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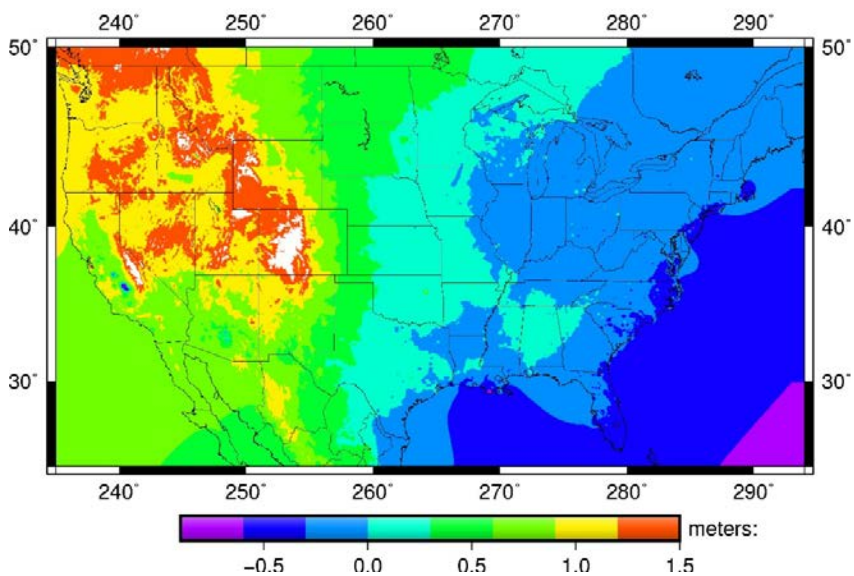
NOAA Technical Report NOS NGS 68

The VERTCON 3.0 Project

Creating vertical transformations for points in the National Spatial Reference System, including *VERTCON 3.0 release 20190601*



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National Oceanic and Atmospheric Administration • National Geodetic Survey

Executive Summary

NOAA Technical Report NOS NGS 68

The VERTCON 3.0 Project

The transformation of physical (orthometric, normal orthometric) heights from one datum to another is a historic service of the National Geodetic Survey (NGS). Only one computer program, implementing one transformation across two datums (NAVD 88 and NGVD 29) in one region (CONUS) has ever existed: VERTCON (for VERTical datum coordinate CONversion program). For a variety of reasons, there was little need to update or expand VERTCON past its 2.0 release in 1994. Though new leveling and height modernization data were incorporated into NAVD 88 over the years, this never led to a new datum name nor a new "realization".

The pending release of NAPGD2022, as well as acknowledgement that there were unsupported historic vertical datums in regions besides CONUS, led to the VERTCON 3.0 project. This report serves as documentation for VERTCON 3.0, a project which created new Linux build software capable of generating VERTCON grids. It further documents the use of that build software to create ***VERTCON 3.0 release 20190601***, which contains, among other things, a set of transformation and error grids which serve as a replacement for all grids in all previous versions of VERTCON.

The re-construction of the build software focused on two areas: 1) maintaining consistency with the rigorous physical models already contained in the earlier VERTCON program, and 2) preparing for the replacement of all vertical datums in the United States in 2022. For ***VERTCON 3.0 release 20190601*** provided with this report, 7 separate transformations (each connecting two datums; six work solely with normal orthometric heights, while one converts between normal orthometric heights and orthometric heights) were computed in 7 different regions.

The report details how data were pre-processed, analyzed, plotted, and released, for each of the transformations. The build software is included in ***VERTCON 3.0 release 20190601*** so that transformations connecting to NAPGD2022 epoch 2020.00 (and future reference epochs) can be quickly generated in a way consistent with ***VERTCON 3.0 release 20190601***, sometime in the future. The final ***VERTCON 3.0 release 20190601*** grids were integrated into the NGS Coordinate Conversion and Transformation Tool (NCAT) available at https://www.ngs.noaa.gov/NCAT/.

Versions

Date	Changes
July 23, 2019	Original Release

Acknowledgements

The authors wish to acknowledge the assistance of specific individuals who contributed directly to the success of this project. First, Tim Hanson, who provided guidance and insight into the diverse nature of the height information stored in the NGS IDB. It was Tim's inspiration that led to "filter 3", which solved a variety of problems.

Also to Bruce Tran and Krishna Tadepalli for their patience in both the numerous database pulls required up front, as well as their work to incorporate VERTCON 3.0 into NCAT.

Nic Kinsman, Ed Carlson and Dennis Milbert all contributed significant information through their various conversations with the build team throughout this project.

Finally, a special thanks to Rosemary Booth for her diligence in editing and formatting this entire report.

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Author's Note

Terminology: Builds and Releases: This report discusses the VERTCON 3.0 project, and its subsequent output ***VERTCON 3.0 release 20190601*** (discussed below). Although the VERTCON 3.0 *project* generated transformation grids, it did not produce a stand-alone computer *program* to apply the transformations to coordinate data. This is in stark contrast to earlier versions of VERTCON (and NADCON), which contained transformation grids and software to apply them, in a single computer program. The new way of doing business is that all of the vertical datum transformation grids computed by the VERTCON 3.0 project are provided to the public as a *release*, and their application is supported by NGS's two primary coordinate transformation and conversion tools: NCAT and VDatum.

This change in approach necessitates a subtle but critical change in terminology, which will be described and adopted throughout the report.

1) VERTCON 3.0 is the name of a ***project***, whose goal was to create transformation grids, error grids and choose the interpolation method used on those grids.
2) VERTCON 3.0 is also the name of the ***build software***, developed within said project and which created the aforementioned transformation and error grids.
3) A ***build*** is the use of build software to create transformation (and error estimate) grids for one or more specific combinations of "old datum", "new datum" and "region" on a specific date, called the ***build date***. A build date is always provided in YYYYMMDD format. Builds are not necessarily released to the public. A build name always contains both the version of the build software and the build date (example: "VERTCON 3.0 build 20181201")
4) A ***release*** is a package of information containing one or more of the grids from a build that NGS has determined are the official NSRS transformations, and which have been released to the public. For completeness, a release will also contain the build software used to make the build. Like the build name, the release name always contains both the version of the build software and the build date (example: "VERTCON 3.0 release 20190601").

Using this terminology, VERTCON 3.0, by itself, is not the name of the set of grids which go into NCAT and VDatum. Instead, once these grids are fully incorporated into application software, it will be more correct to say "the most current official orthometric height transformation grids of the NSRS are contained in NCAT and VDatum, using VERTCON 3.0 release 20190601."

Applying all of the above to the VERTCON 3.0 project and its release, as documented by this report, NGS policy is:

> *As of June 1, 2019, the only official NSRS transformation grids in orthometric height (for now)[1] are those in **VERTCON 3.0 release 20190601**.*

Although ***VERTCON 3.0 release 20190601*** superseded an existing transformation grid, it will be NGS policy going forward that *existing official NSRS transformation grids will never again be superseded*, with one exception: if a blunder were found in an existing transformation grid which was so egregious that failing to correct it would be a dereliction of duty, then the existing grid would be replaced.

However, as new combinations of "old datum", "new datum" and "region" need to be supported (such as with the roll-out of NAPGD2022 epoch 2020.00, et al), they will be provided to the public as a new release. That release name will consist of both the version of the build software, and the build date. By way of example, assume that by 2022 the build software for VERTCON has been updated slightly to version 3.2, and that it is used to build the transformation grid in CONUS between NAVD 88 and NAPGD2022 epoch 2020.0 on December 20, 2022, and that build is released as the official transformation. That particular grid would be part of "VERTCON 3.2 release 20221220", while all earlier grids remain part of "VERTCON 3.0 release 2090601".

Report highlights and a "user guide" for the general public: This extensive report was written primarily for internal NGS usage. As such, many sections contain exhausting detail beyond the level of interest for most ***VERTCON 3.0 release 20190601*** users. As an aid to the general public, the authors recommend the following sections for different readers:

To understand how the transformation grids were built in deeper detail:

- Section 6 : Report on each transformation
- Section 11 : Guide to Digital Archive

To understand how ***VERTCON 3.0 release 20190601*** relates to earlier VERTCON versions:

- Section 1 : History of vertical datums and transformations at NGS
- Section 7 : Comparison to previous transformations
- Section 8 : How well does VERTCON 3.0 perform?

Latitude and Longitude Conventions: Throughout this document, the convention used to designate Latitudes and Longitudes will be as follows. Latitudes will always have a value between -90 degrees (South Pole) and +90 degrees (North Pole). Longitudes will always have a value between 0 degrees (Greenwich meridian) and 360 degrees (eastward back to the Greenwich meridian). While other

[1] "for now" because future official NSRS vertical transformation functionality will be developed when NAPGD2022 epoch 2020.00 is released.

conventions have been used in older NGS products and services, they will only be mentioned herein if it is necessary to clarify some issue with that product or service.

Types of heights: NGS archives many different pieces of information about geodetic control points in its database. Among them are a variety of types of heights, of which two are important to this document: orthometric heights and normal orthometric heights. Both types are typically estimated from some combination of leveling, gravity, GPS or other surveying technologies. The biggest differentiator is this: orthometric heights are defined using *true* gravity while normal orthometric heights are defined using *normal* gravity. Of the datums supported in this document, only NAVD 88 contains estimates of orthometric heights, while all others contain estimates of normal orthometric heights. NGS datasheets may say “orthometric height” for any of these datums when the proper term is “normal orthometric height”. For simplicity, unless it is necessary to draw this distinction, the term “orthometric heights” will be used generally throughout this report.

Transformation Sign Conventions: Throughout this document the convention used to designate the sign of a transformation is always that of “***New coordinate minus Old coordinate***”. For example, consider the transformation between NGVD 29 and NAVD 88. Such a transformation consists of one grid (orthometric heights). The actual values found in that grid are of this form: “NAVD 88 minus NGVD 29”. Therefore, to apply this transformation one should to the following:

H(NAVD 88) = H(NGVD 29) + Grid

or

H(NGVD 29) = H(NAVD 88) - Grid

In generic terms:

- Coordinate in New Datum = Coordinate in Old Datum + Grid
- Coordinate in Old Datum = Coordinate in New Datum – Grid
- Grid = Coordinate in New Datum – Coordinate in Old Datum

Scientific Notebook Documentation: One major part of documenting the process of building VERTCON 3.0 was kept in scientific laboratory notebooks by Dr. Dru Smith. These notebooks contain handwritten notes, plots, derivations and other critical evidence supporting the scientific method spanning the entire VERTCON 3.0 project. Each notebook is named “DRU-##” sequentially (with ## being “12” by 2018) and contains 152 pages. As such, a footnote that reads “see DRU-11 pages 113-121” means in notebook #11 in the series, on pages 113-121 will be found handwritten notes and derivations relevant to that particular part of VERTCON 3.0.

File naming conventions: A systematic naming convention is used throughout the VERTCON 3.0 project. Most file names contain references at least to the “old datum”, “new datum” and “region” to which a particular transformation refers. Additional information in a file name may include the “map flag”, “grid spacing 1”, “grid spacing 2” or “area mapped”. In order to simplify this report, when a file name is mentioned in a generic way, this report will use the following shorthand notation:

od	old datum
nd	new datum
rg	region
coord	coordinate type (always “oht” for VERTCON 3.0)
fi	filter (as input, using the minimum number of digits, so “3” is just “3”)
f0	filter (in file name, reflecting an enforced 3-character version of “fi”, so “3” is “003”)
mf	map flag
g1	grid spacing 1
g2	grid spacing 2
am	area mapped

1. History of vertical datums and transformations at NGS

1.1 Datums at NGS[2]

The National Geodetic Survey (NGS) is the oldest scientific agency in the nation, tracing its roots back through the Coast and Geodetic Survey (C&GS), the Coast Survey and ultimately the Survey of the Coast, established by Congressional act and signed into law by President Thomas Jefferson in 1807. One of the primary functions of NGS and its predecessors has been the establishment of datums. A datum can be considered a coordinate system which is accessed through geodetic control points. These geodetic control points have historically been a metal disk or rod set into the crust of the Earth, and surveyed to the highest possible accuracy. Networks of these marks, and all of the measurements between them could be analyzed through a process called Least Squares Adjustments (or just "an adjustment"), which would minimize errors and yield highly accurate, mutually consistent coordinates on all of the marks. Such an adjustment would establish a datum. Datums are established to provide starting (known) coordinates for other surveyors, map makers, chart makers, etc so that all of the maps created would be consistent with one another.

Historically, two types of datums were established: horizontal and vertical. Until the advent of GPS, these were generally independent of one another and used different geodetic control marks. Horizontal datums defined latitude and longitude, while vertical datums defined elevations (specifically orthometric heights, or, colloquially "height above sea level").

1.2 The first U.S. vertical datums (1807-1991)

Because datums provide *absolute* coordinates to their users, and because surveying tends to involve *differential* measurements, geodesists who establish datums must begin with some way to introduce absolute values. In the case of horizontal datums this historically meant using star catalogues and astronomic observations to determine *astronomic* latitudes and longitudes, long before GPS provided any way to easily establish *geodetic* latitudes and longitudes. In the case of vertical datums, the determination of some absolute height or heights often came from observations of local mean sea level (LMSL) at some tide station.

This report is concerned entirely with *vertical* datums. Because the establishment of a datum was historically a very labor-intensive process, the initial vertical datums were local, often serving only a particular part of a state, or perhaps the coastal regions of a few states, usually close to either a tide station or stream gauge. Unless these regional datums were connected to one another through surveys, they stood independent and not necessarily consistent with one another. The NGS

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[2] For consistency with earlier documents, this section is taken verbatim from the NADCON 5.0 report (Smith and Bilich, 2017).

Integrated Database (NGS IDB) is full of heights which are labeled “Local Tidal”, because they were derived from leveling to a single nearby tide station. Over time, some of these local networks within CONUS became connected to one another through leveling campaigns.

Prior to the creation of the Sea Level Datum of 1929, there were four major adjustments of continental leveling data. None has been given a specific name in the literature, and are simply called the “1st general adjustment”, etc. They took place in 1899, 1903, 1907 and 1912.

With the Sea Level Datum of 1929, the Local Mean Sea Level (LMSL) as computed at 26 tide station in the USA (21) and Canada (5) was held fixed. That means that at each tide station, specifically at one specific bench mark of that tide station, the value of “Normal Orthometric Height” was set equal to the value of “Local Mean Sea Level”. At the time, the general understanding in the geodetic community was that “Mean Sea Level”, by averaging out periodic effects such as the lunisolar tides, was an effective estimate of the location of the geoid, a surface well studied since C.F. Gauss proposed it as a “mathematical figure of the Earth” in 1828 (Gauss, 1828). Since 1828 the geoid had been the target and de facto “zero elevation surface” to the geodetic community.

The use of tide stations for determining vertical datum starting heights, and the use of leveling to disseminate those heights, continued throughout the 20th century. After World War II, interest in Pacific territories held by the United States ramped up, and geodetic surveys in areas like American Samoa and Guam took place. During one of those surveys, an early datum called the Guam Vertical Datum of 1963 was established (Carlson et al, 2009).

LMSL is only a good estimate of the geoid if gravity alone affects the permanent shape of the oceans. However, certain permanent or semi-permanent phenomena can alter the ocean shape. For example, the existence of permanent *currents* in the oceans had been known for centuries (Ben Franklin is credited for having created the first accurate chart of the Gulf Stream), but their impact on ocean *shape* wasn’t fully verified until the mid-20th century. The delay was mostly due to the fact that the magnitude of the impact is so small: an oceanic height change (called either Sea Surface Topography or Ocean Dynamic Topography, depending on who you ask), from one side of the Gulf Stream to the other, is about a 1 meter drop over 100 km. While the equations to estimate the effect were available in the 20th century, it wasn’t until the era of space-based altimetry that such signals were directly measured and verified on a global scale.

However, even prior to this, leveling surveys up and down the coastline of the USA, connecting LMSL at different tide stations, verified what satellites would verify decades later: the *average* ocean surface is *not* the geoid, but is rather some permanently warped version of the geoid. This is now known to be due to permanent currents, prevailing winds, and other physical phenomena that do not average to zero. The effect was important enough that the name “Sea Level Datum of 1929” was changed to “National Geodetic Vertical Datum of 1929” or NGVD 29 in 1973.

The 1970s didn’t just bring a name change to the vertical datum, they brought an entirely new effort to update and expand the leveling network, collect gravity, and improve the vertical datum as a whole. The new datum improved on the previous one in many ways. First, it was anchored at one bench mark (PID TY5255) at a single tide station (Pointe-au-Père, Rimouski), thereby removing all warping that happened due to geoid/LMSL issues. Second, true gravity was used to estimate orthometric heights, whereas the 1929 datum used only the simpler "normal gravity" (a latitude-based formula). Finally, the network was expanded from about 107,000 km to 732,000 km of leveling. This new and improved vertical datum was the "North American Vertical Datum of 1988" or NAVD 88, released to the public in 1991. While no official report of the creation of NAVD 88 exists, several preliminary reports provide significant information about it (Zilkoski, Richards and Young, 1992; Whalen, et al, 1996).

1.3 The first vertical datum transformation tool (1992): VERTCON 1.0

Shortly after the release of NAVD 88 in 1991, NGS released a vertical datum transformation tool called VERTCON, which stands for VERTical datum CONversion. This is something of a misnomer, as it is mostly a datum transformation tool, not just a coordinate conversion tool – though to be fair, it does convert from normal orthometric heights in NGVD 29 to orthometric heights in NAVD 88. Just two years earlier, NGS had released NADCON to support the transformation from NAD 27 to NAD 83. The VERTCON tool, supporting the transformation from NGVD 29 to NAVD 88 in CONUS operated in a similar way – as a grid from which transformation values were interpolated.

Note that, though NGVD 29 and NAVD 88 both exist in Alaska, earlier versions of VERTCON have not supported the transformation between these two datums in that state.

As the official documentation of VERTCON 1.0 only exists in certain archived directories within NGS[3] and there was no published report, very little is known about this initial product except its name and release date.

1.4 Updates: VERTCON 2.0 (1994) and 2.1 (2003)

VERTCON 1.0 was short-lived, and was soon replaced with VERTCON 2.0 (Mulcare, 2004; https://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html). The update included physical models for both atmospheric refraction and gravity. These models were important, since NGVD 29 was not created using refraction corrections, nor did it contain the effects of true gravity. As such, these models helped bridge gaps, providing some partial information about the difference between NGVD 29 heights and NAVD 88 heights in void areas (between level lines). This model was released in a 3 x 3 arcminute grid over CONUS. Its eastern edge actually terminates at 293 degrees longitude, cutting off some 2 ½ miles of the extreme eastern tip of Maine.

VERTCON 2.0's grid has stood as the official tool for transforming NGVD 29 into NAVD 88 in CONUS ever since, despite some 25 years of continual updates to NAVD 88. That is, the tool stayed

[3] /hnbraid/archive/vnb/rudy2/VERTCON/VERSION1

constant while new NAVD 88 heights were added in the database year after year. This is discussed in more detail in the Section 6.1.

In 2003, VERTCON 2.1 was released. This version provided a slight improvement in user functionality for the software, without any change whatsoever to the transformation grid.

1.5 Vertical datums on islands: 2002-2009

Historically, on various island territories, it was frequently the job of the Coast and Geodetic Survey to install tide stations and perform small local leveling projects from those stations to nearby passive marks. The installation and monitoring of such stations has, in more recent decades, fallen to NGS' sister agency within the National Ocean Service, the Center for Operational Oceanographic Products and Services (CO-OPS).

As mentioned earlier, the transfer of the tide station's Local Mean Sea Level (LMSL) height to a nearby mark was recorded in (now) NGS records as a "Local Tidal" height. Very little metadata exists to help determine which tide stations are the reference for such heights, but as these heights were available to the public, they could have been used to build historic maps for various islands.

It is critical to note, however, that these "Local Tidal" heights have not been, and never can be, NGVD 29 nor NAVD 88 heights. As those datums were defined based upon chosen heights at a passive mark (or marks) in CONUS, Canada and Alaska, and distributed via line-of-sight techniques like spirit leveling and trigonometric leveling, they have not ever been available outside of CONUS, Canada and Alaska. However the NSRS user community has frequently made maps in islandic areas such as Puerto Rico and labeled the heights "NGVD 29" or "NAVD 88". Despite its best attempts at educating the NSRS users, NGS must share some blame in this, as some data in the NGS IDB has, for decades, been incorrectly labeled "NGVD 29" in these areas, only having been corrected in the mid/late 2010s.

Recognizing their mission to support all areas of the USA with the NSRS, and specifically vertical datums which could be consistently defined over entire islands, NGS defined the following datums in their respective years:

Puerto Rico Vertical Datum of 2002 (PRVD 02[4]; Doyle and Smith, 2012)

American Samoa Vertical Datum of 2002 (ASVD 02; Carlson, Doyle and Smith, 2009)

Northern Mariana Vertical Datum of 2003 (NMVD 03; *ibid*)

Guam Vertical Datum of 2004 (GUVD 04; *ibid*)

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[4] The official abbreviation for the Puerto Rico Vertical Datum of 2002 was originally released "PRVD02" (no space), in Doyle and Smith (2012) However, as this is inconsistent with the use of a space in all but one other vertical datum in the NSRS, this report will use the abbreviation "PRVD 02" (with space) for this datum.

Virgin Islands Vertical Datum of 2009 (VIVD 09[5]; Doyle and Smith, 2011)

Each datum was defined by setting its normal orthometric height equal to the local mean sea level at one particular tide station on specified islands. The datum access was then distributed through leveling to passive marks on the islands.

Two interesting things should be noted about these datums. First, American Samoa was rocked by an earthquake in 2009, moving the entire island vertically and effectively making all published ASVD 02 heights no longer meaningful. Second, note that the state of Hawaii has never had an official vertical datum in the NSRS.

1.6 A new, all-datums transformation tool (2019): VERTCON 3.0

In 2017, NGS decided to begin, and by 2019 had completed, a project to update the existing VERTCON tool with two primary purposes: First, to expand it to support as many of the vertical datums of the NSRS as possible and second, to prepare the tool for the eventual release of the North American-Pacific Geopotential Datum of 2022 or NAPGD2022 (NGS, 2017b). In many ways, this effort paralleled that of NADCON 5.0 in 2016 (Smith and Bilich, 2017) and this report will therefore reflect a similar layout to the official NADCON 5.0 report.

2. Motivation for VERTCON 3.0

The greatest driver for VERTCON 3.0 was the pending release of NAPGD2022, expected in late 2022. As part of that release, NGS intends to release grids to transform between existing vertical datums and NAPGD2022. As the build software used to create all previous versions of VERTCON was no longer available, it was decided (like NADCON; see Smith and Bilich, 2017) to completely recreate the entire suite of VERTCON build software.

However, unlike horizontal datums, the history of vertical datums at NGS is, as mentioned earlier, quite limited. As a transformation can only exist if two datums are released in a region, this limits what expansion to VERTCON 2.1 might be possible. Nonetheless, most regions at least had “Local Tidal” heights published by NGS as well as some other official vertical datum of the NSRS, so a decision to support transformation in these regions was made.

Knowing that such a re-build would replace VERTCON 2.1, the new project and its build software were designated from the beginning as “VERTCON 3.0”.

Other expected advantages with this project were the chance to update documentation and the delivery of the transformations, through incorporation into newly integrated products and services

[5] The official abbreviation for the Virgin Islands Vertical Datum of 2009 was originally released as “VIVD09” (no space) in Doyle and Smith (2011). However, as this is inconsistent with the use of a space in all but one other vertical datum in the NSRS, this report will use the abbreviation “VIVD 09” (with space) for this datum.

like the NGS Coordinate Conversion and Datum Transformation Tool (NCAT, available at https://www.ngs.noaa.gov/NCAT/) and VDatum (available at https://vdatum.noaa.gov/).

2.1 Data Formats

Transformation tools such as VERTCON run entirely on grids. The original release of VERTCON 1.0 is in the NGS archives (not publicly available) so the grid file format is not addressed herein. The VERTCON 2.0 (and 2.1) release used a grid file format with the extension ".94", which appears to have been developed in-house by NGS. It is a direct-access binary format that does not appear to be used in any other products. Further, code in the VERTCON 2.1 program implies that some parts of the VERTCON 2.0/2.1 grid contain flags equal to "9999.0". Such flags appear to cause the program to inform the user that no value could be interpolated. However, nothing in the available documentation, nor the VERTCON program itself ("vertcon.for") indicates where these flags exist nor why. Section 10 examines this issue in greater detail.

The grid format used in VERTCON 3.0 (called ".b" or "dot b") is the same as that used in NADCON 5.0 (NGS, 2017b). See Section 10 for further details on the actual grid formats.

2.2 Program execution and accessibility

VERTCON 2.0 and 2.1 were each only released as executable (.exe) files which both distributed and applied transformation grids. The source code was written in FORTRAN 77 and was intended for command line running in a DOS environment, though version 2.1 came with browser based support (https://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl). However, that support merely made use of the existing exe file.

Like NADCON 5.0, the approach to VERTCON 3.0 was to create grids, but then to provide access to those grids through a modern tool (NCAT.) NCAT is written in JAVA and includes an improved GUI, as well as support for various input formats and web services.

2.3 Better Documentation

VERTCON 2.0 and 2.1 had very little documentation containing the details of how they were constructed. Thankfully one of the co-creators of VERTCON 2.0, Dr. Dennis Milbert, kept fairly extensive notes (see Scientific Notebook Documentation under Author's Notes). These notebooks were available, as was Dr. Milbert himself, so many of the details were accessible, though the data files themselves had long been lost. Some limited documentation was available in the web pages that NGS hosted in support of VERTCON 2.0 and 2.1. These web pages are listed, and replicated, in Section 12.

In a reversal of previous decisions, NGS felt it was necessary to have a comprehensive documentation available, so part of the project was writing this extensive report.

2.4 Scientific Analysis

Unlike NADCON 5.0 (Smith and Bilich, 2017), the creation of the original VERTCON 2.0 grid for CONUS was a lengthy scientific project, encompassing much more than simple "gridding of coordinate differences". This attention to rigor is laudable, so much so that the method finally chosen for the NGVD 29/NAVD 88/CONUS transformation in VERTCON 3.0 was built around maintaining respect for and (general) continuity with the VERTCON 2.0 grid.

NGS wanted to build upon this history, and approached VERTCON 3.0 as a full scientific research project, which is discussed in the next section.

3. Approach for VERTCON 3.0

The team that built VERTCON 3.0 was the same that built NADCON 5.0 just 18 months prior. As such, and because the two tools have such similar end goals, the approach taken for VERTCON 3.0 was very similar to that of NADCON 5.0, with certain noted exceptions. With regard to historic VERTCON 2.0, certain changes were also made. Those changes included:

- Boundaries of the CONUS grid for the NGVD 29/NAVD 88 transformation
- Transformations supported
- Interpolation method
- Build method
- Not offering transformations in zones where it did not make sense to do so

3.1 Adopt approach and tools used in NADCON 5.0

The ultimate goal of VERTCON 3.0 was to provide users with the ability to transform orthometric heights between datums. How that would be accomplished required a variety of decisions, each discussed below.

3.1.1 Decide: Grids?

The obvious delivery method for VERTCON 3.0 was in the form a grid with an accompanying interpolator. This was the method of VERTCON 2.0, and most other datum transformation tools of the NSRS. No other approaches were seriously considered. We use the same .b grid file format as NADCON 5.0 (Section 10).

3.1.2 Decide: Extents of Grids

The regions that made up NADCON 5.0 sometimes differ from those that made up VERTCON 3.0 because the supported vertical datums did not always have the same regional extent as the horizontal datums. For instance, in NADCON 5.0 a grid region called “prvi” was used, encompassing all the islands of Puerto Rico (PR) and the U.S. Virgin Islands (VI). This joint region was allowed because the horizontal datums of PR40 and the various realizations of NAD 83 were consistent between PR and VI. In terms of vertical datums however, the PRVD 02 datum only exists in PR, while the VIVD 09 datum only exists in VI. As such, new regions were defined to support the extents of the vertical datums within the NSRS.

The final grid extents chosen are noted in Section 5.4.

3.1.3 Gridding Method

For the majority of grids, the method of gridding chosen was identical to that of NADCON 5.0. That is, coordinate differences were evaluated for outliers, thinned using a block median filter, and then gridded using "splines in tension". Users interested in a full discussion are referred to Section 3.3 of the NADCON 5.0 manual.

The one exception to the above method is the NGVD29/NAVD88/CONUS[6] grid. For this grid, the method of gridding was still "splines in tension", but it was applied to *residual* coordinate differences (relative to VERTCON 2.0), not to coordinate differences themselves. This was part of a remove/compute/restore process. Full details are found in Section 3.2.

3.1.4 Interpolator Method

The VERTCON 2.0 program provided transformations to users through bilinear interpolation, relying upon a "window" of 2 × 2 points surrounding the point of interest. While providing continuous answers, it does allow for occasional sharp bends in the values across windows. To completely alleviate such breaks, a complete spline method (encompassing the entire grid) should rightfully be used. However this method requires significant RAM for only modest gains. Therefore, the method chosen for VERTCON 3.0 was biquadratic (using a 3 × 3 window) interpolation, which improves upon bilinear while keeping RAM usage low.

In the interest of completeness, it should be pointed out that this *choice* of biquadratic interpolation can be considered part of ***VERTCON 3.0 release 20190601***, but the actual implementation of that choice is only found within NCAT and VDatum, not in any part of the actual files contained in ***VERTCON 3.0 release 20190601***.

3.2 Maintaining information content from VERTCON 2.0 grid

Although a formal report on the creation of VERTCON 2.0 was never written, the original author was available for consultation on his approach (Dennis Milbert, personal communication.) To summarize, VERTCON 2.0 was not built solely upon height differences between NAVD 88 and NGVD 29. Additional information was also used reflecting the different approaches between NGVD 29 and NAVD 88 for both gravity and atmospheric refraction. Finally, a polynomial surface was also introduced in order to capture large (state/multi-state sized) subsidence/uplift features between the two datums. As most of the original files which created VERTCON 2.0 were no longer available, it would have been nearly impossible to replicate this same process and yield the same or even similar results.

The authors of VERTCON 3.0 were committed to creating an updated grid for this transformation, but did not wish to rely solely upon height differences for it, as that would show significantly less signal than the more complex (and physically meaningful) approach taken in VERTCON 2.0. As such, a special approach was taken, to respect the complex content of VERTCON 2.0, while allowing for large regional updates to NAVD 88 that have taken place since the original VERTCON 2.0 release. That approach was a version of the well-known "remove/compute/restore".

[6] While the official abbreviations for these two datums are "NGVD 29" and "NAVD 88", when presented as a triplicate of "old datum"/"new datum"/"region", the spaces are dropped for ease of reading.

Essentially, the same approach of using splines in tension remained at the core of VERTCON 3.0 for this transformation, but those splines were built around residuals relative to VERTCON 2.0. Specifically, for any given point, the first step was to create "coordinate difference" (cd) values from the actual heights which NGS put on these points on datasheets:

CD = H(NAVD 88) – H(NGVD 29)

Then, the height difference value was interpolated from the VERTCON 2.0 grid, to create "V2" values:

V2 = H(NAVD 88) – H(NGVD 29) , from VERTCON 2.0 grid

Finally, residuals were formed between these two, to get RZ data:

RZ = CD – V2

This represented the "Remove" part of the process.

For the "compute" portion, the RZ data was treated in much the same way as standard CD data for all other builds. That is, outliers were identified and discarded. Then a block-median filter was run prior to gridding. The size of the block for median filtering constituted a decision on what a "regional update" to NAVD 88 should look like. In the end, the authors chose 5 arcminutes (300 arcseconds) as representative of this "regional update". (See Section 6.1.3 for further details.) The gridding process on block-median RZ data was performed using splines in tension. This then constituted the "compute" step.

For the "restore" step, it was important to the authors that the high resolution information content from VERTCON 2.0 not be lost. As such, the original VERTCON 2.0 grid spacing of 3 arcminutes (180 arcseconds) was chosen. Therefore the gridded RZ data from the "compute" step was densified from 5 arcminutes to 3 arcminutes using biquadratic interpolation. This then was added to the original VERTCON 2.0 grid at 3 arcminutes (with the exception of the east edge, see below.) By adding the two grids together, the authors arrived at the final grid for the VERTCON 3.0 CONUS/NGVD 29/NAVD 88 transformation. The error grid creation followed standard practice of all other transformations in this release (which relied solely upon CD data, not RZ data), with actual CD data being compared to the final grid, and no remove/compute/restore was needed to create the error grid.

The only hiccup in this process is that the original VERTCON 2.0 grid is one arcdegree smaller on the eastern edge than the VERTCON 3.0 grid. As such, whenever "the original VERTCON 2.0 grid" is mentioned above, it should be taken to mean "as it was, except that the easternmost edge was cloned at a 3 arcminute spacing eastward by 1 arcdegree".

3.3 Single value transformations

There were multiple instances when very little data (less than 5 points) were available for a particular transformation. Gridding such sparse data, no matter the method, is not likely to yield results that are defensible at locations removed from the data points. Still, the team felt it was necessary to provide some transformation if possible, and in a way that would defensibly respect the data. In the few cases where this happened, one of three approaches was taken:

- If 1 point was available: A flat, constant grid filled with that whole value was used, with an error grid of zero.
- If 2 points were available: A flat, constant grid filled with the average of the two points was used, with an error grid that was flat and constant, filled with the difference between the two points (spread of the data).
- If 3 or more points were available: A flat, constant grid filled with the average of the three or more points was used, with an error grid that was also flat and constant, filled with the standard deviation of the three or more points.

Further details are found in the individual builds of Section 6.

3.4 Data from datasheets, not the database

This decision came late in the VERTCON 3.0 project, when certain inconsistencies in the data were noticed. In short, it was noticed that *NGS loads certain orthometric heights into the database, but then prevents those heights from appearing on datasheets*. Some investigation into why this happens was performed, but ultimately the fix was to build VERTCON 3.0 on heights available to the public (aka "on datasheets") and not on data in the database.

More details on this can be found in Sections 4.2.1 and 4.2.2.

3.5 Define "supported datums"

Like NADCON 5.0, the VERTCON 3.0 project created a definitive list of "supported datums". Unlike NADCON 5.0, all of the datums supported in ***VERTCON 3.0 release 20190601*** have only a single "realization". This will be discussed in Section 3.5.1.

Also unlike the horizontal datums in NADCON 5.0, the list of vertical datums in the NSRS is quite small. In fact, aside from the areas of CONUS, Alaska, and Guam, NGS has only defined one official vertical datum in all other territories, with no official vertical datum at all in Hawaii.

In addition to these official vertical datums, NGS has stored in its database small numbers of historic heights in many regions, tied to various tide stations. Such heights are stored with the vertical datum listed simply as "Local Tidal". They are often available to the public on datasheets, making them a de facto, if not official, vertical datum in many regions. That statement must be taken with a grain of salt, since one island might have multiple "Local Tidal" heights, each tied to potentially different tide stations, without any distinction in the metadata. Still, those heights might have been used as geodetic control by NSRS users, and therefore NGS considered it reasonable to build a transformation tool which supported them. In summary: “Local Tidal” is being treated as a “vertical datum”, despite multiple difficulties with that choice.

3.5.1 On the lack of “realizations” in vertical datums

Except in a few small parts of CONUS, nothing on the NGS datasheets distinguishes an NAVD 88 height from 1991 and one from 2018. Similarly for all other vertical datums in the NSRS. There has been no concerted effort to re-adjust all of the data in any of the vertical datums.

There have, however, been certain small regional updates, specifically in the Gulf Coast area, but rather than issue a new “realization” in the way NAD 83 had realizations, those few points were given an epoch. It should be noted that the original NAVD 88 data did not come with an “epoch”, since the data which went into the original release spanned decades. Because of this confusing situation, the question for VERTCON 3.0 wasn’t just “should VERTCON 3.0 support NAVD 88?” but rather “how should VERTCON 3.0 support NAVD 88 when the data spans so many years without distinction?”. This was exacerbated by the fact that VERTCON 2.0 supported NAVD 88 in 1994, and any changes to heights between 1994 and 2018 were simply called “NAVD 88” and still need to be considered.

A variety of ideas were discussed to address this situation. Ultimately the team decided on the “least bad” of many bad choices. That decision could be summed up with the following logic:

- In general, do not deviate from the VERTCON 2.0 grid unless it is necessary to do so
- “Necessary” meant an “area of change” contained enough updated (or new) NAVD 88 heights that they outweighed any existing NAVD 88 heights

The experiments which determined how big an “area of change” should be are discussed in Section 6.1

3.6 Decide which datums will not be incorporated

Within the NSRS, there have been very few official vertical datums, as mentioned previously. However, the history of vertical datums in CONUS does go back over a century, with some previous national adjustments pre-dating NGVD 29. However, all of the data in these datums is contained in paper records at NGS, not in digital form. As such, while the adjusted heights could be retrieved, there is very little reason to believe that any substantial amount of geospatial data could be traced directly to any of these previous adjustments. As such, the following datums were chosen to be excluded from VERTCON 3.0:

1st general adjustment (1899)

2nd general adjustment (1903)

3rd general adjustment (1907)

4th general adjustment (1912)

3.7 Skip no realizations

Unlike NADCON 5.0, there were very few vertical datums, so skipping consecutive realizations and making "jump over" transformations wasn't even possible, except for one location: Guam. In Guam, the datums of "Local Tidal", GUVD 63, and GUVD 04 all exist. As such, to be complete, it should be stated that no jump over transformations were created in VERTCON 3.0.

3.8 Rigorous outlier removal

A significant portion of the VERTCON 3.0 project was the removal of outliers. As in NADCON 5.0, these points were detected through a combination of computer-based statistical identification tools and simple human visual analysis. Removal of outliers was complete removal. They played no role in making or checking the final transformation grids. This should not be confused with "block median thinning", which is the process that chooses the "best" or "representative" value in each grid cell to which the transformation surface is built. The data processing flow dictates that outliers are removed prior to block median thinning but after the application of a "filter"; see Sections 4.5, 4.6, and 6 for additional information.

The figure below is similar to one in the NADCON 5.0 report, but reflects the situation for the NGVD29/NAVD88/CONUS transformation. It reflects additional steps that were not needed in NADCON 5.0. However, the remove/compute/restore portion is not shown, as that does not affect point counts. Still, it is worth noting that the "thinning" at 5 arcminutes is for gridding residuals, while the restore portion was done at 3 arcminutes. The specifics of the NGVD29/NAVD88/CONUS transformation is covered in Section 6.1.

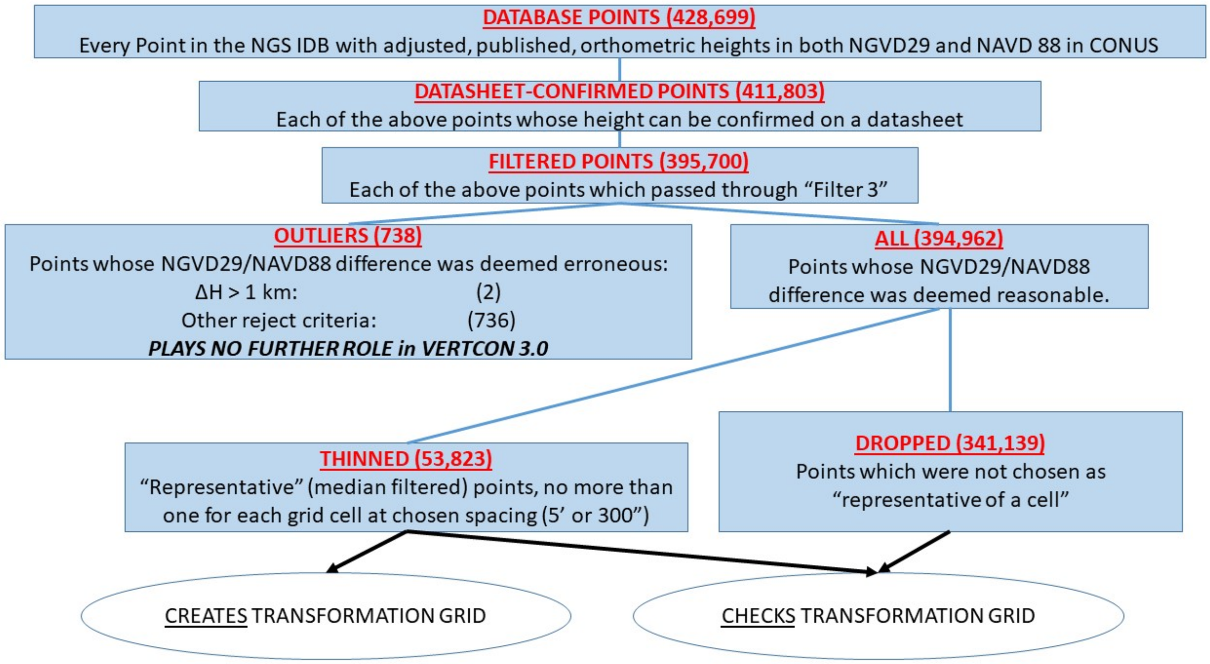

Figure 1: Mapping how all database heights are, or are not, used in VERTCON 3.0 for the NGVD29/NAVD88/CONUS transformation

3.9 Generate new grids from scratch

The only vertical datum transformation grid available from NGS was the NGVD29/NAVD88/CONUS transformation in VERTCON 2.0. Still, it was deemed important, to be both consistent with the entire VERTCON 3.0 project and also incorporate new, local information (Section 6.1.2), to re-build the NGVD29/NAVD88/CONUS grid from scratch. However there was a desire to respect parts of that original grid as well. Full details of that approach are found in Section 6.1.

3.10 Produce local error estimates

In VERTCON 2.0, the estimate of the accuracy was stated as:

> *"…the VERTCON 2.0 model can be considered accurate at the 2 cm (one sigma) level."*

(This from web pages about VERTCON 2.0 (Section 12), as NGS has never formally published a report on this tool in the way a report for NADCON 5.0 was printed). This accuracy had no dependence on location, which is similar to how the earlier (pre-5.0) versions of NADCON stated their accuracies.

As in NADCON 5.0, NGS decided that geographically-dependent error estimate grids should be put out as companions to the transformation grids in VERTCON 3.0. The approach, when data supported it, was identical to NADCON 5.0, being a combination of method noise and data noise.

3.10.1 Method noise, Data Noise and Total Error

The approach of Method noise, Data Noise and the Total Error was identical to that in NADCON 5.0, and readers interested in that approach are directed to Sections 3.12.1, 3.12.2 and 3.12.3 of the NADCON 5.0 report (Smith and Bilich, 2017).

As mentioned in Section 3.3 of this report, areas with sparse data had error grids determined in unique ways, on a case by case basis. More information can be found in Section 6.

4. Preparing for the build

Data preparation and preprocessing was an important and time-consuming step in formulating the VERTCON 3.0 transformations. This section describes how the authors selected and organized data for the transformations. All programs and files discussed in this document are available as part of the electronic archive of ***VERTCON 3.0 release 20190601***; see Section 11 for more information.

4.1 Transition code from Sun UNIX to Linux

The NADCON 5.0 build software should have served as the starting point for much of the code development for VERTCON 3.0. However, the NADCON 5.0 build software was developed on Sun UNIX machines, and used Generic Mapping Tools (GMT) version 4 for plot generation and gridding. By the time the VERTCON 3.0 project began in late 2017, NGS was transitioning from UNIX to Linux, as well as from GMT version 4 to GMT version 5. Therefore, the VERTCON 3.0 team felt it necessary to completely transition to Linux and GMT 5 (by re-constructing the NADCON 5.0 build software in those environments) to properly support the VERTCON 3.0 project. This transition took a few months to fully implement and test. Internally, this project was called "NADCON 5.01". Once the transition was complete, the NADCON 5.01 build software was rigorously tested by creating a full set of grids (***NADCON 5.01 build 20190531***). However, in accordance with the previously stated NGS policy, this build was not released; that is, no grids from ***NADCON 5.0 release 20160901*** were superseded in NCAT or VDatum. As such, there was no formal announcement of this project[7]. Finally, in January of 2018 the transition was complete. The Linux machine on which VERTCON 3.0 was predominantly built was called "ngs-vsu-rheldev".

4.2 Pull data

Unlike NADCON 5.0, the data for VERTCON 3.0 did not only come from a pull of the NGS Integrated Database, but also from collating that data against the actual values of heights which appeared on NGS datasheets. While the NGS IDB contains "Do Not Publish" flags for certain values, it turns out that this is not the only reason that data in the database would not appear on a datasheet. The second reason is that the datasheet program, "datasheet95", contains a variety of filters, effectively implementing a history of NGS policies, documented and undocumented, which

[7] Details about NADCON 5.01 are found in DRU-12, p. 140-143. Readers interested in the details of the NADCON 5.01 project are directed to Smith and Bilich (2019)

affect what appears on the actual datasheets. While this did not impact data for NADCON 5.0, it has a significant impact on data in VERTCON 3.0

4.2.1 Data from the Integrated Database (IDB)

The first formal request for a pull of data from the NGS IDB was made on October 12, 2016, under the idea that such a pull would be as easy as was done for NADCON 5.0. However, the complexity of fields associated with vertical data was significantly greater than that for horizontal, and it was soon obvious that the query would need to be modified. Other work took precedence, and it wasn't until November 9, 2017 (over a year later) that a fresh pull was requested, at which time the VERTCON 3.0 project was officially underway.

Additional refinements were made to the database pull request, broadening which tables were pulled and what fields in those tables until the final database pulls were done between January 10th and February 13th 2018. The final database files, from which the entire project was built, were the following:

```
/home/dru/VERTCON/VERTCON3/DBPulls/20180213/elevation_20180213.csv
/home/dru/VERTCON/VERTCON3/DBPulls/20180213/fa_elevation_20180213.csv
/home/dru/VERTCON/VERTCON3/DBPulls/20180208/usgs_heights_20180208.csv
/home/dru/VERTCON/VERTCON3/DBPulls/20180110/usgstemppids_20180109.csv
/home/dru/VERTCON/VERTCON3/DBPulls/20180110/usgstemppids_gmf_20180109.csv
/home/dru/VERTCON/VERTCON3/DBPulls/20180110/usgstemppids_gmf2_20180109.csv
```

These six files were then converted to a single file, and cleaned up in formatting and generally filtered for blunders and other issues using steps found in DRU-12, p. 121-126. Note that, while USGS height files existed at NGS, they were sparse and contained only information in NGVD 29. As such, none of the data in those four files found their way into VERTCON 3.0.

4.2.2 Data from datasheets

As work progressed on VERTCON 3.0, early working files were distributed to NGS advisors and other technical experts for feedback. In April 2018, the first signs of trouble came in, when it was pointed out that point DO0454 had both a 1991 (leveling based) and 1996 (GPS based) value for NAVD 88 orthometric height in the IDB, but that the datasheet was still showing the 1991 value as the official height for this mark. This is problematic, since the pervasive build philosophy for both NADCON 5.0 and VERTCON 3.0 has been "build to the last loaded value in the IDB". (Some investigation into this showed that NGS was executing a policy, via code in their datasheet95 program, which did not allow GPS derived "height mod" heights to supersede leveling based heights without explicitly allowing for an exception.) This was not a problem in NADCON 5.0 where "last loaded" values for latitude, longitude and ellipsoid height were never seen to disagree with "what is on the datasheet". We note that "what is on the datasheet" is how the general public accesses height information.

This discrepancy in heights between the IDB and the datasheet comes from NGS program "datasheet95", which generates datasheets from the IDB. Significant NGS policy about what is and is not "publishable" is encapsulated in the program (and nowhere else). Unraveling that policy by analyzing the code would not have yielded any real help, since the primary problem was simply that the public had access to and was basing survey work upon heights that were not "last loaded". As such, the philosophy of VERTCON 3.0 shifted to "build to the datasheets", as this is the more logical source of information for a transformation to serve the needs of the general public.

Significant effort to pull the "ORTHO HEIGHT" line from every datasheet of every point in the six database pull files was expended. Numerous programs were created to compare/contrast the IDB "last loaded" values to the datasheet values. All of this is outlined in DRU-12, p. 130-134, and a set of "In Files" (see next section) were created. The build progressed until August of 2018 at which point a bug was found in the in-files. Once fixed, a new (and final) set of in-files were created on August 20, 2018. See DRU-12, p. 139 & 142.

4.3 In-Files

Program "makeinfiles2.f" was run on August 20, 2018 which created files of coordinate pairs ("last datasheet value of height in old datum" and "last datasheet value of height in new datum") These files, which are referred to as "in-files", contain the pairs of coordinates in chronologically adjoining vertical datums. Individual in-files were written for each U.S. state or protectorate sub-region, for example, Guam (GU) or Puerto Rico (PR). The in-files are the fundamental data set from which VERTCON 3.0 transformations are computed.

As an example, here are the first few lines of the in-file for Alaska, for points with realizations in both NGVD 29 and NAVD 88:

```
% hostname
ngs-vsu-rheldev
% pwd
/home/dru/VERTCON/VERTCON3/InFiles
% head vertcon3.alaska.ngvd29.navd88.in
AA1900 AK 232  58.4276804000 224.2933452222 4 4 H G    5.3900 4 4 H G    8.0860
AA6276 AK 020  61.2306682806 210.2165905833 4 4 F N   57.9194 1 2 A N   59.6742
AA6277 AK 020  61.2299383694 210.2208977528 4 4 F N   58.3566 1 2 A N   60.1114
AA7629 AK 020  61.1674019861 210.0273363306 4 4 H B   28.5750 4 4 H G   30.6130
AB7145 AK 122  60.6844444444 208.6066666667 4 4 F N    8.6911 1 2 A N   10.4988
AB7146 AK 122  60.6850000000 208.6086111111 4 4 F N   11.6752 1 2 A N   13.4831
AB7147 AK 122  60.6861111111 208.6097222222 4 4 F N   17.1181 1 2 A N   18.9262
AB7148 AK 122  60.6863888889 208.6111111111 4 4 F N   22.3155 1 2 A N   24.1238
AB7149 AK 122  60.6872222222 208.6119444444 4 4 F N   30.7452 1 2 A N   32.5536
AB7150 AK 122  60.6866666667 208.6127777778 4 4 F N   29.5536 1 2 A N   31.3621
```

From the filename vertcon3.alaska.ngvd29.navd88.in (which takes the form vertcon3.region.od.nd.in), we can see that the original datum or "old datum" is NGVD 29 and the next chronologically adjacent datum or "new datum" is NAVD 88. There are no headers in the

VERTCON 3 in-files (unlike NADCON 5). Each record contains point identification information (PID, 2-character state/region, and 3-digit county code), then the latitude and longitude in the most recent horizontal datum available for each point. The next 5 columns are four codes describing the height in the old datum followed by the actual height in the old datum. This pattern (4 codes, plus height) is then repeated for the new datum. Note that, during processing, these heights are differenced (new datum minus old datum; see note in the header of this document) to form a vector. More details on the processing stages which generate vectors are given in Section 5.

The four codes provide information on the quality and source of the height, and are presented in the following order:

1. Order[8]
2. Class[8]
3. Source for the height (NGS IDB field "ELEV_SOURCE")
4. Technique for the height (NGS IDB field "ELEV_TECH")

4.4 Control files

In order to control the exact in-files which went into each VERTCON 3.0 grid, a set of control files were made, telling the processing engines which datums go with which grids. The directory /Control in the digital archive contains the files which group the in-files; these control files are definitive and not open to change.

The full list of control files is given below. Note that each control file uses the *og.ng.rg* naming convention (see Authors' Note at beginning of this document).

Region: **conus** (lower 48 + DC)
control.ngvd29.navd88.conus

Region: **alaska** (Alaska)
control.ngvd29.navd88.alaska

Region: **as** (American Samoa)
control.lt.asvd02.as

Region: **guam** (Guam)
control.lt.guvd63.guam
control.guvd63.guvd04.guam

Region: **cnmi** (Commonwealth of the Northern Mariana Islands)
control.lt.nmvd03.cnmi

[8] See FGCC (1984)

Region: **pr** (Puerto Rico)

control.lt.prvd02.pr

Region: **vi** (U.S. Virgin Islands)

control.lt.vivd09.vi

4.5 Filters

In NADCON 1.0, a decision to use only 1st and 2nd order data in building the grids was made, effectively defining a "filter". Such an approach was not taken in NADCON 5.0, where all data points were used and only outlier detection and removal were applied.

In VERTCON 3.0 a similar approach to NADCON 5.0 was attempted (allowing all orthometric heights to be used), but some immediate problems came to light. Of particular note in building a new NGVD29/NAVD88/CONUS transformation, the VERTCON 3.0 team found significant differences between NAVD 88 minus NGVD 29 height differences (H88-H29) in the in-files as compared to H88-H29 values in the existing VERTCON 2.0 grid (Figure 4-1).

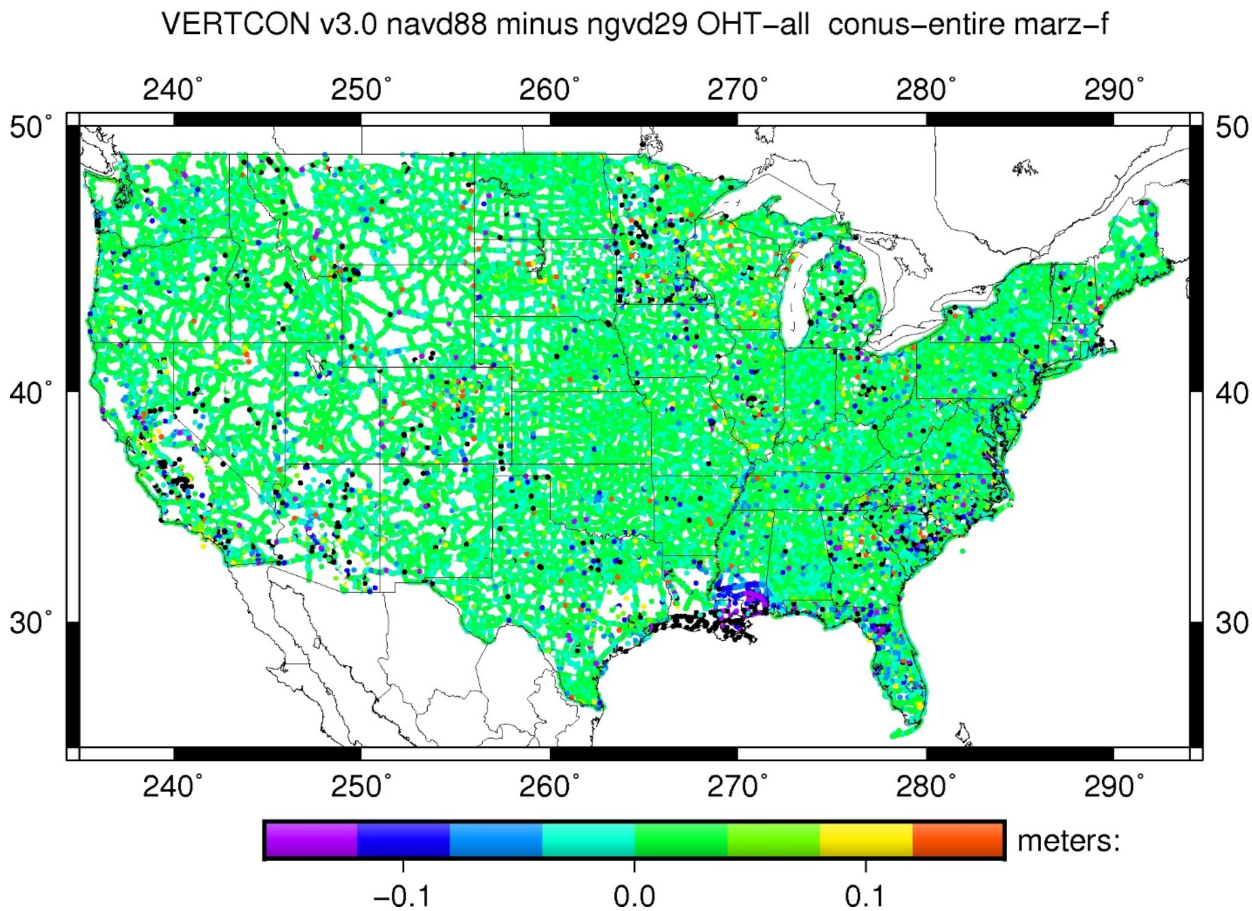

Figure 4-1: Residual (rz) heights, comparing VERTCON 3.0 in-file heights to the VERTCON 2.0 transformation.

The primary concern was the "pock marked" nature of these differences. A great example of this can be seen in a close-up map of Minnesota (Figure 4-2).

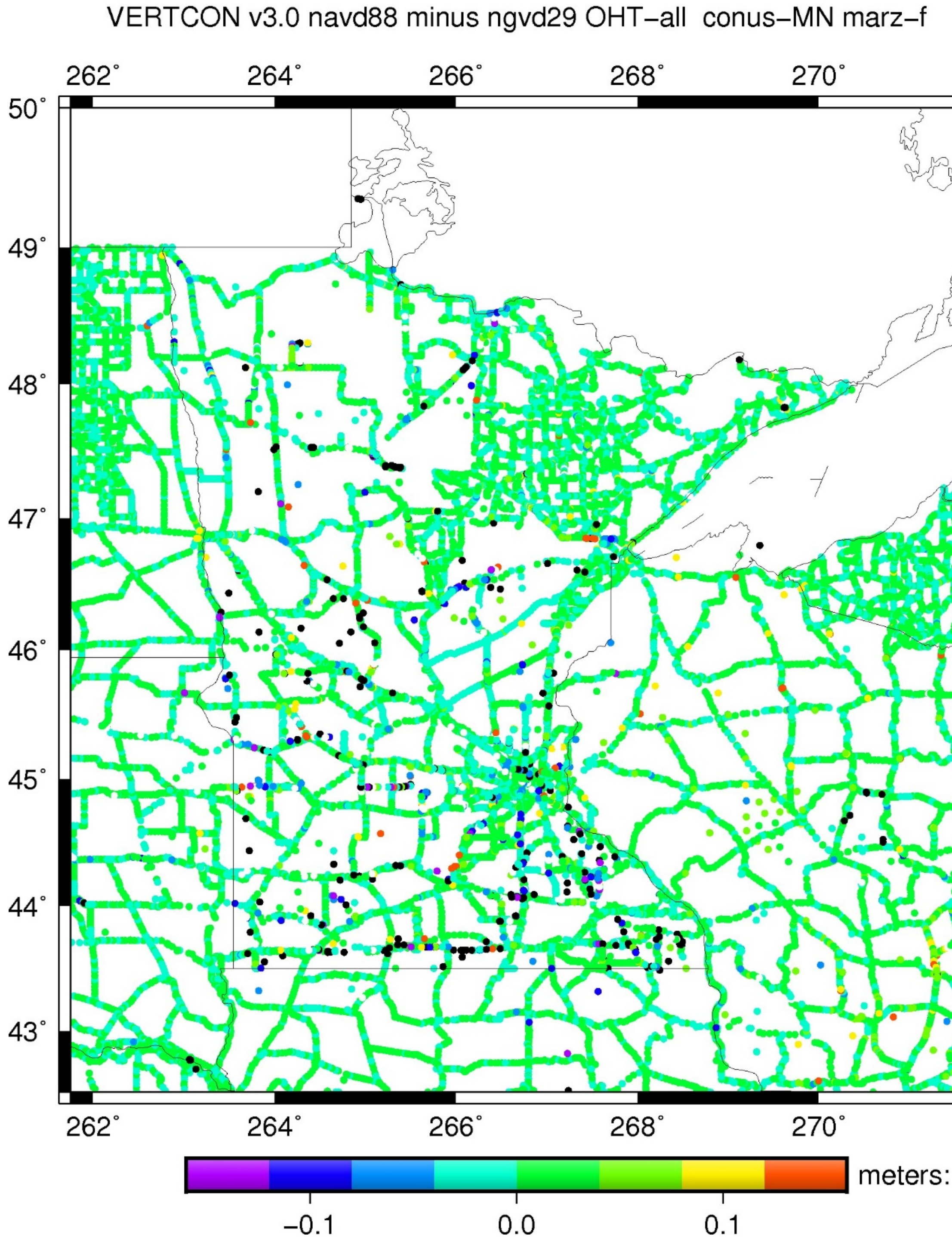

Figure 4-2: Residual differences as in Figure 4-1, zoomed in to show detail in Minnesota.

The various possible reasons for these differences can be summed up as:

1. The NGVD 29 height changed since VERTCON 2.0 was made
2. The NAVD 88 height changed since VERTCON 2.0 was made
3. The point itself was not used in VERTCON 2.0

Unfortunately, the entire set of original build files for VERTCON 2.0 were not available[9]. As such, the exact reason for each point's disagreement cannot easily be determined. But as a whole, each of these possible explanations are discussed below.

The NGVD 29 height changed?: It is possible, but unlikely that this explains many of these discrepancies. Although NGS was quick to deprecate NGVD 29 with the release of NAVD 88, by 1994 (when VERTCON 2.0 was created) the number of projects being turned in to NGS on NGVD 29 was small (but not zero[10]) . However, a discussion with the original builder of VERTCON 2.0 indicated that the input files came directly from the Vertical Network Branch of NGS and not from the NGS IDB. (Dennis Milbert, personal communication.) It is possible that some NGVD 29 heights given to the VERTCON 2.0 team which were changed before loading into the NGS IDB.

The NAVD 88 height changed?: Highly probable. From 1994 through 2017, NGS received both leveling and Height Modernization (GPS based) projects containing original NAVD 88 points. In some of those projects, original heights were superseded. Additionally, it is possible that some NAVD 88 heights were given to the VERTCON 2.0 team which were changed before loading into the NGS IDB (see above comment).

The point was not in VERTCON 2.0?: Probable in some cases. Although the original build files for VERTCON 2.0 were not available, some preliminary files were checked and certain lines (such as in Arizona) were not in the preliminary VERTCON 2.0 files, indicating that they may have been missing from VERTCON 2.0 (Dennis Milbert, personal communication).

After considering these possibilities, the greatest concerns were twofold:

1. Some of the new NAVD 88 heights were GPS-derived, yet not "Height Mod" quality

2. Some of the points being considered were available to the VERTCON 2.0 team, but were of a lower quality (such as trigonometric leveling)

In an attempt to remove lower-quality NAVD 88 heights from consideration, certain filters were introduced at the beginning of the build process. These filters use information contained in the 4-character codes in the in-files (Section 4.3) to assess the quality of the point. Each of these filters is described below; subroutine "applyfilter.f" in the Digital Archive was used to execute each filter:

Filter 0: No filter applied. All points in the in-files pass through into the build.

[9] Though there is a semi-complete set in directories /hnbraid/archive/vnb/gravity/VERTCON, /hnbraid/archive/vnb/rudy2/VERTCON and /hnbraid/archive/vnb/rudy/VERTCON.
[10] See vertical adjustments: SUPRSDD, 00000008, 00000012, 00000017, 00000018,00000021, 00000033,00000037, 00000039, 00000049, 00000071, 00000073, 00000134, 00000315, etc.

Filter 1: Only points of first and second order quality for both the old datum height and new datum height pass through. .

Filter 2: Only GPS-based NAVD 88 heights from the Horizontal Network Branch[11] pass through. That is, ELEV_SOURCE was "H" and ELEV_TECH was "G" for the NAVD 88 values in the in-files.

Filter 3: A customized set of quality checks, established by Tim Hanson of the Observation and Analysis Division of NGS, but modified slightly by the VERTCON 3.0 build team[12]. The best way to describe this filter is as follows:

- Each of third and fourth codes for each height are given a color: red, yellow or green
- If any point has a code that is red, skip that point
- If any point has ELEV_SOURCE and ELEV_TECH both yellow, skip that point

The colors corresponding to the codes are found in the table below:

ELEV_SOURCE = F, O, S or X	(red)
ELEV_TECH = H or P	(red)
ELEV_SOURCE = B, C, G, H, M, N, P or U	(yellow)
ELEV_TECH = F, G, T or E	(yellow)
ELEV_SOURCE = A or R	(green)
ELEV_TECH = B or N	(green)

Neither filter 1 nor filter 2 significantly improved the "pock marked" nature of the data. But filter 3 made significant improvements, though discrepancies remained. However those discrepancies were not quality issues, but rather issues of good data disagreeing with VERTCON 2.0, as discussed in Section 6.1.2.

One final step in creating filters was necessary. For instance, filter 3, while successful in general, did not fully remove all bad data from consideration, making some additional manual outlier detection and removal needed. Because these outliers were most apparent after filter 3 was applied, the final version of the "filter 3 plus outlier removal" came to be known as "filter 3a". The discussion of these additional outliers is found in Section 4.6.

The actual filter chosen for each build is listed in the corresponding part of Section 6.

[11] Up until the 1990s, NGS was very compartmentalized with regard to field surveys, data analysis and database storage. This was best exemplified by the existence, under the Observation and Analysis Division into the Horizontal Network Branch and the Vertical Network Branch. When these two branches finally merged their separate databases in the 1990s, the NGS Integrated Database (NGS IDB) was born.

[12] The changes made were: (a) ELEV_SOURCE = G (USGS 3rd order leveling) was originally RED, but the team changed it to YELLOW to let more points into the transformation

4.6 Additional outlier identification

As mentioned earlier, filter 3 (at least for NGVD29/NAVD88/CONUS) required some additional manual clean-up after being applied. The big issue being addressed was what to do about points "in voids", specifically points which disagreed with the VERTCON 2.0 grid.

The overarching theme was "respect VERTCON 2.0, unless a *regional* signal shows change is warranted". Outliers in voids were *not* considered regional signals. Program "findlonelypts.f" helped identify such outliers in voids. Two settings (10' radius, 10 cm threshold and 5' radius with 5 cm threshold) were used to identify void sizes and allowable disagreement with VERTCON 2.0. This helped identify 736 outliers, after filter 3 was applied. The removal of these 736 additional points came to be called "filter 3a".

In regions with fewer points than CONUS, additional outliers were detected through visual inspection of the data. The number of outliers removed and reasons for doing so are detailed in Section 6.

4.7 Choosing a grid spacing

For the regions with sufficient data density to justify the 'surface under tension' approach, a few overarching principles drove the selection of a grid size. In this study, the best choice of grid size:

1. Is the coarsest grid which adequately explains the data;
2. Should result in small residuals (difference between the transformation and the original coordinate difference for each point);
3. Does not create gaps where vectors are present in the original field (i.e. does not undersample data);
4. Avoids clusters of similar vectors (i.e. does not oversample data).

However, one further criterion was needed, specifically for the NGVD29/NAVD88/CONUS grid decision. In that particular combination, two distinct grid spacings were used. The first was for the median-filtering of residual data. That is, residuals between "H88-H29" in the "in-files" and "H88-H29" as interpolated off of the original VERTCON 2.0 grid. However, unlike in all other builds where the median filter was identical to the final transformation grids, in this case a second, independent grid spacing was chosen for the final transformation grid. More detail on this special situation is in Section 6.1.3.

To kick off the grid size selection process, for each individual datum pair, the authors computed the full transformation for a range of possible grid sizes: 1, 2, 3, 5, 7.5, 10, 15, 30 arcminutes (60, 120, 180, 300, 450, 600, 900, 1800 arcseconds). Computation of the full transformation gave the authors access to transformation residuals and error estimates for each of the tested grid sizes.

With these metrics in hand, the authors reviewed the data and chose a final grid. All attempts were made to follow the guidelines stated above, but there were cases where the statistical data did not lead the authors to an obvious conclusion on the ideal grid size. For example, when localized signals were present which deviated from the overall vector field, it would often be necessary to look at maps of residual fields to qualitatively assess which grid sizes would capture that variation without penalty to the rest of the region. Similarly, some transformation vector fields are so highly variable that special care had to be taken when analyzing the residuals. The exact implementation of these principles and the resultant final choice for each transformation's grid size is detailed in Section 6, where the authors provide details on the quantitative and qualitative considerations which led to the choice of the final grid size for each transformation and region.

5. Performing the build

This section describes how any NGS user could recreate the exact results of VERTCON 3.0 from the fundamental files described in Section 4. In general, the process is fairly automated. Programs and scripts required to conduct the build are part of the NGS distribution of VERTCON 3.0 (see Section 11).

5.1 System setup

VERTCON 3.0 was generated on the NGS Linux cluster, specifically on the machine "ngs-vsu-rheldev". All Generic Mapping Tool (GMT) scripts used GMT version 5 (Wessel et al. 2013).

In order for programs and shell scripts to run properly, it is necessary to modify a few shell variables. The following file contains details:
FinalBuilds.20181201/RunVERTCON3/Code/README.

If these programs and shell scripts are run on a different platform or shell, they may not work properly.

5.2 Sequence of programs

A word of caution is necessary here:

> *The following sequence of programs will (generally[13]) build up all of the grids, plots and supporting files needed for one transformation, provided the grid spacing has already been determined. Obviously such knowledge is not known up front, and as part of the VERTCON 3.0 research process, a "build" was performed using a variety of different grid spacings.*

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[13] The word "generally" has been used because, in a few cases, the automated build process (which consisted of four batch files, named "doit.bat", "doit2.bat", "doit3.bat" and "doit4.bat) was not enough to arrive at the final transformations and error grids. In some cases, not enough data was available to use the "splines in tension" method, which is in doit3.bat and doit4.bat, but rather "flat plane" transformations needed to be built. In other cases, the full set of four batch files were run, but then some editing of the final grids was needed to either cut out a section, create a flat-plane in another section, or both. In all cases except Alaska and CONUS, "flags" were added to grids to avoid their misuse in open ocean areas. When needed (not Alaska, not CONUS), a new script, called "finalize.*rg*" was used to manipulate the build process. More details are found in sections 6.4 through 6.8. See also DRU-12, p. 143-145.

These were then analyzed relative to one another and a final grid spacing determined. At that point, all of the experimental builds were "unbuilt" (erased) and the final build re-done by itself.

The sequence of building one transformation can be described at the highest level as consisting of four batch files. These four batch files are named: *doit.bat*, *doit2.bat*, *doit3.bat* and *doit4.bat*. As each batch file is run, it takes input from prior steps in the process, and creates additional files. An associated set of batch files will un-do (erase) all of the work of a previous batch file. Not surprisingly, the associated un-doing batch files are called *undoit.bat*, *undoit2.bat*, *undoit3.bat* and *undoit4.bat*. To re-iterate, all files created by running *doit.bat* can be erased by running *undoit.bat*, etc. A complete explanation of each batch file is found below. Note that the file naming convention is detailed in the Author's Notes at the beginning of this report.

5.2.1 doit.bat

This batch file creates a "work" file, based on "in" files listed in the appropriate "control" file. A "work" file is in a sense a reformatted version of the "in" file, after outliers have been removed by applying "workedits". The "work" file itself contains a number of pre-computed values, primarily the latitude and longitude of each point, the differences in orthometric height (in meters), and the quality flags. All "work" files get stored in sub-directory Work.

<u>What must exist prior to running:</u>

The manual edits file: *Work/workedits*

1 "control" file: *Control/control.od.nd.rg*

All "in" files mentioned in the Control file: *InFiles/vertcon3.rg.od.nd.in*

<u>Additionally, for NGVD29/NAVD88/CONUS only:</u>

The VERTCON 2.0 grid: */home/dru/VERTCON/VERTCON2/vertcon2.0.v3bounds.b*

<u>doit.bat syntax:</u> *doit.bat od nd rg fi* <return>

<u>undoit.bat syntax:</u> *undoit.bat od nd rg fi* <return>

<u>Example doit syntax:</u> *doit.bat ngvd29 navd88 conus 3* <return>

<u>Example undoit syntax:</u> *undoit.bat ngvd29 navd88 conus 3* <return>

<u>What will be created by running doit.bat:</u>

The "work" file: *Work/work.od.nd.rg.f0*

5.2.1.1 Special information for the NGVD29/NAVD88/CONUS combination:

If this combination is run, then two additional columns will appear at the far right side of each line in the "work file". Those two columns will contain the interpolated value of the height difference from the VERTCON 2.0 grid and the residual between the height difference as implied by the data in the in-files and that from interpolating off of the VERTCON 2.0 grid.

Table 5-1 describes each step that is executed inside of doit.bat.

Table 5-1: Workflow and files generated by executing "doit.bat"

Step	What does it do	What does it create
makework.f	Guided by the "control" file, it reads the appropriate "in" files, and generates height differences (aka "vectors"), geographically located at the latitude and longitude of the "old datum". It will then attempt to write this information to the "work" file, with one record of the "work" file for each point. Each record has the potential to have 1 reject code; this 1-character reject code is located between the state and latitude in the "work" file. Some reject codes will automatically be generated if certain criteria are sensed (such as a vector greater than 10 km, or a point that lies outside the region's boundaries, or a point is rejected by whatever filter was chosen). However, the program generates the majority of its reject codes by accessing the "workedits" file and looking for manually determined edits that were created earlier. If it finds one, it adds a reject code to the record as appropriate, and sets the orthometric height difference to zero.	*work.od.nd.rg.f0*

5.2.2 doit2.bat

This batch file creates “vector” and “coverage” files, as well as writes and executes a batch file to plot the vector and coverage files as JPGs. “Vector” files represent the coordinate shift in orthometric height. “Coverage” files are the location of the points with coordinate shifts in the associated “vector” files.

What must exist prior to running:

The “work” file:	*Work/work.od.nd.rg.f0*

doit2.bat syntax:	*doit2.bat od nd rg fi mf <return>*
undoit2.bat syntax:	*undoit2.bat od nd rg fi<return>*
Example doit2 syntax:	*doit2.bat ngvd29 navd88 conus 3 2* <return>
Example undoit2 syntax:	*undoit2.bat ngvd29 navd88 conus 3*[14]

<return>

What will be created by running doit2.bat:

The first “GMT batch file”:	*gmtbat01.od.nd.rg.f0.mf*
Coordinate Difference[15] Coverage files:	*cvacdoht.od.nd.rg.f0*
True Coordinate Difference Vector files (meters):	*vmacdoht.od.nd.rg.f0*
Coordinate Difference Coverage maps:	*cvacdoht.od.nd.rg.f0.am.jpg*
True Coordinate Difference Vector maps [16](meters):	*vmacdoht.od.nd.rg.f0.am.jpg*

These additional files are created solely in the NGVD29/NAVD88/CONUS combination:

Residual Coordinate Difference Vector files (meters):	*vmarzoht.od.nd.rg.f0*
Residual Coordinate Difference Vector maps (meters):	*vmarzoht.od.nd.rg.f0.am.jpg*
VERTCON 2.0 Coord. Difference Vector files (meters):	*vmav2oht.od.nd.rg.f0*
VERTCON 2.0 Coord. Difference Vector maps (meters):	*vmav2oht.od.nd.rg.f0.am.jpg*

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[14] The undoit2.bat routine requires no mapflag

[15] The term “coordinate difference” will be maintained here, in parallel with NADCON 5.0. However, in VERTCON 3.0 there is only one “coordinate” being differenced – orthometric heights. Still, the file names say “cd” for “coordinate difference” while the “oht” defines the type of coordinate difference. This sort of duplicate way of just saying “height difference” will be maintained solely for its parallelism with NADCON 5.0

[16] The term “vector maps” has carried over from both NADCON 5.0 and some early developmental work of VERTCON 3.0. However, since height differences, if represented as “vectors” on a map are merely arrows pointing up or pointing down, such vector maps are exceedingly difficult to read. As such, these so-called “vector maps” have been replaced with “color dot plots”, showing both location (as a dot) and magnitude (as the color of the dot). However, the JPG names still begin with “v” (for “vector”) and the continued name “vector map” will be continued throughout this report, despite their true appearance as color dot plots, so that a parallelism to NADCON 5.0 can be maintained.

Table 5-2 describes each step that is executed inside of doit2.bat.

Table 5-2: Workflow and files generated by executing "doit2.bat"

Step	What does it do	What does it create
makeplotfiles01.f	Working with the data in the "work" file, this program sets up a number of GMT ready data files of both coverage and coordinate differences in the form of vectors. It then creates a batch file full of GMT scripts.	**Always:** • *gmtbat01.od.nd.rg.f0.mf* • *cvacdoht.od.nd.rg.f0* • *vmacdoht.od.nd.rg.f0* **ngvd29/navd88/conus:** • *vmarzoht.od.nd.rg.f0* • *vmav2oht.od.nd.rg.f0*
gmtbat01.od.nd.rg.f0.mf	Runs GMT scripts to create plots, in JPG format. The number of maps made depends on the "mapflag" given at the "doit2.bat" call. The "mapflag" can be 0, 1 or 2 depending on how fine of a scale is desired for the maps. A "0" means just maps for the entire region. A "1" means additional maps at a sub-regional scale. A "2" is generally not used except for region "conus" where it will create state-by-state maps. Each map contains a shorthand name for its "area mapped", such as "entire" or "northwest" or "OH".	**Always:** • *cvacdoht.od.nd.rg.f0.am.jpg* • *vmacdoht.od.nd.rg.f0.am.jpg* **ngvd29/navd88/conus:** • *vmarzoht.od.nd.rg.f0.am.jpg* • *vmav2oht.od.nd.rg.f0.am.jpg*

5.2.3 doit3.bat

This batch file primarily generates the transformation. First, it applies the median filter, separating the data into one file containing points used in the transformation ("thinned") and saving all other points ("dropped") to a second file for later error analysis. Second, using GMT's *surface* routine with tension 0.4, the thinned data are gridded to generate the transformation; the same data are gridded at tension 0.0 and 1.0 for later analysis. Third, method noise is calculated (see Section 3.10.1) for later error estimate construction. The thinned and dropped vectors and their coverage are plotted, as well as a color contour plots of the gridded transformations and method noise.

For the NGVD29/NAVD88/CONUS transformation only, additional steps are performed. First, the residual (RZ), and not coordinate difference (CD), data are thinned using the median filter. This thinning is done at "***grid spacing 1***" (of 2). (In all other combinations of old datum/new datum/region, there is only 1 grid spacing.) [17]The additional tensions of 0.0 and 1.0 are also performed on the RZ data for the creation of the "method noise" grid. To create the final transformation, the RZ data (at grid spacing 1) is re-gridded (using biquadratic subroutine regrd2.f) to "***grid spacing 2***" (of 2). This is then added to a version of the original VERTCON 2.0 grid[18] which has been pre-computed and stored also on "grid spacing 2" (of 2). This final grid is the transformation grid.

What must exist prior to running:

The "work" file:	*Work/work.od.nd.rg.f0*
Coordinate Difference Coverage files:	*cvacdoht.od.nd.rg.f0*
True Coordinate Difference Vector files (meters):	*vmacdoht.od.nd.rg.f0*

For the NGVD29/NAVD88/CONUS portion only:

The pre-regridded versions of VERTCON 2.0 at various grid spacings (XXXX = four character version of "g2" in arcseconds with leading zeroes):

/home/dru/VERTCON/VERTCON3/VERTCON2 /vertcon2.0.v3bounds.secXXXX.meters.b
/home/dru/VERTCON/VERTCON3/VERTCON2 /vertcon2.0.v3bounds.secXXXX.meters.grd

doit3.bat syntax: *doit3.bat od nd rg fi g1 g2 mf* <return>

undoit3.bat syntax: *undoit3.bat od nd rg fi g1 g2*<return>

Note: In all cases except (od="ngvd29" & nd="navd88" & rg="conus"), g1 must equal g2.

[17] For ease of coding, all runs using doit3.bat require that two grid spacing values be input. However, in all cases except the ngvd29/navd88/conus combination, those two spacing must be identical or the doit3.bat batch file will not run.

[18]The original VERTCON 2.0 grid had an eastern boundary of 293 degrees longitude. This has the unfortunate effect of truncating 2 ½ miles of Eastern Maine from the grid. As such, the first step taken was to "clone" (duplicate) the final column in the VERTCON 2.0 grid from 293 to 294 degrees longitude, at 3 arcminute spacing (the original VERTCON 2.0 grid spacing). This extended form of the VERTCON 2.0 grid will nonetheless be referred to as "the original VERTCON 2.0 grid" for expediency throughout this document.

Example doit3.bat syntax: *doit3.bat ngvd29 navd88 conus 3 300 180 2* <return>

Example undoit3.bat syntax: *undoit3.bat ngvd29 navd88 conus 3 300 180* <return>

What will be created by running doit3.bat (all runs):

The second "GMT batch file":	*gmtbat02.od.nd.rg.f0.g1.g2*
Thinned Coordinate Difference Coverage files:	*cvtcdoht.od.nd.rg.f0.g1.g2*
Thinned True Coordinate Difference Vector files (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2*
Dropped Coordinate Difference Coverage files:	*cvdcdoht.od.nd.rg.f0.g1.g2*
Dropped True Coordinate Difference Vector files (meters):	*vmdcdoht.od.nd.rg.f0.g1.g2*
Gridded Coord. Difference files, Tension 0.4, grd format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.04.grd*[19]
Gridded Coord. Difference files, Tension 0.4, dot-b format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.04.b*[9]
The third "GMT batch file":	*gmtbat03.od.nd.rg.f0.g1.g2.mf*
Thinned Coordinate Difference Coverage maps:	*cvtcdoht.od.nd.rg.f0.g1.g2.am.jpg*
Dropped Coordinate Difference Coverage maps:	*cvdcdoht.od.nd.rg.f0.g1.g2.am.jpg*
Gridded Coordinate Difference maps, Tension 0.4 (meters):	*cmtcdoht.od.nd.rg.f0.g1.g2.04.am.jpg*

What will be created by running doit3.bat (all runs except NGVD29/NAVD88/CONUS):

Surface-ready Thinned True Coordinate Difference files (meters):	*smtcdoht.od.nd.rg.f0.g1.g2*
Gridded Coord. Difference files, Tension 0.0, grd format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.00.grd*
Gridded Coord. Difference files, Tension 1.0, grd format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.10.grd*
Gridded Coord. Difference files, Tension 0.0, xyz format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.00.xyz*
Gridded Coord. Difference files, Tension 0.4, xyz format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.04.xyz*
Gridded Coord. Difference files, Tension 1.0, xyz format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.10.xyz*
Gridded Coord. Difference files, Tension 0.0, dot-b format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.00.b*
Gridded Coord. Difference files, Tension 1.0, dot-b format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.10.b*
Grid Differences, Tensions 1.0 minus 0.0, dot-b format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.d1.b*
Abs[20] Grid Differences, Tensions 1.0 minus 0.0, dot-b format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.d2.b*
Scaled [21]Abs. Grid Diffs, Tensions 1.0 minus 0.0, dot-b format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.d3.b*
Scaled Abs. Grid Diffs, Tensions 1.0 minus 0.0, grd format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.d3.grd*
Thinned Coordinate Difference Vector maps (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.am.jpg*
Dropped Coordinate Difference Vector maps (meters):	*vmdcdoht.od.nd.rg.f0.g1.g2.am.jpg*

[19] Note that for the NGVD29/NAVD88/CONUS combination, this file is NOT generated by pulling a tension of 0.4 across the CD (coordinate difference data). It is created through a remove/compute/restore process (Section 3.2). However, for the purposes of naming convention, when the final transformation grid is created, it is given this name.

[20] Absolute values

[21] Scaled by 0.59070 (Section 3.10).

Scaled Abs. Grid Diff maps (w/cvg), Tensions 1.0 minus 0.0, (meters):*cmtcdoht.od.nd.rg.f0.g1.g2.d3.am.jpg*

<u>What will be created by running doit3.bat (under NGVD29/NAVD88/CONUS only):</u>

Surface-ready Thinned Residual Coord. Diff. files (meters):	*smtrzoht.od.nd.rg.f0.g1.g2*
Gridded Res. Coord. Difference files, Tension 0.0, grd format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.00.grd*
Gridded Res. Coord. Difference files, Tension 1.0, grd format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.10.grd*
Gridded Res. Coord. Difference files, Tension 0.0, xyz format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.00.xyz*
Gridded Res. Coord. Difference files, Tension 0.4, xyz format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.04.xyz*
Gridded Res. Coord. Difference files, Tension 1.0, xyz format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.10.xyz*
Gridded Res. Coord. Diff. files, Tension 0.0, dot-b format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.00.b*
Gridded Res. Coord. Diff. files, Tension 1.0, dot-b format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.10.b*
Grid Res. Differences, Tensions 1.0 minus 0.0, dot-b format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.d1.b*
Abs[22] Res. Grid Diffs, Tensions 1.0 minus 0.0, dot-b format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.d2.b*
Scaled [23] Res. Abs. Grid Diffs, Tens. 1.0 minus 0.0, dot-b format (m):	*vmtrzoht.od.nd.rg.f0.g1.g2.d3.b*
Scaled Res. Abs. Grid Diffs, Tens. 1.0 minus 0.0, grd format (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.d3.grd*
True, Thinned Residual Coordinate Difference Vector maps (meters):	*vmtrzoht.od.nd.rg.f0.g1.g2.am.jpg*
True, Dropped Residual Coordinate Difference Vector maps (meters):	*vmdrzoht.od.nd.rg.f0.g1.g2.am.jpg*
Scaled Abs. Res. Grid Diff maps (w/cvg), Tensions 1.0 minus 0.0, (m):	*cmtrzoht.od.nd.rg.f0.g1.g2.d3.am.jpg*
Gridded V2[24] Coord. Difference files, Tension 0.4, grd format (meters):	*vmtv2oht.od.nd.rg.f0.g1.g2.04.grd* [25]
Gridded V2 Coord. Difference files, Tension 0.4, dot-b format (meters):	*vmtv2oht.od.nd.rg.f0.g1.g2.04.b*[26]
Gridded V2 Coordinate Difference maps, Tension 0.4 (meters):	*cmtv2oht.od.nd.rg.f0.g1.g2.04.am.jpg*

Table 5-3 describes each step that is executed inside of doit3.bat.

[22] Absolute values
[23] Scaled by 0.59070 (Section 3.10).
[24] V2 always refers to something generated directly from the original VERTCON 2.0 grid.
[25] Note that for the NGVD29/NAVD88/CONUS combination, this file is NOT generated by pulling a tension of 0.4 across the V2 (VERTCON 2.0) data. It is simply a copy of file /home/dru/VERTCON/VERTCON2/vertcon2.0.v3bounds.secXXXX.meters.grd (with XXXX=”g2”). However, for the purposes of naming convention throughout this build process, it is given this name.
[26] Note that for the NGVD29/NAVD88/CONUS combination, this file is NOT generated by pulling a tension of 0.4 across the V2 (VERTCON 2.0) data. It is simply a copy of file /home/dru/VERTCON/VERTCON2/vertcon2.0.v3bounds.secXXXX.meters.b (with XXXX=”g2”). However, for the purposes of naming convention throughout this build process, it is given this name.

Table 5-3: Workflow and files generated by executing "doit3.bat"

Step	What does it do	What does it create
mymedian5.f	Reads in the coverage files and the coordinate difference files. It then determines, based on the given grid spacing ("g1", in arcseconds), into which cell each particular coordinate difference (vector) falls. Then, on a cell-by-cell basis, it finds the "median vector" as follows: The absolute value of the orthometric height differences are sorted and the median length used to pick the PID called the "median". This point is then saved into the "thinned" files while all other points in that cell are saved into the "dropped" files. In most cases this is just the "CD" data, being the height in the new datum minus the height in the old datum. In the specific case of the ngvd29/navd88/conus transformation, this is the RZ data (being the CD data minus the V2 data). It then creates a batch file (the "second GMT file") full of GMT scripts, but only for gridding data using the GMT routine "surface", not for creating plots.	**Always:** • *gmtbat02.od.nd.rg.f0.g1.g2* • *cvtcdoht.od.nd.rg.f0.g1.g2* • *vmtcdoht.od.nd.rg.g0.g1.g2* • *cvdcdoht.od.nd.rg.f0.g1.g2* • *vmdcdoht.od.nd.rg.f0.g1.g2* **Not ngvd29/navd88/conus:** • *smtcdoht.od.nd.rg.f0.g1.g2* **ngvd29/navd88/conus:** • *smtrzoht.od.nd.rg.f0.g1.g2*

gmtbat02.od.nd.rg.f0.g1.g2	Runs GMT scripts (surface, xyz2grd and grd2xyz) as well as pre-compiled grid translation and manipulation programs (such as xyz2b.f, subtrc.f, gabs.f, gscale.f, b2xyz.f) to create a variety of gridded data files. Additional steps are performed for the ngvd29/navd88/conus transformation, to 1) Re-grid the RZ data from spacing "g1" to spacing "g2" 2) Add this to the V2 data, pre-calculated on "g2" spacing to yield CD data at "g2" spacing The primary grid files of interest after this program runs are: All: Transformations: "vmtcdoht….04.b" Not ngvd29/navd88/conus: Method noise "vmtcdoht....d3.b" ngvd29/navd88/conus: Method noise "vmtrzoht....d3.b"	**Always:** • *vmtcdoht.od.nd.rg.f0.g1.g2.04.grd* • *vmtcdoht.od.nd.rg.f0.g1.g2.04.b* **Not ngvd29/navd88/conus:**[27] • *vmtcdoht.od.nd.rg.f0.g1.g2.00.grd* • *vmtcdoht.od.nd.rg.f0.g1.g2.10.grd* • *vmtcdoht.od.nd.rg.f0.g1.g2.00.xyz* • *vmtcdoht.od.nd.rg.f0.g1.g2.10.xyz* • *vmtcdoht.od.nd.rg.f0.g1.g2.04.xyz* • *vmtcdoht.od.nd.rg.f0.g1.g2.00.b* • *vmtcdoht.od.nd.rg.f0.g1.g2.10.b* • *vmtcdoht.od.nd.rg.f0.g1.g2.d1.b* • *vmtcdoht.od.nd.rg.f0.g1.g2.d2.b* • *vmtcdoht.od.nd.rg.f0.g1.g2.d3.b* • *vmtcdoht.od.nd.rg.f0.g1.g2.d3.grd* **ngvd29/navd88/conus:** • *vmtrzoht.od.nd.rg.f0.g1.g2.00.grd* • *vmtrzoht.od.nd.rg.f0.g1.g2.10.grd* • *vmtrzoht.od.nd.rg.f0.g1.g2.00.xyz* • *vmtrzoht.od.nd.rg.f0.g1.g2.10.xyz* • *vmtrzoht.od.nd.rg.f0.g1.g2.04.xyz* • *vmtrzoht.od.nd.rg.f0.g1.g2.00.b* • *vmtrzoht.od.nd.rg.f0.g1.g2.10.b* • *vmtrzoht.od.nd.rg.f0.g1.g2.d1.b* • *vmtrzoht.od.nd.rg.f0.g1.g2.d2.b* • *vmtrzoht.od.nd.rg.f0.g1.g2.d3.b* • *vmtrzoht.od.nd.rg.f0.g1.g2.d3.grd* • *vmtv2oht.od.nd.rg.f0.g1.g2.04.grd* • *vmtv2oht.od.nd.rg.f0.g1.g2.04.b*
makeplotfiles02.f	Program to create the third GMT batch file, and fill it with calls which will make a variety of maps based on previously created data files and grids.	• *gmtbat03.od.nd.rg.f0.g1.g2.mf*

[27] The different data formats are because GMT works well in "grd" format, while many grid-manipulation programs are NGS-specific and work in the "dot-b" format, thus necessitating some translation back and forth (but the translation from grd to dot-b or back again requires a step into xyz format, either direction).

gmtbat03.od.nd.rg.f0.g1.g2.mf	Calls GMT scripts to create a variety of coverage and vector maps (of both thinned and dropped data) as color dot plots and a variety of color maps of grids (transformation or "04" grids and method noise or "d3" grids)	**Always:** • *cvtcdoht.od.nd.rg.f0.g1.g2.am.jpg* • *cvdcdoht.od.nd.rg.f0.g1.g2.am.jpg* • *cmtcdoht.od.nd.rg.f0.g1.g2.04.am.jpg* **Not ngvd29/navd88/conus:** • *vmtcdoht.od.nd.rg.f0.g1.g2.am.jpg* • *vmdcdoht.od.nd.rg.f0.g1.g2.am.jpg* • *cmtcdoht.od.nd.rg.f0.g1.g2.d3.am.jpg* **ngvd29/navd88/conus:** • *vmtrzoht.od.nd.rg.f0.g1.g2.am.jpg* • *vmdrzoht.od.nd.rg.f0.g1.g2.am.jpg* • *cmtrzoht.od.nd.rg.f0.g1.g2.d3.am.jpg* • *cmtv2oht.od.nd.rg.f0.g1.g2.04.am.jpg*

5.2.4 doit4.bat

This batch file generates the error estimates. First, it computes the data noise as the RMS of the "double difference vector" (coordinate difference of a point, minus the grid-interpolated transformation value of each point) for each cell that had data; these RMS values are then gridded with tension 0.9. Second, the data noise and the method noise grids are summed (in an RMS sense) to generate final error estimates. All vectors and their coverage are plotted, as well as color contour plots of the data noise (gridded RMS) and the final error estimates. This is the same error estimate calculation as was used in NADCON 5.0.

What must exist prior to running:

Thinned True Coordinate Difference Vector files (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2*
Dropped True Coordinate Difference Vector files (meters):	*vmdcdoht.od.nd.rg.f0.g1.g2*
Gridded Coord. Diff. files, Tension 0.4, dot-b format (meters):	*vmtcdoht.od.nd.rg.f0.g1.g2.04.b*

doit4.bat syntax:	*doit4.bat od nd rg fi g1 g2 mf* <return>
undoit4.bat syntax:	*undoit4.bat od nd rg fi g1 g2*<return>

Example doit4.bat syntax:	*doit4.bat ngvd29 navd88 conus 3 300 180 2* <return>
Example undoit4.bat syntax:	*undoit4.bat ngvd29 navd88 conus 3 300 180* <return>

What will be created by running doit4.bat (all runs):

Grid-Interp. Coord. Diff. Vector files (meters):	*vmagioht.od.nd.rg.f0.g1.g2*
Grid-Interp.,Thinned Coord. Diff. Vector files (meters):	*vmtgioht.od.nd.rg.f0.g1.g2*
Grid-Interp., Dropped Coord. Diff. Vector files (meters):	*vmdgioht.od.nd.rg.f0.g1.g2*
Double Differenced Coord. Diff. Vector files (meters):	*vmaddoht.od.nd.rg.f0.g1.g2*
Double Diff., Thinned Coord. Diff. Vector files (meters):	*vmtddoht.od.nd.rg.f0.g1.g2*
Double Diff., Dropped Coord. Diff. Vector files (meters):	*vmdddoht.od.nd.rg.f0.g1.g2*
Basic Statistics File:	*dvstats.od.nd.rg.f0.g1.g2*
The fourth GMT batch file:	*gmtbat04.od.nd.rg.f0.g1.g2.mf*
Grid-Interp. Coordinate Difference Vector maps (meters):	*vmagioht.od.nd.rg.f0.g1.g2.am.jpg*
Grid-Interp., Thinned Coord. Diff. Vector maps (meters):	*vmtgioht.od.nd.rg.f0.g1.g2.am.jpg*
Grid-Interp., Dropped Coord. Diff. Vector maps (meters):	*vmdgioht.od.nd.rg.f0.g1.g2.am.jpg*
Double Differenced Coord. Diff. Vector maps (meters):	*vmaddoht.od.nd.rg.f0.g1.g2.am.jpg*
Double Diff., Thinned Coord. Diff. Vector maps (meters):	*vmtddoht.od.nd.rg.f0.g1.g2.am.jpg*
Double Diff., Dropped Coord. Diff. Vector maps (meters):	*vmdddoht.od.nd.rg.f0.g1.g2.am.jpg*
The fifth GMT batch file:	*gmtbat05.od.nd.rg.f0.g1.g2*

RMS Double Diff. Coord. Diff. Vector files (meters):	*vmrddoht.od.nd.rg.f0.g1.g2*
Coverage of RMS DD Coordinate Diff. Vectors files:	*cvrddoht.od.nd.rg.f0.g1.g2*
Surface-ready RMS DD Coordinate Diff. files (meters):	*smrddoht.od.nd.rg.f0.g1.g2*
Grid. RMS DD Coord. Diff. files, T=0.9, grd format (m):	*vmrddoht.od.nd.rg.f0.g1.g2.09.grd*
Grid. RMS DD Coord. Diff. files, T=0.9, xyz format (m):	*vmrddoht.od.nd.rg.f0.g1.g2.09.xyz*
Grid. RMS DD Coord. Diff. files, T=0.9, dot-b format (m):	*vmrddoht.od.nd.rg.f0.g1.g2.09.b*
Transformation Error Grids, dot-b format (meters):	*vmeteoht.od.nd.rg.f0.g1.g2.b*
Transformation Error Grids, grd format (meters):	*vmeteoht.od.nd.rg.f0.g1.g2.grd*
The sixth GMT batch file:	*gmtbat06.od.nd.rg.f0.g1.g2.mf*
Coverage of RMS DD Coordinate Difference maps:	*cvrddoht.od.nd.rg.f0.g1.g2.am.jpg*
RMS Double Diff. Coord. Difference Vector maps (m):	*vmrddoht.od.nd.rg.f0.g1.g2.am.jpg*
Gridded RMS DD Coord. Diff. maps, T=0.9 (meters):	*cmrddoht.od.nd.rg.f0.g1.g2.09.am.jpg*
Transformation Error maps (meters):	*cmeteoht.od.nd.rg.f0.g1.g2.am.jpg*

Table 5-4 describes each step that is executed inside of doit4.bat.

Table 5-4: Workflow and files generated by executing "doit4.bat"

Step	What does it do	What does it create
checkgrid.f	Program to interpolate the previously created transformation grids and then compare these grid interpolated values to the true values of coordinate differences. It then sets up calls in the fourth GMT batch file to map all of these vectors.	• *vmagioht.od.nd.rg.f0.g1.g2* • *vmtgioht.od.nd.rg.f0.g1.g2* • *vmdgioht.od.nd.rg.f0.g1.g2* • *vmaddoht.od.nd.rg.f0.g1.g2* • *vmtddoht.od.nd.rg.f0.g1.g2* • *vmdddoht.od.nd.rg.g0.g1.g2* • *dvstats.od.nd.rg.f0.g1.g2* • *gmtbat04.od.nd.rg.f0.g1.g2.mf*
gmtbat04.od.nd.rg.f0.g1.g2.mf	Calls GMT scripts to create a variety of vector maps (of "all", "thinned" and "dropped" data) as color dot plots for both the "Grid Interpolated" coordinate differences and the "Double Differences" ("Grid Interpolated" minus "True")	• *vmagioht.od.nd.rg.f0.g1.g2.am.jpg* • *vmtgioht.od.nd.rg.f0.g1.g2.am.jpg* • *vmdgioht.od.nd.rg.f0.g1.g2.am.jpg* • *vmaddoht.od.nd.rg.f0.g1.g2.am.jpg* • *vmtddoht.od.nd.rg.f0.g1.g2.am.jpg* • *vmdddoht.od.nd.rg.f0.g1.g2.am.jpg*

myrms.f	Program to compute an "RMS Double Difference vector" for each cell that had data. Such a vector consists of the RMS mismatch between Grid Interpolated and True Coordinate differences, computed in lat, lon or eht. The RMS is entirely about magnitude. It registers the RMS vectors at the average latitude and average longitude of all the vectors that went into the RMS. All these data are then stored in files, and the fifth GMT batch file, used to grid this RMS DD data, is created.	• *gmtbat05.od.nd.rg.f0.g1.g2* • *vmrddoht.od.nd.rg.f0.g1.g2* • *cvrddoht.od.nd.rg.f0.g1.g2* • *smrddoht.od.nd.rg.f0.g1.g2*
gmtbat05.od.nd.rg.f0.g1.g2	Runs GMT scripts (surface, xyz2grd and grd2xyz) as well as pre-compiled grid translation and manipulation programs (such as xyz2b.f, gsqr.f, addem.f, gsqrt.f) to create a variety of gridded data files. The different data formats are because GMT works well in "grd" format, while many grid-manipulation programs are NGS-specific and work in the "dot-b" format, thus necessitating some translation back and forth (but the translation from grd to dot-b or back again requires a step into xyz format, either direction) The primary grid files of interest after this run are the Total Transformation Error Grids: "vmeteoht….b"	• *vmrddoht.od.nd.rg.f0.g1.g2.09.grd* • *vmrddoht.od.nd.rg.f0.g1.g2.09.xyz* • *vmrddoht.od.nd.rg.f0.g1.g2.09.b* • *vmeteoht.od.nd.rg.f0.g1.g2.b* • *vmeteoht.od.nd.rg.f0.g1.g2.grd*

makeplotfiles03.f	Takes the previously determined RMS DD data, in either vector form or in gridded form and creates the sixth GMT batch file, which will map all of that data.	• *gmtbat06.od.nd.rg.f0.g1.g2.mf*
gmtbat06.od.nd.rg.f0.g1.g2.mf	Calls GMT scripts to create a variety of coverage and vector maps (of RMS DD data) in black and white plots and a variety of color maps of grids ("method noise" or "09" grids and total error or "ete" grids)	• *cvrddoht.od.nd.rg.f0.g1.g2.am.jpg* • *vmrddoht.od.nd.rg.f0.g1.g2.am.jpg* • *cmrddoht.od.nd.rg.f0.g1.g2.09.am.jpg* • *cmeteoht.od.nd.rg.f0.g1.g2.am.jpg*

5.2.5 finalize.*rg*

This fifth batch file is not run in all regions or transformations. There are, in fact, five different versions of this batch file, each customized to and named for the regions of *pr*, *vi*, *guam*, *cnmi* and *as*. The function of a "finalize" batch file is to:

1. Extract a small sub-grid from the transformation grid (from doit3.bat) and the error grid (from doit4.bat) ***or*** to build a flat-plane transformation grid and flat-plane error grid, if doit3.bat and doit4.bat are skipped for that particular region/transformation. These sub-grids are usually tight bounding boxes around a specific island within the region.

2. To insert all of the individual island sub-grids created from #1 (above) into a full regional grid full of flags. In this way, the regional grid size remains unchanged, but the data in each transformation or error grid will have a flag of "-999" to indicate no transformation is available at a grid node when not near an island with a supported transformation.

The final build of VERTCON 3.0 consisted of customized use of the four "doit" batch files and "finalize.rg" for each region. They are all listed below. More details are found in Sections 6.4 through 6.8.

Region	**Transformation**	**doit.bat?**	**doit2.bat?**	**doit3.bat?**	**doit4.bat?**	**finalize.*rg*?**
conus	ngvd29/navd88	✓	✓	✓	✓	X
alaska	ngvd29/navd88	✓	✓	✓	✓	X
pr	lt/prvd02	✓	✓	✓	✓	✓
vi	lt/vivd09	✓	✓	X	X	✓
guam	guvd63/guvd04	✓	✓	✓	✓	✓
cnmi	lt/nmvd03	✓	✓	X	X	✓

as	lt/asvd02	✓	✓	✓	✓	✓

5.3 Releasing VERTCON 3.0 products

The most fundamental products coming out of ***VERTCON 3.0 release 20190601*** are the transformation grids and their associated error grids. At the conclusion of the process described in Section 5.2, the respective production filenames are:

Transformation grids:
vmtcdoht.*od.nd.rg.f0.g1.g2*.04.b for orthometric height
Error grids:
vmeteoht.*od.nd.rg.f0.g1.g2*.b for orthometric height

Implicit in these production-level filenames is that orthometric height transformations are released with units of meters, and that the grids are provided in the dot-b format described in Section 10.2.

For final distribution of the VERTCON 3.0 grids, the authors thought it was necessary to add the release name to the filenames. This was done so that a new release could be easily differentiated from previous and possible future releases. Also, the grid sizes and filter used were dropped from the filename convention, as they are traceable based on the release. This approach differs slightly from ***NADCON 5.0 release 20160901***, but will be adopted for all transformation grids going forward in both NADCON and VERTCON.

For the June 1, 2019 release of VERTCON 3.0 detailed in this report, the final transformation and error filenames use the format:

Transformation: vertcon_3.0_20190601.*od.nd.rg.coord*.trn.b
Error: vertcon_3.0_20190601.*od.nd.rg.coord*.err.b

where *od*, *nd*, and *rg* are the original datum, new datum, and region as previously described, and *coord* is ‘oht’ for orthometric height. The new filename convention was applied only to the final transformation and error grids; all other products coming out of the processing stream retain the original filenames as detailed in Section 5.2.

5.4 *VERTCON 3.0 release 20190601* in the NGS Coordinate Conversion and Transformation Tool (NCAT)

The transformation and error grids developed here are only useful if they are combined with a user friendly tool which can apply the transformations and correctly report the errors for specific points. In the past (Section 1), NGS has distributed executable software to implement the VERTCON transformations, which either needed to be downloaded locally to a user’s computer, or else was invoked by a web page “wrapper”. Such approaches lacked flexibility and do not represent modern geospatial tool approaches, such as Web Services. With ***VERTCON 3.0 release 20190601***, transformation implementation is available through the NGS Tools NCAT and VDatum.

NCAT contains a fully integrated set of tools to convert between many geodetic coordinate types and transform between datums. It features conversion and/or transformation of single or multiple points through a web GUI, Web services, and software downloads for standalone use of the tools. The transformation and error grids are defined only at specific points on a uniform grid; NCAT uses biquadratic interpolation to provide the local transformation and error for requested points. By way of example, one can now use NCAT to enter State Plane Coordinates in NAD 27 and orthometric heights in NGVD 29 and ask for UTM coordinates in NAD 83(2011) with orthometric heights in NAVD 88. Not only will it perform the proper coordinate type translation, it will transform across datums and provide an error estimate of said transformations.

VERTCON 3.0 release 20190601 datum transformations are valid only within the gridded areas of each region (Table 5-5). If a user requests a datum transformation for coordinates outside of the defined regions, NCAT will issue an error. Outside of these boundaries, NCAT is still able to convert between coordinate types within the same datum.

As of the writing of this report, VERTCON 3.0 in NCAT has not been released to the public, but expect the beta release for public testing by October 2019. The beta site can be found at https://beta.ngs.noaa.gov/NCAT/.

Table 5-5: Grid boundaries for VERTCON 3.0 regions.

	Grid boundaries (degrees latitude or longitude)			
Region	South	North	West	East
conus	24	50	235	294
alaska	50	73	172	232
hawaii[28]	18	23	199	206
pr	17	19	291	294.9 (294° 54’)
vi	17	19	294.9 (294° 54’)	296
guam	12	13.8 (13° 48’)	143	147
cnmi	13.8 (13° 48’)	22	143	147
as	-16	-13	188	193

6. Report on each transformation

In all, 7 separate transformations were computed for 7 different regions. Two different strategies were employed to generate the transformations: the gridded approach described in Section 3.1.3, and a uniform single-valued transformation as described in Section 3.3.

[28] Hawaii has no transformation in VERTCON 3.0, but this region will be used as the tool is expanded to support NAPGD2022

The remainder of this section contains individual reports for each transformation. In each report, we summarize the transformation field and its pertinent characteristics, provide a synopsis of the considerations for selecting the grid size (where appropriate), and include graphics and discussion on the final transformation and its associated error. For some cases, we also discuss the residuals of the transformation, that is, original input data (here, the thinned vectors) minus the model (transformation grid), to assess the goodness of fit of the transformation to the constituent data.

Because these transformations are based upon data on land only, **all transformations of *VERTCON 3.0 release 20190601* should only ever be applied to land areas, within the country, island, state or territory in which the data exists**. That means, for example, that the NGVD29/NAVD88/CONUS transformation should not be used in Mexico, Canada or any oceanic areas.

Table 6-1 provides some basic statistics for all of the transformations:

- **# of points**: All points which were evaluated by the VERTCON 3.0 team as of sufficient quality to be included in the transformation, e.g. are *not* outliers.
- **# of outliers**: Points identified as outliers, see Sections 3.8 and 4.6. As a reminder, such points were removed from the list of points early in the build process, prior to any median filtering or gridding algorithms. The total number of outliers is broken into two subclasses:
    - **filtered**: These points were eliminated through the use of whatever filter was chosen for the region/old datum/new datum combination, as discussed in Section 4.5.
    - **manual**: These points were manually eliminated through qualitative analysis or through additional outlier identification steps.

The reports include summary graphics for the field, transformation, and errors, but a full suite of detailed plots is available in a digital archive. See Section 11 for the description of the archive contents and structure.

Table 6-1: VERTCON 3.0 Transformations

region	***datum1***	***datum2***	***# of points***	***# of outliers (filter/manual)***	***filter***	***grid size (arcsec)***	***method***
conus	NGVD 29	NAVD 88	394,962	16,103 / 736	3a	300 / 180*	surf
alaska	NGVD 29	NAVD 88	3,023	24 / 8	3	60	surf
hawaii	*No data*						
pr	LT	PRVD 02	58	0 / 150	0	60	surf
vi	LT	VIVD 09	7	0 / 0	0	60	flat
guam	GUVD 63	GUVD 04	30	0 / 5	0	60	surf
cnmi	LT	NMVD 03	4	0 / 9	0	60	flat
as	LT	ASVD 02	14	15 / 0	3	120	surf/ flat**

In the *method* column, “surf” is the surface under tension and “flat” is a flat plane transformation.

* note that the NGVD29/NAVD88/CONUS transformation uses two different grid sizes, see Section 6.1.

** The gridded surface was only used on Tutuila; other islands use planar transformations

6.1 Conterminous United States + Washington DC (conus) – NGVD 29 / NAVD 88

One warning is associated with this transformation:

- ***The transformation of data between NGVD 29 and NAVD 88 in CONUS was not designed to be used in Canada or Mexico.***

For VERTCON 3.0, the "conus" region encompasses the conterminous United States, with a bounding box of 24-50 latitude, 235-294 longitude for the gridded area. To facilitate analysis over such a huge area, the digital archive includes plots at the regional level (subdividing CONUS into 9 regions of roughly equivalent size; mapflag = 1) and the state level (48 states plus Washington DC; mapflag = 2). Due to the huge number of points, finer-scaled plots are helpful for discerning details and trends in the data.

Due to the large point density for this transformation, the authors were able to rely more heavily on statistical measures to drive outlier detection and the selection of the two different grid sizes (see Section 6.1.3). The authors recognize that the large number of points leads to a lack of clarity for the CONUS maps – for a better assessment of the field's details, please see regional and state maps in the digital archive.

6.1.1 Outlier detection and removal

Data analysis began by applying filter3 (Section 4.5 and 4.6), which eliminated 16,103 points from the total initial dataset of 411,803 possible points. [29]It was then necessary to manually identify and remove certain points, due mostly to one reason: all "H/G[30]" points (all GPS-based orthometric heights) are not the same. The VERTCON 3.0 team wanted to retain Height Mod and Primary Airport Control Stations/Secondary Airport Control Stations points, but found that other GPS points were not agreeing well with the overall field. As such, certain analysis programs were developed and run on the post-filter-3 work file in order to determine a list of marks that were then to be manually entered into the "workedits" file as rejected points. These are points possessing the following three criteria:

1. have no neighboring points within 5 arcminutes of themselves
2. have an H88-H29 value that disagrees with the VERTCON 2.0 grid by over 10 cm
3. are published to an accuracy of only 0.1 meters

The primary program for this work was "findlonelypoints.f", with some manual "grep" work afterwards. Once completed, this program combined with some points identified by direct inspection

[29] Initial tests with filter 0 led to the conclusion that thousands of outliers were in the original database pull. Initial attempts to identify those outliers led to some simple experimental filters (1 and 2). However, it wasn't until NGS's Observation and Analysis Division developed a filter based upon actual observational sources and techniques that the majority of these outliers were readily identified and removed. That filter came to be called "filter 3".
[30] H/G = Source is "Horizontal Network Branch" and Technique is "GPS".

of the maps resulted in an additional 736 points removed from consideration. This generally allowed us to retain confidence that the physics built into the VERTCON 2.0 grid was to be trusted over questionable GPS-based orthometric heights. Once these additional points were removed, this combination of filter3 plus extra point removal came to be called “filter3a”.

6.1.2 Regional signals

In aggregate, the residuals between the VERTCON 2.0 grid and the VERTCON 3.0 input data averaged zero. Figure 6-1 presents an overview map of the 394,962 RZ points which were passed to the median filter. Areas with regional signals are present and are discussed in detail below. However we note that the median and mean of the data are 0.0 meters, as shown in the histogram of residuals in Figure 6-2. Of the 394,962 points, only 2685 points exceed 0.15 meter in absolute value.

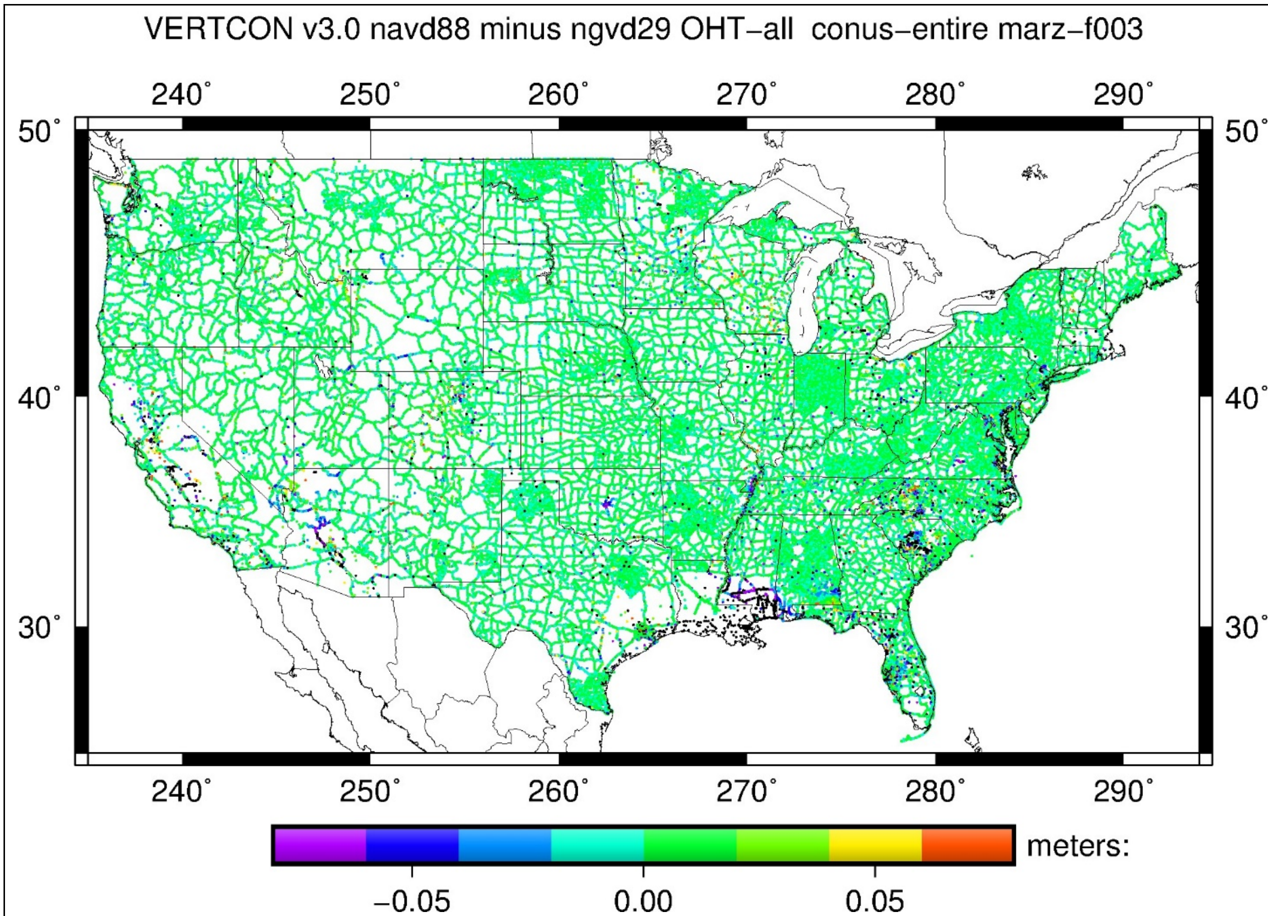


Figure 6-1: All residuals (coordinate differences, minus the VERTCON 2.0 value) in meters for NGVD29/NAVD88/CONUS. File name vmarzoht.ngvd29.navd88.conus.003.entire.jpg.

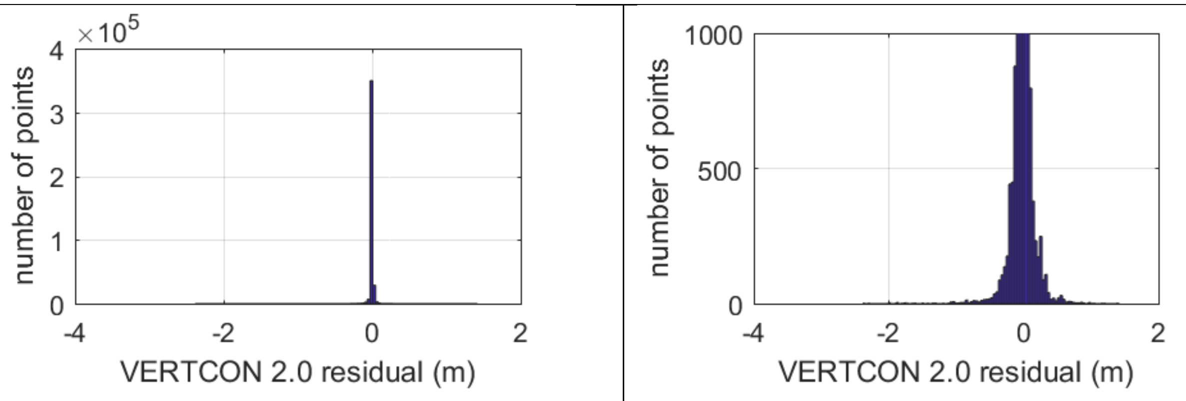


Figure 6-2: Histogram of all residuals shown in Figure 6-1, shown for the full range of the data (left) and zoomed in to better display the distribution tails (right).

Notable areas with regional departures from the VERTCON 2.0 grid include Central California, Southern Louisiana, Arizona, and North and South Carolina. The remainder of this section goes through these areas and discusses what grid sizes would be appropriate to capture these regional signals. Note that the decision to capture these signals in the VERTCON 3.0 grid was already discussed in Section 3.2.

The Central Valley of California is a known area of active subsidence due to groundwater pumping, so it is not surprising that this region has high RZ residuals, as it has likely experienced significant vertical movement since VERTCON 2.0 was first developed. Two E-W lines are immediately noticed by the eye, at approximately 37.0N and 36.5N (Figure 6-3). The lines indicate a depression feature in the residuals, with maximum deviations of -1.6 and -2.4 meters. These features are the largest magnitude signals in the entire VERTCON 3.0 dataset. In order to correctly capture these up-down signals, a minimum of 3 cells (each containing one median point) should span the line. From the list of grid sizes we were willing to use, the 5’ (0.083 deg/300 arcseconds), 7.5’ (0.125 deg/450 arcseconds), and 10’ (0.166 deg/600 arcseconds) choices would adequately sample the line while also leaving a cluster of points within each cell for the median filter process. A grid size of 10’ (600 arcseconds) is the coarsest cell size that would still result in 3 or more points across each line. The authors felt that 300 and 450 arcsecond grids captured more of the detail across the two lines.

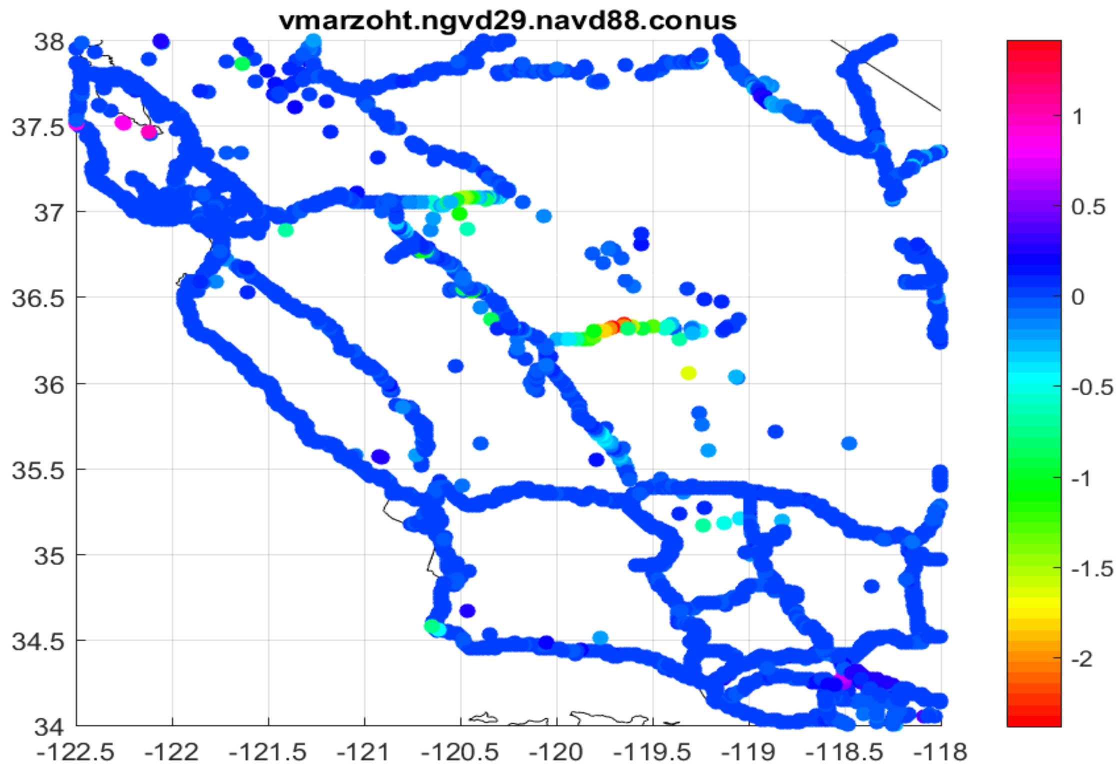


Figure 6-3: All residuals in meters for Central California, NGVD29/NAVD88/CONUS.

Southern Arizona contains a region just to the south of Phoenix with sections of large negative residuals (Figure 6-4). Inspection of the area in Google Earth shows this to be a farming area with desert in all other directions, suggesting that this area may experience significant height changes due to irrigation and/or groundwater pumping.

Curiously, the points at which these residuals occur all have NGVD 29 and NAVD 88 values in the NGS IDB which are original loads. That is, there has been no update to any of these points' heights since being loaded into the IDB. This raised the question of whether these points had been used in the original VERTCON 2.0 grid at all, and if not, why were they excluded? A discussion with the original builder of VERTCON 2.0 (Dennis Milbert, Personal Communication via email July 2018) indicated that the IDB itself was not actually the source of data for VERTCON 2.0. Rather, data came from the (then) Vertical Network Branch (VNB) of NGS. The reason for this is that the IDB was still being constructed in the late 1980's and early 1990's. (The "I" in "IDB" stands for Integrated – meaning it was the integration of the datasets from the Horizontal Network Branch and Vertical Network Branch).

Although some of the original files used to build VERTCON 2.0 have been misplaced, enough evidence points to the fact that these particular points were not used in the original VERTCON 2.0 grid. It is unfortunate that some data which the VNB would *eventually* put into the IDB did not make its way into the dataset for VERTCON 2.0.

The existence of these points' heights in the NGS IDB (and availability via datasheets) means that users of the NSRS have had access to this data for decades. Therefore, it was deemed important for the VERTCON 3.0 grid to reflect these points.

As in the California case, a variety of grids were tested for their adequacy in capturing this particular signal, with both 300 and 450 arcseconds being the leading contenders.

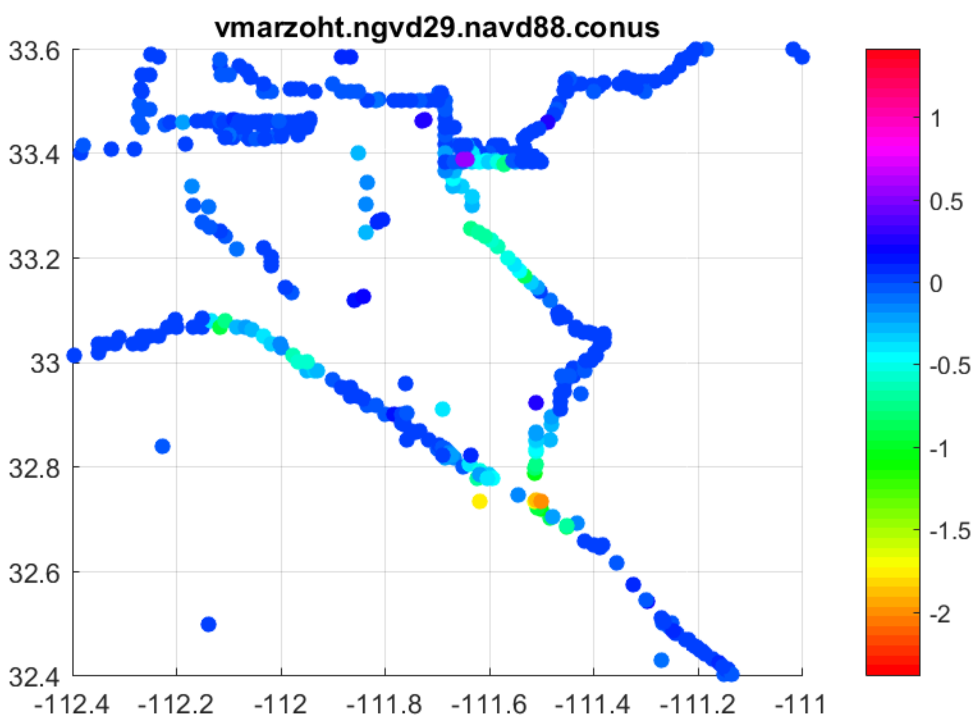


Figure 6-4: All residuals in meters for Arizona, just south of Phoenix, NGVD29/NAVD88/CONUS.

The Mississippi River Delta is a known area of active subsidence, so it is not surprising that this region has high RZ residuals, as it has likely experienced significant vertical movement since VERTCON 2.0 was first developed. The region of discrepancy spans approximately 29-30.5N, 89.5-93.5W (Figure 6-5). In this region, 104 points are available. These points clearly diverge from the VERTCON 2.0 grid, with median -0.21 meters. The data are somewhat sparse and span the range -0.10 to -0.38 meters, so a smaller grid size may be necessary to sample the detail of the regional signal. In all cases, the 5' (0.083 deg), 7.5' (0.125 deg), and 10' (0.166 deg) grid would result in 3 or more points across each of these features.

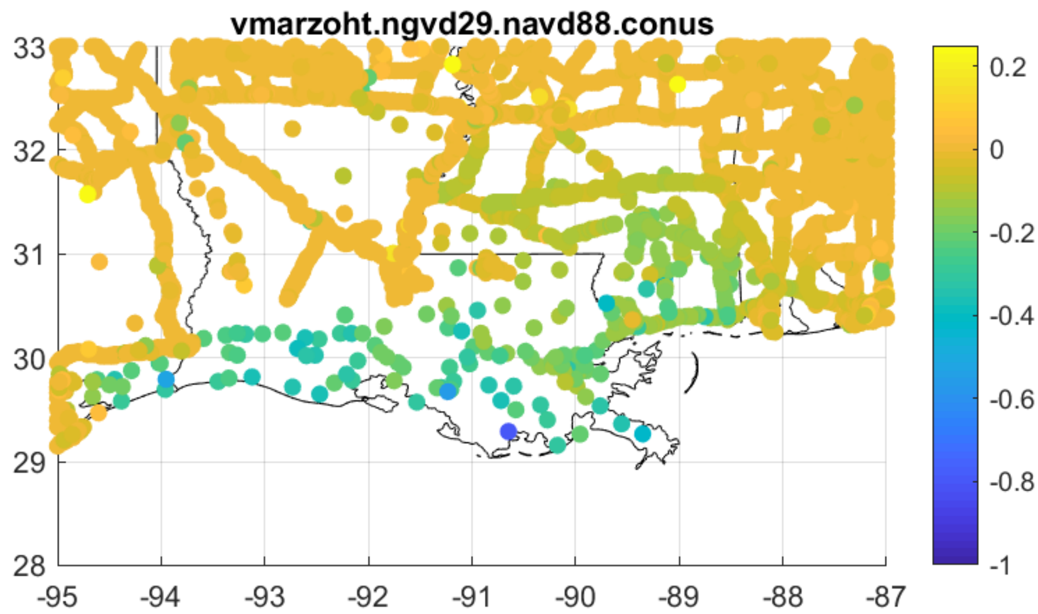


Figure 6-5: All residuals in meters for southern Louisiana and Alabama, NGVD29/NAVD88/CONUS. Note the change in color scheme and color range, relative to other regional data plots in this report.

The eastern US overall shows RZ of approximately 0.0 meters, but there are localized patches with high and low RZ values throughout South and North Carolina. The Carolinas have been extremely active in Height Modernization (Height Mod) work, and the VERTCON 3.0 transformation should capture the information from the Height Mod projects. Figure 6-6 and Figure 6-7 show the RZ values for this region, which are overall zero but have very localized signals. Residuals from VERTCON 2.0 can reach up to 30 cm on points that are usually off of leveling lines (Figure 6-8).

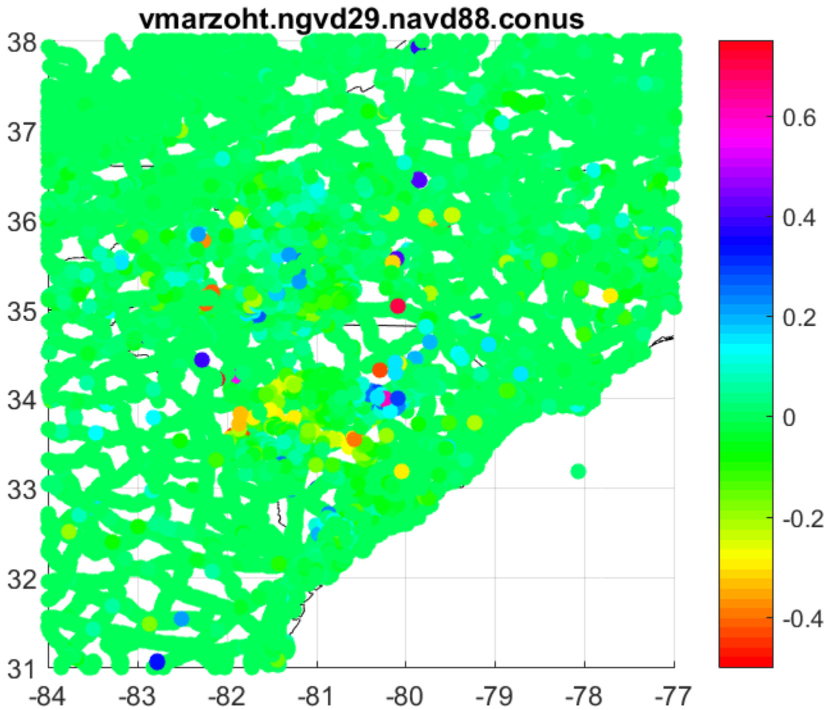


Figure 6-6: All residuals in meters for North and South Carolina, NAVD88/NGVD29/CONUS. Note that the scale bar has changed from previous plots, to better observe the localized information.

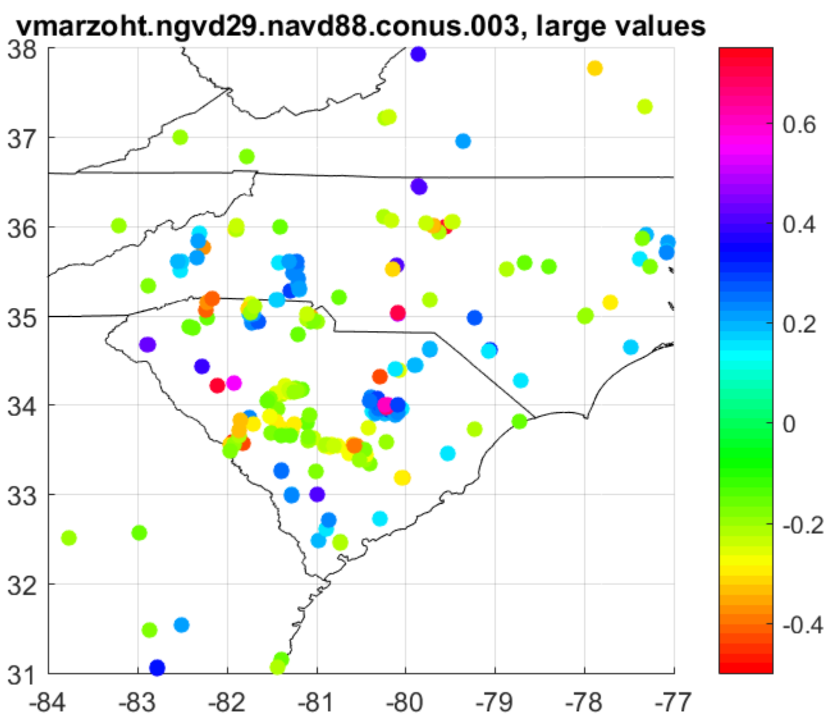


Figure 6-7: Residuals with absolute value greater than 0.15 meters, for North and South Carolina, NAVD88/NGVD29/CONUS.

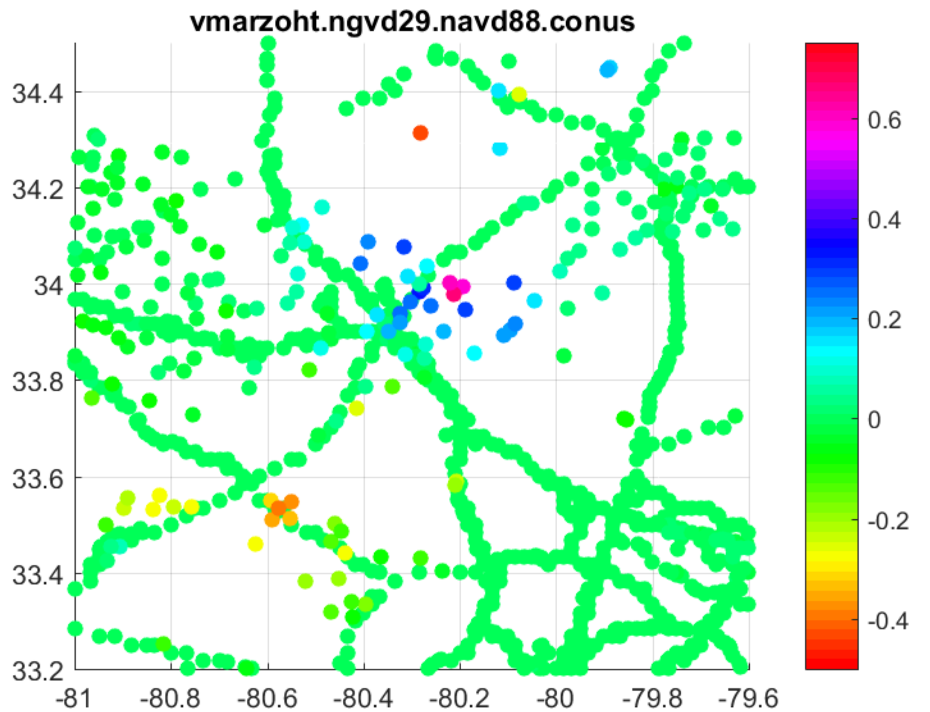


Figure 6-8: Same data as Figure 6-6, zoomed in to show a zone in greater detail.

6.1.3 Transformation

Vertical changes over time can be highly localized. However, the overarching goal of VERTCON 3.0 was, due to the failure of NGS to provide "realizations" of NAVD 88 (nationwide, epoch-specific versions as was done with NAD 83), to only update the existing CONUS/29/88 grid if a "regional signal" showed enough change. Thus not every single point was to be captured, but a "regional signal" did not need to be a massive statewide signal either, since vertical changes can be very localized. See also Section 3.2.

Height Mod surveys have the potential to add, or update, just a few, or even just a single NAVD 88 point in a region, leaving all other points unchanged. When compared to old leveling lines, this limited/singular new piece of information in just one grid cell that *also* contains old leveling has the potential to disagree with the leveling. This was, by mutual agreement of the VERTCON 3.0 team, *not* a "regional change". In such a case, an isolated point would likely be removed by the median filter.

However, if *enough* new points disagree with leveling, it is a "regional change." So, a compromise was made between being true to old leveling and being respectful of new Height Mod data. Thus, a filter size able to let through "enough" new data that would cause the median filter to pick *new* data over *old* data was needed. There was a lot of “human element” in this decision. The authors weighed the following questions in their qualitative analysis:

- Did the filter allow enough new points to reflect an entirely new line of leveling?
- For a single standalone Height Mod point located in an area otherwise void of all other heights, should that Height Mod point be included in the grid or thrown out?
- What is the regional nature of clusters of Height Mod points?

All of these questions were evaluated against a variety of filters, but the leading contenders immediately stood out as 300, 450 or 600 arcseconds. However, a look at Georgia is the best example of why 600 was quickly thrown out. As shown in Figure 6-9, all of the new work in Atlanta is lost with the 600 arcsecond filter. This was judged to be unacceptable, as it failed to capture the new “regional signal” of the Atlanta region.

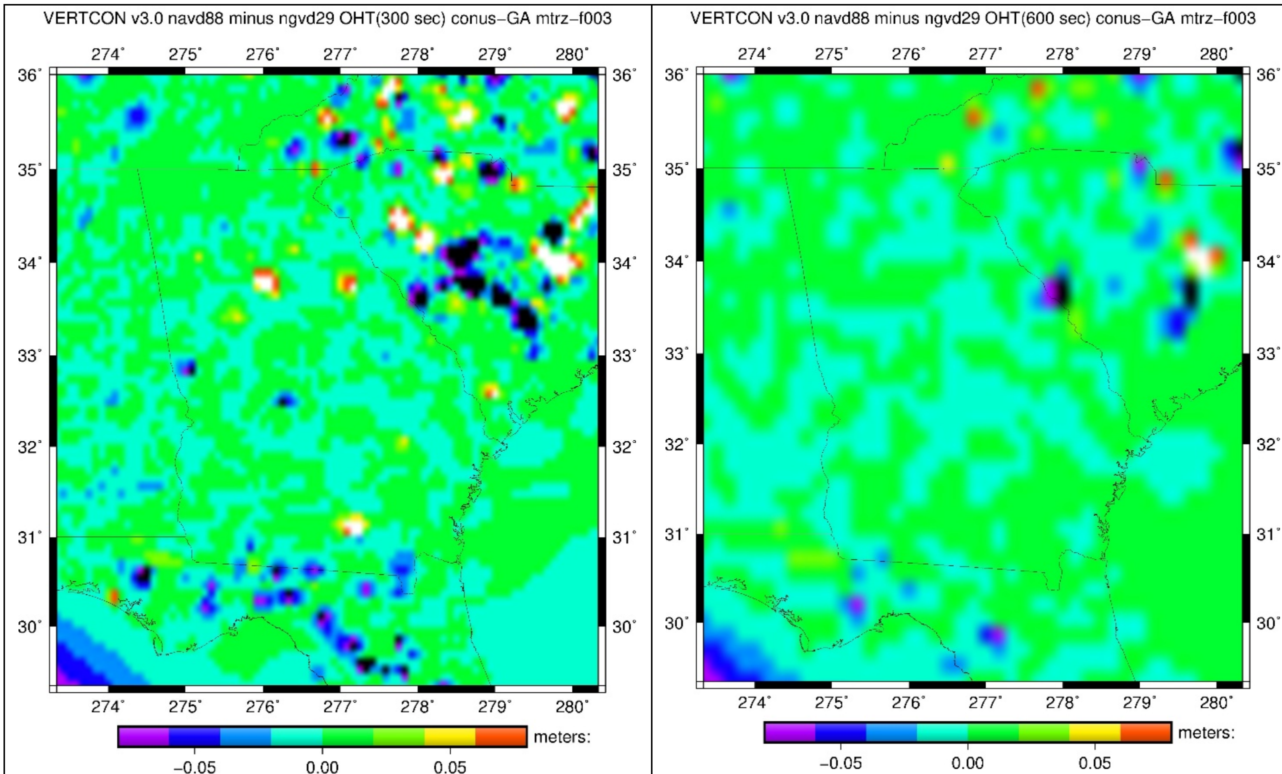


Figure 6-9: Gridded “compute” portion of the NGVD29/NAVD88/CONUS transformation (cmtrzoht*04*) for Georgia, shown here for an initial grid size of 300 arcseconds (left) and 600 arcseconds (right).

Between 300 and 450 arcseconds, data which led to definitive choices were difficult to come by. Two issues finally made us lean toward 300 arcseconds: First, that new leveling lines in California

(Figure 6-3) were best captured at 300 arcseconds, and secondly because, in general, vertical change is local, and 300 arcseconds captures more local information than 450 arcseconds.

All of the above discussion centered around finding the right grid spacing to capture “regional signals” of disagreement between the VERTCON 2.0 grid and the data as it currently exists on datasheets (based on data in the NGS IDB) available to the public.

A second decision had to be made, and that was the grid spacing for the final transformation grid itself. This decision required significantly less analysis. As the intent was to retain as much of the original VERTCON 2.0 information as possible while respecting regional changes, the obvious choice was to issue the VERTCON 3.0 transformation for NGVD29/NAVD88/CONUS on the same grid spacing as the original VERTCON 2.0 grid, namely 180 arcseconds.

To summarize, the final transformation for CONUS, NGVD 29 to NAVD 88, was formed through the following sequential operations:

1. Apply filter 3a to the input data
2. Form coordinate differences (CD), which are H88-H29.
3. Interpolate the original VERTCON 2.0 grid (originally gridded at 180 arcseconds) at the exact latitude and longitude of every point coming out of filter3a to create V2 data.
4. Difference the CD and V2 to form the residual RZ (Figure 6-1).
5. Apply a **<u>300</u>** arcsecond median filter to the RZ to yield the thinned dataset (Figure 6-10).
6. Pull a surface across the thinned RZ data at a surface tension of 0.4 (Figure 6-11).
7. Regrid the data from the previous step to **<u>180</u>** arcseconds.
8. Add the data from the previous step to the original VERTCON 2.0 grid, to yield the final transformation (Figure 6-12).

The **<u>300</u>** and **<u>180</u>** values above, which are in bold and underlined, reflect exactly where the “two grid spacing” decision affects this particular transformation. In no other combination of region/old datum/new datum was there any need for more than a single grid spacing (and in those cases, that grid spacing was simply the spacing of the final transformation grid. No RZ data exist for any grids but NGVD29/NAVD88/CONUS).

The errors for the transformation are provided in Figure 6-13.

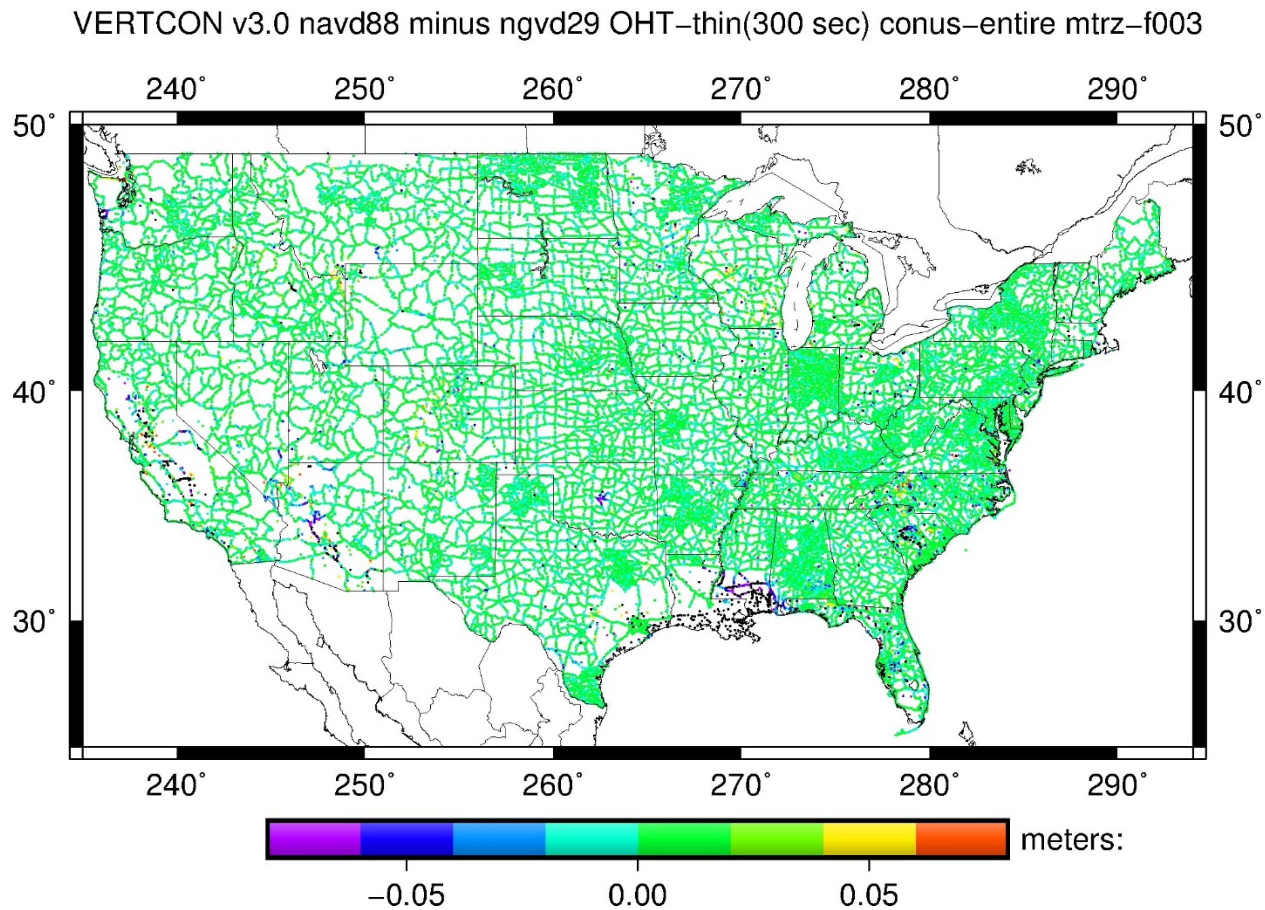


Figure 6-10: Thinned residuals after applying 5' (300 arcsecond) grid spacing for NAVD88/NGVD29/CONUS. File name vmtrzoht.ngvd29.navd88.conus.003.300.180.entire.jpg. Black is off the color scale.

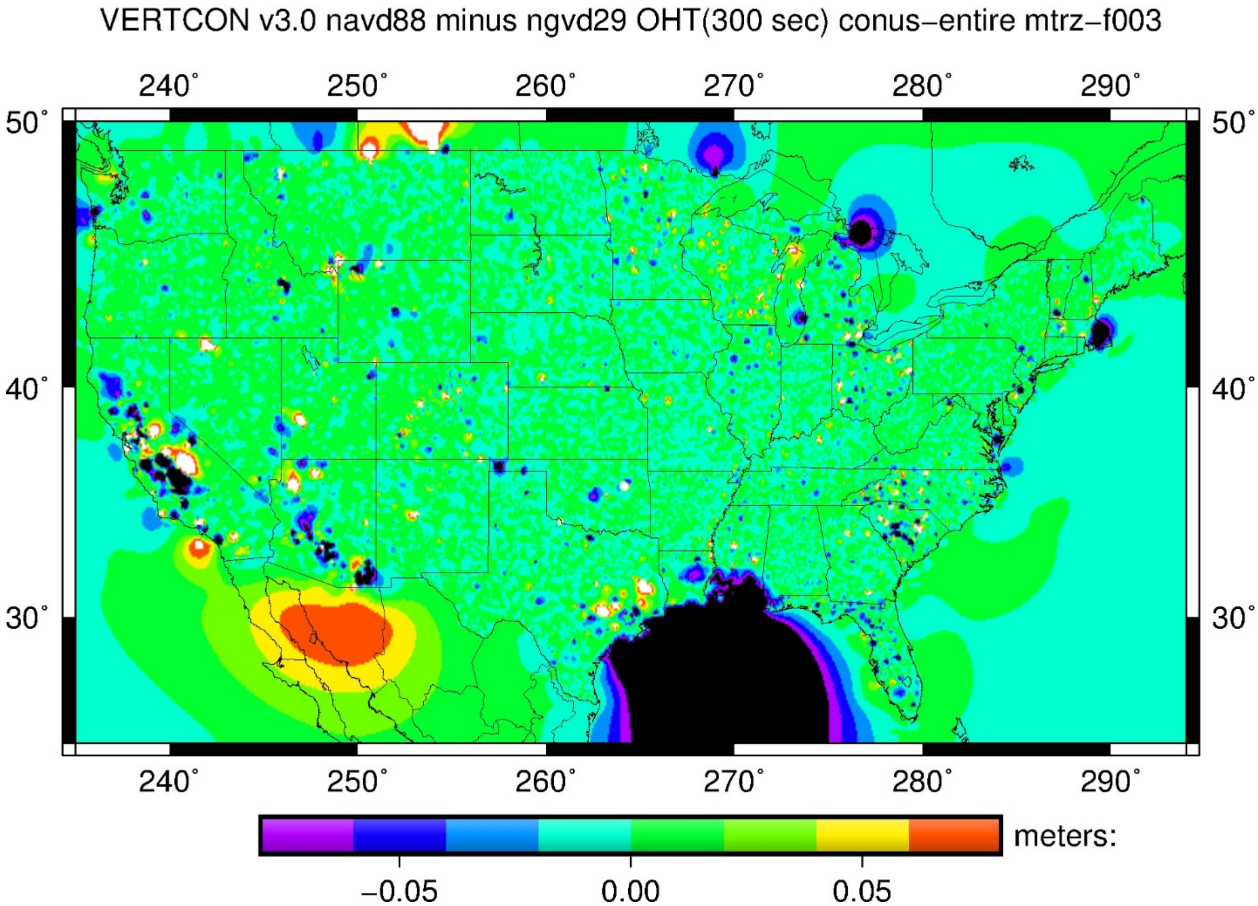


Figure 6-11: Gridded "compute" portion of the NAVD88/NGVD29/CONUS transformation, formed by taking the difference between VERTCON 2.0 and VERTCON 3.0 data and pulling a surface of tension 0.4 across those data.

(cmtrzoht*.003.300.180.04*)

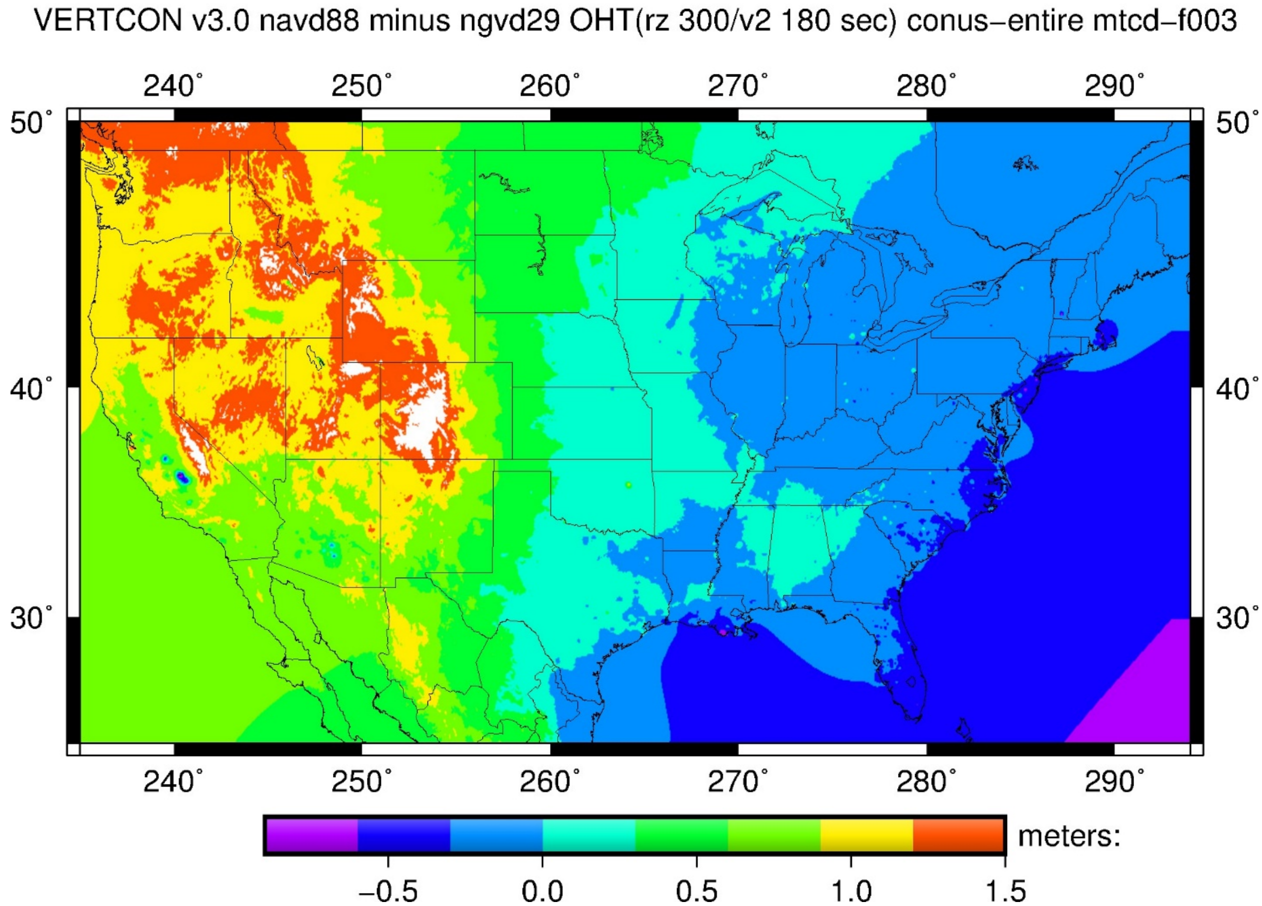


Figure 6-12: Final transformation in meters for NAVD88/NGVD29/CONUS, with 300 arcsecond final grid size.

(cmtcdoht*.003.300.180.04*)

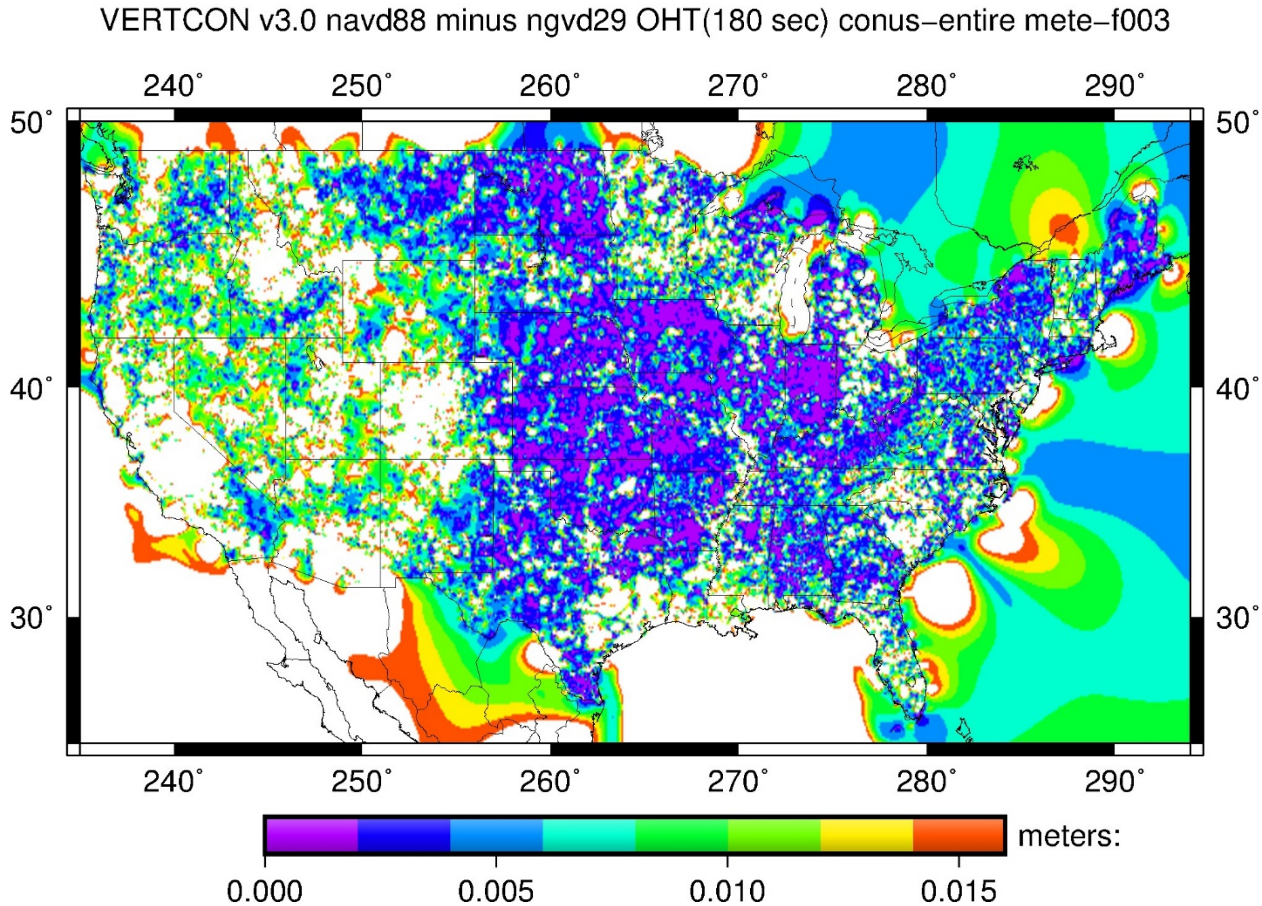


Figure 6-13: Total error for NAVD88/NGVD29/CONUS transformation.

6.2 Alaska (alaska) - NGVD 29 / NAVD 88

Two warnings are associated with this transformation:

- ***The transformation of data between NGVD 29 and NAVD 88 in Alaska should be treated with caution due to extremely limited data availability***.

- ***The transformation of data between NGVD 29 and NAVD 88 in Alaska was not designed to be used in Canada.***

The Alaska region encompasses the Alaskan mainland as well as the Aleutian Islands, bounded by 50-73 latitude and 172-232 longitude. To facilitate analysis over such a huge area, the digital archive includes plots at a secondary level, subdividing mainland Alaska into 4 quadrants (mapflag=1), with an additional subplot level for the Aleutian Islands.

Despite the huge area, Alaska has historically been undersampled in leveling campaigns and Height Modernization work. The initial datasheet pull yielded 3055 points for the NGVD 29 to NAVD 88 transformation. The authors implemented filter3, which removed 24 points from consideration, and also manually identified an additional 8 points as meriting manual removal. This brought the final point count to 3023 points in Alaska.

There are 4 zones with geodetic control for this transformation, as shown by the data distribution in Figure 6-14:

- the Alaskan mainland around Fairbanks and Anchorage, with leveling line connections to Prudhoe Bay and Canada
- some points to the southeast near Juneau
- one point on the western coast on Norton Bay
- one point on Kodiak Island to the south.

This transformation should only be used in mainland Alaska, and then only in those areas near actual geodetic control which created the transformation. Such areas can be broadly described as the south central part of Alaska between Anchorage and Fairbanks, with a single line of data running from Fairbanks to Prudhoe Bay.

To build the transformation, the authors examined regional and local data trends. The bulk of the Alaskan mainland leveling lines trend from north to south, creating a “low to high” signal that should be the most significant feature of the transformation. At a more local level, Fairbanks presented a unique issue, with two leveling lines of different magnitude which meet and overlap in a small zone (Figure 6-15). This overlap zone is well known to the Alaskan surveying community as the “Fairbanks Bowtie” (Nicole Kinsman, personal communication), and as such the authors wanted to respect and capture this very local signal in the VERTCON 3.0 transformation. A point of clarification is warranted here: The line from Prudhoe Bay (north shore of Alaska) to Fairbanks comes from datasheets that show both NGVD 29 and NAVD 88 heights available. However, the

NGVD 29 network never extended to Prudhoe Bay. The source of this error has not yet been discovered (and may never be), but there is no denying that the public had access to datasheets which showed both NGVD 29 and NAVD 88 heights along this line. As such, the VERTCON 3.0 team felt obligated to respect these values in the transformation grid.

The goal was to build a transformation that satisfied the following criteria:

- Overall transformation has ENE-WSW stripes and looks largely like a tilted plane
- Capture the detail in the Fairbanks area, so that surveyors working in this area have a valid transformation - do not average through the zone
- Areas of overlap for the two Fairbanks lines have an appropriately large error on the transformation
- Respect the datasheets that show both NGVD 29 and NAVD 88 heights in the 3 isolated regions, despite the likelihood that (from a purist standpoint) neither NGVD 29 nor NAVD 88 were actually available in those regions.

The level of detail in the Fairbanks area immediately led the authors toward a 60 arcsecond grid. However it is possible that too fine of a grid would violate the criteria for the regional pattern to look like a tilted plane. The authors compared 60 arcsecond and 1800 arcsecond grids and verified that both grids captured the overall regional trends, so there was no penalty in using the 60 arcsecond grid. The authors also verified that the 60 arcsecond transformation grid very accurately captured the Fairbanks bowtie.

The final 60 arcsecond transformation grid and total error are given in Figure 6-16 and Figure 6-17. It is worth noting again that it is not recommended to use this transformation in regions without geodetic control, which is reflected in the very large errors (Figure 6-17) for areas distant from the input data (Figure 6-14).

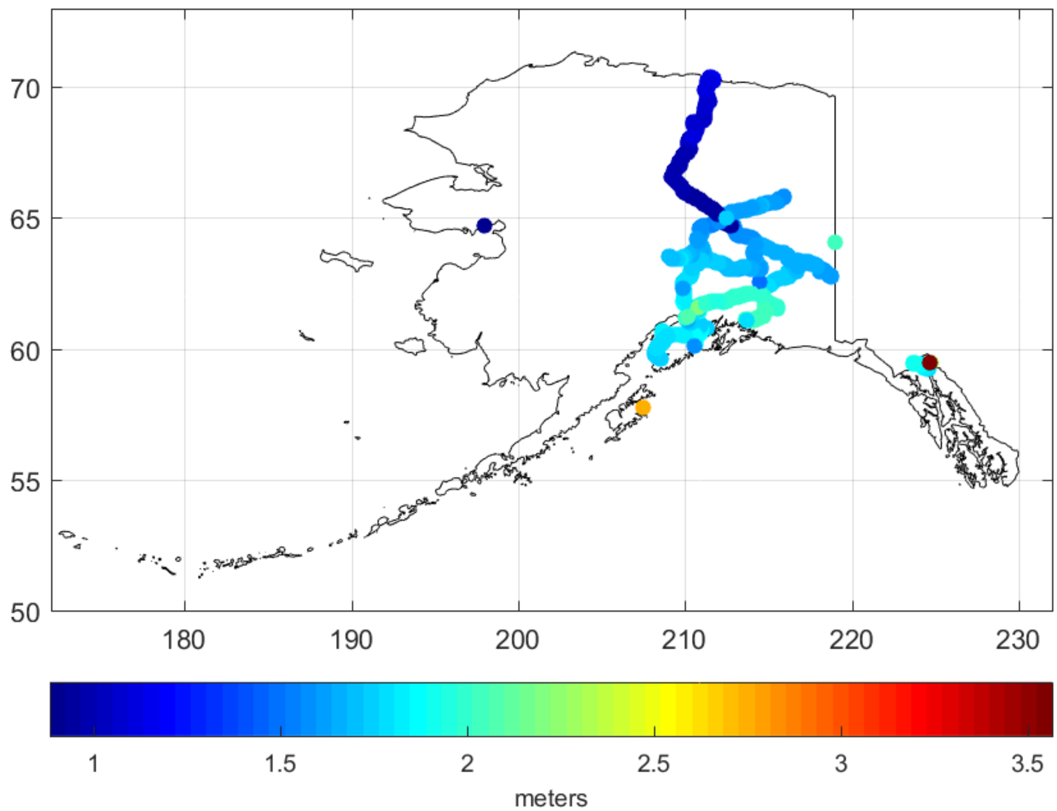


Figure 6-14: Coordinate differences (vmacdoht) for the 3023 points contributing to the NGVD29/NAVD88/ALASKA transformation.

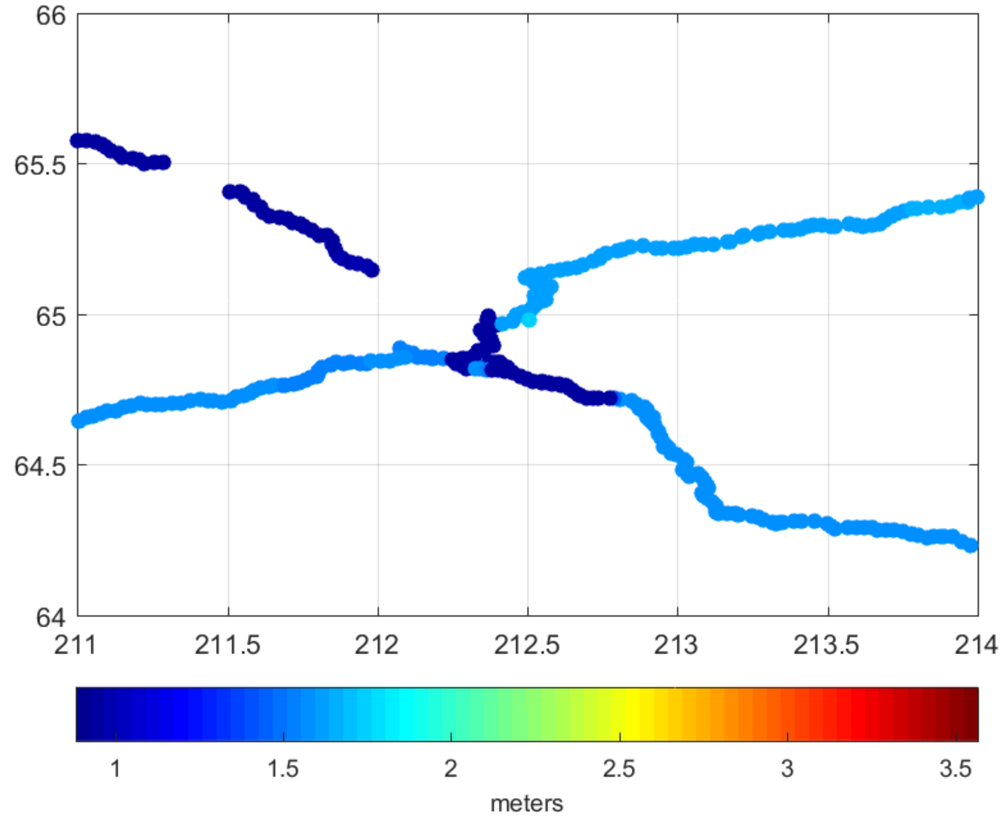


Figure 6-15: Coordinate differences in the Fairbanks area, showing the overlap zone (AKA "The Fairbanks Bowtie") for two different leveling regimes.

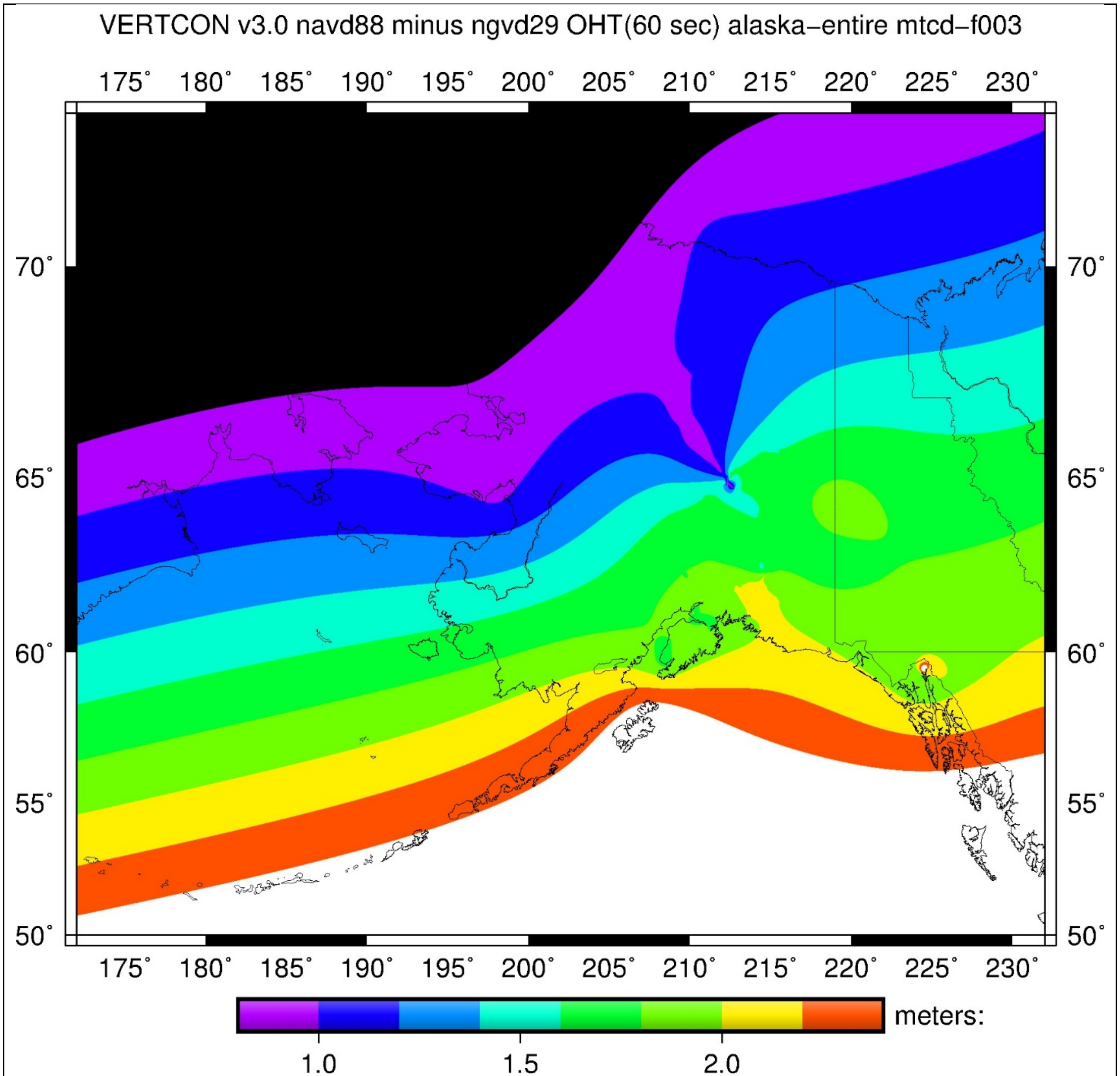


Figure 6-16: Final transformation in meters for NGVD29/NAVD88/ALASKA, with 60 arcsecond final grid size.

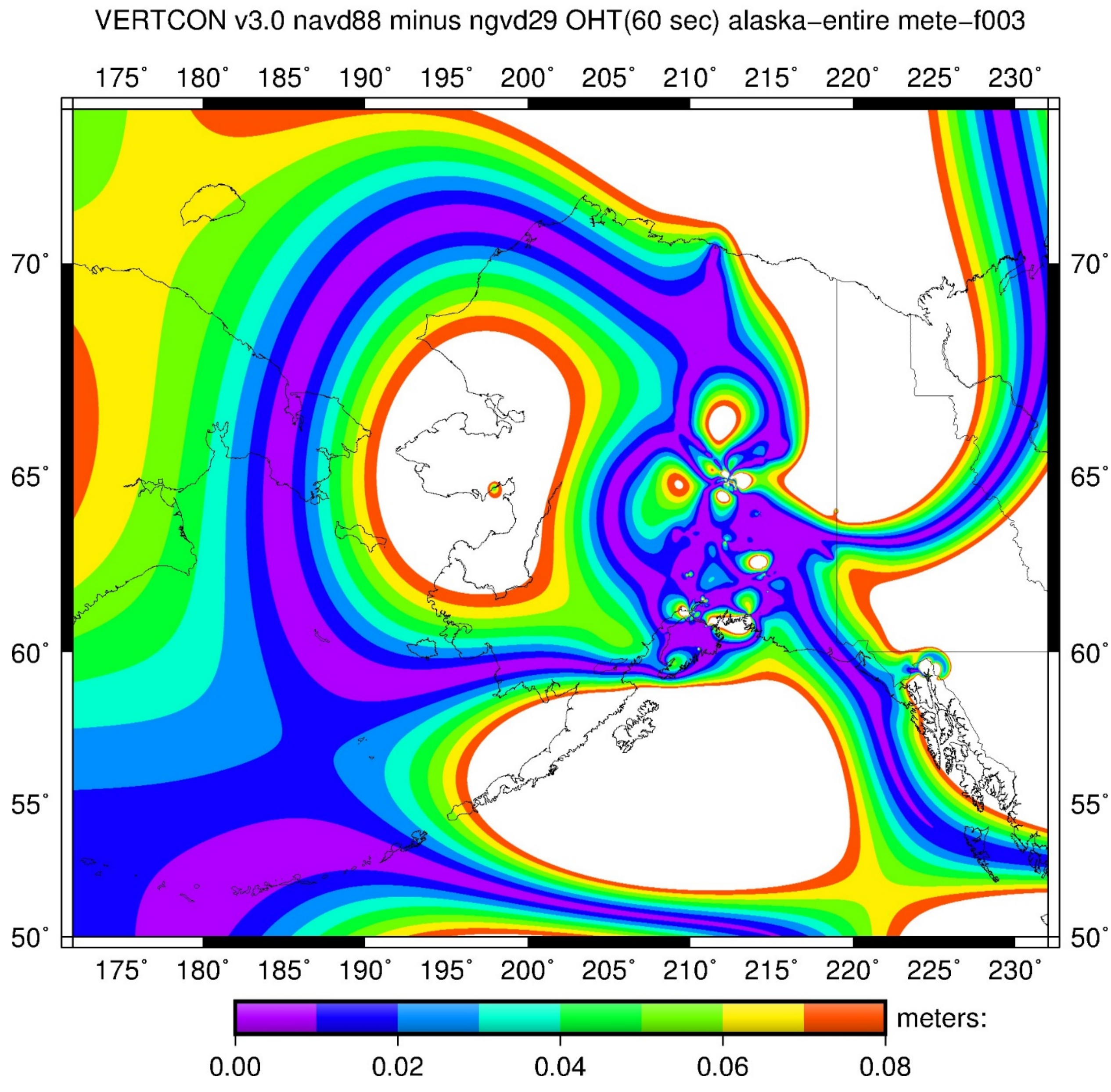


Figure 6-17: Total error for the NGVD29/NAVD88/ALASKA transformation.

6.3 Hawaii (hawaii)

The only vertical datums on Hawaii are Local Mean Sea Level at individual tide stations[31]. Without any other datums, no transformation can be built.

6.4 Puerto Rico (pr) – local tidal (LT) / PRVD 02

The region of Puerto Rico had 208 points from the initial data sheet pull, but 150 of those points were removed during a process of collating the data in the IDB with data as it appears on the datasheet. To be specific: those 150 points all had a "Local Tidal" height loaded into the IDB, but none of the datasheets for those 150 points showed that value to the public. And, as the purpose of the transformation is to support data that was available to the public, these points were removed. All of the removed points lie along the northern coast. The authors examined the remaining 58 points (Figure 6-18) and verified their quality as sufficient for inclusion in the transformation data set.

The transformation grid size was dictated by the spatial separation between different height regimes; the authors wanted to choose a grid size that would accurately capture these very local signals shown in Figure 6-19. The cluster of 3 points near the west coast was comprised of two groups with different values, with physical separation of about 0.01 degrees (approximately 60 arcseconds). The group of points on the southern coast was comprised of two groups, again with different mean values, and a physical separation that would require 60 or 120 arcsecond grids to pick up the separation between the two regimes. The northern group of points had extremely consistent values; therefore, these points did not drive grid size selection.

The authors chose the 1' (60 arcsecond) grid size for the final transformation. There are two areas where disagreeing yet equally valid data quantities exist, separated by 0.6' (west coast) and 2.0' (south coast). Therefore a high frequency (1') grid was necessary to capture their local signals. This high frequency grid did not have any wild oscillations on the rest of the island, which provided us with a general trust of the grid itself. We were concerned over the possible interpretation of the near zero error grid on the SE corner, but as it is an artifact of the data values and distribution, it cannot be helped. The authors viewed this as a minor difficulty among an otherwise acceptable solution.

As shown in Figure 6-18, data are only available on the main island of Puerto Rico and are not present on the minor islands of Culebra, Desecheo, Mona, or Vieques. Therefore, the transformation (Figure 6-20) and errors (Figure 6-21) are defined only for a tight region encompassing Puerto Rico itself. For all other parts of the "PR Puerto Rico" region (291-294.9W, 17-19N), the transformation is not available. To enforce this rigorously, batch file "**finalize.pr**" (Section 5.2.5) was run after "doit4.bat". That batch file essentially keeps the transformation and error grid values around the island of Puerto Rico and replaces the remainder of the grids with flag values of "-999". The exact

[31] NGS has not yet defined an official vertical datum for this state, though as of 2019 there is an ongoing leveling project, funded and executed by the state, which NGS had intended to use in the creation of a Hawaiian Vertical Datum. However, as the creation of NAPGD2022 is pending, the creation of an independent leveling based vertical datum is not guaranteed to occur prior to 2022.

bounds of the retained transformation/error grid data around the island of Puerto Rico can be described by a concave hexagon[32], consisting of lines of either constant latitude or constant longitude, using these six vertices:

18.55/292.7, 18.55/294.5, 18.2/294.5, 18.2/294.4, 17.9/194.4, 17.9/292.7

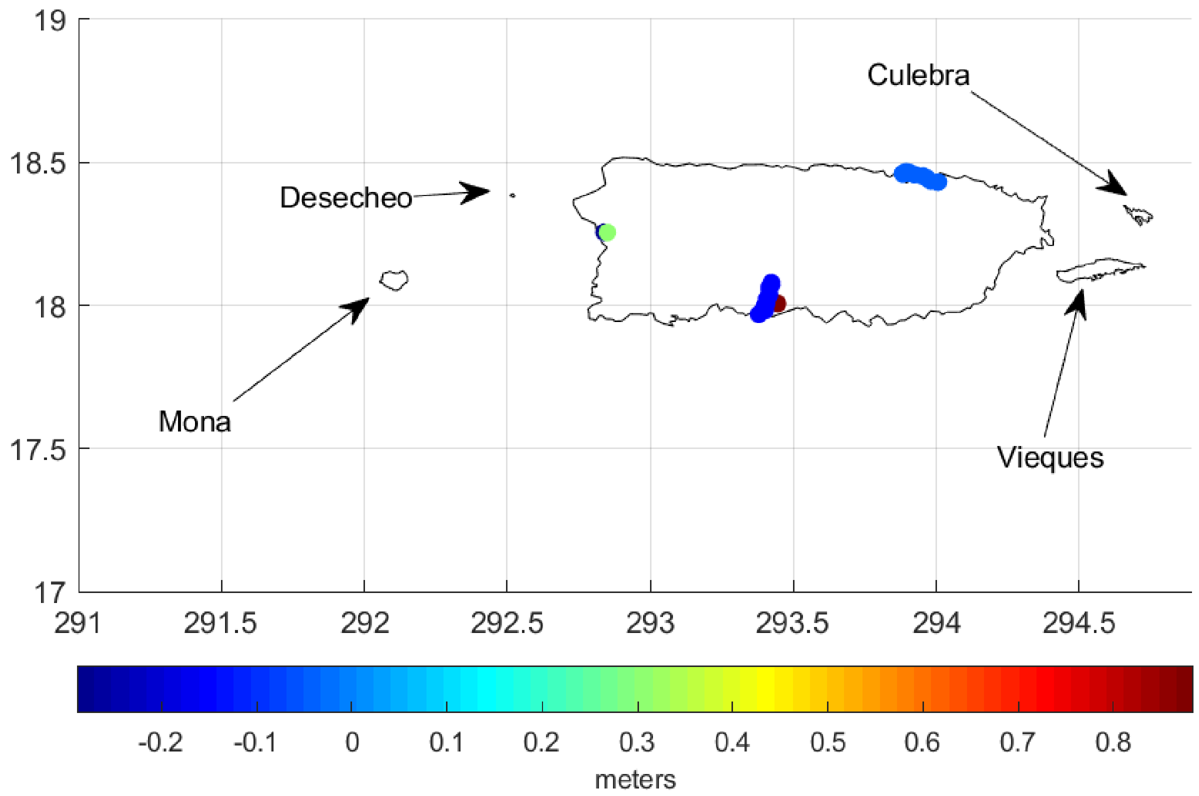


Figure 6-18: Coordinate differences (vmacdoht) for the 58 points contributing to the LT/PRVD02/PR transformation.

[32] A bounding rectangle wouldn't work for the island of Puerto Rico, as any rectangle which contains that island will also contain at least part of the western portion of Vieques. As such, the bounding hexagon "goes around" Vieques while still containing all of the island of Puerto Rico.

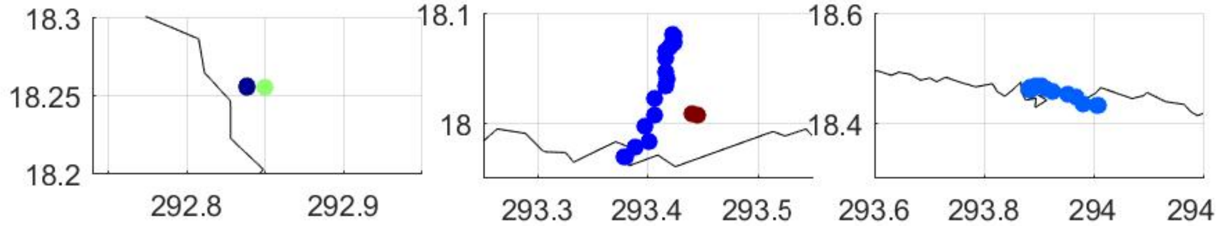


Figure 6-19: Coordinate differences from Figure 6-18, zoomed in to show the western (left panel), southern (center panel), and northern (right panel) points. This figure uses the same color bar as Figure 6-18.

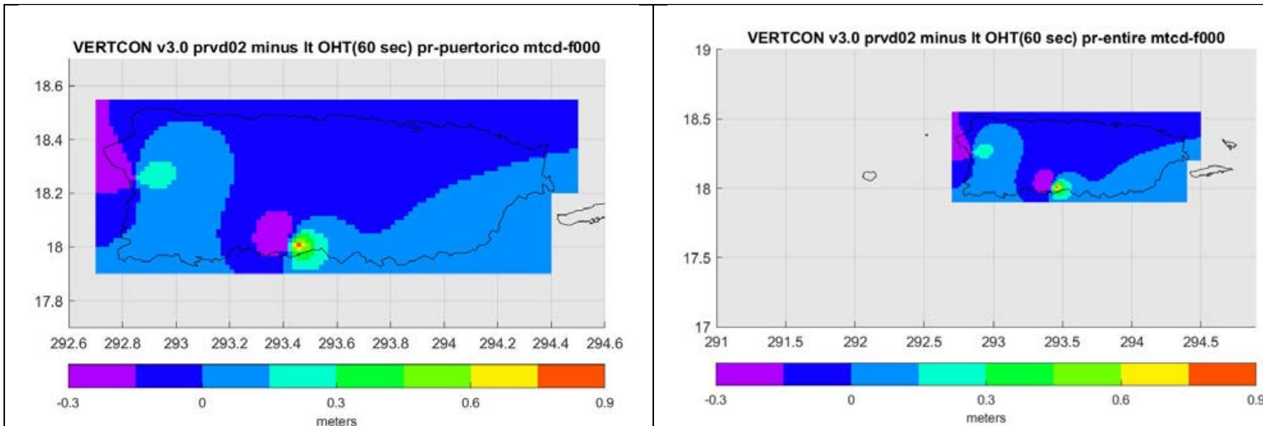
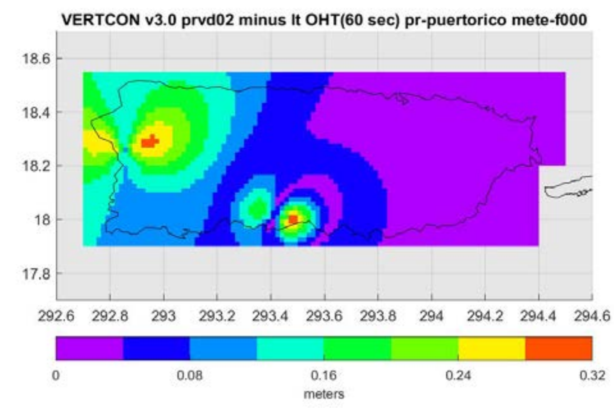


Figure 6-20: Final transformation in meters for LT/PRVD02/PR, with 1' final grid size, showing the Puerto Rico main island area where the transformation is defined (left) and the extent of the full grid as provided by VERTCON 3.0 (right).



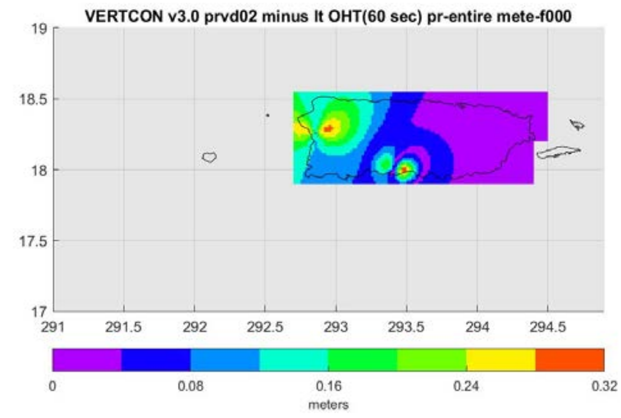


Figure 6-21: Total error for LT/PRVD02/PR transformation, showing the Puerto Rico main island area where the transformation is defined (left) and the extent of the full grid as provided by VERTCON 3.0 (right).

6.5 US Virgin Islands (vi) – local tidal (LT) / VIVD 09

The region of the US Virgin Islands had only 7 points from the initial data sheet pull (Figure 6-22). The authors examined the data sheet for each point and determined that they were all of sufficient quality for inclusion in VERTCON 3.0.

The VIVD 09 datum is a single name which covers effectively three independent sub-datums, one for each of the three islands: St. Croix, St. John, and St. Thomas (Doyle and Smith, 2011). Each island should be treated independently, with a local transformation that respects local data and does not influence other islands.

To begin, no data exist on St. John, therefore a transformation is not available for this island.

St. Thomas has 4 points (Figure 6-23), geographically clustered on the south shore, and numerically clustered with an average of 0.2407 m and standard deviation 0.0136 m. The authors examined the full range of grid sizes tested for the surface-under-tension fit to the data and found them all to be unsatisfactory for describing these points. The 60 arcsecond grid was overly small, with nonsensical transformation values for the areas of St. Thomas where data were not present. Even at 900 arcsececonds, the gridding process yields a tilted plane across the island – again, unrealistic and unsupported by the data. No trustworthy surface could truly be fit through such geographically clustered points, so the authors felt the safest, yet still useful method was to build a constant (flat plane) transformation grid at 0.2407 m (Figure 6-25), with a constant (flat plane) total error “ete” grid of 0.0136 m (Figure 6-27).

Similarly, St. Croix has 3 points (Figure 6-23), geographically clustered on the south shore. However, the points differ in magnitude, with two points at 0.17 m (TV1512 and TV1535) and one point at -0.111 m (TV1536). Unfortunately, after a careful examination of the sources of each, the quality of these points could not be discerned from each other, and were therefore allowed to stand as acceptable points. The three points taken together have a mean of 0.0787 m and standard deviation of 0.1643 m. Pulling a surface across these points yielded the same issues as for St. Thomas. Therefore the authors chose to build another constant transformation grid using the mean of 0.0787 m for the transformation (Figure 6-25) and a total error of 0.1643 m (Figure 6-27). The large error estimate cannot be helped, as the quality of the three points cannot be discerned from each other, leaving only the standard deviation as a reasonable error estimate.

The authors further justified the use of flat-plane transformations by examining the error estimates that would have resulted from the surface-under-tension fitting approach applied to other regions. The error grid at a moderate grid size (900 arcseconds) led to unrealistically large error estimates – 25 cm on St. Croix and 50 cm on St. Thomas. This is likely due to the variability in pulling at different tensions without data to control the oscillations and extrapolations. These unrealistic numbers do not properly reflect the tight (1.3 cm) standard deviations on St. Thomas, and are a bit too high for those on St. Croix too. As such, the build to a constant transformation with constant error grid for each island seems justified.

Even for flat plane transformations such as these, a grid spacing must be chosen so that the final transformation and error products can be distributed in a *.b file and so that areas where "no transformation is provided" can be clearly delineated. For the Virgin Islands, the authors chose a 60 arcsecond grid size.

Thus, for this region, the build process only uses the "doit.bat" and "doit2.bat" routines, followed by a new batch file called "**finalize.vi**". That batch file builds the flat-plane transformation and error grids for the island of St. Thomas and St. Croix, and replaces the remainder of the grids with flag values of "-999". The exact bounds of the "flat plane" transformation/error grid data around those two islands are found in the table below:

Island	**South**	**North**	**West**	**East**
St. Thomas	18° 18'	18° 24'	294° 56'	295° 11'
St. Croix	17° 36'	17° 48'	295° 04'	295° 28'

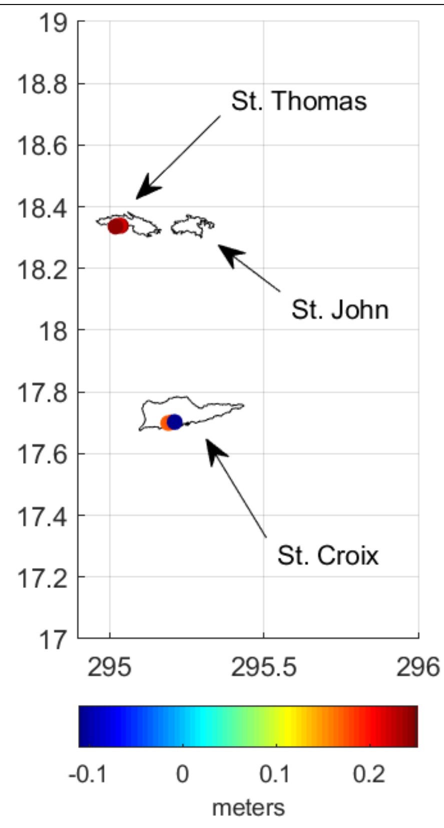


Figure 6-22: Coordinate differences (vmacdoht) for the 7 points contributing to the LT/VIVD09/VI transformation.

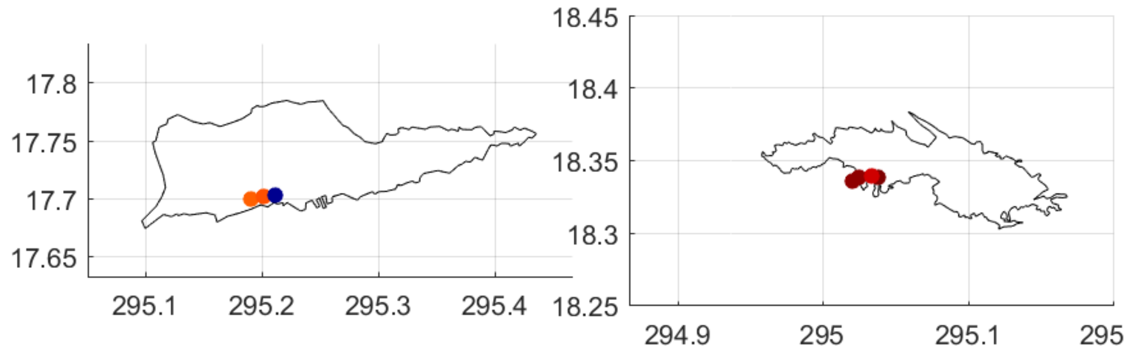


Figure 6-23: Coordinate differences from Figure 6-22, zoomed in to show detail on St. Croix (left) and St. Thomas (right). This figure uses the same color bar as Figure 6-22

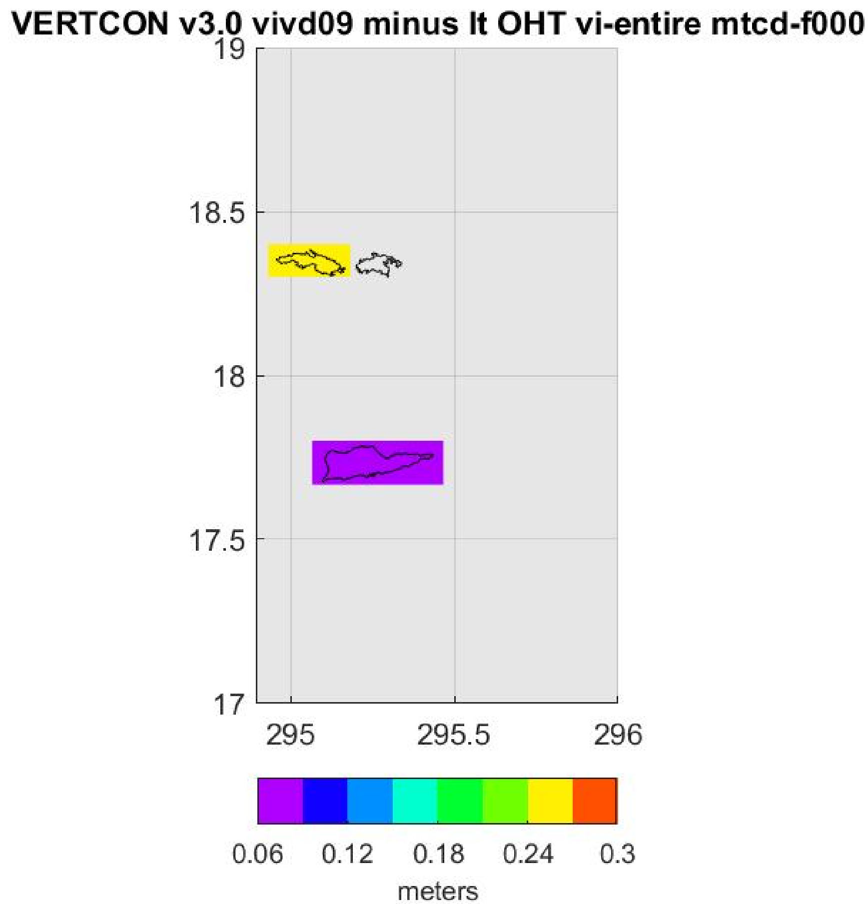


Figure 6-24: Final transformation in meters for LT/VIVD09/VI.

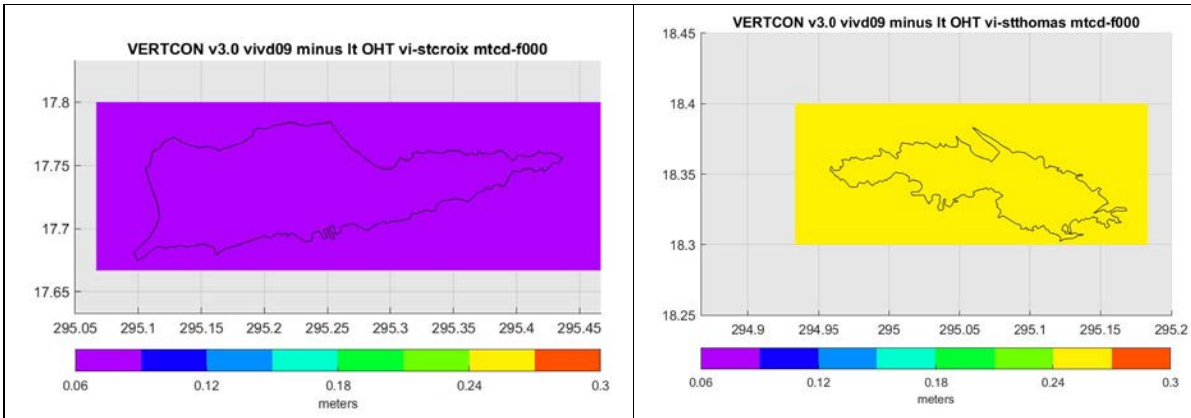


Figure 6-25: Final transformation in meters for LT/VIVD09/VI, zoomed in to show detail for St. Croix (left) and St. Thomas (right).

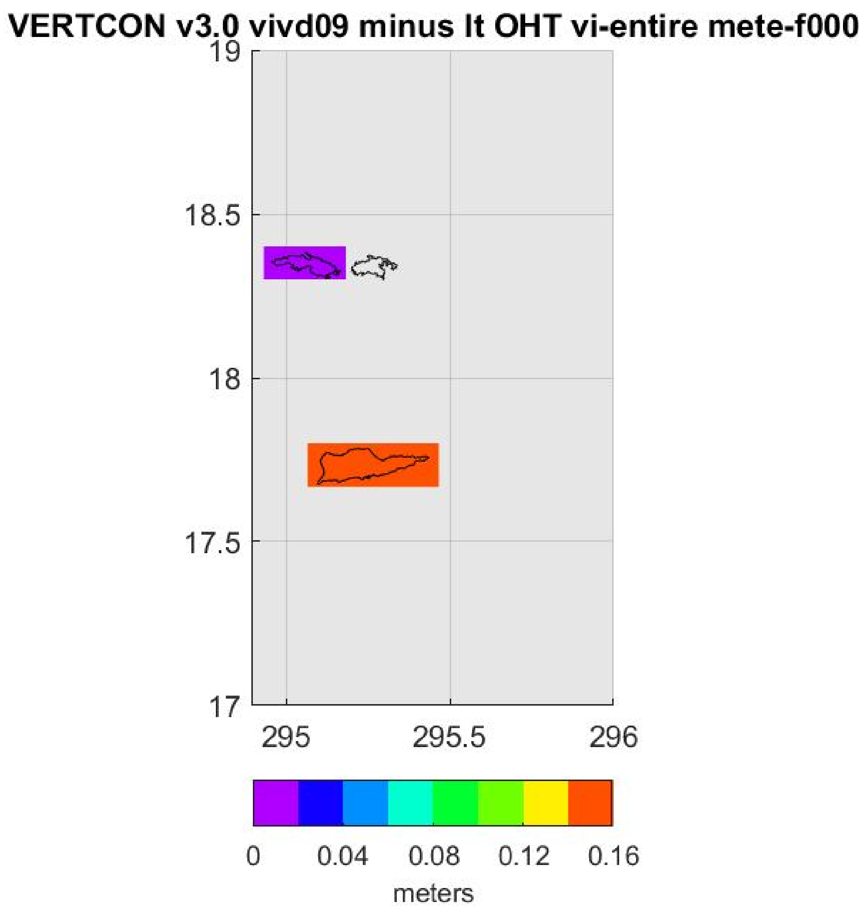


Figure 6-26: Total error for the LT/VIVD09/VI transformation.

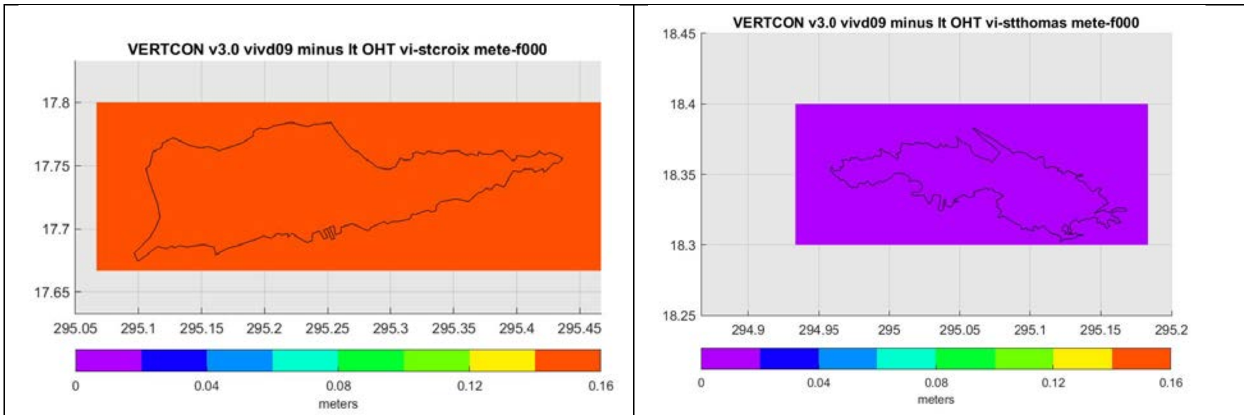


Figure 6-27: Total error for LT/VIVD09/VI, zoomed in to show detail for St. Croix (left) and St. Thomas (right).

6.6 Guam (guam)

Although "LMSL" as a generic datum for heights existed in all other regions of the United States, NGS does not have any points in the IDB with this datum in Guam. The absence of data occurs partly because, of all the island territories of the United States, Guam has an historic, geodetic (not "Local Tidal"), vertical datum. Therefore, unlike other regions, no transformations using LMSL are available in this region.

6.6.1 GUVD 63 / GUVD 04

For the GUVD 63 - GUVD 04 datum pair, the region of Guam had 35 points from the initial data sheet pull. The authors determined that 5 of the points should be eliminated because the heights were not recorded with sufficient precision (indicating they were not Height Modernization points) or would have been removed by filter3. The remaining 30 points (Figure 6-28) were of sufficient quality for inclusion in the transformation data set.

We note that the datum definition for GUVD 63 is not known, nor whether it was tied to multiple tide stations or even temporary stations. Therefore it is important that the final transformation follows all available data as closely as possible. There are two spots on Guam where the neighboring points are very close, yet disagree and which do not lend themselves to one being chosen over another. One prominent example exists in the southwest part of Guam, where TW0398 and TW0406 disagree by 20 cm. Without a way to weigh one over the other, both are treated equally by the gridding algorithm. A fine transformation grid of 60 arcseconds (Figure 6-29) is best able to capture the high frequency signal generated by these two neighbors. The error grid (Figure 6-30) shows that the error on the island tends toward 0 cm, but the error in the two zones of disagreeing neighbors rises as high as 15 cm or so. The 60 arcsecond (1 arcminute) grid is the only one capable of capturing both of these signals. As with other island areas, we chose to define the transformation only in the area supported by data, and mask out the remaining area as "no transformation available."

Thus, for this region, the build process consists of all four "doit" batch files, followed by one final batch file, "**finalize.guam**". That batch file retains the transformation and error grids in a bounding box tightly surrounding the island of Guam and replaces the remainder of the grids with flag values of "-999". The bounding box around Guam is found in the table below:

Island	South	North	West	East
Guam	13° 12'	13° 42'	144° 36'	145° 00'

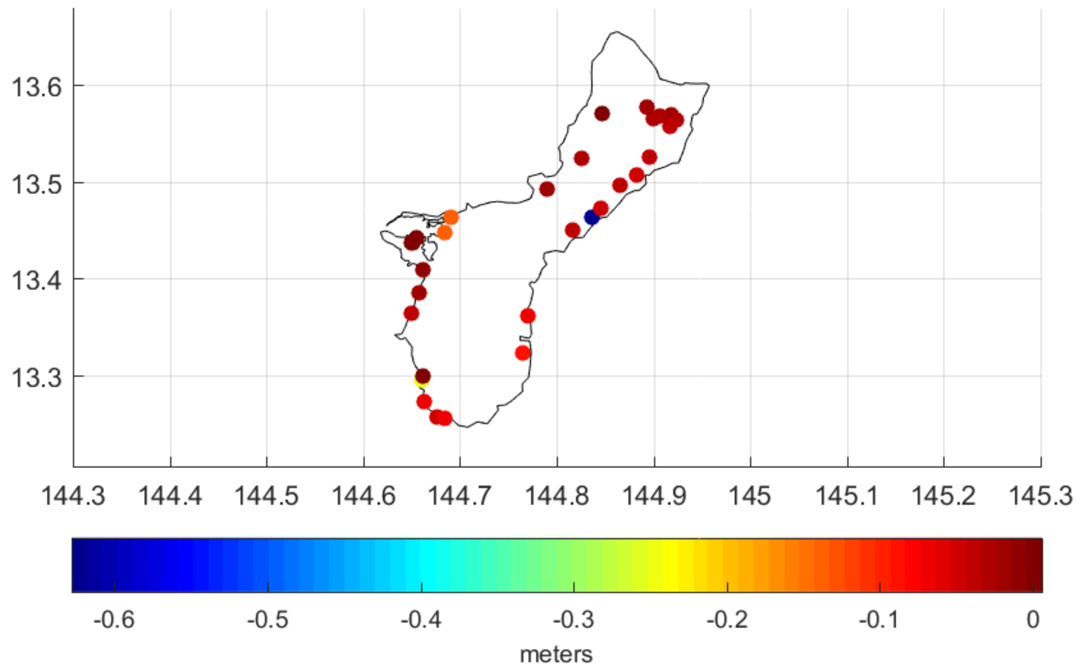
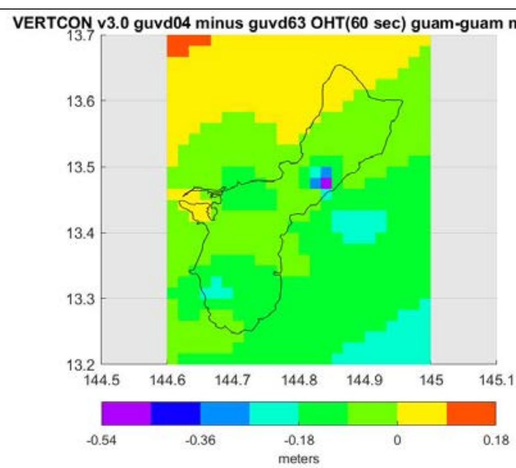


Figure 6-28: Coordinate differences (vmacdoht) for the 30 points contributing to the GUVD63/GUVD04/GUAM transformation.



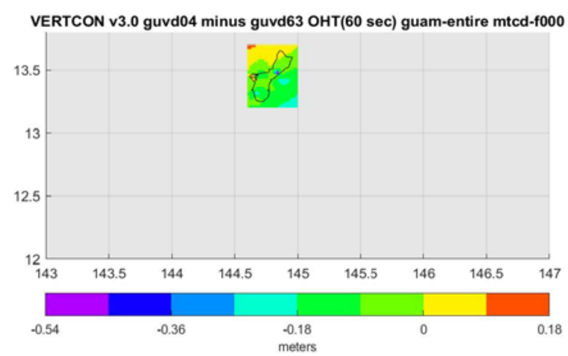
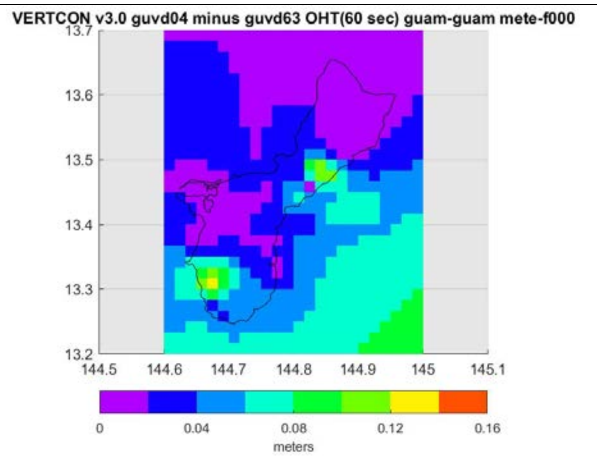


Figure 6-29: Final transformation in meters for GUVD63/GUVD04/GUAM, with 60 arcsecond final grid size, showing the Guam main island area where the transformation is defined (left) and the extent of the full grid as provided by VERTCON 3.0 (right).



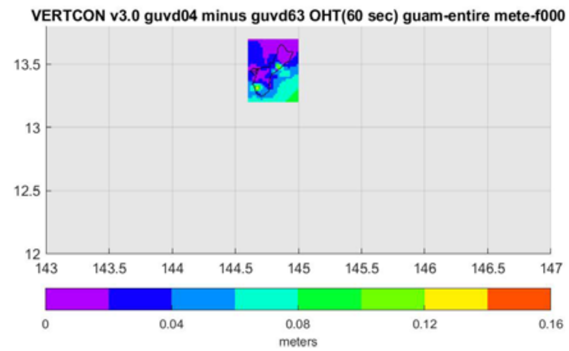


Figure 6-30: Total error in meters for the GUVD63/GUVD04/GUAM transformation at 60 arcsecond grid size, showing the Guam main island area where the transformation is defined (left) and the extent of the full grid as provided by VERTCON 3.0 (right).

6.7 Commonwealth of the Northern Mariana Islands (cnmi) – local tidal (LT) / NMVD 03

The region encompassing the Commonwealth of the Northern Mariana Islands is quite large, spanning 13.8-22N and 143-147W. Over this region, only 13 points were available in the initial data sheet pull. The authors determined that 9 of the points should be eliminated because the heights were not recorded with sufficient precision (indicating they were not Height Modernization points) or would have been removed by filter3. The remaining 4 points were of sufficient quality for inclusion in the transformation data set.

The remaining 4 points are located on the islands of Rota, Tinian, and Saipan (Figure 6-31). Two of the points are on Rota and disagree by only 2.5 mm, whereas the Tinian and Saipan islands have one point each. Each island has one tide station, so it makes sense to have each island have its own unique transformation. Further, much like VIVD 09 (see earlier), NMVD 03 is a single datum name effectively encompassing 3 sub-datums, one for each of the islands Rota, Tinian and Saipan (Carlson, Doyle and Smith, 2009). We noticed that the surface under tension approach, even at the finest grid size possible (60 arcseconds), resulted in the transformation on Tinian and Saipan bleeding from one island into the other.

Therefore, the authors chose to apply flat plane transformations to each of the three islands with data. Tinian and Saipan have zero-error transformations, as their transformations result from only one point each (Tinian +0.036 m and Saipan -0.305 m). Rota’s transformation is the mean of the two points (-0.0325 m), with the error provided by the spread between the two values (0.0025 m). The transformations and errors are show in Figure 6-32 through Figure 6-35. The transformation and error grids are provided at a 60 arcsecond grid resolution.

Thus, for this region, the build process only uses the “doit.bat” and “doit2.bat” routines, followed by a new batch file called “**finalize.cnmi**”. That batch file builds the flat-plane transformation and error grids for the island of Rota, Tinian and Saipan, and replaces the remainder of the grids with flag values of “-999”. The exact bounds of the “flat plane” transformation/error grid data around those three islands are found in the table below:

Island	**South**	**North**	**West**	**East**
Rota	14° 06'	14° 13'	145° 06'	145° 18'
Tinian	14° 54'	15° 07'	145° 34'	145° 41'
Saipan	15° 05'	15° 18'	145° 41'	145° 51'

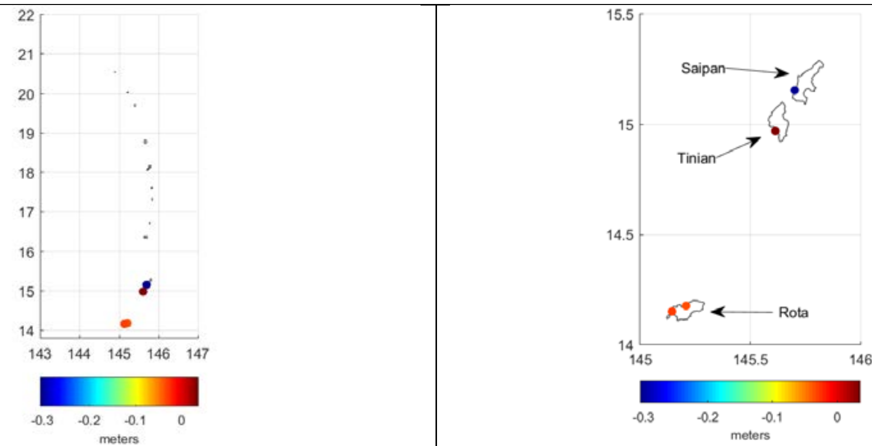


Figure 6-31: Coordinate differences (vmacdoht) for the 4 points contributing to the LT/NMVD03/CNMI transformation, showing the full grid extent (left) then zoomed in to show the three islands with data (right).

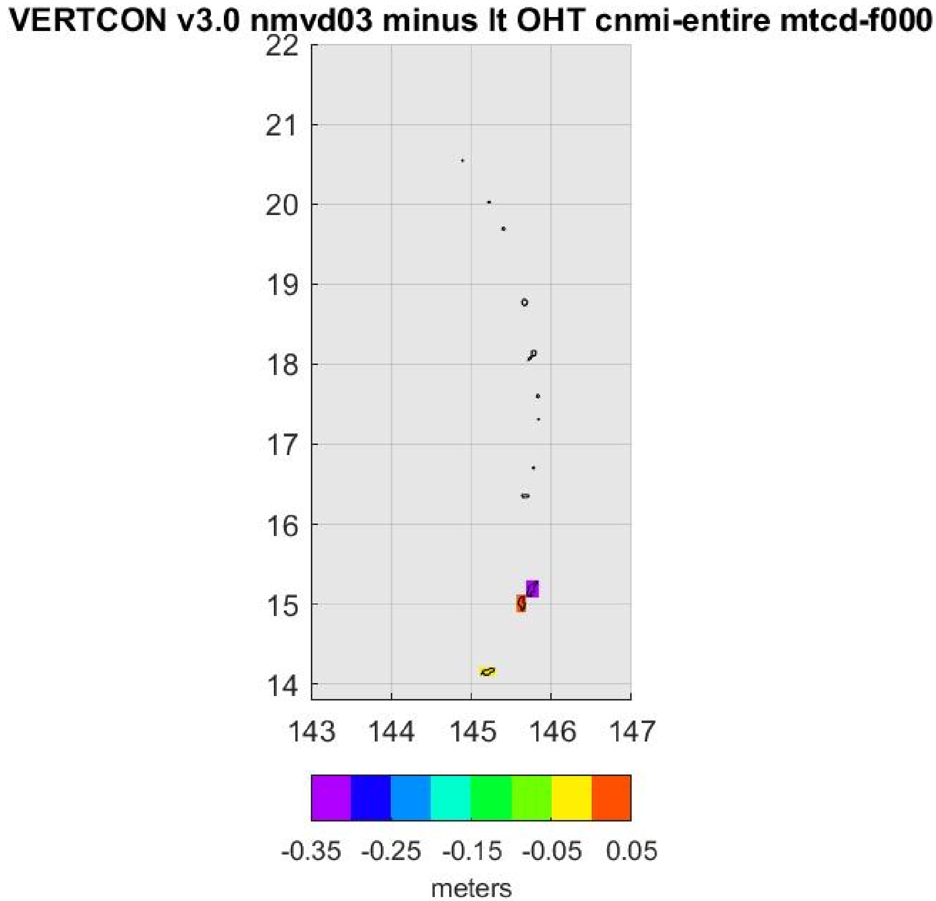


Figure 6-32: Final transformation in meters for LT/NMVD03/CNMI.

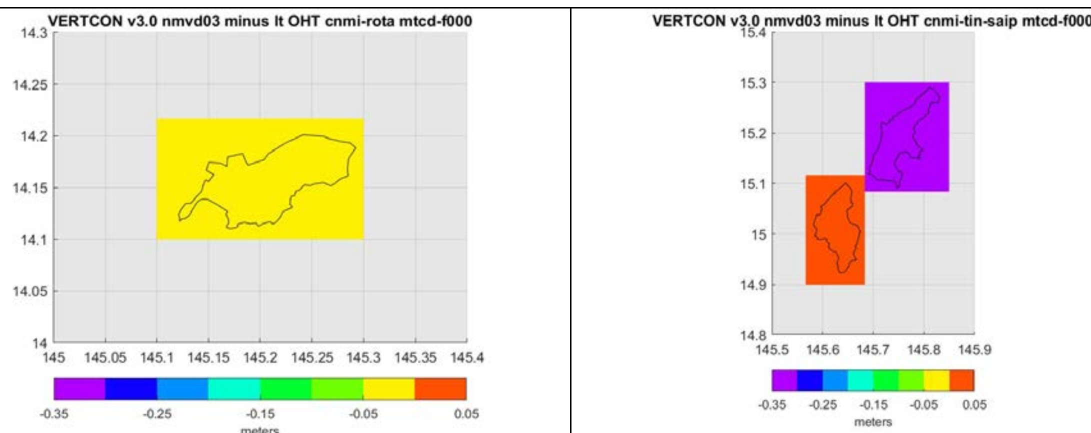


Figure 6-33: Final transformation in meters for LT/NMVD03/CNMI, zoomed in to show detail for Rota (left) and Tinian/Saipan (right).

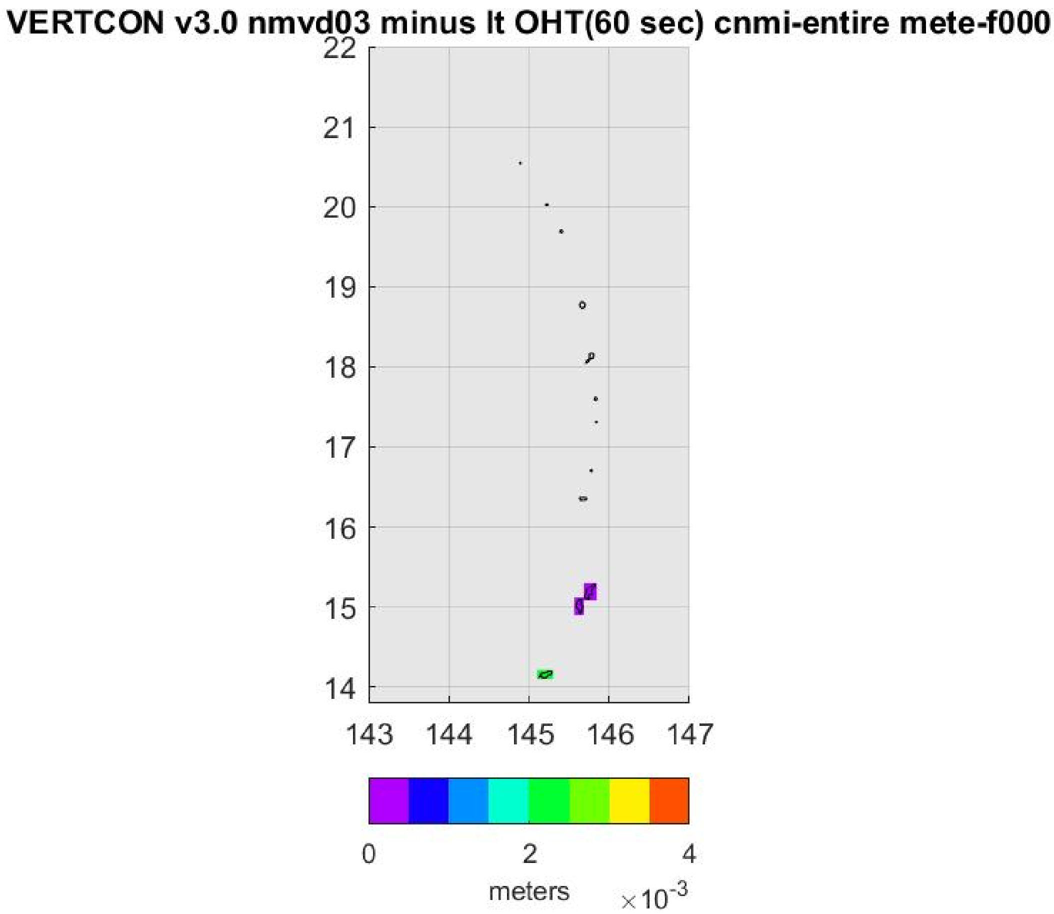
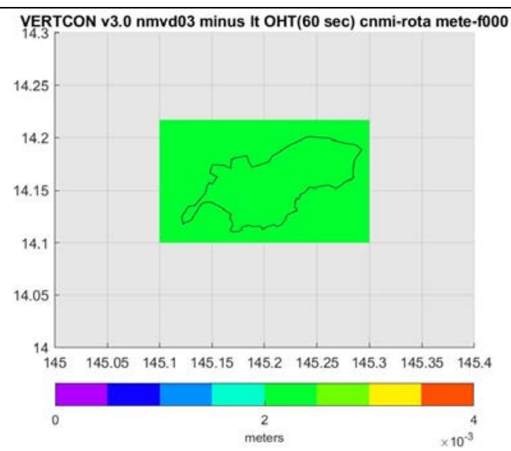


Figure 6-34: Total error for LT/NMVD03/CNMI transformation. Note that the scale bar has units of 10^(-3) meters.



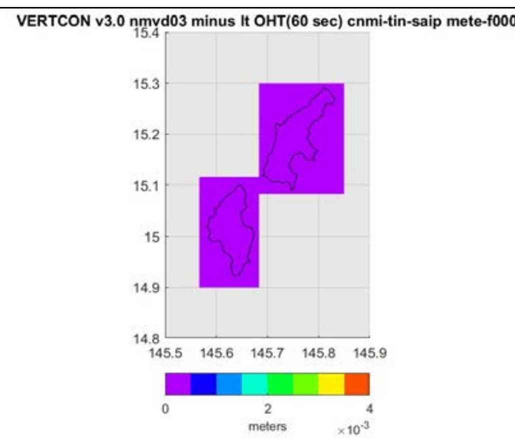


Figure 6-35: Total error for the LT/NMVD03/CNMI transformation, zoomed in to show detail for Rota (left) and Tinian/Saipan (right).

6.8 American Samoa (as) – local tidal (LT) / ASVD 02

There is only one datum pair available for American Samoa - LMSL / ASVD 02. Unfortunately, due to an earthquake in 2009, all points in American Samoa were declared “non publishable”. That means, while the data was (and remains) in the NGS IDB, the datasheets for American Samoa showed no heights available after 2009. Originally the authors decided to provide no transformation, as a main organizational rule behind VERTCON 3.0 was to use only data available to the public. However, the Regional Advisor for the Pacific area, Ed Carlson, requested a transformation using these unpublishable points, in support of *historic* maps between LT and ASVD 02.

After allowing unpublishable points for American Samoa[33], there are 29 points available. There are no data on Swain’s Island or Rose Atoll, so transformations will not be built for those locations. Data were available for Tutuila and the Manu’a island pair (Ta’u and Ofu-Olosega). A point of clarity is due here: the ASVD 02 datum was defined solely for the island of Tutuila (Carlson, Doyle and Smith, 2009). As such, the publishing of ASVD 02 heights on the Ta’u or Ofu-Olosega is of questionable validity. Nonetheless, as the data had once been available on NGS datasheets, the transformation honored this (seeming) error.

An overview of the height determination techniques and the coordinate differences led the authors to apply filter3 to the dataset. Filter3 removed 15 points over all of American Samoa, notably removing 3 of the 4 points on Ta’u, and 12 points on Tutuila. However we note that filter3 has a positive effect on Tutuila, so that the points are now very consistent with each other, and that a point which is adjacent to the tide station (AI9467) is still present in the dataset. After filter3, 14 points remained: 12 on Tutuila (Figure 6-36), 1 on Ofu-Olosega, and 1 on Ta’u.

The point density led to a blended approach for the final American Samoa transformation: a gridded surface-under-tension transformation for Tutuila, and uniform planar transformations for Ofu-Olosega and Ta’u. After filter3, Ofu-Olosega and Ta’u each had only one point remaining; therefore, the transformation on each island is the value of that single point, with zero error. For Tutuila, the authors noted that grid sizes larger than 300 arcsecond resulted in a planar transformation that did not capture the high/low/very-high west-to-east pattern seen in the actual data (Figure 6-36). The 120 arcsecond grid adequately captured the high/low/high signal, has a gridded result at the tide station which is nearly identical to the AI9467 value, and averaged through the group of points at 170.7W, 14.34S. The final transformations and total errors are presented in Figure 6-37 through Figure 6-40.

Thus, for this region, the build process uses all four “doit” batch files, followed by a new batch file called “**finalize.as**”. That batch file extracts the transformation and error grid data from a bounding box around Tutuila, and it also builds the flat-plane transformation and error grids for the islands of Ofu-Olosega and Ta’u. It then puts these island-based sub-grids into the larger regional grid filled

[33] The special “makeinfiles2.f” program is required to generate data for the LT/ASVD 02 pair.

with flag values of “-999”. The exact bounds of the three island-based sub grids are found in the table below:

Island	South	North	West	East
Tutuilla	- 14° 24'	- 14° 12'	189° 08'	189° 28'
Ofu-Olsega	- 14° 12'	- 14° 08'	190° 18'	190° 24'
Ta’u	- 14° 18'	- 14° 12'	190° 28'	190° 36'

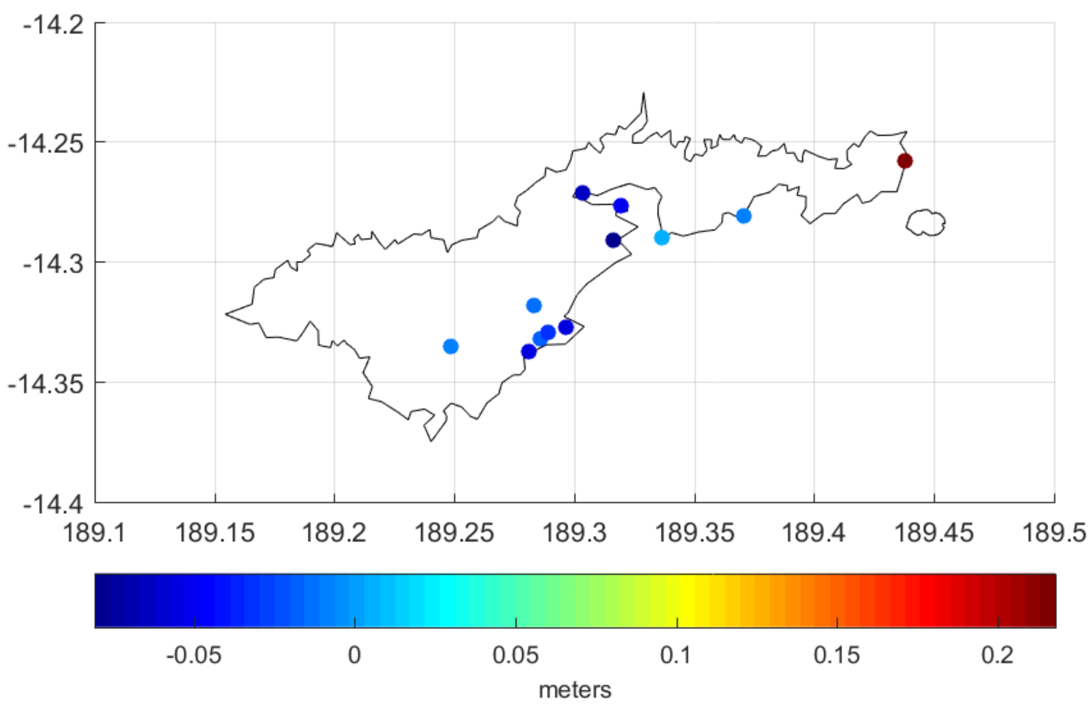


Figure 6-36: Coordinate differences (vmacdoht) on Tutuila for data contributing to the LT/ASVD02/AS transformation.

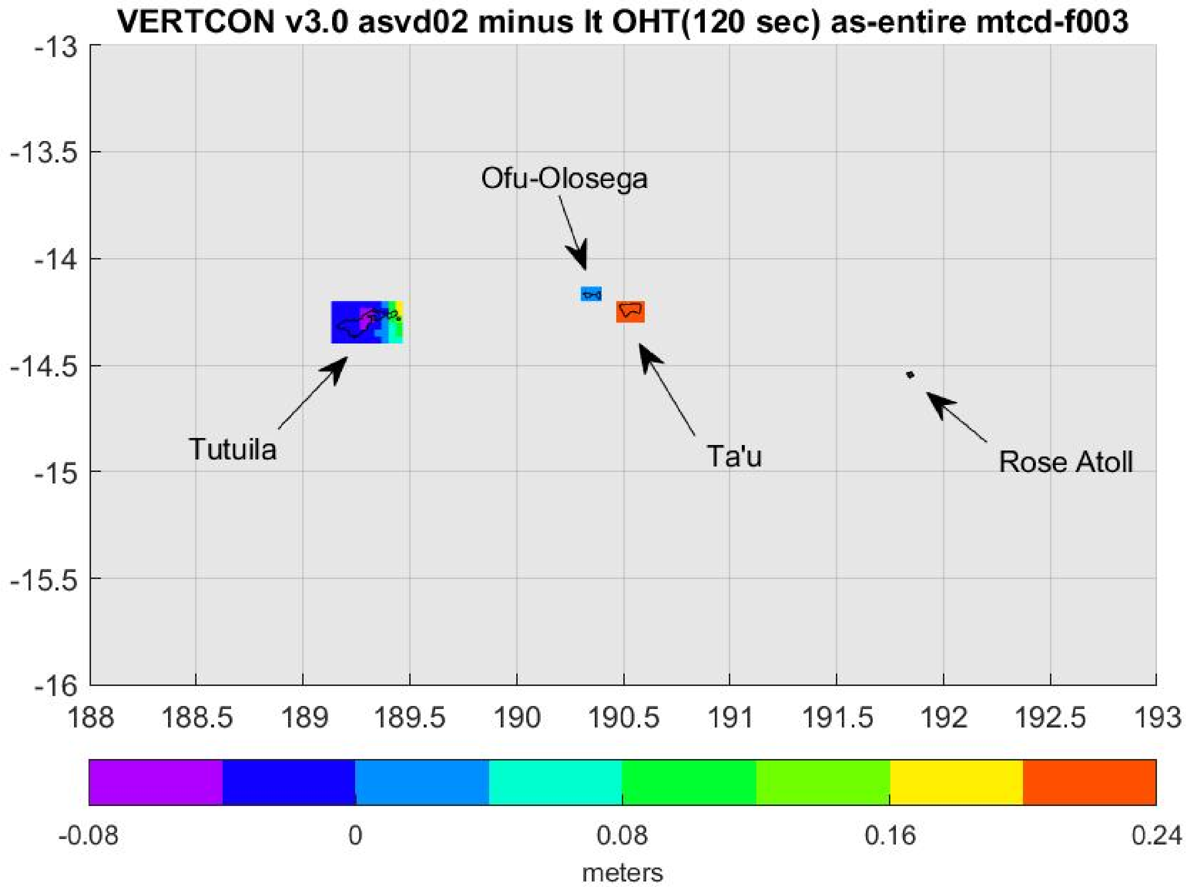
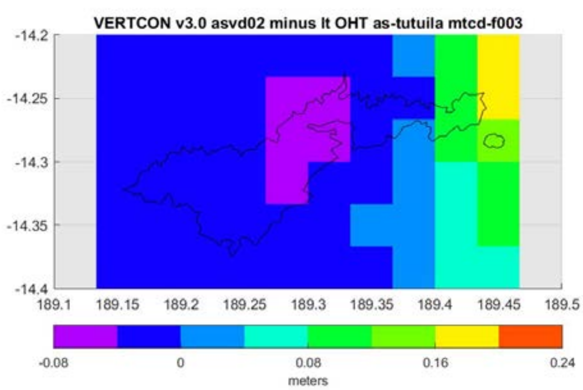


Figure 6-37: Final transformation in meters for LT/ASVD02/AS.



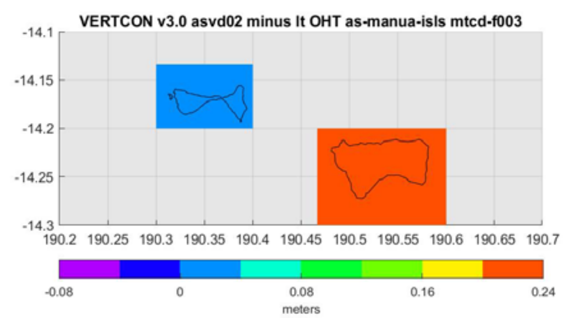


Figure 6-38: Final transformation in meters for LT/ASVD02/AS, zoomed in to show detail for Tutuila (left) and Ofu/Ta'u (right).

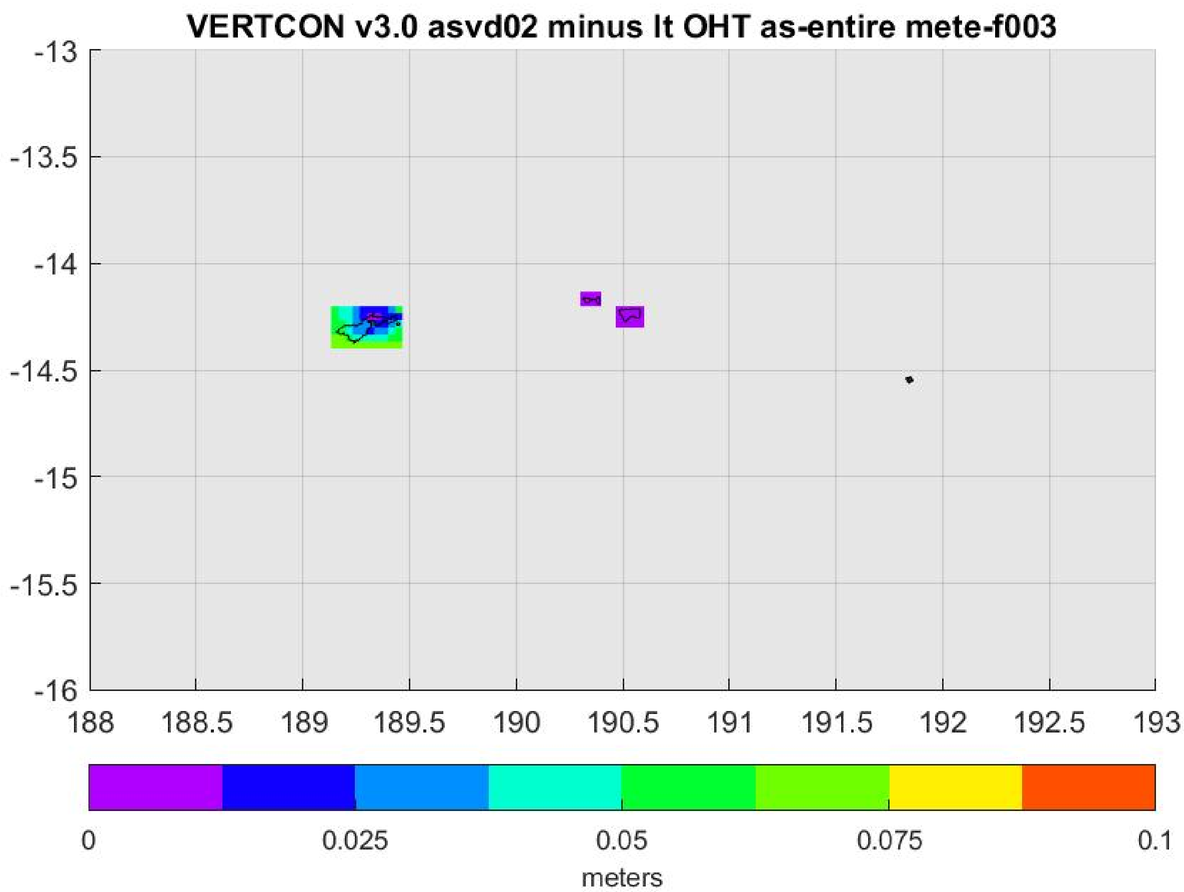
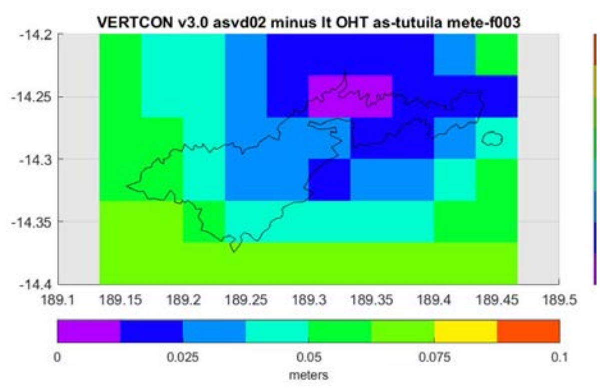


Figure 6-39: Total error for the LT/ASVD02/AS transformation.



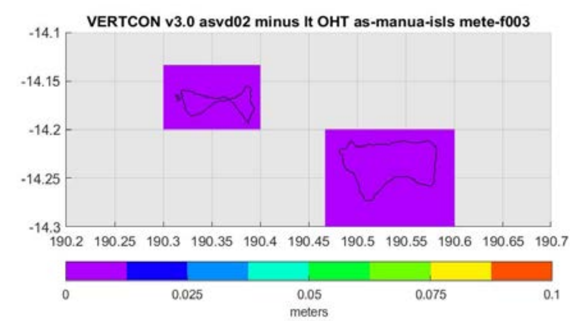


Figure 6-40: Total error for the LT/ASVD02/ AS transformation, zoomed in to show detail for Tutuila (left) and Ofu/Ta'u (right).

7. Comparison to previous transformations

Unlike the horizontal/geometric transformation tool NADCON, NGS has only ever distributed a single transformation for orthometric heights. That was between NGVD 29 and NAVD 88 in the CONUS region, with the underlying grid unchanged since the release of VERTCON 2.0 around 1994. As mentioned earlier, the driving goal of VERTCON 3.0 was to maintain as much of the original grid as possible, while respecting significant regional changes since 1994. Therefore the only really substantial comparison between ***VERTCON 3.0 release 20190601*** and previous transformations is between the NGVD29/NAVD88/CONUS grids. All other transformations distributed as part of ***VERTCON 3.0 release 20190601*** are entirely new.

Readers familiar with NADCON 5.0 may recall that one of the philosophies of the project was to undo mistakes of the past, at least in how transformations were built. Unfortunately, one mistake of the past can't be corrected in ***VERTCON 3.0 release 20190601*** **–** the fact that NGS has never issued realizations and/or country-wide re-adjustments of leveling data. Rather NAVD 88 was created in 1991 and has only been modified, bit by bit, point by point, survey by survey over the last 24 years, always under the continuing name of "NAVD 88". Thus, the ***VERTCON 3.0 release 20190601*** transformation connects NGVD 29 to NAVD 88, just as the VERTCON 2.0 grid does, but they frankly support different versions of NAVD 88 (one being "data available through 2016" and the other "data available through 1991"). A full discussion of this difficulty was found earlier (Section 3.5.1), but it felt necessary to re-iterate that here before actually performing a comparison.

Consider first the boundaries of the grids: VERTCON 3.0 expanded the CONUS region by 1 degree on the east (from 293 to 294.) This was because VERTCON 2.0 had an east boundary that actually truncated the eastern 2 ½ miles of the state of Maine. All other boundaries are the same. Because of this, the comparison between the old and new grids will be restricted to the smaller bounds of the VERTCON 2.0 grid.

Figure 6-1 shows the differences between VERTCON 2.0 and ***VERTCON 3.0 release 20190601*** in CONUS for the transformation between NGVD 29 and NAVD 88. Because of the remove/compute/restore process used, the *general* signal can be seen as zero. Most of the differences are large regional changes in data (Section 6.1.2), mostly because of new NAVD 88 data that was either not available in VERTCON 2.0 or which has superseded data that was available in VERTCON 2.0. Since the intent of VERTCON 3.0 was to respect VERTCON 2.0 first, and only change the grid for large regional shifts, it is expected that the ***VERTCON 3.0 release 20190601*** and VERTCON 2.0 transformations should have reasonably similar performance. This is discussed in the next section.

8. How well does *VERTCON 3.0 release 20190601* perform?

Very little information is available about VERTCON 1.0, and for VERTCON 2.0/2.1, without a formal report, the only available accuracy statements are broad ones from one technical web page (see Section 11). In that section is this statement:

> *Tests of the predictive capability of the physical model show a 2.0 cm RMS agreement at our 381,833 data points. For this reason, the VERTCON 2.0 model can be considered* ***accurate at the 2 cm (one sigma) level****. Since 381,833 data values were used to develop the corrections to the physical model, VERTCON 2.0 will display even better overall accuracy than that displayed by the uncorrected physical model. This higher accuracy will be particularly noticeable in the eastern United States.*

This sort of comparison is very informative, and has been continued for VERTCON 3.0. Although broad, region-wide statistics will be provided below, it should be remembered that ***VERTCON 3.0 release 20190601*** provides actual point-by-point error estimates as part of its functionality.

8.1 Comparison between VERTCON 3.0 and VERTCON 2.1

There are a number of things preventing a direct one-to-one comparison of the performance of VERTCON 2.0 to ***VERTCON 3.0 release 20190601***. First is that VERTCON 3.0 did not explicitly build upon any particular survey order or class of points. If a point had an adjusted set of coordinates in NGVD 29 and NAVD 88, it was part of the overall pool of considered points. Second, VERTCON 2.0 was built using a variety of physical models in addition to actual height differences at point, while VERTCON 3.0 built upon that pre-existing information and looked at residual height differences relative to VERTCON 2.0. Although it is assumed that an outlier thinning was performed in VERTCON 2.0, similar to what was done in VERTCON 3.0, that assumption cannot be definitively proven.

With all those caveats in place, the tables below show how well each of the two grids agree with input data, for both VERTCON 2.0 and ***VERTCON 3.0 release 20190601***, as a way of seeing how well the new grids perform compared to past performance. The tables below reflect the residuals between published coordinates and coordinates transformed with the proper grid from the respective software.

Table 8-1: Residual Orthometric Height Statistics for Transformation NGVD 29/NAVD 88/CONUS

VERTCON Version (Grid Spacing)	Type of Points Used	Number of Points	Ave	Std	Min	Max
2.0 (3’)	All	381,833	0.000 m (assumed)	0.020 m	Unknown	Unknown

3.0 (3') ***release 20190601***	Thinned	53,823	0.000 m	0.012 m	-0.647 m	+0.463 m
	Dropped	341,139	0.000 m	0.026 m	-1.302 m	+1.308 m
	All	394,962	0.000 m	0.024 m	-1.302 m	+1.308 m

In examining Table 8-1 it is reassuring to see that an RMS agreement of 2.4 cm is achievable at all points with ***VERTCON 3.0 release 20190601***, which is in line with the stated 2.0 cm accuracy of VERTCON 2.0, while remaining generally "consistent with" the original release. The larger standard deviation for ***VERTCON 3.0 release 20190601*** for "All" points is likely due to the inclusion of points that were not considered in the "All" comparison of VERTCON 2.0, as well as slight changes occurring in the large regional shifts that were allowed between VERTCON 2.0 and ***VERTCON 3.0 release 20190601***.

8.2 Statistical Summaries of *VERTCON 3.0 release 20190601* performance

Although there are no historic transformations against which the rest of ***VERTCON 3.0 release 20190601*** may be compared, it is still informative to see how well each transformation compares against its own input data, particularly comparing statistical differences between the "thinned" and "all" data sets. The table below summarizes such statistics for all transformations in ***VERTCON 3.0 release 20190601***. Statistics are in meters.

Table 8-2: Residual Orthometric Height Statistics for other *VERTCON 3.0 release 20190601* transformations

Region	Old Datum	New Datum	Grid Spacing	Types of Points	Number of Points	Ave	Std	Min	Max
Alaska	NGVD 29	NAVD 88	1'	Thinned	2465	0.000	0.014	-0.520	+0.266
				Dropped	558	0.002	0.053	-0.290	+0.480
				All	3023	0.000	**0.026**	-0.520	+0.480
Puerto Rico	Local Tidal	PRVD 02	1'	Thinned	21	-0.005	0.067	-0.186	+0.172
				Dropped	29	0.014	0.037	-0.056	+0.174
				All	50	0.006	**0.052**	-0.186	+0.174
U.S. Virgin Islands	Local Tidal	VIVD 09	1'	Thinned	N/A	N/A	N/A	N/A	N/A
				Dropped	N/A	N/A	N/A	N/A	N/A
				All	7	0.000	**0.095**	-0.190	+0.964
Guam	GUVD 63	GUVD 04	1'	Thinned	25	-0.002	0.039	-0.123	+0.129
				Dropped	5	-0.047	0.100	-0.224	+0.004
				All	30	-0.009	**0.054**	-0.224	+0.129
CNMI	Local Tidal	NMVD 03	1'	Thinned	N/A	N/A	N/A	N/A	N/A
				Dropped	N/A	N/A	N/A	N/A	N/A
				All	4	0.000	**0.002**	-0.003	+0.002
		ASVD 02	2'	Thinned	11	-0.003	0.019	-0.040	0.032

American Samoa	Local Tidal			Dropped	3	0.000	0.016	-0.020	0.032
				All	14	-0.013	**0.031**	-0.040	0.020

The table speaks for itself, but one highlight might be pointed out: it is encouraging to see that the Alaska transformation is replicating published height differences to just 2.6 centimeters. However that good performance should always be tempered with the previously stated warning that this transformation should only be relied upon in very specific parts of Alaska (Section 6.2).

8.3 *VERTCON 3.0 release 20190601* formal error estimates

One of the innovations that first came with NADCON 5.0, and continued in VERTCON 3.0, are geographically dependent error estimates. But just how accurate are they? That question was answerable, we felt, if the actual mismatches between transformed coordinates and published coordinates compared to the formal error estimates in a normal distribution. By way of example, consider the following: Take all points with a published coordinate set in NGVD 29 and also a published coordinate set in NAVD 88 in CONUS which have passed through both “filter 3” as well as the manual outlier detection used to create the “work” file (*work.od.nd.rg.fi*). Using the VERTCON 3.0 grid and interpolation software, input the NGVD 29 coordinate and request a transformed NAVD 88 coordinate. What ***VERTCON 3.0 release 20190601*** will give you is not just the transformed NAVD 88 coordinate but also a formal error estimate (an estimate of how much error ***VERTCON 3.0 release 20190601*** thinks might be associated with that transformed NAVD88 coordinate). If one then compares the *transformed* NAVD 88 coordinate to the *published* NAVD88 coordinate, a difference is generated. What is hypothesized is that this difference will be smaller than the formal error estimate about 68% of the time. Further it is hypothesized that the difference will be smaller than twice the formal error estimate about 95% of the time, and smaller than three times the formal error estimate about 99.7% of the time. That is, the formal error estimates compared to the true differences will follow a normal distribution. To test this hypothesis, the statistics of transformed minus published coordinates were compared to the formal error estimates coming out of the transformation. The results are in Table 8-3.

The statistics in Table 8-3 indicate that the formal error estimates coming out of ***VERTCON 3.0 release 20190601*** are doing their job as far as representing the expected error of the transformed coordinate, at least in those areas with sufficient data to support believable accuracy estimates. If it were perfect, it should be expected that the 1 σ column would show generally 68%, the 2σ column about 95% and the 3σ column about 99.7%. The method developed (mixing method noise with data noise) had been untested prior to ***NADCON 5.0 release 20160901***. In the NADCON 5.0 report, the method was seen to be sound. Further, examination of the first row of Table 8-3 indicates that the error estimates are robust for that transformation. Unfortunately the behavior is less robust for other regions, but this may be because the number of points in those regions is so small that it may not be possible to validate or invalidate the robustness of error estimates on such a small sample size.

Table 8-3: Percentage of time VERTCON 3.0 transformations and error estimates match published coordinates

Transformation	1 σ	2 σ	3 σ
NGVD 29 / NAVD 88 / CONUS	73.5	95.8	99.0
NGVD 29 / NAVD 88 / Alaska	89.8	98.7	99.5
Local Tidal / PRVD 02 / Puerto Rico	80.0	100.0	100.0
Local Tidal / VIVD 09 / U.S. Virgin Islands	71.4	100.0	100.0
GUVD 63 / GUVD 04 / Guam	83.3	100.0	100.0
Local Tidal / NMVD 03 / CNMI	50.0	100.0	100.0
Local Tidal / ASVD 02 / American Samoa	51.7	58.6	65.5

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Zilkoski, D.B., J.H. Richards and G.M. Young, 1992: Results of the General Adjustment of the North American Vertical Datum of 1988. *Surveying and Land Information Science*, v 52, no. 3, pp. 133-149.

10. Grid file formats

Versions 2.0 and 2.1 of VERTCON used grids. Specifically, three grids were released, each covering a portion of CONUS for the one transformation (NGVD 29 / NAVD 88) supported. These three grids all had the extension ".94". The use of "94" as an extension is unique among NGS products, and seems to have no other meaning than "this product was released in 1994." For this reason alone, it was not considered as the grid format for VERTCON 3.0. Nonetheless, for historic completeness, a full description of this file format follows.

10.1 ".94" grids (VERTCON 2.1 and 2.0)

The grids in VERTCON 2.1 and 2.0 were named "vertconw.94", "vertconc.94" and "vertcone.94". No documentation exists describing the ".94" file format, but a careful review of the FORTRAN code (convasci.for) which reads and uses it allowed us to reverse engineer the format so it may be documented here.

The ".94" format is a binary format stored as "direct access". This means that each record is stored directly next to its preceding and following record in the computer storage system. Contrast this with "unformatted" files (such as the ".b" format. See Section 10.2 of the NADCON 5.0 report), which are also binary but which have a "buffer" at the beginning and ending of each record. Each record in a .94 file is 1848 bytes long. The .94 format begins with one header record consisting of 96 bytes of information about the grid and 1752 bytes of unspecified data. After that, the rest of the file is filled with records representing actual data in the grid. The first record after the header will contain all of the gridded values on the southernmost row of the grid, with the values in that record arranged from west to east. Each subsequent record contains data for one row northward from the previous row until the final record contains the gridded data (still west to east) of the northernmost row of the grid. This layout was chosen so that the column index would increase with increasing (east) longitude and the row index would increase with increasing latitude.

The header record is laid out as follows:

Table 10-1: Header contents for .94 format

ident	**pgm**	**nlo**	**nla**	**nz**	**glomn**	**dglo**	**glamn**	**dgla**	**margin**	**(unspecified)**

These values are described as such:

Table 10-2: Header details for .94 format

Name	Type	Bytes	Units	Description

ident	Character	56	N/A	11 bytes of file name,45 bytes blank
pgm	Character	8	N/A	Name of program for using file
nlo	Integer	4	N/A	Number of rows in file
nla	Integer	4	N/A	Number of columns in file
nz	Integer	4	N/A	Number of layers in file (?)
glomn	Real	4	Decimal Degrees	Longitude of west edge of grid
dglo	Real	4	Decimal Degrees	Longitude spacing of grid
glamn	Real	4	Decimal Degrees	Latitude of south edge of grid
dgla	Real	4	Decimal Degrees	Latitude spacing of grid
margin	Real	4	Decimal Degrees	Buffer for rounding on east edge (?)
(unspecified)	N/A	1752	N/A	N/A

Certain values are constant in the VERTCON 2.0/2.1 release of the .94 files:

- **ident** is "vertCONe.94", "vertCONc.94" or "vertCONw.94" depending on the file
- **pgm** is always "vertc2.0"
- **nlo** is always 461
- **nla** is always 521
- **nz** is always 1
- **glomn** is -89.0 , -107.0 or -125.0 for the "e", "c" or "w" files, respectively
- **dglo** is 0.05
- **glamn** is 24.0
- **dgla** is 0.05
- **margin** is 0.0

Certain differences and similarities from the ".b" format should be pointed out:

1) The **dgla** and **dglo** values in .94 are equivalent to the dlat and dlon values in .b with identical meanings, except:

    a. In .b, these values are 8 byte real values, but they are 4 byte reals in .94

2) The **nlo** and **nla** values in .94 are the same as **nlon** and **nlat** in .b

3) The **glomn** and **glamn** values in .94 are the same as **xlatsw** and **xlonsw** in .b except:

a. In .b, these values are 8 byte real values, but they are 4 byte reals in .94

b. In .b, longitudes (thus **xlonsw** specifically) always range from 0 to 360, whereas in the .94 files released with VERTCON 2.0/2.1, the **glomn** values use the -180 to +180 convention

4) The addition of **nz** is unique only to the .94 format. As it is set to equal 1, and there is no other metadata to support layer information it is effectively useless.

5) The value of **margin** in the .94 files appears (from context in the associated program **vertcon.for**, released with VERTCON 2.1) to be an attempt to help avoid round-off errors in the eastern edge of the grid, yet by being set to 0 this value is effectively useless.

6) There is no **ikind** value in .94. In the .b format, this value told what kind of data was in the grid (real, integer, etc). In .94 apparently it is expected the data are only 4 byte reals.

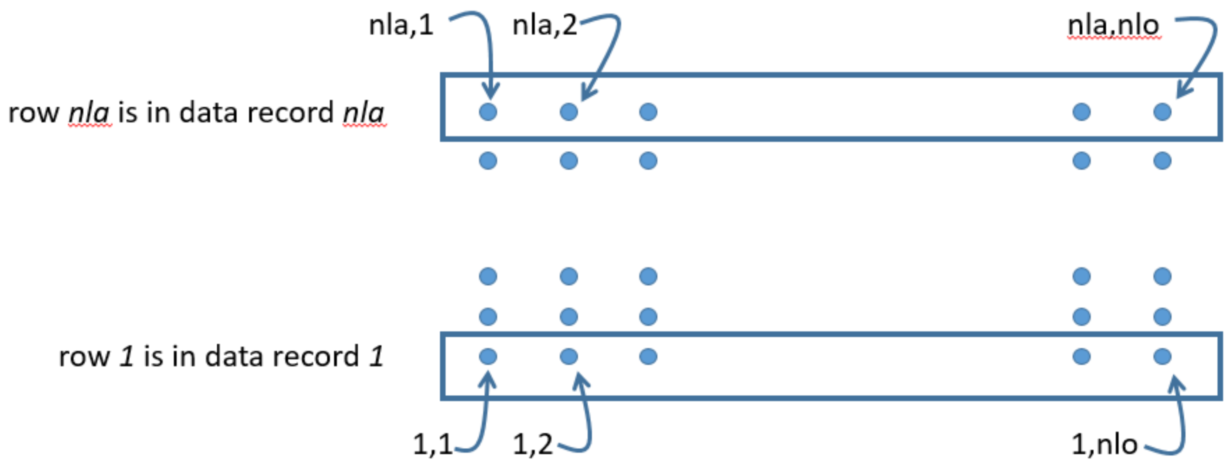
Following the header record, each row of the grid fills subsequent records. Each variable below is a four byte real value. The records look like this:

Table 10-3: Data layout by row for .94 format

dummy	**d(1,1)**	**d(1,2)**	**…**	**d(1,nlo)**
dummy	**d(2,1)**	**d(2,2)**	**…**	**d(2,nlo)**
…	**…**	**…**	**…**	**…**
dummy	**d(nla,1)**	**d(nla,2)**	**…**	**d(nla,nlo)**

Note that the variable **dummy** has no purpose. It takes up space but contains no information that was used in the **vertcon.for** program which came with VERTCON 2.0/2.1. The **d(*,*)** variables are all gridded values of the transformation between NGVD 29 and NAVD 88 at a particular grid note.

Do not confuse the layout in Table 10-3 (showing records from top to bottom) with how the data itself actually falls geographically (which is south to north). The first record contains data in the southernmost row:



The latitude of row 1 (which is actually "record 2", because it comes after the header record which is record 1) is **glamn**. The latitude of row 2 (record 3) is **glamn**+**dgla**. The latitude of row 3 (record 4) is **glamn**+2*__dgla__, etc. The latitude of the final row (**nla**) is **glamn**+(**nla**-1)*__dgla__.

Similarly, the longitude of the first grid point in any record is **glomn**. The next grid point to the east has longitude **glomn**+**dglo**, etc. The final grid point (easternmost) in any record will have longitude of **glomn**+(**nlo**-1)*__dglo__.

While not a property of .94 files specifically, there are two final things to mention, both specific to the actual files released with VERTCON 2.0/2.1. First, they contain a "no data" flag at locations where no transformation is supported. When this is the case, the value of "9999.0" is contained in the data record at that point. Second, the actual data stored in the grids is in *millimeters*, a critical point when transforming data that is usually recorded in *meters*.

10.2 .b file format

The ".b" format was fully documented in Section 10.2 of the NADCON 5.0 report (Smith and Bilich, 2017). Readers interested in the details are directed to that report. Because this format was chosen for NADCON 5.0, it was chosen as the grid format for VERTCON 3.0 as well.

11. Guide to the Digital Archive

A full digital archive of data, programs, and plots has been included as part of ***VERTCON 3.0 release 20190601***. The archive is entitled *FinalBuilds.20190601* clearly tagging the origin of the release at June 1, 2019. The archive is accessible on the web at: ftp://ftp.ngs.noaa.gov/pub/vertcon3/20190601release/.

This section provides an overview of the archive contents; specifics are available in various README files at appropriate levels in the archive itself.

The archive is broken into three main directories:

Table 11-1: Digital archive directories

Builds	Final results and VERTCON 3.0 products.
RunVERTCON3	Code and supporting files to generate results.
AnalyzeVERTCON3	Code used for outlier identification and figure generation.

All of the final transformations comprising ***VERTCON 3.0 release 20190601*** are contained in the *Builds* sub-directory. Each transformation is contained in a subdirectory one level down, titled by *od.nd.rg* (see Author's Notes on file naming convention). Each directory contains the data files used to generate each grid, the final transformation and error grids themselves, GMT scripts used to generate plots, as well as all products which were derived along the way. A guide to the individual files is contained in Section 5.2.

Each transformation has a *plots* subdirectory, containing all the JPG plots generated during processing. For ease of navigation, the plots are grouped into subdirectories as follows:

Table 11-2: Details of plots directory in digital archive

coverage	Location plots for data points.
vectors	Vector plots for data points, where the "vector" is formed as "new coordinate minus old coordinate." The name "vector" is retained for parity with NADCON 5.0 plots, but the up/down orthometric heights are plotted using colored dots rather than arrows.
datanoise*	Colored surface plots for noise introduced by variation within the data themselves; see Section 3.10.
methodnoise*	Colored surface plots for error potentially introduced by the GMT surface routine and the choice of tension = 0.4; see Section 3.10.
errors	Transformation errors, which are the sum of data noise and method noise; see Section 3.10.
transformation	Colored surface plot depicting the transformation itself, with orthometric height transformations shown in meters.

* Note that only the NGVD 29 to NAVD 88 transformations for Alaska and CONUS include *datanoise* and *methodnoise* directories. The transformations in all other regions involved masking out large oceanic areas, and the authors decided to omit plots for the error estimate interim products.

The *RunVERTCON3* directory is structured so that a user can copy the full directory tree to a local machine, compile the code using the provided script, then run the code to generate VERTCON 3.0 results. Contained within the *RunVERTCON3* directory is a README file and a number of sub-directories:

Boundaries	Boundaries of continents, islands, and states, used for drawing maps.
Code	All code needed to generate this release; see Section 5.
Control	Files which group realizations into regional grids; see Section 4.4.
Data	Supporting grid and boundary files for the runs.
InFiles	The fundamental data files for VERTCON 3.0; see Section 4.3.
VERTCON2	Grid files for the VERTCON2 transformation, used in the remove/compute/restore process; see Section 3.2.
Work	Contains only file "workedits", which lists the points marked for deletion; see Section 5.2.1.

Finally, the *AnalyzeVERTCON3* directory contains helper programs used for user-friendly analysis of the data. These codes were useful for mapping heights, identifying outliers, and choosing the appropriate grid size for each transformation. There are also codes in this directory to generate final transformation and error plots for regions with masked-out oceanic areas. The README file at this level gives an overview of the code.

12. VERTCON 2.0 and 2.1 documentation

There is no formal report for VERTCON 2.0 nor 2.1. The following sections replicate information found on NGS web pages which serve as the only public documentation of the details behind the tool. In some cases, formatting has been changed for readability. Although an article about VERTCON appeared in Professional Surveyor magazine in 2004 (Mulcare, 2004) it mostly contains a rehash of these NGS web pages.

12.1 Method

The following text is reproduced from,
https://www.ngs.noaa.gov/TOOLS/Vertcon/vert_method.html accessed on November 1, 2018.

National Geodetic Survey (NGS) Height Conversion Methodology

This process is designed to provide datum shift between the NAVD 88 and NGVD 29 vertical datums at specified geographic position.

Dennis G. Milbert, Ph.D.

05/12/1999

METHOD

Program VERTCON computes the modeled difference in orthometric height between the North American Vertical Datum of 1988 (NAVD 88) and the National Geodetic Vertical Datum of 1929 (NGVD 29) for a given location specified by latitude and longitude.

The VERTCON 2.0 model was computed on May 5, 1994 using 381,833 datum difference values. A key part of the computation procedure was the development of the predictable, physical components of the differences between the NAVD 88 and NGVD 29 datums. This included models of refraction effects on geodetic leveling, and gravity and elevation influences on the new NAVD 88 datum. Tests of the predictive capability of the physical model show a 2.0 cm RMS agreement at our 381,833 data points. For this reason, the VERTCON 2.0 model can be considered accurate at the 2 cm (one sigma) level. Since 381,833 data values were used to develop the corrections to the physical model, VERTCON 2.0 will display even better overall accuracy than that displayed by the uncorrected physical model. This higher accuracy will be particularly noticable in the eastern United States.

It should be emphasized that VERTCON 2.0 is a datum transformation model, and can not maintain the full vertical control accuracy of geodetic leveling. Ideally, one should process level data using the latest reduction software and adjust it to established NAVD 88 control. However, VERTCON 2.0 accuracy is suitable for a variety of mapping and charting purposes.

Most horizontal positions of the bench marks used to generate VERTCON were scaled from USGS topographic maps. The estimated uncertainty of the scaled positions, 6", is greater than the differences between NAD 27 and NAD 83. Therefore, the latitude and longitude provided to VERTCON can be on either the NAD 27 or NAD 83 datum.

The VERTCON 2.0 model expresses datum differences between NAVD 88 and NGVD 29 due to removal of distortions in the level data, as well as due to the physical differences in the height systems. In some rare cases, these local NGVD 29 distortions could be 20 cm or more. If both ends of your old vertical survey were tied to one of these "problem" lines, then the datum difference of the problem line is appropriate to use to transform the survey data. If both ends of a vertical survey are tied to "undistorted lines", then it is appropriate to use a slightly distant point to compute the transformation, no matter how close your survey data may approach a given problem line. The possible presence of a problem NGVD 29 line in the vicinity of your survey will become evident if dramatically different datum transformation values are computed within a small area.

It must also be emphasized that VERTCON 2.0 is not to be considered reliable beyond the boundaries of the lower 48 United States. Future versions of VERTCON may be extended into neighboring countries. The National Imagery and Mapping Agency (NIMA - previously the Defense Mapping Agency) has been of immense help in this endeavor. NIMA has provided a major portion of the NGS land gravity data set. NIMA has also been instrumental in the creation of the various 30" elevation grids in existence. Although the work of the NIMA generally precludes public recognition, their cooperation in this work is gratefully acknowledged.

12.2 Sign Convention

The following text is reproduced from https://www.ngs.noaa.gov/TOOLS/Vertcon/vert_sign.html, accessed on November 1, 2018.

National Geodetic Survey (NGS)

Height Conversion Algebraic Sign Convention

This process is designed to provide the datum shift between the NAVD 88 and NGVD 29 vertical datums at a specified geographic position. The correct use of algebraic signs to convert NGVD 29 heights to NAVD 88 heights, or NAVD 88 heights to NGVD 29 heights, is illustrated with examples.

Rudolf J. Fury M.S.,M.Eng.

05/12/1999

```
  Data grids of (NAVD 88 - NGVD 29) height differences represent the datum shift
model.

                    ----------------------------------------------
                   | from    NGVD 29  ---->   NAVD 88 |
                    ----------------------------------------------

If a NAVD 88 height is desired when a NGVD 29 height is given, ADD the model
value ALGEBRAICALLY to the NGVD 29 height.

FORMULA:  height (NAVD 88) =  height (NGVD 29) + datum shift (correction) value

Examples:
  1. The NGVD 29 height is 500 meters (1640.420 feet) at
                        36° 10’ 35.0”  latitude
                       098° 40’ 10.0”  longitude
       After keying this position into VERTCON, the returned
       (NAVD 88 - NGVD 29) datum shift (correction) value is
                         + 0.202 meter   (+0.663 ft)
    --------
   | ADD | this value ALGEBRAICALLY [ keep the sign ] to the NGVD 29 height:
    --------
                               500.000
                              +  0.202
                              ---------
       the NAVD 88 height is 500.202 meters  (1641.083 feet).

  2. the NGVD 29 height is 120 meters (393.701 feet) at
```

```
                         36° 10’ 35.0”  latitude
                        078° 40’ 10.0”  longitude
       After keying this position into VERTCON, the returned
       (NAVD 88 - NGVD 29) datum shift (correction) value is
                         - 0.267 meter   (-0.876 ft)
    --------
   | ADD | this value ALGEBRAICALLY [ keep the sign ] to the NGVD 29 height:
    --------
                                 120.000
                                -  0.267
                                ---------
       the NAVD 88 height is 119.733  meters  (392.825 feet).

     -    -    -    -    -    -    -    -    -    -    -   -   -   -    -

                    ----------------------------------------------
                   | from    NAVD 88  ---->   NGVD 29 |
                    ----------------------------------------------
```

If a NGVD 29 height is desired when a NAVD 88 height is given, SUBTRACT the model value ALGEBRAICALLY from the NAVD 88 height.

FORMULA: height (NGVD 29) = height (NAVD 88) - datum shift (correction) value

Examples:

```
  1. the NAVD 88 height is 500.202 meters (1641.083 feet) at
                         36° 10’ 35.0” latitude
                        098° 40’ 10.0” longitude
       After keying this position into VERTCON, the returned
       (NAVD 88 - NGVD 29) datum shift (correction) value is
                         + 0.202 meter    (+0.663 ft)
  -----------------
 |SUBTRACT| this ALGEBRAICALLY [ flip the sign ] from the NGVD 29 height:
  -----------------
                                 500.202
                                 - 0.202
                                ---------
       the NGVD 29 height is 500.000  meters  (1640.420 feet).

  2. the NAVD 88 height is 119.733 meters (392.825 feet) at
                         36° 10’ 35.0” latitude
                        078° 40’ 10.0” longitude
       After keying this position into VERTCON, the returned
       (NAVD 88 - NGVD 29) datum shift (correction) value is
                         - 0.267 meter   (-0.876 ft)
  -----------------
 |SUBTRACT| this ALGEBRAICALLY [ flip the sign ] from the NGVD 29 height:
  -----------------
                                 119.733
                                +  0.267
                                ---------
       the NGVD 29 height is 120.000  meters  (393.701 feet).
```

12.3 Users Guide / README

The following text is reproduced from https://www.ngs.noaa.gov/PC_PROD/VERTCON/README.TXT, accessed on November 1, 2018.

```
"@(#)vertcon.doc       1.1 - 00/04/17 10:27:24 NGS"
----------------------------------------------------------------------
README file for VERTCON v2.0     199408.18   RJF/dgm
README file for VERTCON v2.1     200309.29   RWS

PURPOSE: Program VERTCON computes the modeled difference in orthometric
          height between the North American Vertical Datum of 1988 (NAVD 88)
          and the National Geodetic Vertical Datum of 1929 (NGVD 29) for a
          given location specified by latitude and longitude.

A partial list of contents of the VERTCON distribution is:

   vertcon.exe    VERTical datum CONversion program
                  (compiled from VERTCON.FOR, a FORTRAN source code)

   vertcone.94    VERTCON datum transformation grid file;  eastern USA
                  (non-readable, i.e., binary, file)

   vertconc.94    VERTCON datum transformation grid file;  central USA
                  (non-readable, i.e., binary, file)

   vertconw.94    VERTCON datum transformation grid file;  western USA
                  (non-readable, i.e., binary, file)

   README.TXT     User's instruction file  (this file you are reading)

A number of sample output and batch files are included as examples, in
addition to some utility routines described later in this document.

To install:
   1) Open a DOS window (or a Command Prompt window).
   2) Make a subdirectory on hard disk;
        for example: mkdir NGVDCONV
   3) Go into subdirectory;
        for example: cd NGVDCONV
   4) Copy the downloaded files into the subdirectory

To execute:
   Type     vertcon           and follow the prompts.

To terminate:
   VERTCON computations can be stopped at any time by the Control-C
   (i.e., <ctrl-c>) key combination. Interactive processing
   can also be terminated by entering 0. (i.e., zero WITH DECIMAL POINT)

BUT PLEASE DON'T START YET;  KEEP READING THIS DOCUMENT.

How program VERTCON works:
   The software and three files of datum transformation grids for the
conterminous United States (CONUS) are provided in the distribution. VERTCON
returns the orthometric height difference between NAVD 88 and NGVD 29 at the
geodetic position specified by the user. VERTCON interpolates the datum
transformation at a point from the appropriate grid in your subdirectory.
```

Data Input:
The user can key in latitude and longitude on a point-by-point basis or can create an input file using a text editor. Several file formats are provided, including the internal bench mark file record format of the Vertical Network Branch, NGS. These formats are detailed in a "Help" menu option which appears when the input filename is specified.

Most horizontal positions of the bench marks used to generate VERTCON were scaled from USGS topographic maps. The estimated uncertainty of the scaled positions, 6", is greater than the differences between NAD 27 and NAD 83. Therefore, the latitude and longitude provided to VERTCON can be on either the NAD 27 or NAD 83 datum.

Data Output:
Results are collected into an output file. The default name of this file is VERTCON.OUT, but the user can choose any legal filename. (A word of advice: don't use misleading extensions such as .EXE, .BAT, etc.). The format of the output file is linked to the format of the input file to maintain consistency.

------------------------> THE SENSE OF THE SIGNS <--------------------------

The grids contain a model of (NAVD 88 - NGVD 29) height differences.

If a NAVD 88 height is desired when a NGVD 29 height is given,
ADD the model value ALGEBRAICALLY to the NGVD 29 height.

If a NGVD 29 height is desired when a NAVD 88 height is given,
SUBTRACT the model value ALGEBRAICALLY from the NAVD 88 height.

The VERTCON 2.0 Model
The VERTCON 2.0 model was computed on May 5, 1994 using 381,833 datum difference values. A key part of the computation procedure was the development of the predictable, physical components of the differences between the NAVD 88 and NGVD 29 datums. This included models of refraction effects on geodetic leveling, and gravity and elevation influences on the new NAVD 88 datum. Tests of the predictive capability of the physical model show a 2.0 cm RMS agreement at our 381,833 data points. For this reason, the VERTCON 2.0 model can be considered accurate at the 2 cm (one sigma) level. Since 381,833 data values were used to develop the corrections to the physical model, VERTCON 2.0 will display even better overall accuracy than that displayed by the uncorrected physical model. This higher accuracy will be particularly noticable in the eastern United States.

Using VERTCON 2.0
It should be emphasized that VERTCON 2.0 is a datum transformation model, and can not maintain the full vertical control accuracy of geodetic leveling. Ideally, one should process level data using the latest reduction software and adjust it to established NAVD 88 control. However, VERTCON 2.0 accuracy is suitable for a variety of mapping and charting purposes.

The VERTCON 2.0 model expresses datum differences between NAVD 88 and NGVD 29 due to removal of distortions in the level data, as well as due to the physical differences in the height systems. In some rare cases, these local NGVD 29 distortions could be 20 cm or more. If both ends of your old vertical survey were tied to one of these "problem" lines, then the datum difference of the problem line is appropriate to use to transform the survey data. If both ends of a vertical survey are tied to "undistorted lines", then it is appropriate to use a slightly distant point to compute the transformation, no matter how close your survey data may approach a given problem line. The possible presense of a problem NGVD 29 line in the vicinity of your survey will become evident if dramatically different datum transformation values are computed within a small area.

It must also be emphasized that VERTCON 2.0 is not to be considered reliable beyond the boundaries of the lower 48 United States. The VERTCON program will interpolate values in Canada, Mexico, or in the ocean, due to the grid structure of the model. Those values do not contain important model components present in the conterminous U.S. model. Future versions of VERTCON may be extended into neighboring countries.

The Defense Mapping Agency

The Defense Mapping Agency (DMA) has been of immense help in this endeavor. DMA has provided a major portion of the NGS land gravity data set. DMA has also been instrumental in the creation of the various 30" elevation grids in existence. Although the work of the DMA generally precludes public recognition, their cooperation in this work is gratefully acknowledged.

Other Programs:

The datum shift grids and VERTCON software are provided on standard disc operating system (DOS) controlled (IBM-compatible) personal computers (PC). In support of other computer systems, the following utility software is included:

```
convasci  --  copy unformatted (binary) grid files into ASCII files for
              transfer to other systems

convbin   --  will restore the ASCII files into binary grid files on the new
              system.
```

Other Future Plans:

A continuing development effort is underway to improve VERTCON results. NGVD 29 normal orthometric heights are being analyzed for localized monument and/or crustal motion effects, for inconsistent adjustments, and other effects. Computed height differences which are significantly influenced by such effects will be flagged and rated for reliability in future versions.

For More Information

For Products Available From the National Geodetic Survey:

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A special word of thanks goes to our colleague, Sandford R. Holdahl, who has recently retired. Sandy made the first predictions of the vertical datum differences in 1983, and is a co-author of the VERTCON 2.0 model.

README file   199408.18   RJF/dgm

Vertcon 2.10 is a modification of Vertcon 2.0 code to make it accessible via the National Geodetic Survey (NGS) Geodetic TOOL Kit on the Web and allow negative orthometric heights to be entered.

The program was modified to accept a single command line parameter. The parameter may be either a blank, OHT or WEB. No parameter, the blank option, will be cause the program to execute with the normal output. If the "OHT" option is used, e.g. vertcon oht, the program will execute so that the user may see the program prompts and enter an orthometric height and select either the NGVD29 or NAVD88 datum. The "WEB" option is used only for web execution, e.g. vertcon web.

Warnings to those who compile the source code: (1)The grid files are in binary format. If you download these files from the NGS web site, you should receive the binary data in little endian form, which is correct for Intel processors. (2) The grid files are opened for direct access with a record size of 1848 bytes. The Fortran standard says that the unit of measurement of the record size is implementation dependent, and the default for some compilers is to measure this in (4 byte) words. Most compilers allow the user to override the default.

README file   200309.29   RWS