Geodetic Control Subcommittee (FGCS) specifications and procedures to determine the orthometric height (see Federal Geodetic Control Committee (FGCC) 1984).
3. All GPS and leveling data refer to NAD 83 or NAVD 88, respectively.

Although 6341 points fulfilled these criteria, this was reduced to 6169 though the detection and rejection of outliers (Smith and Roman 1999). Of the 6169 points, a tally for each combination of GPS order and leveling order is shown in Table 1.

The most numerous bench marks are from the most accurate leveling (first-order), while the most numerous GPS is the least accurate (again, called first-order). Although there were many first-order (leveling) bench marks the full set of bench marks was utilized in GEOID99 to make that model useful to users of all orders of bench marks.

Between 1996 and 1999 new GPSBMts were added and some old ones were re-observed, re-adjusted, or had errors detected and repaired. This change from one value of \( h \) (or \( H \)) in 1996 to a new value in 1999 will have a direct impact on the hybrid geoid model. There were 2819 points that were common to both GPSBM data sets for both GEOID96 and GEOID99, and were not