NEON DISCRETE LIDAR DATUM RECONCILIATION REPORT

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Change Record

REVISION	DATE	ECO #	DESCRIPTION OF CHANGE
A	08/26/2014	ECO-02189	Initial release
B	03/25/2022	ECO-06791	• Revised logo and fine print • Minor formatting updates

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1 DESCRIPTION

During production of the discrete LiDAR observations (RD [03]), an output horizontal and vertical datum must be selected in order to geo-locate observations within a nationally recognized reference frame. According to AD[01], NEON products shall have horizontal reference to WGS84, and vertical reference to a geoid determined from the EGM96. However, to provide coordinates with the most current vertical reference, the Geoid12A geoid model is selected as the vertical reference surface for the LiDAR observations. Discrete LiDAR processing is performed in Optech's LMS (Laser Mapping Suite) software, which provides an option to geo-locate observations with reference to WGS84 horizontally and to Geoid12A vertically. Analysis of the LiDAR observations collected in the 2014 summer airborne field campaign revealed that LMS was not handling the conversion of vertical coordinates to Geoid12A correctly. This document provides background information to mapping datums, a description of the erroneous conversion, and a methodology for correction.

1.1 Scope

This document applies to AOP's processing of airborne observations. The document is particularly relevant to the processing of the discrete (RD[03]) and waveform LiDAR data, as the described error directly affects the absolute accuracy of vertical coordinates. The error is also potentially relevant to the ray-tracing algorithm used in geo-locating spectrometer observations RD [04].

1.2 Purpose

The purpose of this document is to provide background information into the error, the evidence which supports its existence, and a methodology for correction.

2 RELATED DOCUMENTS AND ACRONYMS

2.2 Applicable Documents

Applicable documents contain information that shall be applied in the current document. Examples are higher level requirements documents, standards, rules and regulations.

AD [01]	NEON.DOC.005011	NEON Coordinate System Specification

2.3 Reference Documents

Reference documents contain information complementing, explaining, detailing, or otherwise supporting the information included in the current document.

RD [01]	NEON.DOC.000008	NEON Acronym List
RD [02]	NEON.DOC.000243	NEON Glossary of Terms
RD [03]	NEON.DOC.001292	NEON L-0 to L-1 Discrete Return LiDAR ATBD
RD [04]	NEON.DOC.001289	NEON Imaging Spectrometer Level-1 Processing Overview Document

3 INTRODUCTION

3.1 Background to Geodetic Datums

To geo-locate objects for mapping purposes, a recognized reference frame must be selected. Geo-location of mapping observations within a recognized frame facilitates data sharing with external organizations and consistency in multi-temporal data collections. Contemporary reference frames for large scale mapping are typically defined as a 3-D Cartesian coordinate system, that has an origin coincident with the earth's geo-center, z-axis coinciding with the principle axis of the earth's rotation, and x-axis passing through the Greenwich meridian. The y-axis is defined to complete a right handed system. Objects can de geo-located within the 3-D Cartesian coordinate system with coordinate tuples, however, such a coordinate system does not facilitate intuitive measurements on the earth's surface. Since mapping activities typically occur on or near the physical surface of the earth, a reference surface which approximates the earth's surface allows for a more intuitive reference frame. This is accomplished with a reference ellipsoid, which is a mathematical construct used to approximate the earth's surface through selection of appropriate lengths for its semi-major and semi-minor axes. The placement of the reference ellipsoid with orientation and location parameters defined with respect to the origin and axes of the 3D Cartesian reference frame defines a datum. Any mapped position can be uniquely defined with reference to the ellipsoid's surface through horizontal geodetic coordinates (latitude, longitude) and a height above the ellipsoid. The height above the ellipsoid is measured along a vector normal to the ellipsoid's surface. The two most common datums in use in North America today are NAD83 and WGS84. Both adopt the same reference ellipsoid (GRS-80), however, each have adopted minor differences in its location and orientation. Comprehensive details into the creation of datums can be found in Vanicek and Krakiwsky (1981), while introductory information can be found in Junkins and Garrard (1998).

For practical purposes, elevations are not typically referenced to the surface of the reference ellipsoid defined within the datum (hereafter referred to simply as the ellipsoid). This is due to the theoretical nature of the ellipsoidal surface, which can allow abnormal properties of physical processes. For example, utilizing heights above an ellipsoid allows surface water to flow from lower elevations to higher elevations. To overcome these abnormalities, a vertical datum which better represents the physical surface of the earth is desirable. Such a physical surface is termed the geoid, which is selected as a surface of constant gravitational potential, derived from the gravitational observations. The absolute location of the geoid is related to a horizontal datum through its vertical separation to the reference ellipsoid (**Figure 1**). The separation between a geoid and reference ellipsoid is commonly referred to as a geoid height, geoidal undulation, or geoidal separation and is symbolized by *N*. The relationship between the geoid, ellipsoid and *N* can be written as

$$H = h - N \tag{1}$$

where *h* is the height above the ellipsoid and *H* is the height above the geoid, or ortho-metric height.

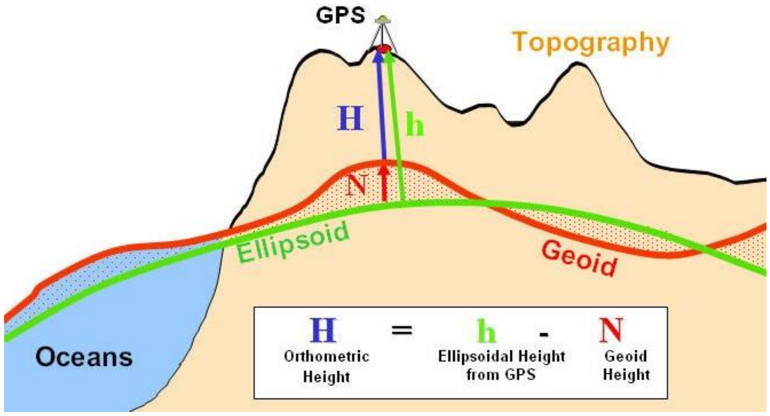


Figure 1. Surface comparison of the ellipsoid, geoid and physical topography (Ahern, 2007).

3.2 Datum Reference for Processing NEON AOP Data

The processing datum for the discrete LIDAR information will be in the same datum as the airborne trajectory. The airborne trajectory is produced in POSPac MMS, which natively references all airborne trajectories in ITRF00 (International Terrestrial Reference Frame of 2000). The WGS84 (G1150) datum can be considered equivalent to ITRF00 (True, 2004; Soler and Snay, 2000), therefore, no coordinate conversion is necessary to output the discrete LiDAR observations to the WGS84 (G1150) datum (G1150 indicates the epoch of the WGS84 realization). Although NEON horizontal coordinates are output with respect to WGS84 (G1150), NEON elevations are output with reference to the Geoid12A [AD 01]. Details of the Geoid12A model are provided by NOAA and NSA at http://www.ngs.noaa.gov/GEOID/. The Geoid12A model is provided as a series of *N* values at a regular grid across the contiguous United States. Note that NGS (2014) states that:

> "NAD 83 has been officially adopted as the legal horizontal datum for the United States by the Federal government, and has been recognized as such in legislation in 48 of the 50 states."

Since NAD83 is the officially adopted datum by the United States federal government, NGS only provides values of *N* between the NAD83 (2011) datum and Geoid12A (values can be found at http://www.ngs.noaa.gov/GEOID/GEOID12A/.) Discussions with Optech revealed that the grid of *N* values provided by NGS were included with the distribution of LMS. This indicates that the geoidal undulations provided with LMS can only be used to convert NAD83 (2011) ellipsoidal heights to Geoid12A ortho-metric heights. To correctly convert WGS84 (G1150) ellipsoid heights to Geoid12A ortho-metric heights, an intermediary step must be implemented which first transforms the observations from the WGS84 (G1150) datum to the NAD83 datum. The conversion of ellipsoidal elevations to Geoid12A occurs internally within Optech's LMS software using GeoCalc, a coordinate conversion module provided by BlueMarble Geographics (http://www.bluemarblegeo.com/). For converting elevations from WGS84 (G1150) ellipsoidal heights to Geoid12A orthometric heights, an option within LMS entitled "NAVD88 via Geoid12A on WGS84" is selected (**Figure 2**).

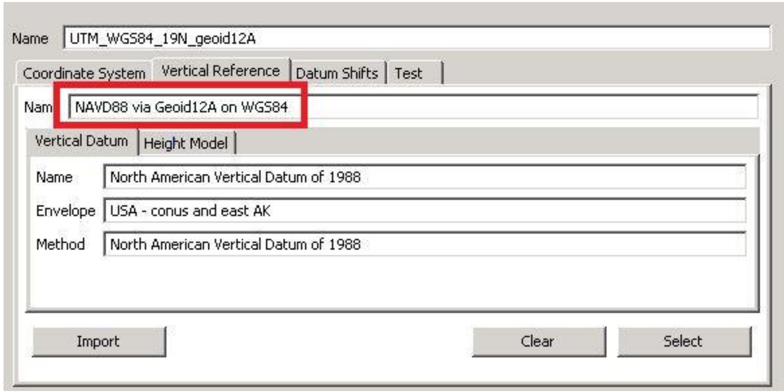


Figure 2. Option selected in LMS for transforming WGS84 ellipsoidal heights to Geoid12A ortho-metric heights.

4 INVESTIGATIONS INTO THE CAUSE OF GEOLOCATION ERROR

During the summer 2014 field campaign in D03, independent GPS observations were collected to validate the LiDAR observations. GPS validation observations consisted of static GPS occupations for a minimum period of twenty minutes. The GPS observations were processed with the 'rapid-static' option of the on-line positioning and user service (OPUS, http://www.ngs.noaa.gov/OPUS/). OPUS can provide horizontal coordinates with reference to NAD83 (2011) and vertical coordinates with reference to Geoid12A to a high level of accuracy (< 5cm). Horizontal coordinates can then be transformed to WGS84 (G1150) using the HTDP (horizontal time dependent positioning, https://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml) service provided by NGS and NOAA. To compare the validation observations with the LIDAR observations, a surface of the LiDAR data was created using a TIN model, and the elevation of validation observations were compared against the elevation of the LiDAR surface at the horizontal location of the validation observation.

Results of the comparison between validation elevations and LiDAR surface elevation revealed that a vertical offset existed. The mean magnitude of the offset was approximately equal to the vertical separation between the WGS84 (G1150) ellipsoid and the NAD83 (2011) ellipsoid. An example of the validation data and associated LiDAR surface elevations obtained on May 6th 2014 at the OSBS site are provided in **Table 1**. The similar magnitude of the mean error (1.458 m) and the vertical separation between the two ellipsoid models (1.500 m) suggests that the source of the error exists in the conversion of heights from WGS84 (G1150) to Geoid12A within LMS.

Table 1. Comparison of GPS validation observation elevations and LiDAR surface elevations at the OSBS site.

Point number	GPS Validation Elevation (m)	LiDAR surface elevation (m)	Difference (m)
12600	47.476	44.748	1.425
12610	47.535	44.802	1.430
12620	48.753	46.061	1.389
12630	48.906	46.135	1.468
12640	48.356	45.483	1.570
12650	30.362	27.593	1.466

Mean difference = 1.458 m
Difference b/w ITRF00 and NAD83 = 1.500 m

Further investigation from the outputs from the LMS software showed that elevations output with reference to Geoid12A were dependent on the ellipsoid model selected (WGS84 vs. NAD83, **Figure 3**). **Table 2** provides a sample of data in which the WGS84 (G1150) data was produced with the "NAVD88 via Geoid12A on WGS84" selection (**Figure 2**), and the NAD83 data was determined by first converting the WGS84 (G1150) data into NAD83, and then converting to Geoid12A using the "NAVD88 via Geoid12A on NAD83" option. Since heights referenced to Geoid12A are independent of the ellipsoid model used, the resulting ortho-metric heights should be nearly equivalent. Small variations (< cm) could exist due to errors present in the transformation process. The transformation values used to convert coordinates from WGS84 to NAD83 can be found in the EPSG registry with code 1900 (OPG, 2014), and are provided in **Table 3**.

Table 2 shows that LMS correctly output different elevations when referenced to the reference ellipsoid in both WGS84 and NAD83. Information obtained from the interactive geoidal undulation tool found at the NGS Geoid12A webpage (http://www.ngs.noaa.gov/cgi-bin/GEOID_STUFF/geoid12A_prompt1.prl) revealed that the separation between NAD83 and Geoid12A (*N*) at this location was 27.183 m. Inspecting the resulting Geoid12A ortho-metric heights in **Table 2** shows that the same *N* was applied to both the WGS84 (G1150) ellipsoidal height and NAD83 ellipsoidal height. This demonstrates that WGS84 (G1150) coordinates are not being transformed to NAD83 prior to the application of *N*. The direct addition of *N* to WGS84 (G1150) coordinates leaves them in error by a value equivalent to the vertical separation between the NAD83 and WGS84 ellipsoids. The HTDP software utility confirms that the separation between WGS84 (G1150) and NAD83 (2011) at the locations identified in **Table 2** to be approximately 1.17 m. The 1.17 m offset is consistent with the separation observed between the WGS84 Geoid12A ortho-metric height and the NAD83 Geoid12A ortho-metric height.

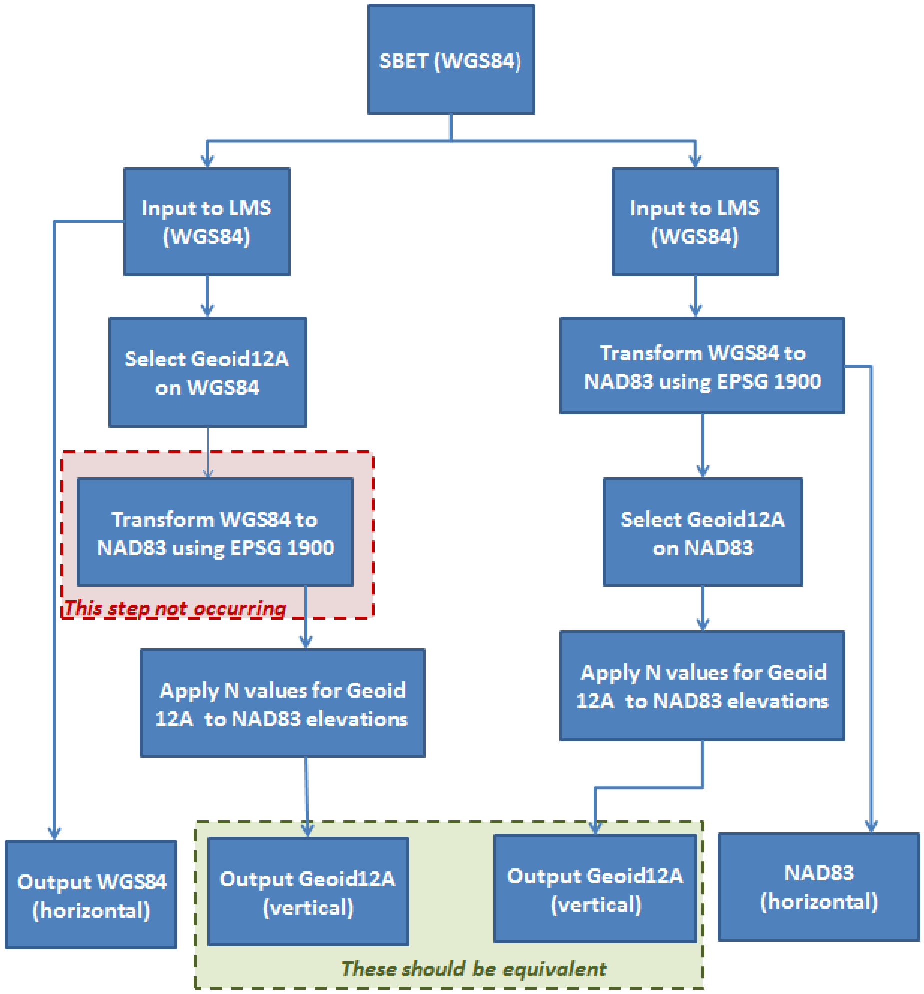


Figure 3. Flow chart of troubleshooting processes in LMS. Left hand side of the flow chart indicates the typically processing flow and the step in which the error is introduced. Right hand side of the flow chart shows the process followed for producing comparable elevation results.

Table 2. Differences between NAD83 and WGS84 coordinates.

Datum reference	Easting (m)	Northing (m)	Elevation (m)
WGS84 ellipsoid	320939.630	4870776.469	411.342
WGS84 Geoid12A	320939.630	4870776.469	438.525
NAD83 ellipsoid	320939.632	4870775.483	412.515
NAD83 Geoid12A	320939.632	4870775.483	439.698

Table 3. Transformation parameters between WGS84 and NAD83 (HARN) (OPG, 2014).

Transformation parameter	Value	Units
dx	-0.9738	m
dy	1.9453	m
dz	0.5486	m

k	0	ppm
rx	-0.00000013357	rad
ry	-0.00000004872	rad
rz	-0.00000005507	rad

5 DETERMINATION OF ROOT CAUSE OF GEOLOCATION ERROR

After discussions with Optech and Blue Marble, it was confirmed with a representative from BlueMarble Geographics that:

> "GeoCalc's NAVD88 via Geoid12A on WGS84 is not absolutely correct having been modelled on the original WGS84 (0) and NAD83 (1986) datums in which a vertical shift was not applied." (Appendix A)

This statement indicates that Blue Marble considered only the horizontal difference between WGS84 (0) and NAD83 (1986). Therefore, the values of *N* obtained from NGS for NAD83 (2011) were being directly applied to WGS84 (G1150) coordinates. Since the required conversion between WGS84 and NAD83 was not occurring, this left final elevations in error by the vertical separation between the WGS84 (G1150) datum and NAD83 (2011). Within the contiguous Unites States, the separation between the two datums varies spatially, and ranges between 0.266 m and 1.630 m (**Figure 3**).

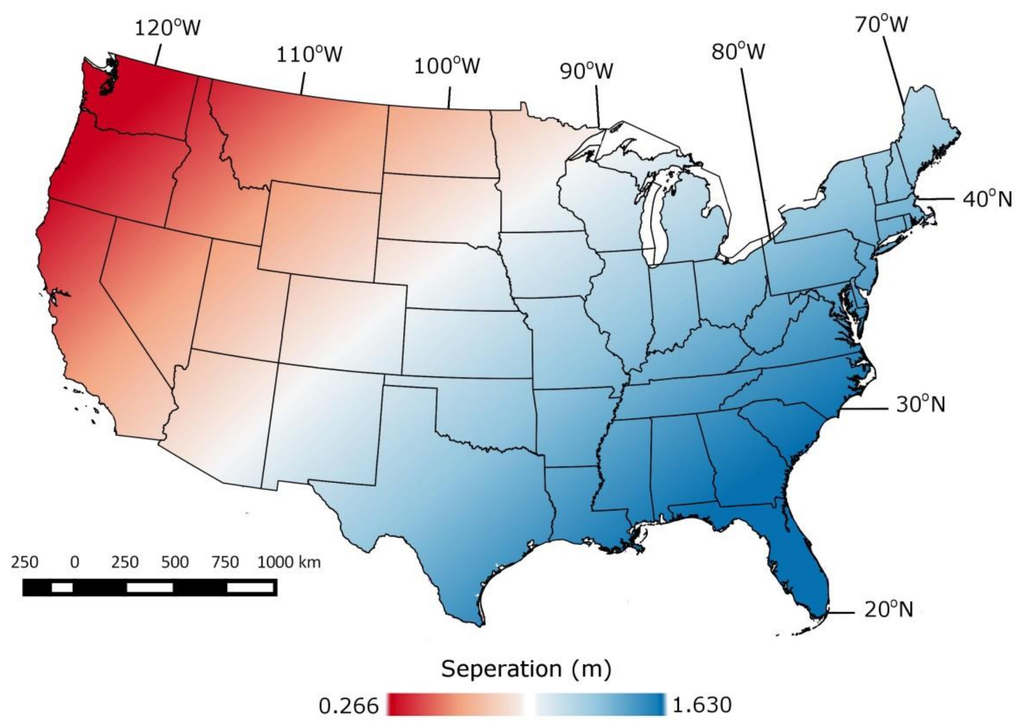


Figure 4. Vertical separation between WGS84 (G1150) and NAD83 within the contiguous United States.

6 PATH FORWARD

Through discussions with Blue Marble, it was discovered that a new GeoCalc module (7.0), released in April of 2014, addressed the deficiencies in vertical datum reconciliation. The release notice on the Blue Marble's website states the new module contains (Bluemarble, 2014):

> "Completely reworked Vertical Coordinate system handling. This allows more flexible transformation options when working with high accuracy elevation based data."

The integration of this module by Optech into LMS is the most ideal solution, as it does not require in-house corrective action. However, a follow-up discussion with an Optech representative revealed that the new Blue Marble implementation was significantly different from the module currently implemented in LMS (GeoCalc 6.7) and there is no current timetable for updating LMS.

To correct the elevation data in-house, a translation which is equal to the vertical separation between the WGS84 (G1150) and NAD83 (2011) ellipsoids must be applied to the elevation of all LiDAR observations. The spatial variability of the shift is minor, typically changing by approximately 1 mm over 5 km. Since a NEON flight area is typically 10 km by 10 km, a single shift can be applied to each site with a negligible loss in accuracy. For example, **Table 4** identifies the vertical separation required to correct each site in D17, as well as the difference between the vertical separation obtained in the north-west corner of the site and the south east corner of the site. SJER contained the largest discrepancy between the corrections at the NW and SE positions, which was approximately 0.005 m. Therefore, simplifying the correction to a single shift, obtained at the center of the SJER site, will introduce a maximum additional error in the elevation coordinates of only 0.0025 m. This magnitude of introduced error is negligible to the overall error budget of the LIDAR sensor.

Table 4. Vertical correction for elevation data at D17 sites.

Site	Required vertical shift (m)	Difference b/w NW and SE (m)
PROV	0.617	0.002
SJER	0.603	0.005
SOAP	0.616	0.003
TEAK	0.617	0.002

The introduction of the vertical translation is most easily facilitated in-house through LAStools. LAStools contains built-in functionality to translate elevations by a specified amount. For example, if all the LAS files produced by LMS for the Providence Creek site (PROV, **Table 4**) were held in a folder named PROV, the following command in LAStools is capable of applying the constant correction:

```
las2las -i PROV/*.las -translate_z 0.617
```

The magnitude of the shift can be acquired from the HTDP website by transforming a coordinate within the desired NEON site from WGS84 (G1150) to NAD83 (2011), with the elevation set to 0.0 (**Figure 4**). The resulting transformed elevation will be equal to the desired corrective vertical separation (**Figure 5**).

In-house, a grid of the separations has been compiled across the continental U.S. (**Figure 3**). In the absence of HTDP, the appropriate value can be pulled directly from the raster and applied to the LAS files.

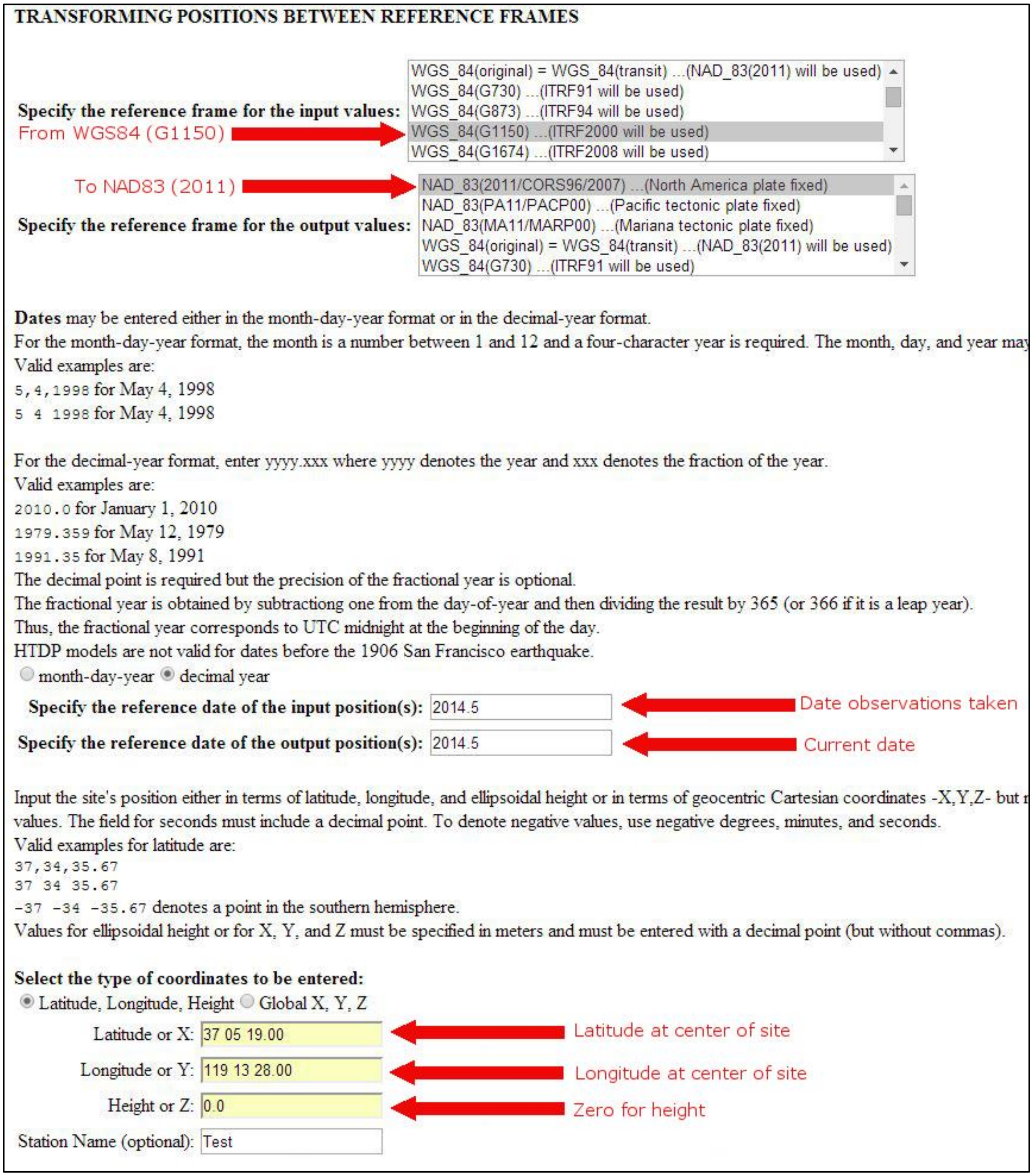
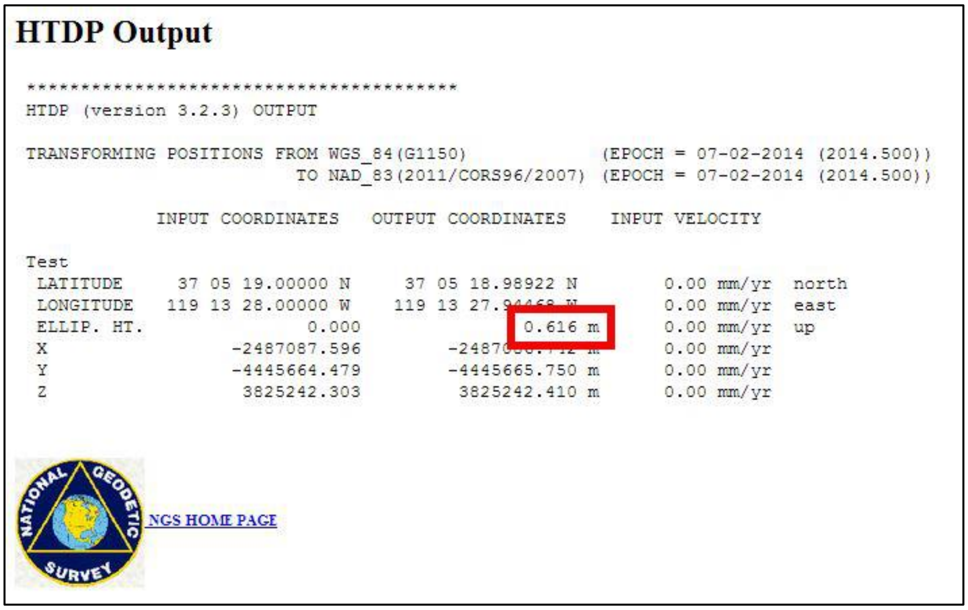


Figure 5. Information entry to HTDP to determine a corrective vertical shift.



HTDP Output

```
******************************************
HTDP (version 3.2.3) OUTPUT

TRANSFORMING POSITIONS FROM WGS_84(G1150)          (EPOCH = 07-02-2014 (2014.500))
                         TO NAD_83(2011/CORS96/2007) (EPOCH = 07-02-2014 (2014.500))

            INPUT COORDINATES    OUTPUT COORDINATES    INPUT VELOCITY

Test
 LATITUDE      37 05 19.00000 N     37 05 18.98922 N       0.00 mm/yr  north
 LONGITUDE    119 13 28.00000 W    119 13 27.94468 W       0.00 mm/yr  east
 ELLIP. HT.               0.000               0.616 m      0.00 mm/yr  up
 X                 -2487087.596        -24870[illegible] m      0.00 mm/yr
 Y                 -4445664.479        -4445665.750 m      0.00 mm/yr
 Z                  3825242.303         3825242.410 m      0.00 mm/yr
```


Figure 6. Results of HTDP output with corrective shift highlighted.

7 REFERENCES

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APPENDIX A PERTINENT EMAILS

re[6]: NAD83 / WGS84 elevation conversion to geoid12A

Hi Tristan,

I have spoken with one of our internal geodisists. It is apparent that the NGS does apply a vertical shift with HTDP transformations and so your original workflow is actually correct. GeoCalc's NAVD88 via Geoid12A on WGS84 is not absolutely correct having been modelled on the original WGS84 (0) and NAD83 (1986) datums in which a vertical shift was not applied. This was by design for legacy purposes but has since been changed in GeoCalc 7.0.

In short, using the EPSG: 1900 shift with an input vertical reference of WGS84 ellipsoidal height and an output vertical reference of NAVD88 via Geoid12A on NAD83 is the correct workflow. For the particular area of use, you should see approximately a 1.2 meter vertical difference between NAD83 and WGS84.

Thanks for your patience and I hope this clarifies everything.

Regards,

Sean Crowley
Product Development & Support

RE: ST #6658 NEON - LMS - Datum Transformation

Hi Tristan,

Hope you are enjoying your holiday.

Currently LMS uses BlueMarble GeoCalc SDK 6.7. GeoCalc 7.0 was released in April, 2014, the API for their implementation is quite different from 6.7. Particularly, the concept of vertical reference has been removed and replaced by the slightly different concept of vertical coordinate system.

I have sent you request to our Product Mangers and Developers to try to make this possible in the future.

Unfortunately, we do not have a timeframe when it will be integrated in LMS.

Best regards,

DHARANEY