TECHNICAL MEMORANDUM
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INVESTIGATION OF THRESHOLD CROSSING HEIGHT VARIATIONS FOR WIDE AREA AUGMENTATION SYSTEM (WAAS) LOCALIZER PERFORMANCE WITH VERTICAL GUIDANCE (LPV) APPROACH PROCEDURES

This report documents an analytical investigation to determine the cause of threshold crossing height (TCH) variations observed during the flight inspection of Wide Area Augmentation System (WAAS) Localizer Performance with Vertical-guidance (LPV) approach procedures. In the context of this report, the phrase "TCH variation" refers to the difference between the TCH intended to be achieved by the procedure developer versus the actual TCH measured during flight inspection of the procedure. The cause is identified to be the use of a geodetic reference frame during the procedure design phase that is not sufficiently equivalent to the one used by GPS receivers. The simulation data generated to characterize the magnitude of the variation that could be introduced are provided and analyzed. The analysis consists of assessing both the vertical and horizontal variations that could result. Conclusions and recommendations are presented herein.

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I. INTRODUCTION

The Federal Aviation Administration (FAA) is responsible for safe and efficient operation of the United States National Airspace System (NAS) and must accomplish a variety of activities daily to ensure achieving its mission. Within the FAA, the Office of Aviation Systems Standards (AVN) provides for the development, publication, and certification of instrument flight procedures, including the flight inspections of the electronic navigation aids that support these procedures. This work includes the flight inspection of instrument procedures supported by the Wide Area Augmentation System (WAAS), which is a differentially-corrected, satellite-based system that uses the Global Positioning System (GPS) [1]**.** WAAS is currently being used in the NAS to support a specific type of precision instrument approach procedure referred to as a WAAS Localizer Performance with Vertical-guidance (LPV) approach procedure. In this case, WAAS is used to provide both lateral and vertical guidance during the approach, and it is desired operationally to use WAAS to support instrument approach procedures with decision altitudes down to a 200-foot height above threshold (200' HAT) and at least 1/2 statute mile visibility [2].

Under Contract DTFAAC-03-A-15689, the Avionics Engineering Center (AEC) at Ohio University supports the review, development and assessment of flight inspection requirements, methodologies and procedures, as tasked by AVN. This support includes both ground-based and satellite-based technologies. Task Order 0001 provides for support related to WAAS. Under this task order, AEC has been tasked to perform an analytical investigation to determine the cause of threshold crossing height (TCH) variations observed during the flight inspection of WAAS LPV approach procedures. At the onset of this work, it was speculated that the variations observed were due to the use of a geodetic reference frame during the procedure design phase that is not sufficiently equivalent to the one used by GPS/WAAS receivers. That is, due to coordinate system and datum differences between North American Datum 1983 (NAD 83) and the various versions of the World Geodetic Survey 1984 (WGS 84).

This report describes the study performed to investigate the TCH variations that could result due to differences between NAD 83 and WGS 84 coordinate systems. Herein, the phrase "TCH variation" refers to the difference between the TCH intended to be achieved by the procedure developer versus the actual TCH measured during flight inspection of the procedure. The simulation data generated during this effort are discussed and analyzed to characterize both the vertical and horizontal variations that could result. Conclusions and recommendations are then presented based on the results of the analysis performed.

II. BACKGROUND

During the flight inspection of WAAS LPV approach procedures, AVN flight inspection personnel observed an overall vertical bias in TCH measurements [2]. The magnitude of these vertical biases, or TCH variations were approximately four feet based on inspection of initial WAAS LPV procedures, and the value observed appeared somewhat dependent on the location of the procedure. These initial observations led AVN personnel to conduct a series of tests to

identify the cause of the TCH biases. These tests and the results obtained are summarized in the section below, and additional detail can be found in Reference 2.

A. Initial AVN Investigation

As previously mentioned, AVN personnel investigated potential causes of the observed TCH variation. They have determined that a discrepancy does exist between the elevations of runway thresholds, typically surveyed using the NAD 83 datum, and the aircraft altitudes reported by the onboard WAAS enabled GPS receivers, which use the current WGS 84 datum. The position variation that can be introduced is illustrated conceptually in Figure 1, and this position variation can be decomposed into a vertical and horizontal variation.

Using the National Geodetic Survey (NGS) tool known as the Horizontal Time-Dependent Position (HTDP) software, AVN personnel obtained coordinate transformations between NAD 83 and WGS 84 referenced positions for four example airports around the country. The height differences were derived from differences in input and output ellipsoid height values and the results are shown in Table 1. Again, AVN personnel have documented the results of their initial investigation in Reference 2.

Table 1. NAD 83 vs. WGS-84 Height Above Ellipsoid (HaE) Sample Data Points [2].

Airport	Ident	Runway	Latitude Longitude	NAD 83 Vertical Error
Will Rogers World (Oklahoma City, OK)	KOKC	17R	N 35° 24' 21.4200" W 097° 36' 20.6000"	3.7 ft
Daytona Beach International (Daytona Beach, FL)	KDAB	07R	N 29° 10' 33.7160" W 081° 03' 24.6303"	5.0 ft
Denver International (Denver, CO)	KDEN	07	N 39° 50' 27.4000" W 104° 43' 35.9700"	2.9 ft
Los Angeles International (Los Angeles, CA)	KLAX	06L	N 33° 56' 56.7900" W 118° 25' 52.1600"	2.3 ft

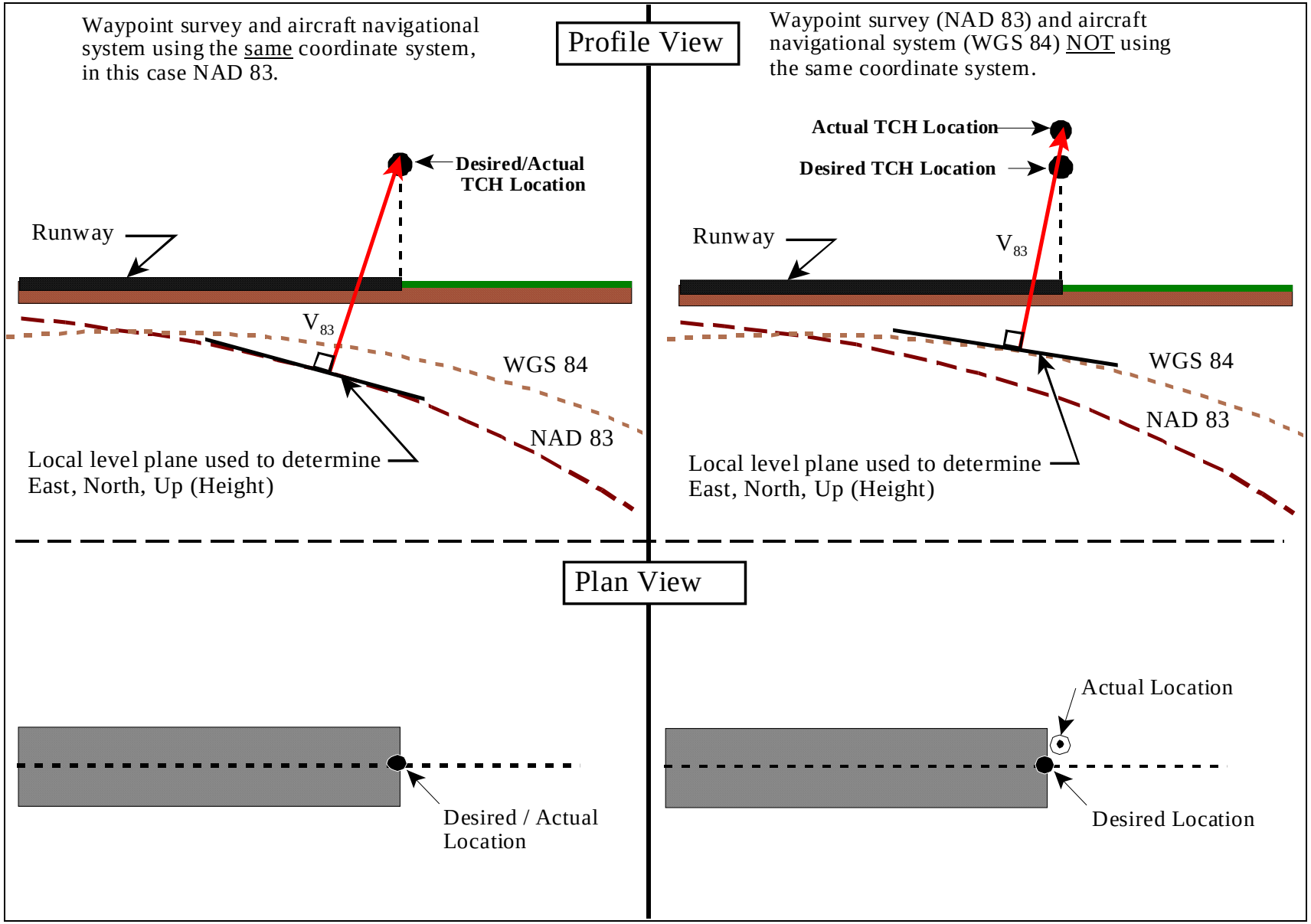

Figure 1. Illustration Showing Scenarios Using Similar and Dissimilar Datum for Both Waypoint and Aircraft.

B. Discussion of Geodetic Reference Systems and Aviation

Unlike traditional ground-based precision approach systems, satellite-based systems operate in an absolute, three-dimensional, global coordinate system that is referenced to the earth in a prescribed fashion. Simplistically speaking, one can design a WAAS LPV approach procedure once the coordinates of the runway ends are known. These coordinates define the three-dimensional position of the runway ends in a given coordinate system. Based on the runway coordinates, approach procedure coordinates more commonly known as waypoints can be defined to produce the desired vertical and lateral course to be flown during the approach procedure. Although the procedure design process may appear simple conceptually, the actual implementation is complex for a number of reasons. One such reason is the complexity of making absolute position (coordinate) measurements, which is discussed briefly in this section.

Figure 2, obtained using Google Earth, shows the contiguous United States (CONUS) with lines of constant latitude and longitude. At first glance, the Earth is generally perceived to be a solid sphere or ellipsoid. Thus, one might think that absolute position measurements can be made and coordinates determined using a simple geometrical process. However, this is not the case as a specialized field of mathematics, Geodesy, is dedicated to this measurement process. According to Reference 3, Geodesy may be defined as *"the branch of applied mathematics that deals with the measurement of the shape and area of large tracts of country, the exact position of geographical points, and the curvature, shape, and dimensions of the earth."* Dr. Snay and Dr. Soler, Manager and Chief Geodesist for NGS, respectively, provide insight into the complexity of making position measurements stating, *"What initially appears to be a simple geometric procedure is complicated by Earth's dynamic behavior. For example, Earth's center of mass is moving relative to Earth's surface. Also, there are variations of Earth's rotation rate as well as motions of Earth's rotation axis both with respect to space (precession and nutation) and to Earth's surface (polar motion). Moreover, points on the earth's crust are moving relative to one another as a result of plate tectonics, earthquakes, volcanic/magmatic activity, postglacial rebound, people's extraction of underground fluids, solid Earth tides, ocean loading, and several other geophysical phenomena. Modern terrestrial reference systems, hence, need to account for these motions"* [4].

Figure 2. A Google Earth View of the CONUS.

The previous paragraph provides insight into the deficiencies of modeling the earth as a static solid mass for the purpose of position measurements. Taken to extreme, one might think of earth as a highly-dynamic pliable spinning mass, such as a droplet of water on board one of NASA's shuttles while in space (see Figure 3). The reality is somewhere in the middle of these two extremes; the Earth having a solid inner core, a molten middle core, and a solid outer crust composed of slowly moving plates.

Figure 3. NASA Photograph of Free-Floating Water Bubble in Micro-gravity.

Making a position measurement on a "real" Earth surface, or relative to the Earth's surface as in the case of aviation applications, is facilitated by the use of geodetic reference systems. The use of these systems helps mitigate the challenges discussed in the preceding paragraphs, and the degree of mitigation depends on the particular reference system one chooses to use. There are over a dozen recognized reference systems, but the three germane to this study are the NAD 83, WGS 84, and the International Terrestrial Reference Frame of 2000 (ITFR00).

1. Emergence of NAD, WGS, and ITRF Geodetic Reference Systems

NAD 83 is a reference to the North American Datum of 1983 which incidentally was not initially adopted until 1986. Therefore, the initial version of NAD 83 became NAD 83 (86). It is the successor datum for NAD 27. NAD 83 (86) began as a horizontal reference datum but has evolved into a 3-dimensional reference system using GPS since that time [5]. NAD 83 (86) was based upon the Geodetic Reference System of 1980 (GRS80) ellipsoid [4, 5]. The center of the Earth's mass or the origin for this reference ellipsoid was based upon Doppler satellite observations that are now considered less than accurate by today's standards. Therefore, NAD 83 (86) was a horizontal reference system which was geocentrically based. A few short years after this first realization of NAD 83 (86), GPS technology made vertical measurements for this first realization possible. GPS technology later revealed that the center of mass used by the GRS80 ellipsoid is displaced by approximately 2 meters, meaning the origin is approximately 2 meters from the Earth's Center of Mass as measured by Satellite orbit [5, 6, 7]. NAD 83 has gone through many adjustments to make it more precise over the years. However, its origin has not been changed to reflect the recent more accurate estimate of the Earth center of mass.

Four additional realizations of NAD 83 have followed. Networks of GPS control points formed the High Precision Geodetic Network (HPGN) which is currently referred to as the High Accuracy Reference Network (HARN). These systems led to a realization of NAD 83 being NAD 83 (HARN). Next, in 1994, a network of continuously operating reference stations (CORS) was used to form NAD 83 (CORS). Then, in 1998, NGS used the CORS positions to formulate the ITRF96 realization. Later these same ITRF96 positions were then transformed into the fifth overall realization of NAD 83 referred to as NAD 83 (CORS96**)** [8]. A new update to NAD 83, denoted as NAD 83 (NSRS2007), is slated to be completed by February 2007 [9].

Furthermore, NAD 83 provides ellipsoidal heights via the GRS80 ellipsoid and orthometric heights via the North American Vertical Datum of 1988 (NAVD 88**)** [10]. NAVD 88 is the vertical datum counterpart of NAD 83. GEOID99 is the gravitational geoid model used for NAD 83 / NAVD 88 and is the relational link between the two [7].

WGS 84 is a reference to the World Geodetic Survey of 1984. In 1987, it was created using Doppler observations by the National Geospatial Intelligence Agency (NGA) on behalf of the U.S. Department of Defense (DoD**)** [4, 11]. At the time WGS 84 was created, it used the same reference ellipsoid (GRS80) as NAD 83. As a historical note, the NGA was formerly known as the National Imagery and Mapping Agency (NIMA), which was formerly the Defense Mapping Agency. WGS 84 is the standard physical model of the Earth used by GPS [1].

Multiple versions of WGS 84 exist with the original version defined by the Bureau International de l'Heure (BIH) via the Conventional Terrestrial System (CTS) using reference epoch "RE (84.0)" [12]. NAD 83 (86) and WGS 84 shared the same origin at the time WGS 84 was defined. Since then WGS 84 has gone through three updates. WGS 84 (G730) was introduced by the DoD in 1994 and is completely based upon GPS observations. Next, WGS (G873) was realized in 1996, and in 2001 WGS 84 (G1150). The version identifiers (G730), (G873), and (G1150) are indicative of the GPS week of the GPS orbits utilized to make adjustments to the reference frame [12]**.** WGS 84 currently uses the Earth Gravitational Model (EGM96) to produce the WGS 84 geoid [7].

ITRF00 - International Terrestrial Reference Frame of 2000 (ITFR00)

The International Terrestrial Reference Frame (ITRF) was provided by the International Earth Rotation Service (IERS) which was established in 1987. In January of 2003, the IERS was later renamed to be the International Earth Rotation and Reference Systems Service (IERS - keeping the same acronym). The intent of the ITRF was to provide highly accurate positional coordinates for international geodetic purposes. The first version of ITRF was referred to as ITRF88 and every so often a new realization is published with current geodetic data (i.e., positions and velocities) accumulating an additional period of historical data (between each realization). Additionally, each new reference frame incorporates the latest understanding of Earth's dynamics. The accuracy and rigorous techniques used to develop each new ITRF has proven to be quite popular and it is said to be the first widely accepted international reference system to specifically take plate tectonics and other crustal movements into account. The ITRF is established as an international standard and according to the FAQ found on the NGS website it is the most accurate geocentric reference system currently available [5]. The latest release of the ITRF is ITRF2005, however, the WGS 84 (G1150) is known to be closely aligned with ITRF2000 which is the ITRF used in this study [12].

2. Commonalities Among NAD 83, WGS 84, and ITRF

There are a certain number of commonalities between all three reference systems. For instance, all three (NAD 83, WGS 84, and ITRF) take into account or deal with topography, a reference ellipsoid, and a geoid (see Figure 4).

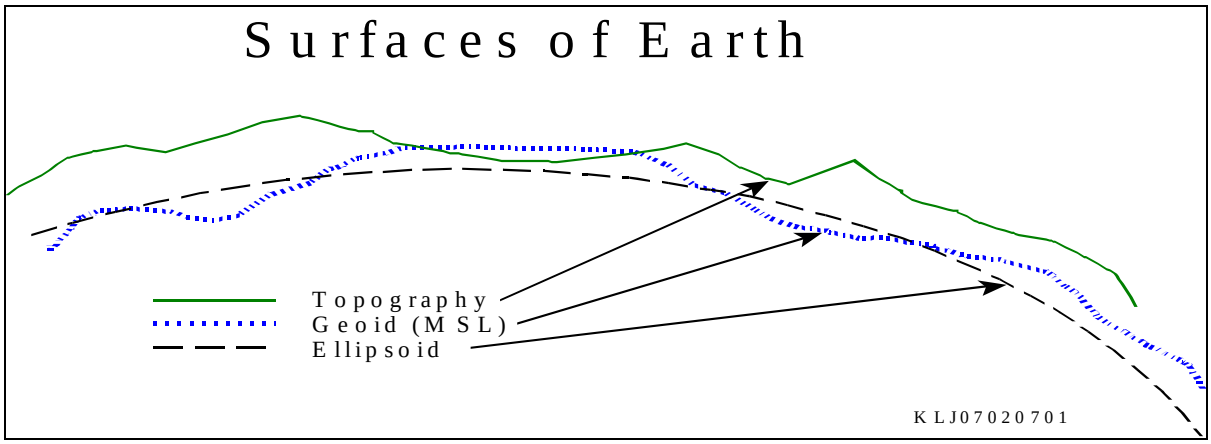

Figure 4. Illustration of Three Earth Surfaces, Topography, Geoid, and Ellipsoid.

a. Topography

The topography of earth is simply described as being the terrain. A more succinct description is that the topographic surface is "where the Lithosphere meets either the Atmosphere or the Hydrosphere [13].

Since this study addresses GPS/WAAS as a means of landing aircraft, the topographic surface is the primary surface of interest for approach and landing operations. Further, the topographic surface is the only surface that surveyors can physically access, raising the question "why not work with this surface directly for GPS/WAAS coordinate calculations." The answer can be found in the Defense Mapping Agencies document entitled "GEODESY for the Layman" where it states that "the topography is the surface on which actual measurements are made", however, it goes on to say, "It is not suitable, for exact mathematical computation because the formulas which would be required to take the irregularities into account would necessitate a prohibitive amount of computations" [14]. Another way to state this is that the topographic surface is not a geometric shape that is easily defined mathematically.

b. Reference Ellipsoid

Although the topography of Earth is immediately and most visible, for the reason stated above, its shape cannot be easily described mathematically for calculations. A Spherical Earth representation is a simple geometric shape for dealing with the various mathematical calculations involved, however, it turns out to be an oversimplification. The next best shape is a slightly flattened oblate spheroid or a better name for it is an oblate 'ellipsoid of revolution'. This oblate ellipsoid shape is most representative of Earth because the Earth is "flattened slightly at the poles and bulges somewhat at the equator" [5]. This representative shape is actually an ellipsoid that has been rotated about the minor axis. It is also the shape chosen by the geodetic community as the best geometric shape to represent the 'figure' of the Earth for the purposes of geodesy and geodetic related calculations. Typically, this shape is defined by two values, the major axis "a" and the flattening factor "f" to become the reference ellipsoid.

c. The Geoid

A geoid is defined by NGS as "The equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level" [5]. This equipotential surface is a function of the Earth's gravitational field. Figure 5 shows a representation of anomalies within the Earth's gravitational field which range from -50 to +50 milligals. These same gravitational field anomalies can cause deviations in the geoid which range from -100m to +60m (from the theoretically smooth ellipsoid) over the entire geoidal surface.

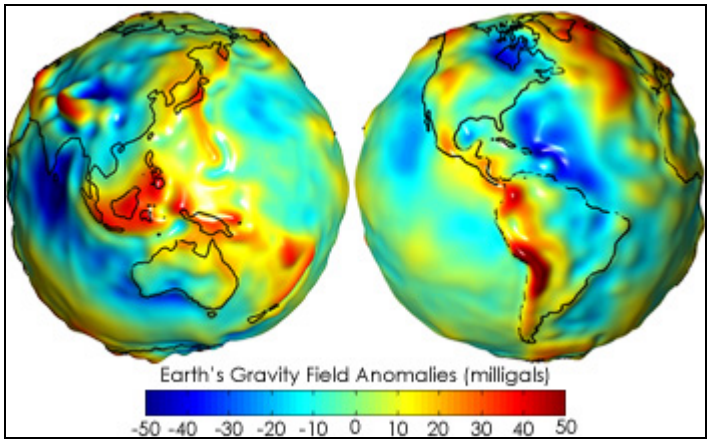

Figure 5. Representations of Earths Gravity Field (obtained from a NASA website)

*"These "*gravity anomaly*" maps show where models of the Earth's gravity field based on gravity recovery and climate experiment (GRACE) data differ from a simplified mathematical model that assumes the Earth is perfectly smooth and featureless. Areas colored yellow, orange, or red are areas where the actual gravity field is larger than the featureless-Earth model predicts—such as the Himalayan Mountains in Central Asia (top left of the left-hand globe)—while the progressively darker shades of blue indicate places where the gravity field is less—such as the area around Hudson Bay in Canada (top center of right-hand globe)"* [15].

3. Differences Between NAD 83, WGS 84, and ITRF

During the literature search phase of this study, the authors encountered the following two statements in a number of sources:

Statement #1: "NAD 83 and WGS 84 are 'identical' or the 'same' "

Statement #2: "NAD 83 and WGS 84 differ by ~2 meters"

There are at least two reasons why these somewhat contradictory statements are both true. The first reason is that the complete names of the reference systems are not explicitly stated. The complete names are needed to identify the particular version of the geodetic reference system being referenced. It is true that NAD 83 (86) and WGS84 (original) are considered identical (although they differ theoretically by a tenth of a millimeter in the ellipsoid height at the Earth's poles) [7]. While they were once identical, they no longer are due to movement of the WGS 84 (original) reference ellipsoid origin by approximately two meters. This two-meter adjustment, which led to WGS 84 (G730), was based on more accurate methods for determining the Earth's center of mass [5, 6, 7, 8]. Therefore, NAD 83 (86) differs from WGS 84 (G730) by approximately two meters. Since the origins of the various NAD 83 reference ellipsoids have not moved, it can be said that NAD 83 (CORS96) differs from WGS 84 (G730) by approximately two meters. Lastly, it can be said that the latest realization of WGS 84 (G1150) and the ITRF2000 reference frames differ by less than 1 cm [7].

NOTE: Similar seemingly contradictory statements for the same reasons stated above can be made about other pairs of reference frames.

The ellipsoid definitions used by each reference system can differ in their origin and orientation, semi-major or minor axis, and their flattening factors. Both the NAD 83 and the original WGS 84 ellipsoid were based upon the GRS80 reference ellipsoid. WGS 84 later moved to an ellipsoid adopted by the National Imagery and Mapping Agency. ITRF uses an ellipsoid definition provided by the IERS. Table 2 shows the values of the defining semi-major axis "a" and the flattening factors "f" for each reference systems reference ellipsoid.

Table 2. Differing Ellipsoids Currently Used by each Reference System.

Reference System	**Semi-Major Axis (m)**	**Flattening Factor (Unitless)**
NAD 83	6,378,137.0	1/298.257222101
WGS 84	6,378,137.0	1/298.257223563
ITRS	6,378,136.49	1/298.25645

The second reason is that for some applications being "the same" or "different" is relative to the scale of the work being undertaken. For some mapping purposes (at large scales) two meters

may not be a problem, thus for all intents and purposes, reference frames which vary by two meters may be seen as relatively equal. However, if the purpose is to study glacier movements typically measured in cm or millimeters, then a two-meter variance is intolerable. For most applications, it is unlikely that the end users will be aware of the differences in these reference frames. It is only after rigorous processing or attempts to utilize these differing reference frames in applications requiring higher precision that one becomes aware of these differences [7].

An investigation was needed to determine the extent and impact of the differences between reference systems both vertically for TCH deviations in elevation and horizontally for characterizing combined along-track and cross-track deviations.

III. INVESTIGATION

As part of the investigation into WAAS TCH anomalies, the FAA Engineering Report was first reviewed and then a literature search on the relevant subjects was performed. The latest version of the NGS Horizontal Time-Dependent Positioning (HTDP) software was obtained from the NGS website and used to perform a series of coordinate transformational tests.

The coordinate transformation functionality of the HTDP software allows the user to convert coordinates from one reference frame (e.g., NAD 83 (CORS96)) to any one of several output coordinate reference frames (e.g., WGS 84 (G1150) or ITRF00). The output results file produced by the HTDP program displays, among other items, the input latitude, longitude and ellipsoid height, and the transformed or output latitude, longitude and ellipsoid height. An ellipsoid height delta (dEHt) can then be calculated by subtracting the input ellipsoid height from the output ellipsoid height.

At this point, it was realized that a large number of coordinate transformations would need to be performed for a thorough investigation of the TCH variation. Since a functional method of automating the batch execution of HTDP was desired, AEC personnel developed an automation tool denoted as the Horizontal Time-Dependent Positioning Automator (HTDP-A) to support the simulation work required for this study. Details about the HTDP-A program may be found in Reference 16.

Assuming that the input reference frame is NAD 83 (CORS96) and the chosen output reference frame was ITRF00, then the dEHt should be the difference in TCH elevations observed when using a WAAS enabled GPS receiver flying against and referencing a NAD 83 (CORS96) surveyed runway threshold elevation. Using this concept, the first task was to investigate the TCH discrepancies (dEHts) at each of the four airport runway thresholds considered in Reference 2. The task of replicating the FAA results would be the first test performed. Successive tests discussed herein involve: investigation of the deviation of TCH height deltas over a single large airport (e.g., Dallas Fort Worth – DFW); performing the same calculations over a larger number of airport locations; performing these calculations over a large calculated grid to observe the trend in dEHts over the selected area; characterizing the trend over the North-Western quadrasphere; and, characterizing the trend over the entire globe. Next, global comparisons of the various reference frames were performed. Lastly, all these tests culminated

in a final series of gridded coordinate transformations from NAD 83 (CORS96) to ITRF00 over the CONUS, Alaska, Hawaii, and then later the North-Western quadrasphere and the entire globe.

Before discussing each test and the results, two items need noted that are common to all the analysis work. First, the date of 01 January 2000 was used for all input and output epoch dates for the purposes of consistent static comparisons. Second, unless specified otherwise, the input reference frame specified was NAD 83 (CORS96) and the output reference frame specified was ITRF00. It should also be noted when viewing the results of this investigation that some reference frames and their corresponding ellipsoids are good representations of a local geographical area on Earth. These ellipsoids do not tend to be good representations of the Earth globally [17]. The various versions of NAD 83 including NAD 83 (CORS96) were developed for the North American geographic area and as such are not the best approximations of Earth over the entire globe.

A. Test 1 & 2 - Reproducing the FAA Results

As stated above, the first task was to investigate the TCH discrepancies (dEHts) at each of the four airport runway thresholds considered in the FAA engineering report [2]. The results obtained from this first investigation were found to be identical to the results obtained by AVN personnel. These results are presented in Table 3 and the full HTDP output may be found in Appendix A.

Table 3. Sample Height Differences Between NAD 83 and WGS-84 Elevations.

#	Airport (City, State)	Ident	Runway	Latitude Longitude	Height Differences
1	Will Rogers World (Oklahoma City, OK)	KOKC	17R	N 35° 24' 21.4200" W 097° 36' 20.6000"	3.7 ft
2	Daytona Beach International (Daytona Beach, FL)	KDAB	07R	N 29° 10' 33.7160" W 081° 03' 24.6303"	5.0 ft
3	Denver International (Denver, CO)	KDEN	07	N 39° 50' 27.4000" W 104° 43' 35.9700"	2.9 ft
4	Los Angeles International (Los Angeles, CA)	KLAX	06L	N 33° 56' 56.7900" W 118° 25' 52.1600"	2.3 ft

This test was performed the first time using an input ellipsoid height of zero (test 1) and then run a second time using the actual ellipsoid height provided by the online AVN datasheet for each candidate airport (test 2). The resulting dEHts were identical from both sets of tests, the full HTDP output for the second test may be found in Appendix B of this report. Since, for the purpose of this report, we are primarily interested in the dEHts and not the absolute values, an input ellipsoid height of zero would yield the same desired results as using the actual absolute values. This played an important role throughout the investigation by allowing calculations to be performed across large grids without knowing the absolute input ellipsoid heights.

B. Test 3 – Variation of Ellipsoid Heights Over a Single Large Airport

For the third test, it was desirable to look at the variation of dEHts over all the runway thresholds at a single large major airport. For this purpose the Dallas-Fort Worth (DFW) International Airport was chosen as the candidate site. DFW has runway thresholds covering an area of approximately 26,000‘ by 13,500’ which is approximately 5 mi by 2.5 mi or 8 km by 4 km. The results of the test indicate a 2mm deviation over this area and are presented in Table 4. The airport diagram for DFW is found in Figure 6.

Table 4. Variations in dEHts for all Runway Thresholds at DFW.

				Ellipsoid Height Deltas (dEHt)				
#	**RWY**	**LAT**	**LON**	**M**	**cm**	**mm**	**Ft**	**in**
1	13L	32 54' 45.19"	97 1' 17.32"	-1.204	-120.4	-1204	-3.95013	-47.401
2	31R	32 53' 41.93"	97 0' 3.04"	-1.205	-120.5	-1205	-3.95341	-47.440
3	13R	32 54' 34.47"	97 4' 59.28"	-1.203	-120.3	-1203	-3.94685	-47.362
4	31L	32 53' 24.97"	97 3' 47.79"	-1.204	-120.4	-1204	-3.95013	-47.401
5	17C	32 54' 56.54"	97 1' 33.5"	-1.204	-120.4	-1204	-3.95013	-47.401
6	35C	32 52' 43.96"	97 1' 34.22"	-1.205	-120.5	-1205	-3.95341	-47.440
7	17L	32 53' 53.95"	97 0' 35.2"	-1.204	-120.4	-1204	-3.95013	-47.401
8	35R	32 52' 29.85"	97 0' 35.67"	-1.205	-120.5	-1205	-3.95341	-47.440
9	17R	32 54' 56.6"	97 1' 47.58"	-1.204	-120.4	-1204	-3.95013	-47.401
10	35L	32 52' 44.02"	97 1' 48.29"	-1.204	-120.4	-1204	-3.95013	-47.401
11	18L	32 54' 56.88"	97 3' 2.65"	-1.203	-120.3	-1203	-3.94685	-47.362
12	36R	32 52' 44.3"	97 3' 3.33"	-1.204	-120.4	-1204	-3.95013	-47.401
13	18R	32 54' 56.933"	97 3' 16.711"	-1.203	-120.3	-1203	-3.94685	-47.362
14	36L	32 52' 44.35"	97 3' 17.4"	-1.204	-120.4	-1204	-3.95013	-47.401
			Max	-1.203	-120.3	-1203	-3.94685	-47.362
			Min	-1.205	-120.5	-1205	-3.95341	-47.440
			Mean	-1.204	-120.4	-1204	-3.95013	-47.401
			Delta	0.002	0.2	2	0.006562	0.0787

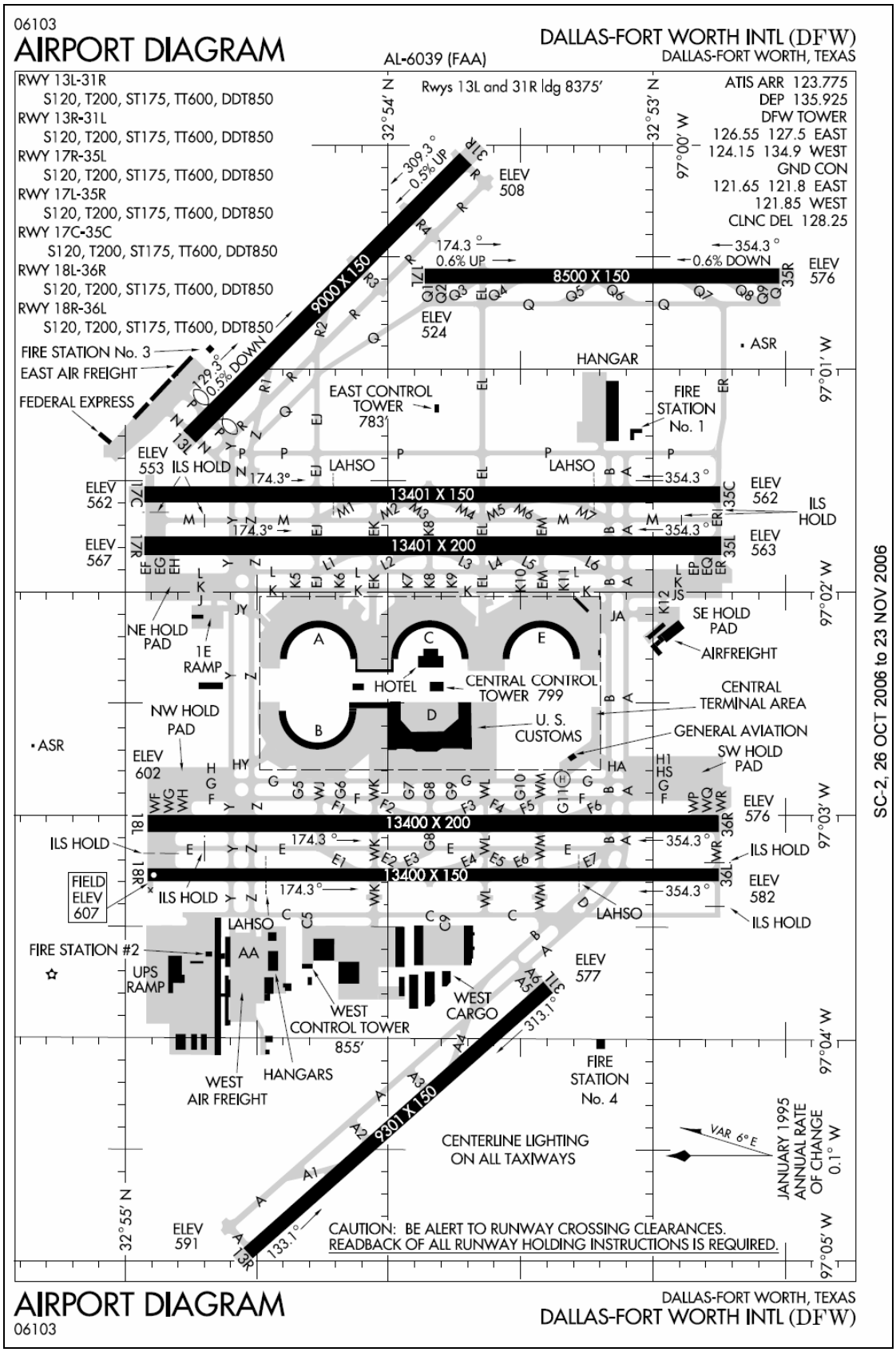

Figure 6. Airport Diagram for DFW.

C. Test 4 – Superset of Airports (the 4 original airports plus 12 additional airports)

The next task was to look at the TCH crossing height deviations or dEHTs for a larger superset of airports (see Table 5). This superset would include the original four airports from the FAA report as well as 12 additional airports. The dEHts from these 16 airports ranged from a minimum dEHt of -1.617 m at Miami International to a maximum dEHt of -0.377 m at Portland International and a deviation of 1.240 m across the entire group of airports. Additional details from this test are found in Appendix D of this report.

Table 5. A Superset of U.S. Airports and Their Corresponding dEHt Values.

#	Airport (City, State)	Ident	Rwy	Latitude Longitude	Ellipsoid Height Deltas dEHts (m)
1	Will Rogers World (Oklahoma City, OK)	KOKC	17R	N 35° 24' 21.4200" W 097° 36' 20.6000"	-1.132
2	Daytona Beach International (Daytona Beach, FL)	KDAB	07R	N 29° 10' 33.7160" W 081° 03' 24.6303"	-1.526
3	Denver International (Denver, CO)	KDEN	07	N 39° 50' 27.4000" W 104° 43' 35.9700"	-0.888
4	Los Angeles International Los Angeles, CA)	KLAX	06L	N 33° 56' 56.7900" W 118° 25' 52.1600"	-0.706
5	Portland International (Portland, OR)	KPDX	03	N 45° 34' 56.7300" W 122° 37' 00.5300"	-0.377
6	Billings Logan International (Billings, Montana)	KBIL	07	N 45° 48' 27.6300" W 108° 33' 30.2300"	-0.666
7	Chicago-O'Hare International (Chicago, Illinois)	KORD	04L	N 41° 58' 53.9600" W 087° 54' 50.1000"	-1.096
8	Cleveland-Hopkins International (Cleveland, OH)	KCLE	06C	N 41° 24' 16.5000" W 081° 51' 41.4300"	-1.178
9	La Guardia New York (La Guardia, NY)	KLGA	13	N 40° 46' 56.2700" W 073° 52' 42.6700"	-1.258
10	Ronald Reagan Washington National (Washington, DC)	KDCA	01	N 38° 50' 32.6000" W 077° 02' 12.5700"	-1.296
11	Charlotte Douglas International (Charlotte, NC)	KCLT	36R	N 35° 12' 03.4462" W 080° 56' 02.8225"	-1.368
12	Miami International (Miami, FL)	KMIA	08L	N 25° 48' 10.4332" W 080° 18' 05.5600"	-1.617
13	Dallas Fort-Worth International (Fort Worth, TX)	KDFW	13L	N 32° 54' 45.1900" W 097° 01' 17.3200"	-1.204
14	Salt Lake City International (Salt Lake City, Utah)	KSLC	14	N 40° 47' 08.5700" W 111° 58' 16.4500"	-0.717
15	Albuquerque International Sunport (Albequerque, NM)	KABQ	03	N 35° 01' 20.0900" W 106° 37' 50.1700"	-0.964
16	Lambert St. Louis International (Saint Lousie, Missouri)	KSTL	29	N 38° 44' 48.4560" W 090° 22' 59.3881"	-1.157
				Max	-0.377
				Min	-1.617
				Avg	-1.072
				Delta	1.240

D. Test 5 – Trend of Ellipsoid Height Deltas over the CONUS

This test involved calculating a grid of latitude longitude coordinate pairs to be used as input into the HTDP program. The grid would be generated using latitude values from 20 to 60 degrees in 1-degree increments and longitude values from -140 to -60 degrees also in 1-degree increments. A screen capture of the HTDP-A setup window is shown in Figure 7.

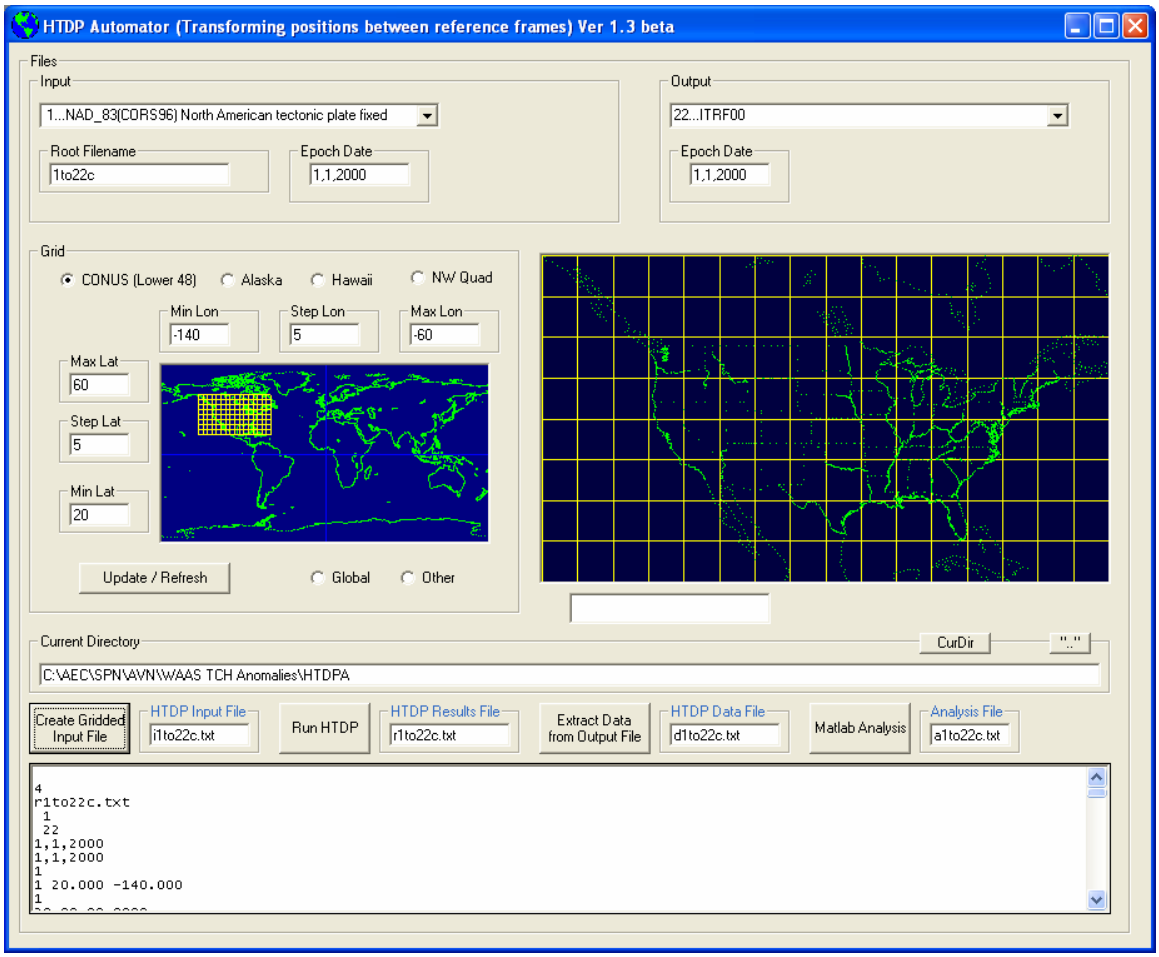

Figure 7. A Screenshot of the HTDP-A Utilities Main User Window.

The results from this test are plotted in Figure 8. This plot shows a well-behaved trend in dEHts over the CONUS ranging anywhere from -1.6 m in the Southeast corner of the CONUS to -0.1 m in the Northwest corner. Note: This plot is actually a plot of -dEHt to reveal the entire trend more effectively to the viewer. Figure 9 shows the same -dEHt data plotted in feet with the –dEHts from the previously mentioned superset of airport runway thresholds. Note that the superset of dEHts from each airport follows the trend by the very nature of the calculation method being the same. Additional details of this test can be found in Appendix E of this report.

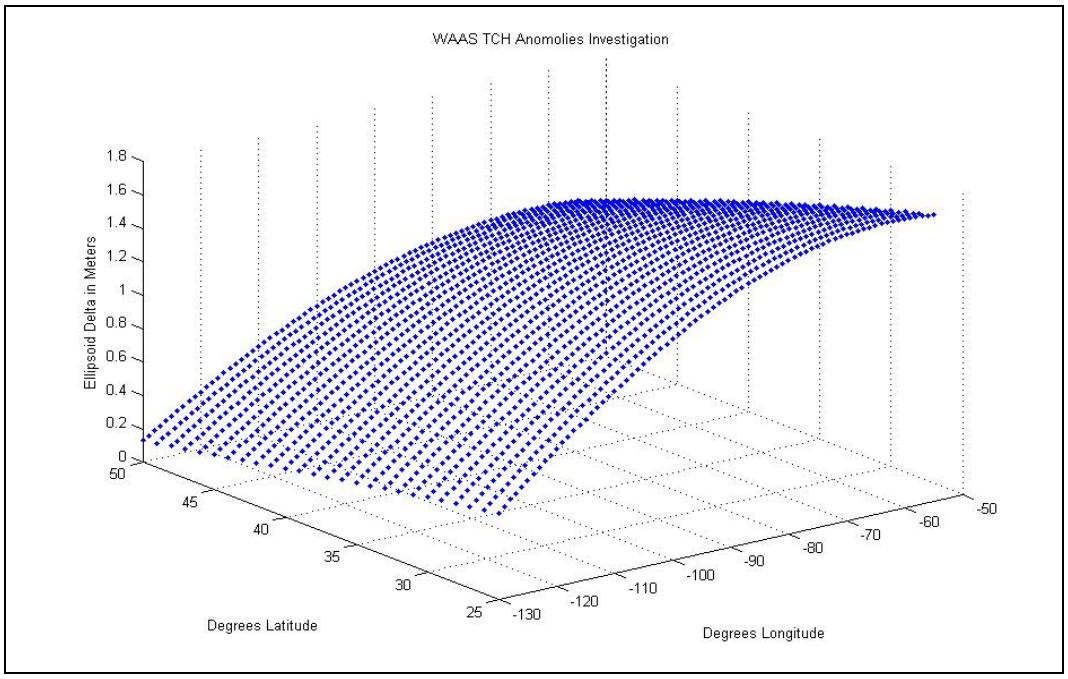

Figure 8. Trend of Negative Ellipsoid Height Deltas (-dEHts) over the CONUS.

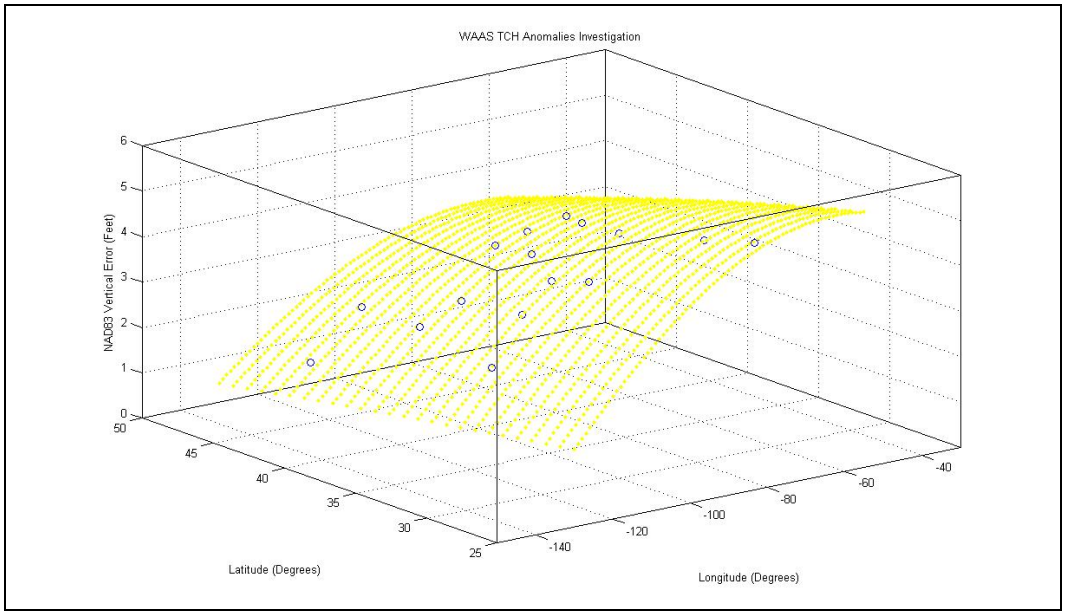

Figure 9. Trend of Negative Ellipsoid Heights Deltas **(**-dEHts**)** over the CONUS with the dEHts from the Superset of Airports Indicated by Blue Circles.

E. Test 6 – Trend of Ellipsoid Ht. Deltas over the North-Western Quadrasphere

The purpose of this test was to expand upon the previous test by using a grid which covered the entire North-Western quarter of the globe, or quadrasphere. This would allow for the same dEHt trend to be observed over a larger area and cover all the immediate areas of interest in one

complete grid. This grid was defined to be from -180 to 0 degrees of longitude while the range for latitude was from 0 to 90 degrees. The resolution for both latitude and longitude was 5-degree increments.

The results of this test showed that the relative dEHt were largest, on the order of -2 meters, along the South-Southeastern edge of the North-Western quadrasphere. Additionally, the results showed that the dEHt values transition through zero and obtain positive values. This transition is shown in Figure 10 by the locations where the red lines disappear, i.e., go beneath the surface of the NAD 83 (CORS96) Globe. This transition occurs before reaching the eastern Alaskan border, substantially off the western coast of the United States, and before reaching the Hawaiian Islands. Further details of this test may be found in Appendix F.

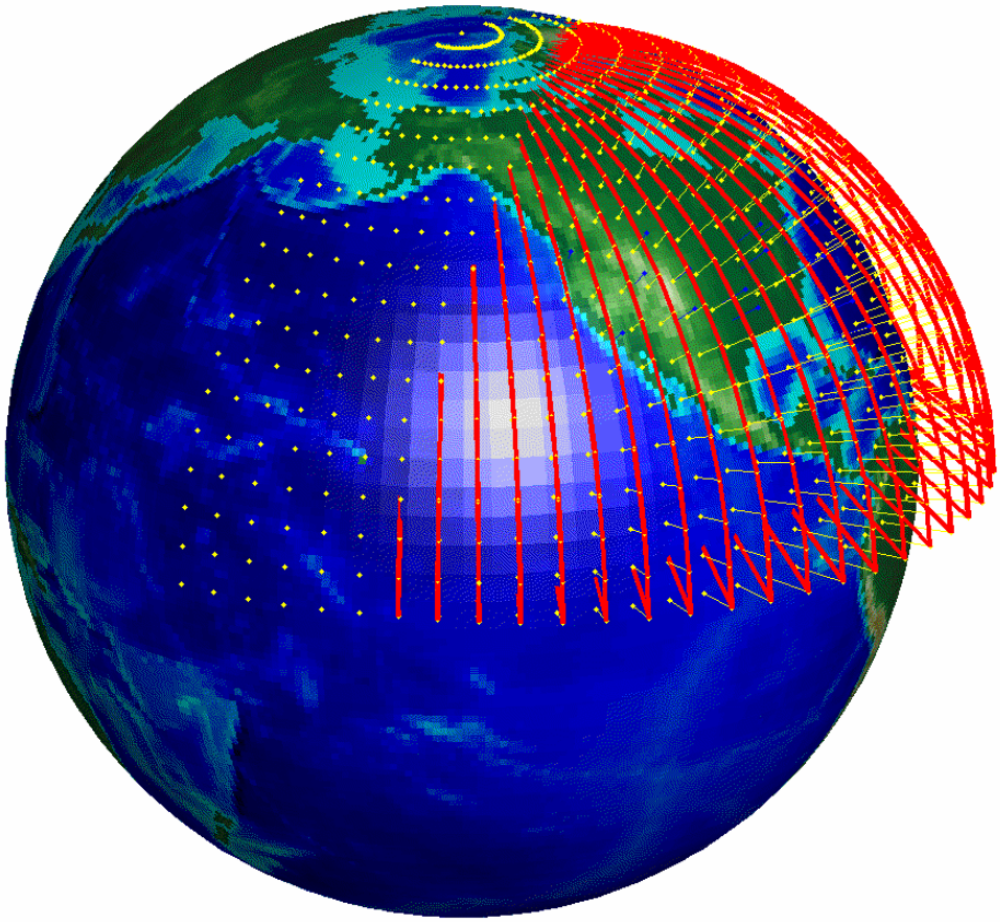

Figure 10. Relative dEHt for North-Western Quadrisphere of the Globe.

Further description of (Figure 10): 1) Red/yellow “stem” plot symbols indicate the area on the search grid where the actual Threshold Crossing Height (TCH) will be higher than the planned TCH; 2) The yellow “dot” plot symbols indicate the area on the search grid where the actual TCH will be lower than the planned TCH; and, 3) The blue stem plot symbols are the locations of the 16 airports selected for investigation.

Interpretation: 1) If NAD 83 coordinates are used for WAAS/LNAV/VNAV/LPV procedures in the CONUS (lower 48 states), the actual TCH is prone to being higher than the procedure the designer intended with the magnitude varying as function of location or position; and 2) If NAD 83 coordinates are used for WAAS/LNAV/VNAV/LPV procedures in Alaska or Hawaii, the actual TCH is prone to being lower than the procedure designer intended with the magnitude varying as function of location or position.

F. Test 7 – Global Grid Comparison of Reference Frames

The purpose of this test was to look at the global differences between each reference frame. Table 6 shows the various reference frame comparisons while Figure 11 through Figure 20 show the relative dEHt variations.

In summary, the first and second comparisons were done for a matter of testing and completeness, providing numerical validation of HTDP-A. They show that if one compares NAD 83 to NAD 83, one would expect to find no differences and when one compares NAD 83 to WGS 72 the difference is unusual and interesting, however, once again this was done as somewhat of a functional comparison check. The third comparison shows that NAD 83 and WGS 84 (original) are, in effect, identical. The fourth comparison shows that the biggest leap in differences within the various flavors of WGS 84 is between WGS (original) and WGS 84 (G730). The fifth comparison is again, for completeness. The sixth comparison shows that the largest jump between NAD 83 and WGS 84 is when the “flavor” of WGS 84 is (G1150). The seventh comparison shows that the dEHTs can be as large as 2.205 meters for NAD 83 (CORS96) versus ITRF00. The eighth comparison is identical to the sixth. The ninth comparison is identical to the sixth and eighth comparisons. The tenth comparison shows that WGS 84 (G1150) is identical to the ITRF00 ref frame.

Table 6. Global Grid Comparison of Reference Frames.

Coordinate Transformation			Summary of Ellipsoid Height Deltas (dEHts) (m)
#	**From**	**To**	
1	1...NAD_83(CORS96)	1...NAD_83(CORS96)	Max 0 Min 0 Mean 0
2	1...NAD_83(CORS96)	4...WGS_72	Max 2.993 Min -5.87 Mean -1.441117647
3	1...NAD_83(CORS96)	5...WGS_84(original)	Max 0 Min 0 Mean 0
4	1...NAD_83(CORS96)	6...WGS_84(G730)	Max 2.196 Min -2.204 Mean 1.278060413E-02
5	1...NAD_83(CORS96)	7...WGS_84(G873)	Max 2.205 Min -2.203 Mean 1.799046104E-02
6	1...NAD_83(CORS96)	8...WGS_84(G1150)	Max 2.205 Min -2.204 Mean 1.770747217E-02
7	1...NAD_83(CORS96)	22...ITRF00	Max 2.205 Min -2.204 Mean 1.770747217E-02
8	5...WGS_84(original)	8...WGS_84(G1150)	Max 2.205 Min -2.204 Mean 1.770747217E-02
9	5...WGS_84(original)	22...ITRF00	Max 2.205 Min -2.204 Mean 1.770747217E-02
10	8...WGS_84(G1150)	22...ITRF00	Max 0 Min 0 Mean 0

Note: From/to column format is HTDP option number followed by abbreviated reference frame name, (e.g., 1...NAD_83 (CORS96)).

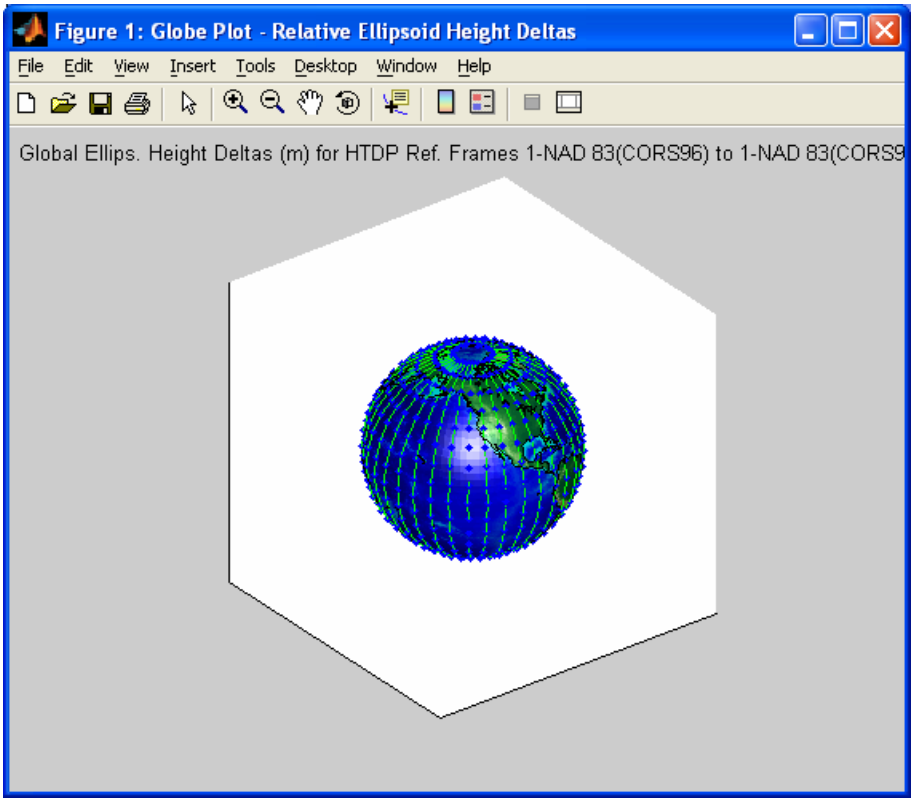

Figure 11. NAD 83 to NAD 83.

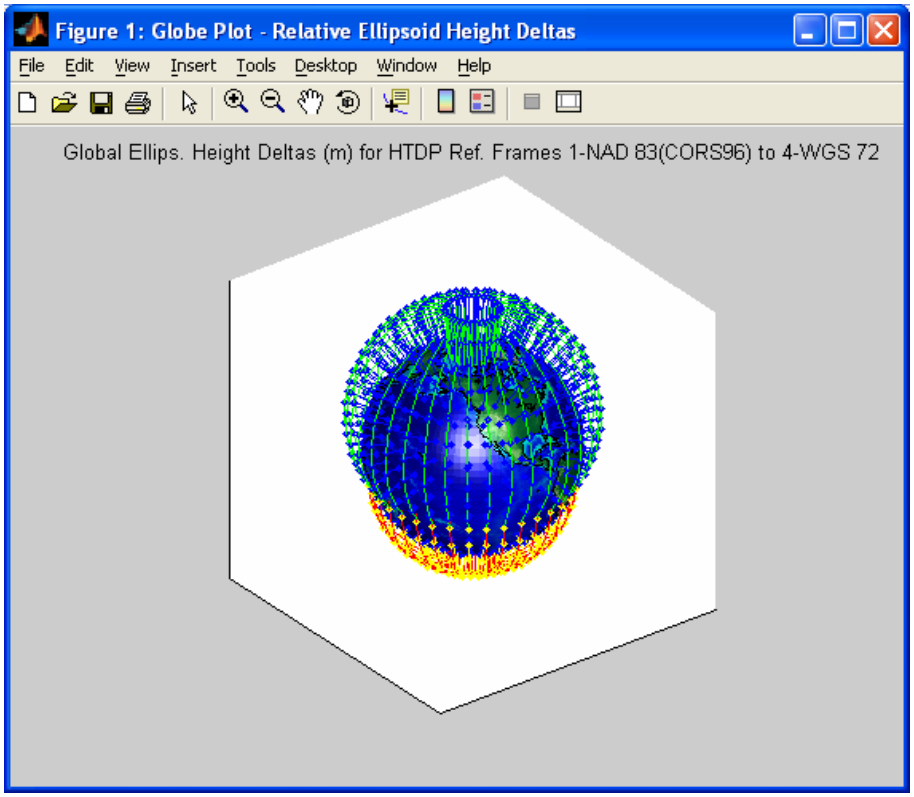

Figure 12. NAD 83 to WGS 72

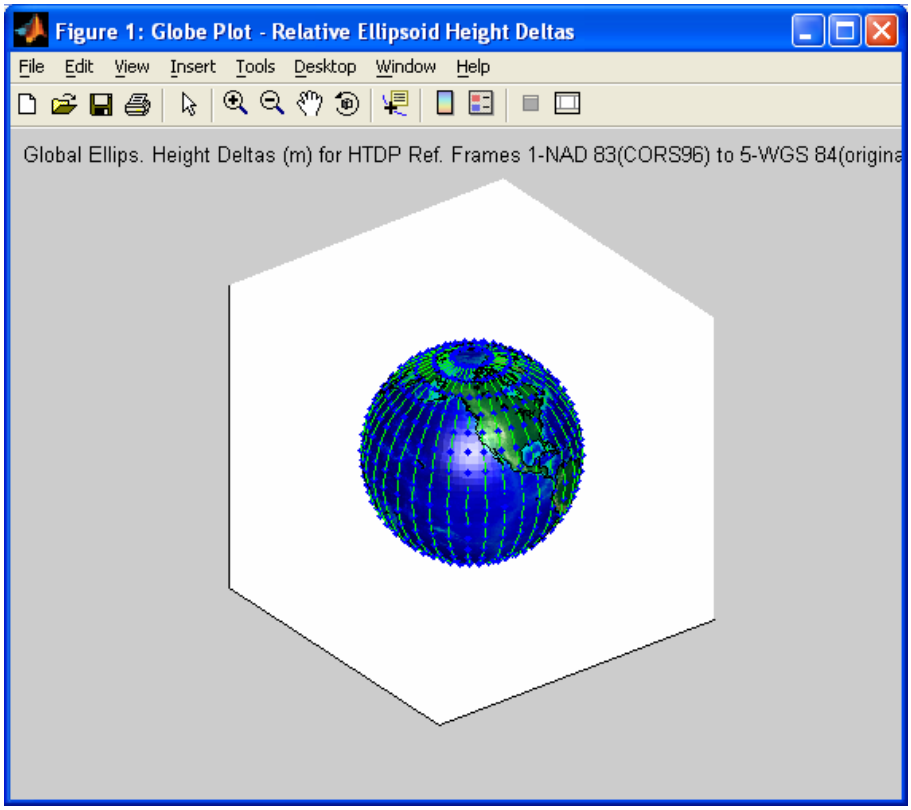

Figure 13. NAD 83 to WGS 84 (original)

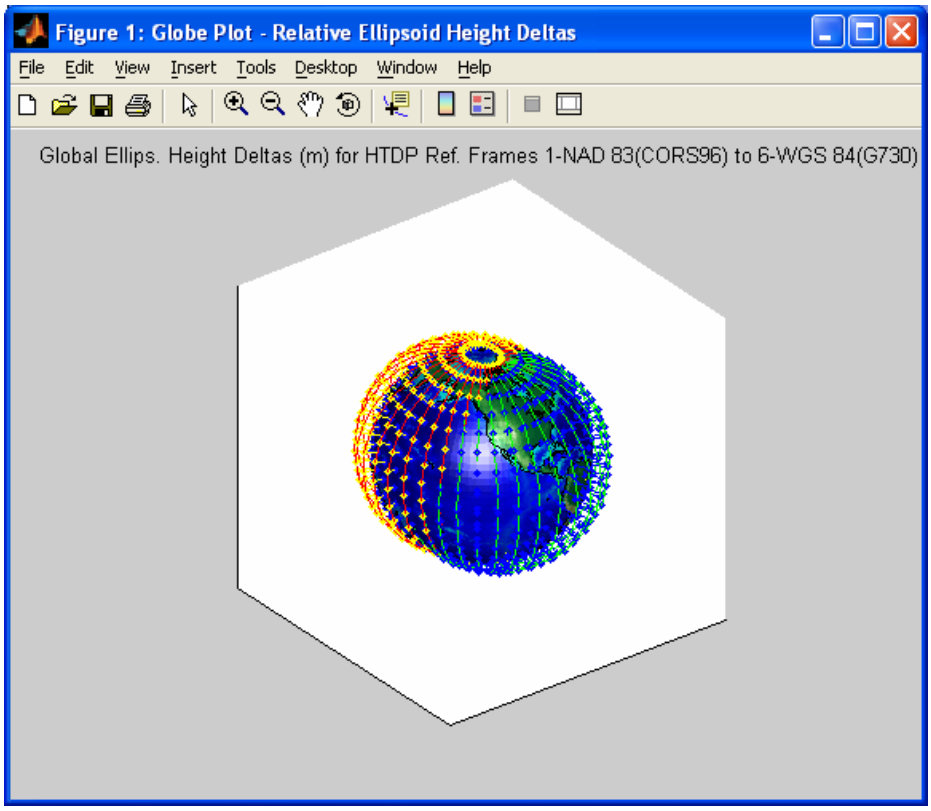

Figure 14. NAD 83 to WGS 84 (G730)

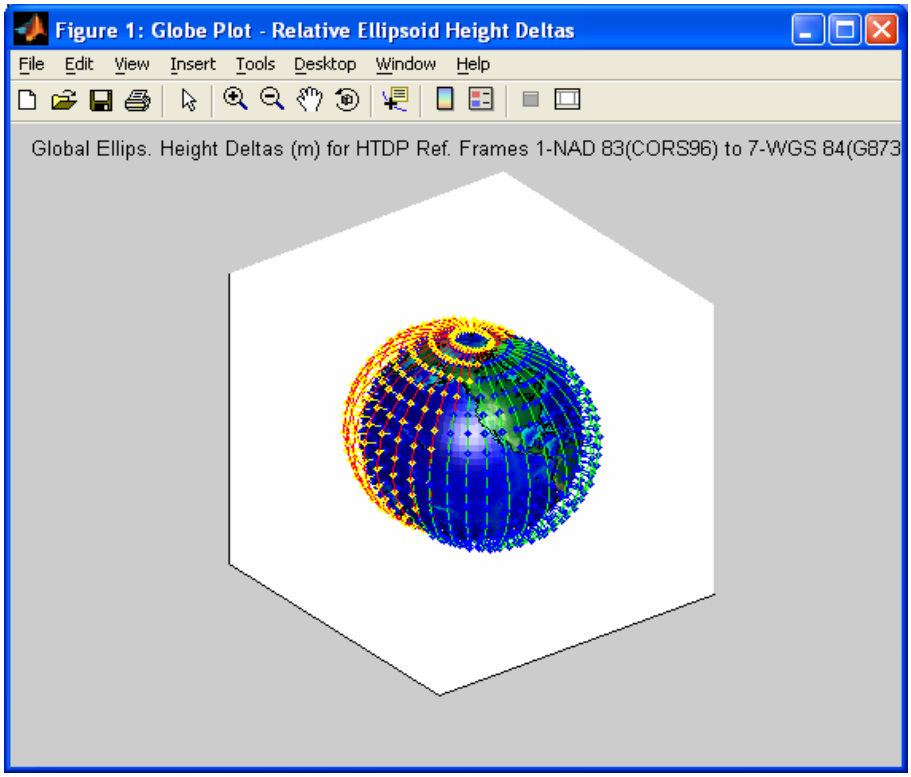

Figure 15. NAD 83 to WGS 84 (G873)

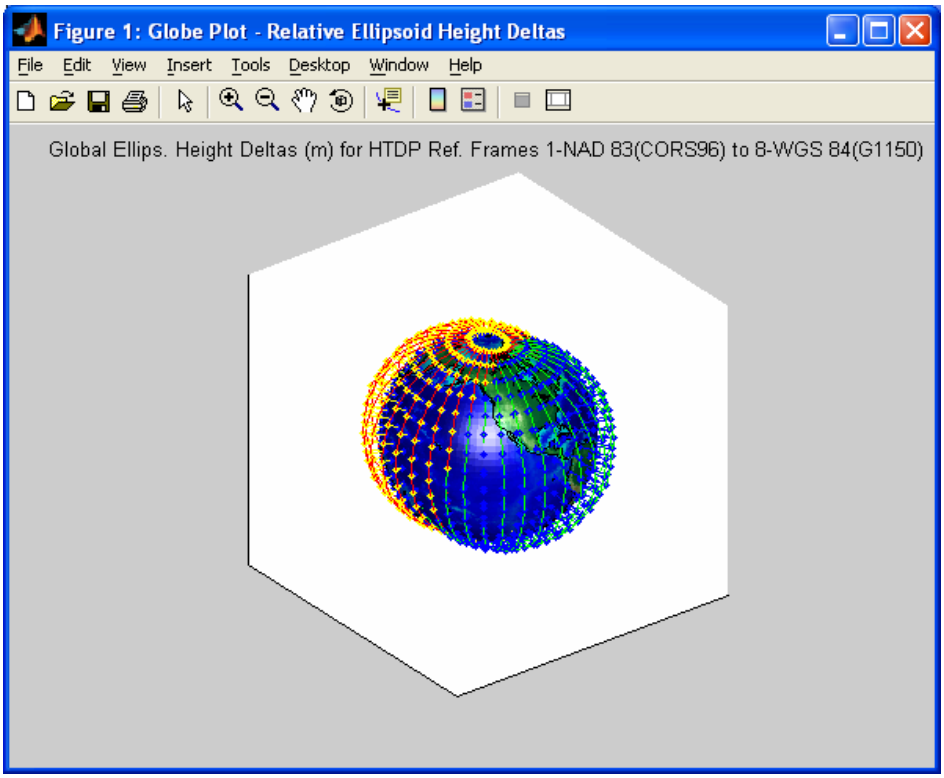

Figure 16. NAD 83 to WGS 84 (G1150)

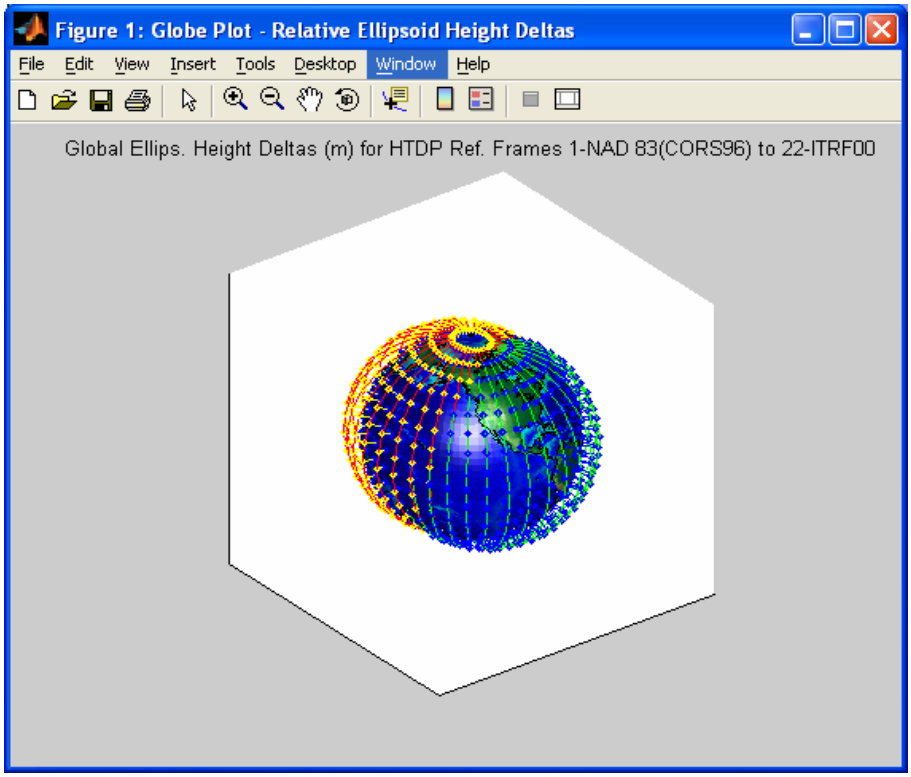

Figure 17. NAD 83 to ITRF00

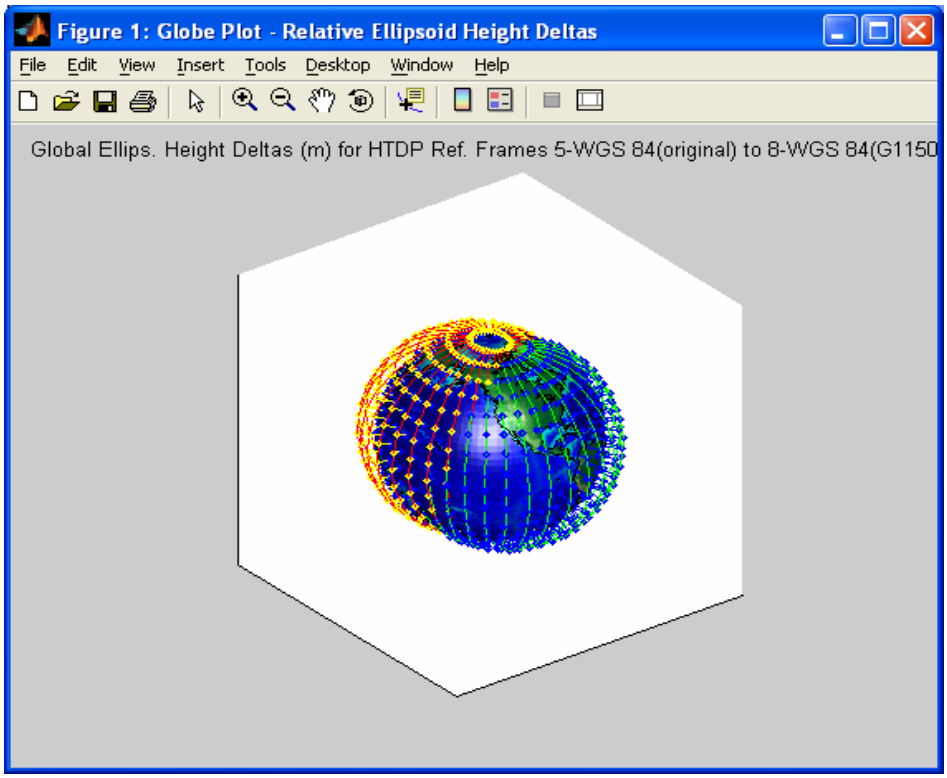

Figure 18. WGS 84(original) to WGS 84(G1150)

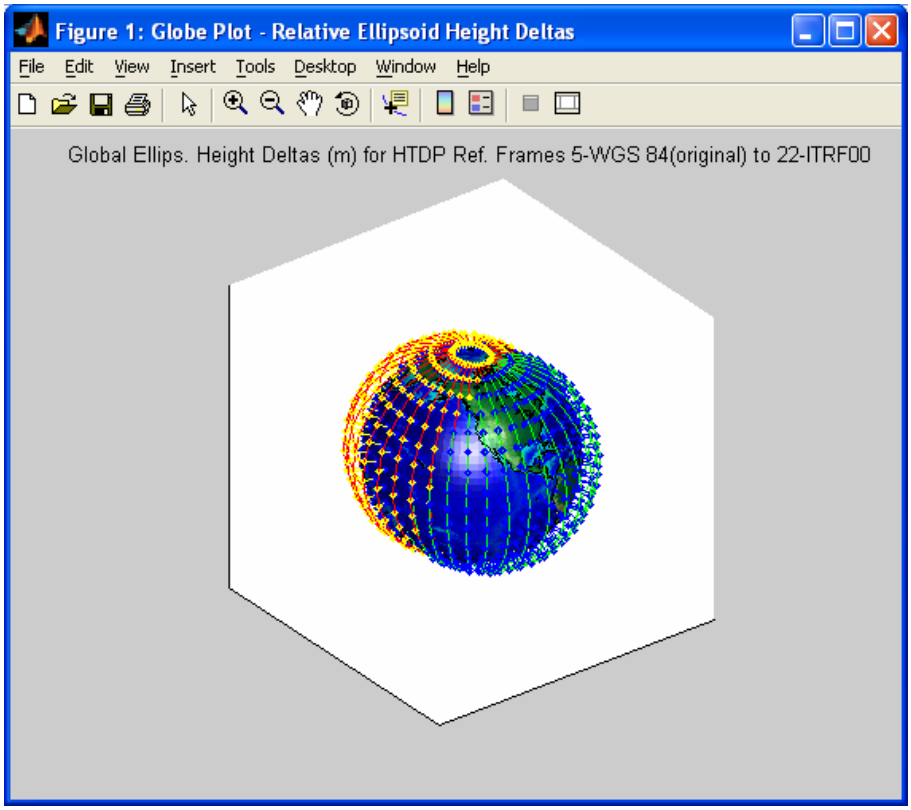

Figure 19. WGS 84 (original) to ITFR00

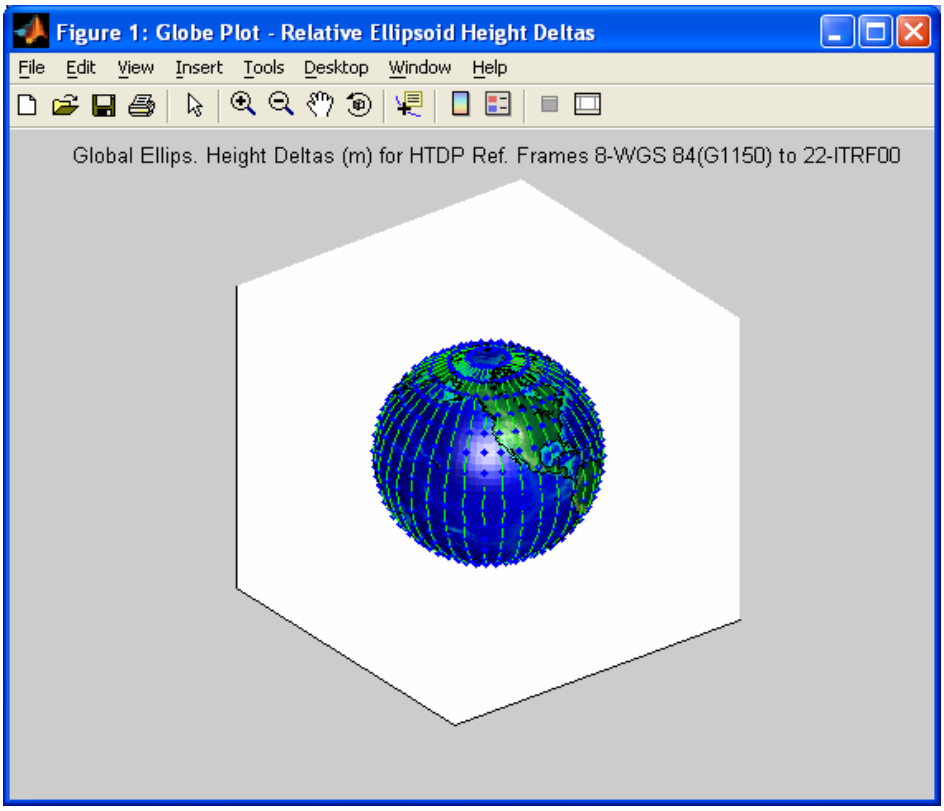

Figure 20. WGS 84 (G1150) to ITFR00

G. Test 8 – Comprehensive Investigation Over FAA Primary Areas of Interest

This last but rather comprehensive test leads to a culmination of findings for dEHts due to differences between NAD 83 (CORS96) and WGS 84 (G1150) / ITRF00, in the geographical areas of the CONUS (lower 48 states), Alaska and Hawaii. Furthermore, in this final and comprehensive set, the horizontal deltas (dH) or deviations in position error due to the same set of circumstances as listed for the TCH variation are characterized. These dHs represent the maximum along-track or cross-track error expected when the procedure track, typically runway centerline, is aligned either parallel or perpendicular to the direction of the horizontal shift.

NOTE: If NAD 83 (CORS96) coordinates are used for WAAS LNAV/ VNAV/ LPV procedures, a positive dEHt indicates that the actual TCH is prone to being lower than the procedure designer intended, while a negative dEHt indicates that the actual TCH is prone to being higher than the procedure designer intended. Table 7 summarizes the findings for this test and contour plots are provided in Figure 21 through Figure 30.

Table 7. Global Grid Comparison of Reference Frames.

#	Geographic Scope	See Figures	Summary of (dEHts) m	Summary of (dHs) m
1	CONUS (Lower 48 States)	Figure 21 and Figure 22	Max 0.219 Min -1.842 Mean -0.834	Max 1.536 Min 0.382 Mean 1.120
2	Alaska	Figure 23 and Figure 24	Max 1.040 Min 0.102 Mean 0.582	Max 1.334 Min 1.081 Mean 1.237
3	Hawaii	Figure 25 and Figure 26	Max 0.572 Min 0.003 Mean 0.304	Max 1.693 Min 1.415 Mean 1.562
4	NW Quad	Figure 27and Figure 28	Max 1.124 Min -2.148 Mean -0.491	Max 2.277 Min 0.073 Mean 1.302
5	Globe	Figure 29 and Figure 30	Max 2.205 Min -2.204 Mean 0.0177	Max 3.113 Min 0.0725 Mean 1.883

For completeness, this same process was performed over the North-Western Quadrisphere of the globe and for the entire globe as well. Figure 31 provides an example of the scenario/analysis summary report generated by HTDP-A. Further details regarding this test may be found in Appendix H of this report.

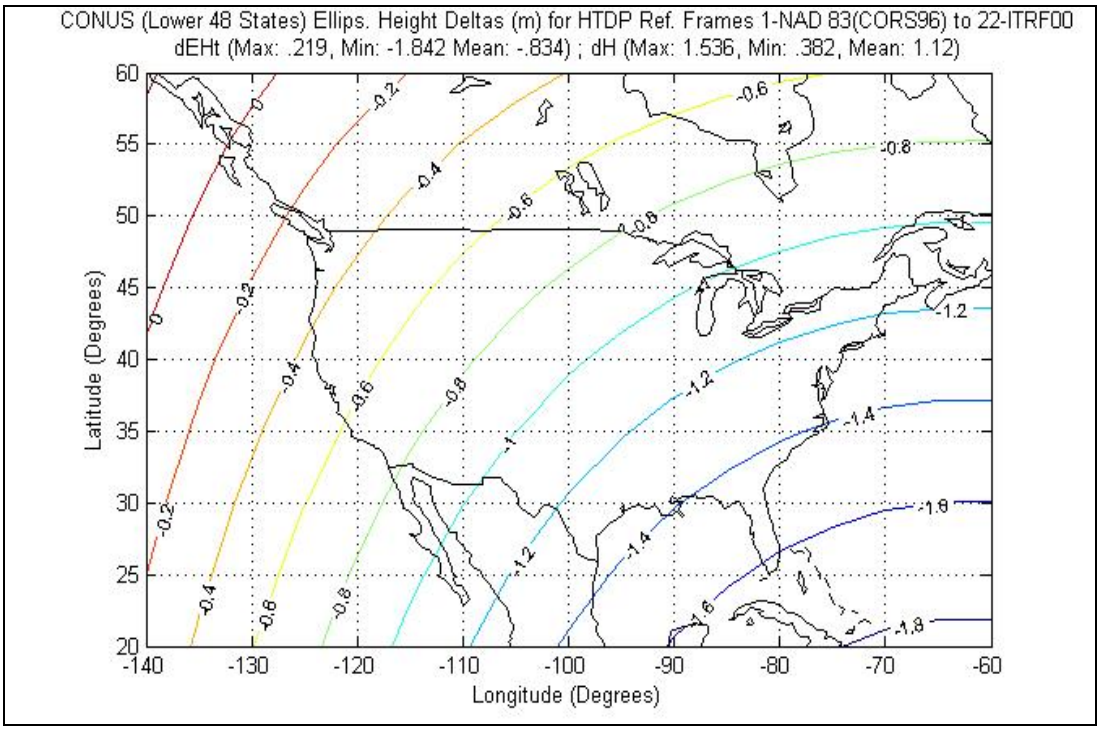

Figure 21. Contour Plot of dEHts for CONUS

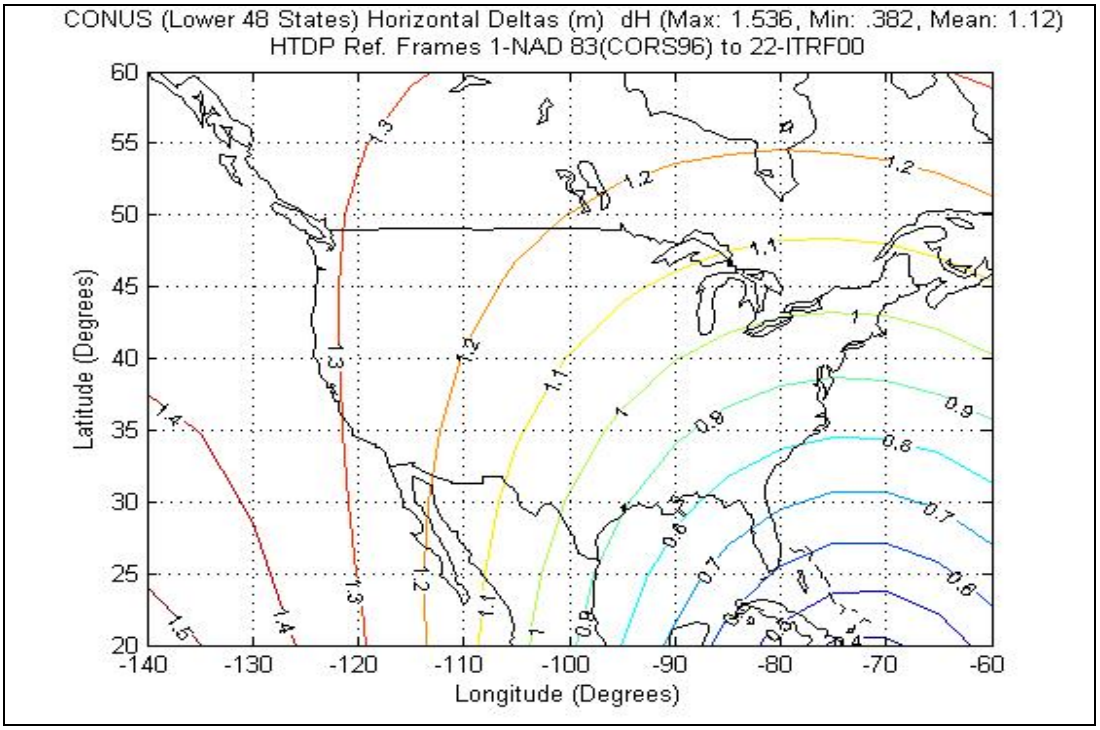

Figure 22. Contour Plot of dHs for CONUS

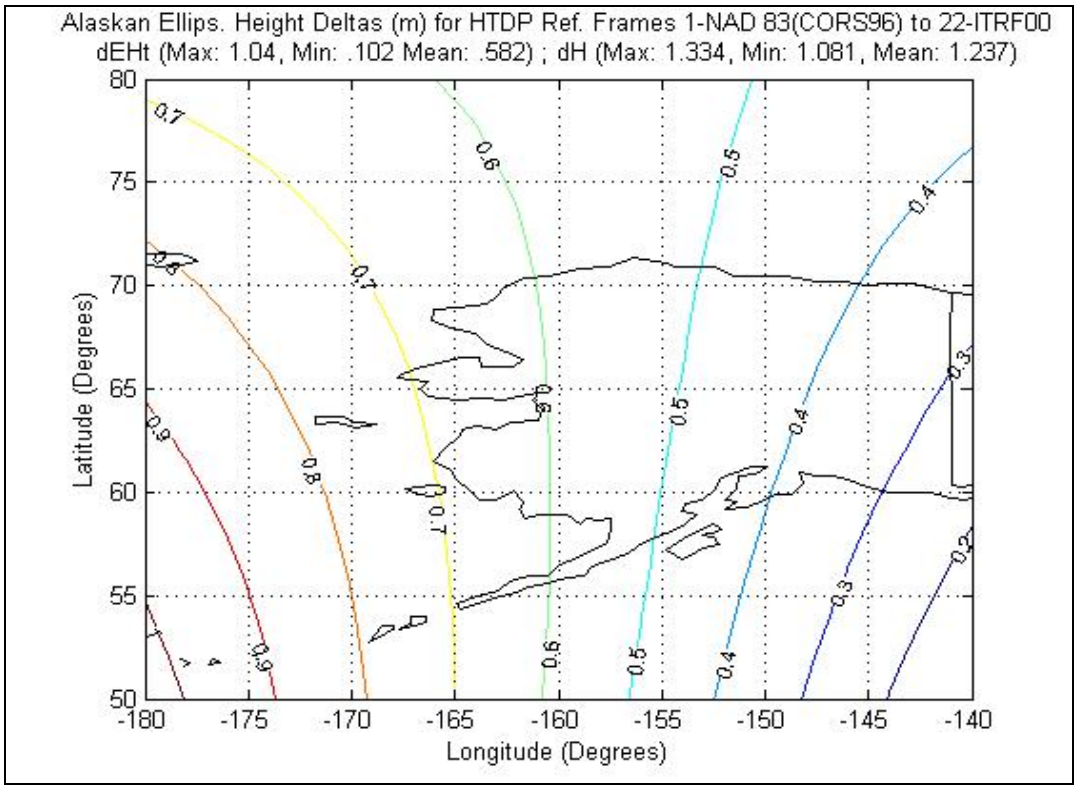

Figure 23. Contour Plot of dEHts for Alaska

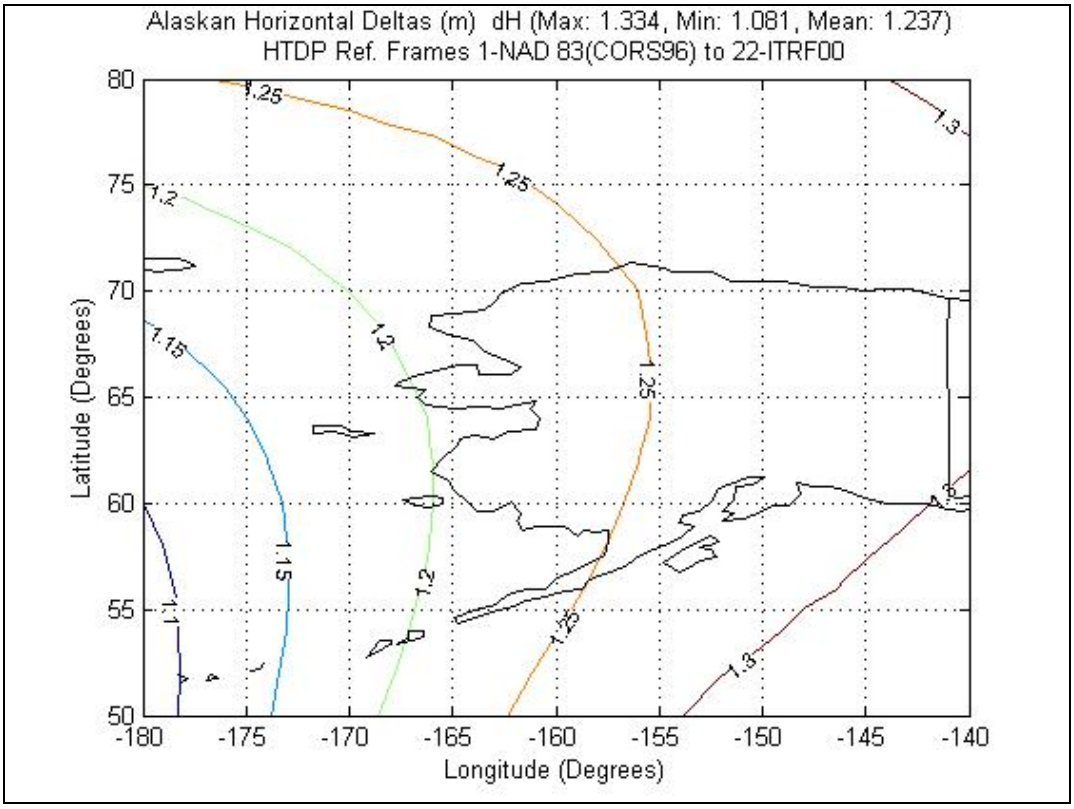

Figure 24. Contour Plot of dHs for Alaska

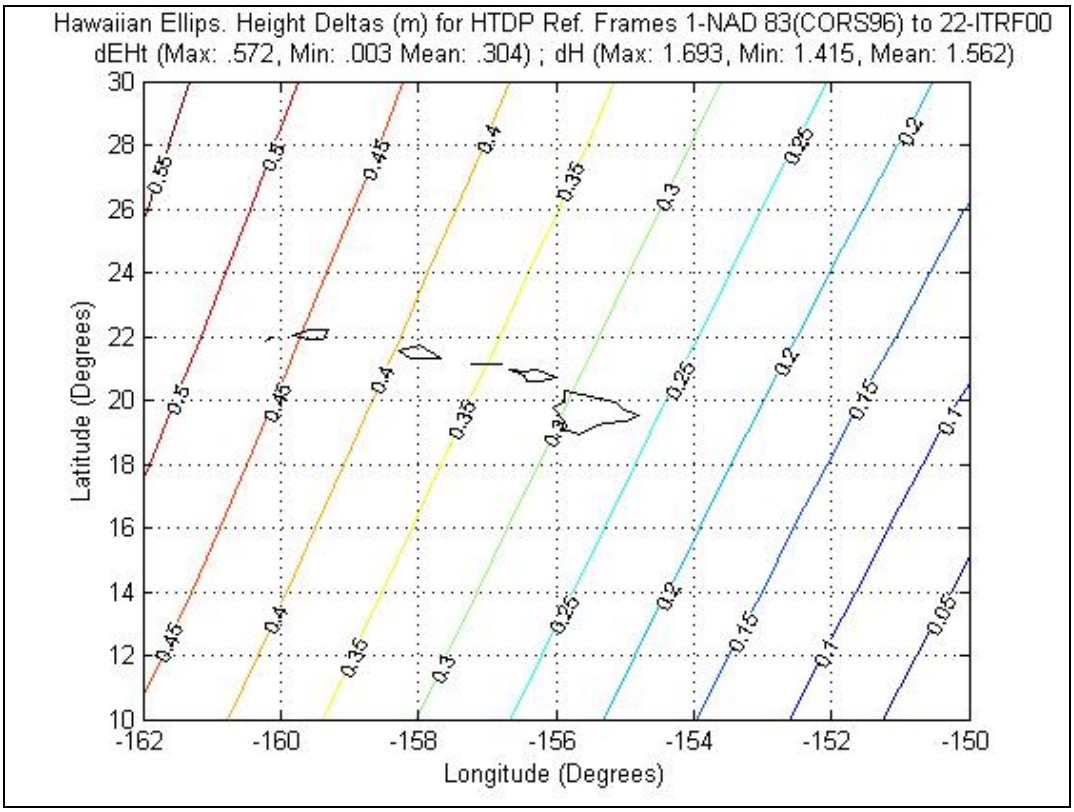

Figure 25. Contour plot of dEHts for Hawaii

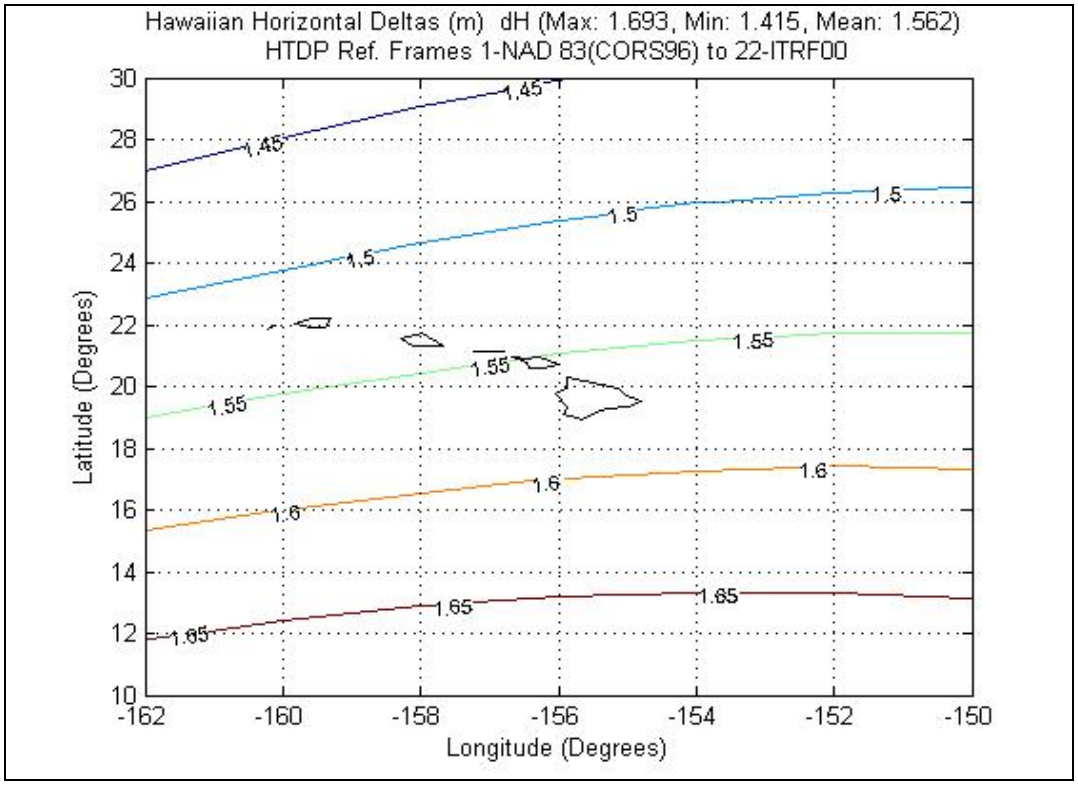

Figure 26. Contour Plot of dHs for Hawaii

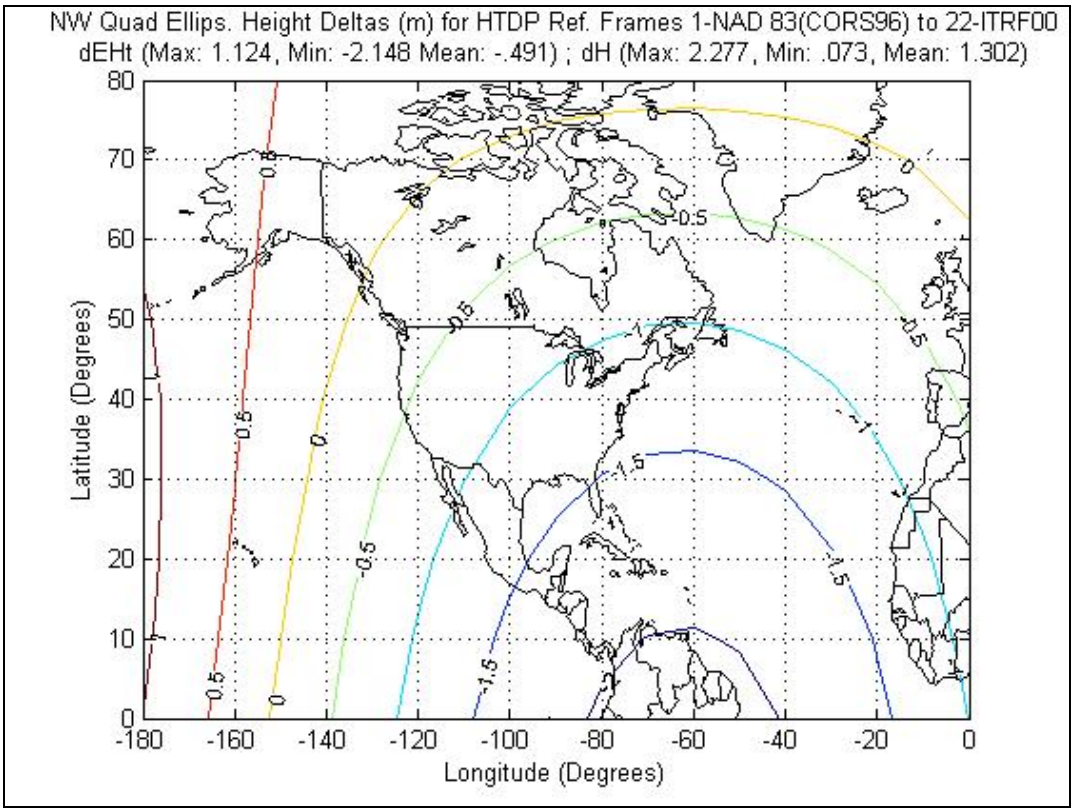

Figure 27. Contour Plot of dEHts for Northwest Quad

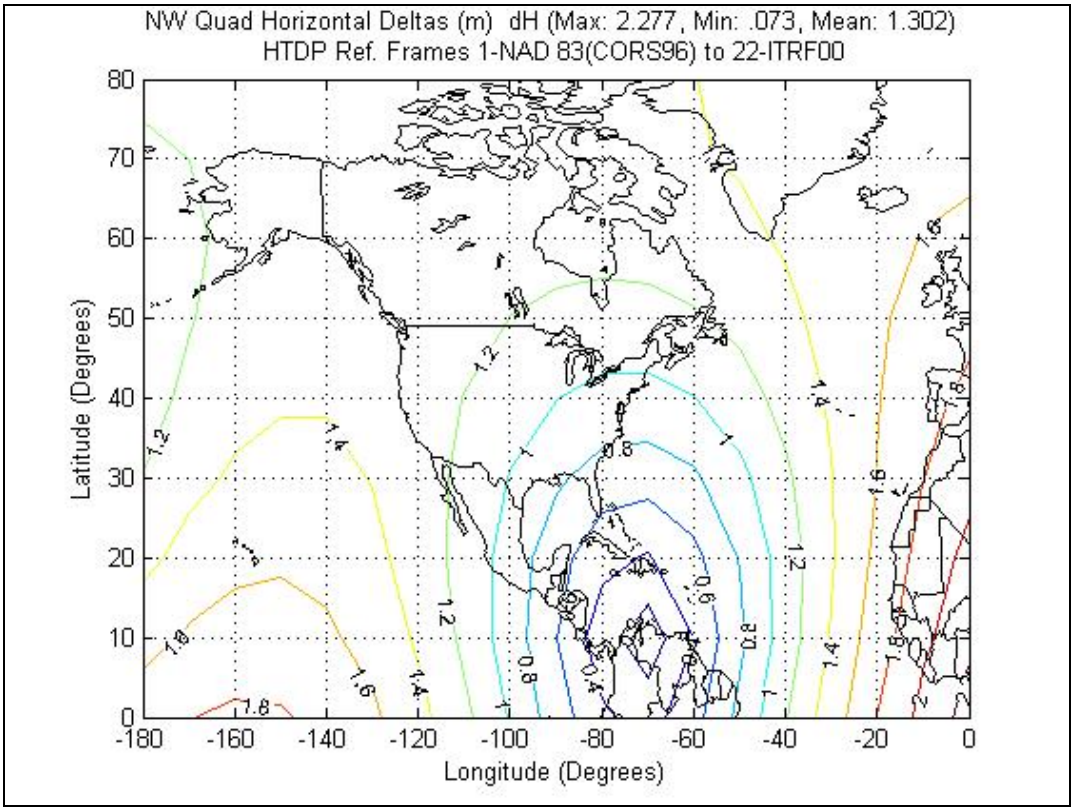

Figure 28. Contour Plot of dHs for Northwest Quad

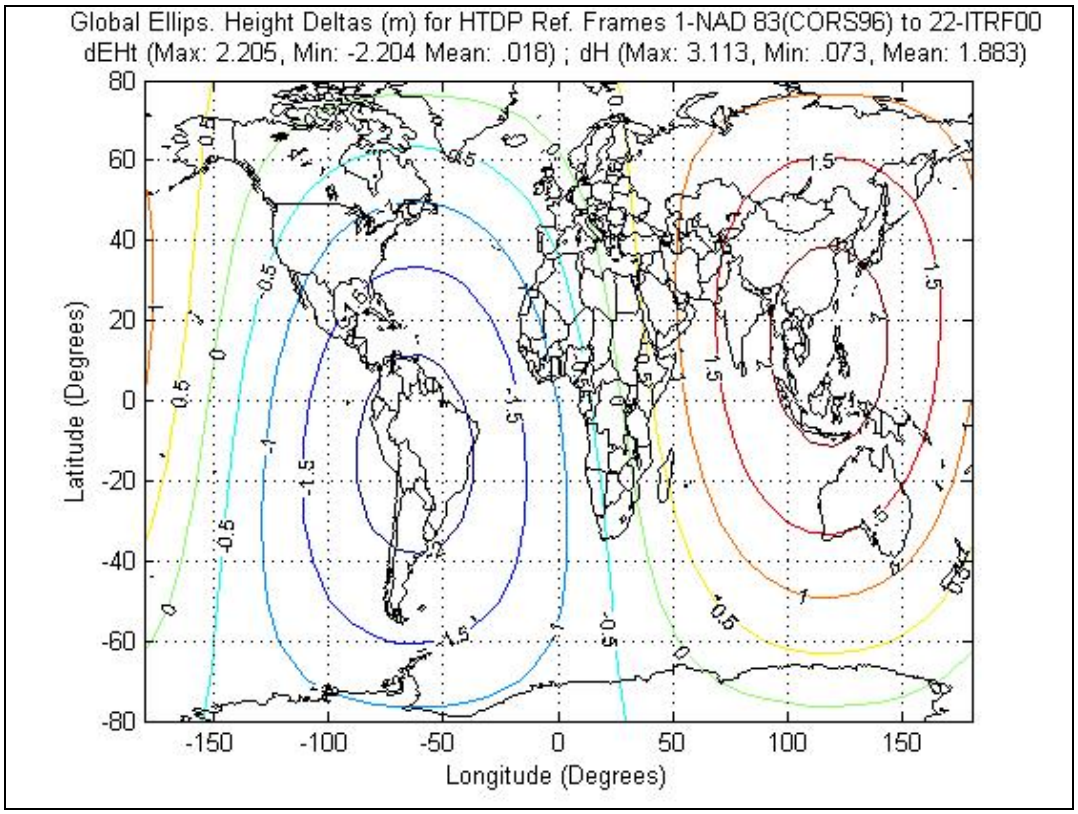

Figure 29. Contour Plot of Global dEHts

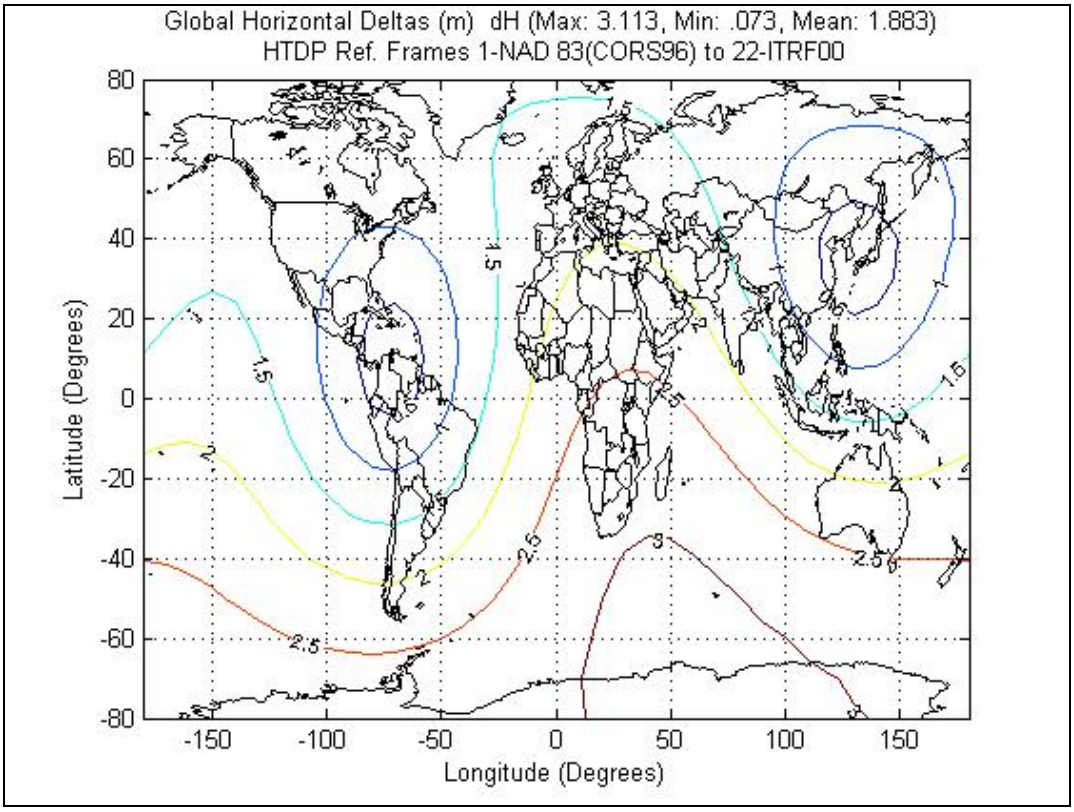

Figure 30. Contour Plot of Global dHs

```
WAAS / LAAS TCH Anomalies Investigation
Global Data (m) for HTDP Ref. Frames 1-NAD 83(CORS96) to 22-ITRF00
Number of Points: 629

Col# HTDPData (MAX, MIN, MEAN)
0 lpt         629    1      315
1 lLat        80     -80    0
2 lLon        180    -180   0
3 inLat       80     -80    0
4 inLon       180    -180   0
5 outLat      80.0000125333333     -80.000025425 2.01256780604277E-03
6 outLon      359.986092366667     9.98598190833333     184.857598005286
7 inEHt       0      0      0
8 outEHt      2.205  -2.204 1.77074721780605E-02
9 inX         6378137-6378137      -116031.170591415
10 inY        6378137-6378137      -8.27307612983146E-11
11 inZ        6259542.961   -6259542.961  2.96128004647211E-12
12 outX       6378136.002   -6378137.997  -116032.16826709
13 outY       6378138.903   -6378135.096  1.89698569108374
14 outZ       6259543.626   -6259542.586  0.524095389495984
15 dLat       1.39159305555978E-02 -1.38998055555959E-022.0125678060424E-03
16 dLon       360.000135830556     -1.40180916666708E-02184.857598005286
17 dEHt       2.205  -2.204 1.77074721780605E-02
18 dX         -0.581 -1.414 -0.997675675677183
19 dY         2.781  1.026  1.89698569156938
20 dZ         1.355  -0.314 0.524095389500924
21 dXY        3.04139523899815     1.27278002810567     2.1551828903959
22 dXYZ       3.11365588942846     1.31295506427121     2.25994489555526
23 dH         3.11334498534495     7.25809780628784E-02 1.88255795584202
```

Figure 31. Example Scenario/Analysis Summary Report from HTDP-A, Global Transformation from NAD 83(CORS96) to ITRF00.

H. Recent NAD 83 Developments

Recent developments in the geodetic community relevant to this topic may warrant an update to findings. The updates include a National Re-Adjustment Survey to NAD 83 (CORS96) which will produce an updated NAD 83 with a new subtitled (i.e., NAD 83 (NRS2007). This update is due out during February 2007 [5]. Although NAD 83 (NRS2007) may turn out to be more equivalent to WGS 84 (ITRF00), the improvement may only be realized over North America. Also, the availability of this update would not be expected to provide “retroactive” correction of NAD 83 (CORS96) coordinate values unless they are transformed using a tool such as the NGS HTDP, and there is no assurance that the NAD 83 and WGS84 system will not diverge again in the future.

A new version of HTDP, version 2.9 released January 2007, was discovered on the NGS website at the conclusion of this study. For the purposes of cross plat-form compatibility, this latest release comes in the form of the FORTRAN source code only. This requires the source code to be compiled via a FORTRAN compiler to be used on the end-user platform (e.g., Windows, Linux, Unix, et cetera). Lastly, several new updated reference frames, available within the newer HTDP, are now available to HTDP users.

I. Commentary on Pertinent FAA Orders and Standards

AVN maintains a comprehensive database that contains geographical and geometrical data for runways and navigation facilities in the United States [2]. For instrumented runways, the database includes latitude, longitude, orthometric height (mean sea level), and height above ellipsoid (HaE) information. Typically, the National Geodetic Vertical Datum of 1929 (NGVD 29) or the North America Vertical Datum of 1988 (NAVD88) is the reference used for the orthometric heights. The HaE data was added to the database in 2005 to address the need for describing altitude consistent with GPS positioning, which was spawned by the implementation of satellite-based navigation as a means of supporting WAAS LPV approaches. Due to the demand for rapid implementation of these approach procedures, the HaE values for most runways were estimated based upon the associated orthometric heights. A more detailed discussion of this matter is presented in Reference 2.

Based on discussions with AVN personnel and the review of select, relevant FAA orders performed during this study, the authors gained insight into how one may encounter, or at least perceive conflicts within FAA standards and guidance material. These seemingly conflicting guidelines can be attributed to either imperfect or insufficiently qualified statements regarding the equivalency of NAD 83 and WGS 84. Several examples are provided in this section for the purpose of aiding the reader in gaining similar insight. Since the objective of this study was not the identification of FAA orders and standards that may contain imprecise guidance, the examples taken herein may not represent a comprehensive list of documents.

FAA Standard #405 [18]: This standard addresses aeronautical surveys and the development of related products. Narrative in this standard discusses that conventional navigation relies primarily on accurately tracking a ground-based guidance signal, with position or coordinates being a secondary objective. Conversely, satellite-based navigation depends on knowing both the aircraft and destination coordinates as the primary means of supporting navigation. Thus, coordinate and geodetic datum accuracy becomes an important matter for satellite navigation, specifically GPS/WAAS. This standard states that ideally, coordinates should be referenced to a high accuracy global datum, e.g., ITRF. It conveys that surveys are conducted relative to control stations (bench marks), which may be tied to a regional datum. Although it is anticipated that regional datums will eventually be replaced by global systems, the use of regional datums will need to continue until global control stations or global coordinates are readily available to surveyors. In accordance with this standard, regional datums may be used provided they meet the following three criteria:

> 1) The datum, or more specifically, the positions and/or elevations of control stations that physically represent the datum, must be sufficiently accurate to support required surveys.
>
> 2) The datum must be represented on the ground by a control station network that is readily available to the surveyor.
>
> 3) The datum should be consistent (at about the two meter or better level) with a global datum, such as ITRF, thereby ensuring smooth flight transitions between datums.

The standard states "NAD 83 fully meets these criteria and has been selected as the FAA No. 405 standard for positions and ellipsoid heights in the United States…..In addition, NAD 83 has been adopted by the Federal Geodetic Control Subcommittee as the official geodetic datum for the United States…"

Technical Standard Orders (TSO) C145b/C146b [19, 20]: In these TSOs, the FAA states the minimum performance standards for equipment/sensors using GPS augmented by a satellite based augmentation system (SBAS) such as WAAS. Although these TSOs do not directly contain requirements about the datum, or coordinate system to be used for position determination, it does call out RTCA DO-229D, which is discussed in the following paragraph.

RTCA DO-229D [21]: This document provides the minimum operational performance standards for GPS/WAAS. The requirements set forth in this document indicate that the equipment shall determine a position for navigation that represents the WGS 84 of the antenna or navigation reference point. In addition, navigation databases shall provide location or path construction information referenced to WGS 84. This standard allows the option to use other datums provided the equivalency to WGS 84 has been determined, and it is the responsibility of the approving authority to determine if an alternate datum is equivalent. In regard to NAD 83 DO-229D contains the statement near the top of page 93, "The FAA has determined the NAD 83 is equivalent to WGS 84 without a conversion algorithm." The validity of this statement is both time dependent, since reference frames are routinely updated, and dependent on the flight operation to be supported. For example, NAD 83 and WGS 84 may be sufficiently equivalent to enroute and non-precision approach operations, but not sufficiently equivalent for Category II/III precision approach operations. Further, Appendix D of DO-229D contains guidance on the generation of data blocks. The initial general statement that geodetic coordinates are based on WGS 84 coordinate system is followed up with a more detailed discussion that explicitly states the geodetic coordinates for the landing threshold point (LTP), fictitious threshold point (FTP), and flight path alignment point (FPAP) are based on WGS 84. This statement seems to conflict with the requirement set forth in FAA Order 8260.19, see next paragraph.

FAA Order 8260.19C CHG3 [22]: As stated in the purpose section, this order provides guidance for the administration and accomplishment of responsibilities assigned to the FAA Flight Procedures and Airspace Program. Paragraph 272 addresses the implementation of the North American Vertical Datum of 1988 (NAVD 88). Narrative in this paragraph states that National Geodetic Vertical Datum of 1929 (NGVD 29) and NAVD 88 are considered equivalent since the difference between the datums is less than the vertical accuracy of the obstructions. Subparagraph c states that determination of the LTP HaE must be based on NAVD 88 when developing WAAS/Local Area Augmentation System (LAAS) procedures. One has to assume that NAVD 88 and WGS 84 ellipsoid are equivalent to avoid perceiving a conflict with the requirements set forth in RTCA DO-229D, as discussed above. In terms of supporting satellite based navigation, this equivalency is time dependent as well as dependent on the flight operation to be supported.

AFS Memorandum [23]: This memorandum addresses geospatial standards for the automation of procedure development for Area Navigation (RNAV) Terminal Instrument Procedures (TERPS). This memorandum states "The semi-major and semi-minor axes of the WGS 84 and NAD 83

ellipsoids are essentially equivalent. Calculations based upon the WGS 84 ellipsoid applied to NAD 83 positions effectively result in NAD 83 positions; therefore, the standard reference-ellipsoid for calculation of track and fix position is the "WGS-84 (G1150)" ellipsoid." Although the axes and flattening ratios may be essentially equivalent, one is not generally assured to get the same exact position unless the ellipsoids use the exact same origins and axis orientation (i.e., no relative rotation). This situation is likely realized by personnel with expertise in geodesy, but not likely by a "non-expert."

Also, the equivalency is addressed in qualitative or relative terms. For example, "effectively equivalent" is a qualitative statement. Based on the results of this study, this statement would hold true if a 2 meter difference is acceptable for the intended application. This memorandum clearly states that the standards put forth specifically apply to obstacle evaluation area (OEA) construction and the evaluation of obstacle and terrain position and elevation data relative to RNAV OEAs and obstacle clearance surfaces (OCSs). Given the intended application, equivalency on the order of 2 meters seems reasonable to the authors, who admittedly are not subject matter experts in OEA/OCS evaluations. Also, this level of agreement is consistent with that currently specified in FAA Standard No. 405.

The use of quantified statements would improve the clarity of the memorandum for the non-expert. For example, the intent of the memorandum may be better conveyed if a phrase like "result in positions that differ by less than 2 meters" was used in place of a phrase like "effectively equivalent." Such an approach would better inform the casual reader about the tolerance used to assess the level of agreement. The authors realize it is always challenging for subject matter experts to write material that conveys all the nuances to a broader audience.

IV. CONCLUSIONS AND RECOMMENDATIONS

During the course of this study, the results obtained by AVN personnel as presented in Reference 2 were reproduced. A series of tests was conducted using the NGS HTDP-based automation tool developed by Avionics personnel. These tests served to provide numerical validation of the software tool and to generate the data needed for characterizing both vertical and horizontal variations that may occur under specified conditions. An analysis of the resulting simulation data indicate that using NAD-83 coordinates with a sensor technology that requires WGS-84 coordinates, i.e., GPS, can result in positioning errors.

Although this study focused on characterizing the resulting horizontal and vertical (TCH) component variations that could result, it should be realized that the actual affect is the introduction of a linear bias in the vertical path/vertical track of WAAS LPV approach procedures. To get an idea as to the extent of the effect, AVN personnel requested and obtained a report to determine the number of LPV procedures in AIRNAV that will require conversion from NAD 83 to WGS-84. The result was a report showing that there are 780 LPVs (PROC/S) at 440 airports in the system [24]. A listing of these procedures can be found in Appendix I of this report.

Map datums are continually refined, and new datums or geodetic reference frames emerge. Historically, such evolutions have motivated the FAA to update its standard datum reference, changing from NAD 27 to NAD 83, for example. The results of this study indicate the FAA may need to revisit this matter again given the implementation of satellite-based navigation, specifically GPS/WAAS, which utilize sensors operating in WGS 84 coordinates. FAA Standard 405 states that ideally coordinates should be referenced to a high accuracy global datum [18]. Although it is anticipated that regional datums will eventually be replaced by global systems, the use of regional datums will need to continue until global control station or global coordinates are readily available to surveyors. The FAA currently considers NAD 83 equivalent to WGS 84 since these datums yield position differences of approximately 2 meters, or less [18]. However, the validity of this statement is both time dependent, since reference frames are routinely updated, and dependent on the flight operation or application to be supported.

The results of the study performed have produced the following conclusions:

1) The Geodesy community is continually refining geodetic reference systems to improve accuracy and account for the dynamic characteristics of the Earth;

2) The accepted equivalency of NAD 83 and WGS 84, which previously had not been a critical issue for enroute and terminal operations, can be a significant source of navigation error for WAAS LPV and LAAS approaches to minimums of less than 250 feet height above threshold (HAT);

3) Using NAD-83 coordinates with a sensor technology that requires WGS-84 coordinates, i.e., GPS, can result in positioning errors, thus the NAD-83 and WGS-84 reference frames should not be considered equivalent for WAAS LPV/LAAS approach operations to minimums of less than 250 feet HAT (i.e., approach procedures with minimums similar to the lowest authorized for ILS Category I);

4) These positioning errors can result in the actual TCH for WAAS LPV procedures being both higher and lower than the procedure designers intended by as much as 2.2 meters (global basis, excluding contribution due to along-track variation, see #7) and the authors do not believe this error source is considered in the Total System Error (TSE) for WAAS and thus would be in addition to existing error budget allocations;

5) These positioning errors can result in horizontal positioning errors as large as 3.1 meters (global basis), and how this error translates into cross-track or along-track error depends on both the location on the earth and orientation of the procedures;

6) The effect of horizontal position variations may consume a notable portion of the lateral accuracy requirement for Category II/III approach procedures and airport surface surveillance/guidance operations during low-visibility conditions, and;

7) Publicly available software tools for the conversion of coordinates from one geodetic reference frame to another exist and the development of an automation tool for batch

transformation of a large quantity of coordinates from one reference frame to another is readily realizable.

The following recommendations are offered for consideration:

1) The office of Aviation Safety (AVS) should reevaluate and clarify FAA guidance material and requirements for map datums given the existing implementation of satellite-based (WAAS LPV/LAAS), vertically guided procedures to minimums of less than 250 feet HAT, including the accepted equivalency of NAD 83 and WGS 84;

2) Develop an action plan describing the approach that will be implemented to mitigate the TCH height variation resulting from the use of NAD-83 coordinates with a sensor technology that requires WGS-84 coordinates.

3) If verification of the study results is desired, the results can be compared to flight inspection observation for multiple airports as one means of verification;

4) Develop WAAS LPV procedures using the same coordinate system used by GPS (WGS-84, ITRF00); and,

5) Develop LAAS procedures using the same coordinate system used by GPS (WGS-84, ITRF00), particularly when supporting Category I/II/III precision approach procedures;

It is recommended that the action plan address the following:

1) The development of an implementation plan based on a prioritized, phased approach;

2) The development of policy, guidance and training material for ensuring procedures intended to be supported by satellite-based technology are developed, published, and inspected using the appropriate geodetic reference system, including revised guidance on requirements regarding the use of regional datums;

3) The near-term actions(s) necessary to prevent the promulgation of TCH variations when developing new WAAS LPV procedures;

4) The development of screening criteria to be used in categorizing existing WAAS LPV procedures as either critical or non-critical in terms of needing corrective action;

5) The screening of existing WAAS LPV procedures and the corrective action required for those procedures categorized as critical;

6) Assessing the impact that horizontal position variation may have on Category II/III precision approach and airport surface operations supported by satellite technology;

7) The magnitude of the TCH height variations introduced due to using NAD-83 coordinates compared to WAAS LPV TCH tolerances should be considered when developing the screening criteria;

8) Since the WGS-84 datum will continue to evolve over time, a process should be developed and implemented that monitors changes in threshold/procedural coordinates, including establishing a tolerance that determines when updated surveys should be performed;

9) The other error sources that can introduce TCH height variations for WAAS LPV procedures should be considered when developing the screening criteria; and,

10) The TCH tolerances used for other precision approach aids.

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