UPDATING AND IMPROVING THE ACCURACY OF A LARGE 3D DATABASE THROUGH THE CAREFUL USE OF GCPS AND ICESAT DATA: EXAMPLE OF REFERENCE3D

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Commission VIII

KEY WORDS: SPOT, DEM/DTM, Database, Updating, Accuracy, Precision, Three-dimensional, Quality

ABSTRACT:

Onboard SPOT 5, the HRS instrument systematically collects stereopairs around the Globe since 2002. Each stereopair can encompass an area up to 600 km x 120 km within a single pass (i.e. 72 000 km² stereoscopic strips). From this time, SPOT 5 stereoscopic imagery becomes one of main satellite data sources for accurate DEM extraction.

Spot Image and French National Cartographic Institute (IGN) decided in 2002 to design and build a worldwide accurate database called Reference3D™ using HRS data. This database consists of three information layers: Digital Elevation Model at 1-arc-second resolution (DTED level 2), Orthoimage at 5m resolution and Quality Masks. Huge efforts have been made to standardize the process in order to offer affordable prices. From 2002 to 2008, the targeted accuracies were 16mCE90 for circular horizontal accuracy, and 10mLE90 for elevation accuracy. These accuracy requirements were achieved without any control points nor map support, as demonstrated by numerous scientific assessments of the Reference3D products performed by independent users.

The introduction of the paper briefly reminds the most significant assessments performed by major players within the geospatial community, and more specifically the one by ImageONE Co., Ltd.(Tokyo) on two Reference3D geocells over the Northern coast of Japan, Hokkaido province. This work was published in 2008 during the last Beijing ISPRS congress.

In 2009, it was decided to introduce reliable GCPs within the Reference3D production process, to increase the horizontal accuracy down to 10mCE90. In addition, two new layers were added to the product, which provide the user with i) the horizontal accuracy for every single pixel of the Reference3D orthoimage and ii) the vertical accuracy for every single elevation value within the Reference3D DEM.

The paper shows how the extensive use of ICESat data, correctly selected and filtered, brings extremely valuable information regarding the effective vertical accuracy, and how ICESat data allows to fully quantify the elevation accuracy of a dataset. This will be illustrated by the presentation of the V&V works that took place over the above quoted 2 geocells in Hokkaido province.

In conclusion, we present the road map for the update of the whole Reference3D database, which currently spreads over more than 45 millions of sq. km. (being more than 4,200 1° by 1° geocells), already funded and started up to 2014, towards 80 M km² of Reference3D products.

1. INTRODUCTION

Reference3D is a world wide accurate 3D data base generated from HRS sensor on board SPOT 5. Assessments performed worldwide showed that Reference3D met its standard specifications, both for DEM and orthoimage.

Three most significant assessments are reminded in this paper, one (NGA) comparing against STRM DEM, another (European Commission JRC) comparing against geodetic points of network and nation-wide DTM, and one performed by ImageONE Co., Ltd. comparing against a set of points of Japan Triangulation Network and National DEM of GSI.

In a second time, the use of ICESat data for validating large DEM databases will be discussed and an example over Japan presented.

2. REFERENCE3D

Reference3D is produced by Spot Image and the French National Cartographic Institute (IGN) from HRS data. This worldwide data base consists of three information layers: a Digital Elevation Model of 1-arc-sencond resolution (full DTED level 2 specifications), a 5m-resolution orthoimage and a set of Quality Masks.

Reference3D product frame is 1 degree by 1 degree (geocell).

Reference3D DEM absolute vertical requirements are depending on the slope:

- 10m LE90 for slopes lower than 20 degrees
- 18m LE90 for slopes between 20° and 40 degrees
- 30m LE90 for slopes greater than 40 degrees

From 2002 to mid-2008, Reference3D absolute horizontal accuracy requirement was 15m CE90 (circular error for 90% of the points). This was achieved without using any GCPs or GPS data, as shown by more than 20 assessments performed by independent international users (mostly customers), 3 of them reminded here below.

In 2009, it was decided to increase the horizontal accuracy better than 10m CE90; this obviously meant introducing reliable GCPs within the Reference3D production process. To reflect this improvement, two new layers were added to the product, which provide the user with

i) the horizontal accuracy for every single pixel of the Reference3D orthoimage and
ii) the vertical accuracy for every single elevation value within the Reference3D DEM.

3. ASSESSMENTS OF REFERENCE3D UNTIL 2008

Until 2008, numerous accuracy assessments of the Reference3D products have been performed at international level by independent users. All results showed that the Reference3D product met all its specifications. We would like to present three of these assessments.

3.1 Assessments by NGA (USA)

In 2004, a cross evaluation of the SRTM and the Reference3D DTED level 2 DEMs was simultaneously conducted by NGA and IGN [*Bouillon et al*., 2006] over twelve 1° x 1° geocells. This test was followed in 2006 by two other tests performed by NGA (concerning 14 geocells).

All the results confirmed the full compatibility of SRTM DTED level 2 DEM (NGA classified) and the Reference3D products over various landscapes, from very flat desert areas up to very high mountain areas.

NGA found that all Reference3D geocells met the above listed vertical requirements along slopes.

Regarding the horizontal accuracy of Reference3D, NGA (JACIE tests) evaluated it better than 9m CE90, through 8 products over the Middle East area (whereas internal evaluation by IGN over others zones ranged from 5m to 16m CE90).

3.2 Assessment by JRC(Europe) and FÖMI (Hungary)

Figure 1 summarizes another evaluation of the Reference3D performed by the Joint Research Center Ispra (JRC) and FÖMI [*Kay, Winkler*, 2004]. One important feature is the detailed evaluation of the elevation accuracy, through segmented classes describing

i) the local slope (10°, 20° and 40° thresholds)
ii) the land use (agriculture, forest, urban).

All of them confirmed that the Reference3D accuracy specifications were met at each slope class.

Figure 1. Elevation accuracy of Reference3D, displayed by classes of slopes and land uses (from Kay, Winkler, 2004)

3.3 Assessment by ImageONE (Japan)

This assessment was conducted by ImageONE Ltd over two geocells (N43E144 and N43E145) located in Hokkaido Island, in Northern Japan. The N43E144 geocell includes a significant ratio of mountains with maximum elevation 1400m, and volcanoes, and lakes.

3.3.1 Assessment of the vertical accuracy over Japan
Two reference DEM data sets were used for this assessment:

i) a set of 2207 points from Japan Triangulation Network maintained by GSI, with cm-level horizontal and vertical accuracies
ii) a +/- 50m mesh DTM produced by GSI from the 1:25,000 topographic maps, with a vertical accuracy "not better than 5m".

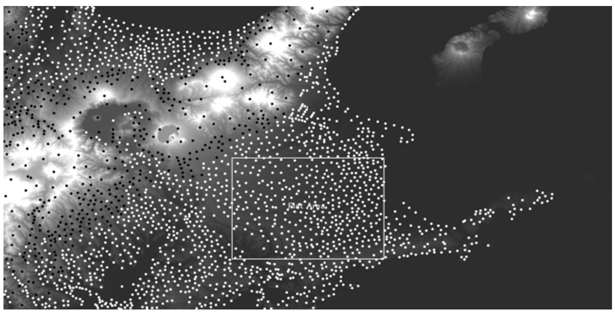

Figure 2. Japan Triangulation Network Points over DEM layer from Reference3D. White rectangle shows the "Flat Area".

Tables 1 and 2 below show the overall results of the evaluation against the Triangulation Network, which concluded that Reference3D was far better than its specification in this area.

	Whole area	Flat Area
Mean (m)	-2.2	-1.7
STDEV (m)	5.3	1.9
Max (m)	11.7	3.3
Min (m)	-91.7	-8.3
LE90 (m)	6.7	4.1

Table 1: Reference3D vs Japanese Triangulation Network: global results for the 2,207 points

Difference intervals	Whole area 2,207 points	Flat area 367 points
-5 / +5m	85.5%	98.4%
-10 / +10m	96.6%	100%
-15 / +15m	98.3%	100%
-20 / +20m	99.0%	100%

Table 2: Reference3D compared vs Japan Triangulation Network: error intervals

The evaluation against GSI 50m-DTM produced similar results. Large differences were noted in an area with very steep cliffs (caldera lake) with slopes locally higher than 50°, where the conversion and bilinear resampling of the Reference3D DEM into Tokyo datum could also have played a role.

Table 3 shows the natural degradation of the results, mainly due to the fact that GSI elevations are bare-soil figures, 50m posting, moreover coming from the contour lines of the 1:25,000 scale GSI map series.

Difference	N43E144	N43E145
-5 / +5m	73.6%	83.6%
-10 / +10m	89.7%	95.6%
-15 / +15m	95.2%	98.3%
-20 / +20m	97.7%	99.3%

Table 3: Reference3D compared against GSI DTM.

90% to 95% of the differences are within a 10m range, which is far better than the 10m / 18m / 30m specification of Reference3D, considering the large mountains within N43E144.

3.3.2 Assessment of the horizontal accuracy over Japan

The horizontal accuracy of the orthoimage was assessed over N43E144 geocell using 120 Points measured form the 1:25,000 digital map of GSI, which can be freely accessed online.

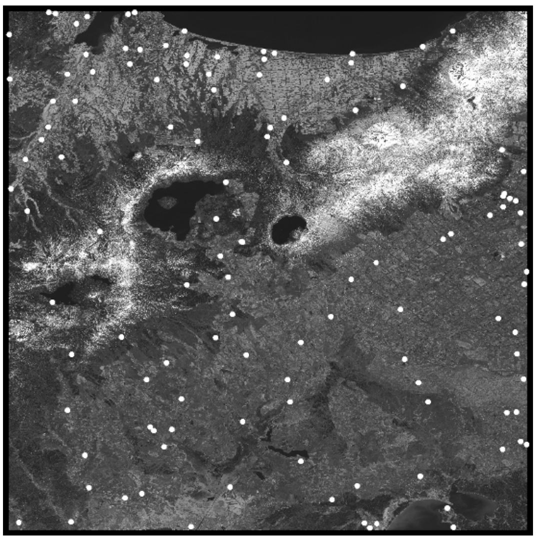

Figure 3: Check Points (White dots) in tile N43E144

The statistic of the 120 check points showed a 4m bias (X: 3m ; Y: 2m) and a 12.1m CE90 horizontal accuracy (bias not removed).
This evaluation was published within the frame of the 2008 ISPRS Congress in Beijing [*Yoshino et al.* ; 2008].

4. EVALUATION OF THE ABSOLUTE VERTICAL ACCURACY OF REFERENCE3D USING ICESAT DATA

From 2009, we began to systematically use ICESat data to qualify the existing Reference3D geocells to enrich the existing on-the-shelf products with 2 quantified accuracy layers, including a “vertical performance mask”. This layer provides an estimation of the vertical error for each elevation post within the DTED level 2 DEM file (see above, section 2).

The computation of the Vertical Performance is based upon ICESat data, adequately filtered and selected to keep only the most reliable measurements.

4.1 Use of ICESat data to estimate local Reference3D vertical accuracy

From *Carabajal and Harding* (2005), the Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud, and land Elevation Satellite (ICESat) provides a globally-distributed data set well suited for evaluating the vertical accuracy of digital elevation models (DEMs). These authors quote horizontal error (2.4 ± 7.3 m) and vertical error (0.04 ± 0.13 m per degree of incidence angle). As compared to the Reference3D posting size and specifications, these figures are small enough to entitle ICESat a perfect data source to assess Reference3D local accuracy.

The first step of the production process is filtering the adequate ICESat dataset (release 28, dataset 14) to carefully select elevations that can be used with no doubt as “ground truth”. The filtering process is based upon the local slope ; land cover is not considered.

From a global number of 1000 to 20000 (on average) ICESat measurements within one Reference3D 1° x 1° geocell, some 150 to 1000 points are selected (mainly depending upon the relief and the latitude), and the elevation differences against Reference3D DEM are computed.
The points selection includes two steps :
- On the area of interest we separate by orbit all the data collected, so that we have the altitudes measured at different dates at the same place within some 500m maximum distance.
- We select flat areas by constraining the height difference to a given value dh, comparing measures at a maximum distance dd using data collected on a different day (by constraining the date difference). This is a way to avoid measurements of cloud, to work only on locally flat areas and to verify the repeatability of the measures. After this verification, one measure is selected and is considered to be valid.

4.2 Generation of the Reference3D vertical accuracy layer

These values are then used to generate the Vertical Performance Mask, with the help of the DTED 1 SRTM DEM from the Internet. The generalisation process includes several steps:
- Water areas and areas defined as “possibly outside specification” by the production control process are excluded from the computation of the vertical accuracy.

- The average (Av_{ICESat}) and the standard deviation (Std_{ICESat}) for all the elevation differences between ICESat and Reference3D are computed on the areas of slope lower than 20 %. The Vertical Accuracy Map value for these areas is given by the formula:

$$VPM_{<20} = \sqrt{[Av_{ICESat}^2 + (1{,}6 \times Std_{ICESat})^2]}$$

- For the areas of slopes greater than 20 %, we compute the difference between SRTM DEM and Reference3D DEM, and then deduce the average and the standard deviation for all the slope classes (lower than 20%, 20 to 40% and greater than 40 %). The formulas for the VAM values are:

$$VPM_{20-40} = \sqrt{[Av_{20-40}^2 + (1{,}6 \times Std_{ICESat} \times Std_{20-40}/Std_{<20})^2]}$$
$$VPM_{>40} = \sqrt{[Av_{>40}^2 + (1{,}6 \times Std_{ICESat} \times Std_{>40}/Std_{<20})^2]}$$

- After the computation, a look-up table is applied on the vertical accuracy map, in order to get a classified visualisation.

Thus, the Vertical Accuracy Map expresses the commitment of the producer regarding the accuracy of the delivered elevations. A maximum ratio of 5% of the extent of the geocell can be qualified with an “unknown” accuracy.

This computing is done independently for each geocell (which explains the non-seamless look at tile edges)

Studies are currently on-going to extend the method to N60°+ (and S58°+) areas, where SRTM is not available.

5. ABSOLUTE VERTICAL ACCURACY OF ELEVATION DATASETS OVER HOKKAIDO (JAPAN)

The 2008 evaluation of both N43E144 and N43E145 geocells was revisited during Q1 2010 for this paper, and ICESat data was used to assess the vertical absolute accuracies of several DEMs over these 2 geocells: SRTM DTED 1 DEM, GSI DTM and Reference3D DEM. The results are presented in the Tables below, where figures are in meters and relate to DEM elevation value *minus* ICESat elevation.

(m)	SRTM	REF3D	GSI
Average	-1.7	0.0	0.0
Std dev.	5.0	3.0	4.8
Minimum diff.	-27	-22	-29
Maximum diff.	29	14	40
Differences > 10m	35	6	34

Table 4: N43E144. comparison vs 559 ICESat measurements from 4 different tracks (2 ascendant, 2 descendant).

(m)	SRTM	REF3D	GSI
Average	-1.3	0.0	-0.9
Std dev.	1.6	1.7	2.1
Minimum diff.	-5	-8	-8
Maximum diff.	4	6	9

Table 5 : N43E145, comparison vs 270 ICESat measurements from 3 different tracks (1 ascendant, 2 descendant). N43E145 is very flat and 75% covered by sea.

6. DISCUSSION

The average alignment of Reference3D and ICESat measurements is impressive, while SRTM shows a slight bias of -1.5m. This could be due to the difference of penetration into the canopy, as the ICESat tracks fly over large areas of sparse or deciduous forest, consistently with [*Carabajal and Harding*, 2005].

Over N43E144, Reference3D really shows less large differences, and far inferior maximum difference with the ICESat “ground truth” than SRTM DEM and GSI DTM. This might come from the vegetation and from its better resolution.

Regarding GSI DTM, being a bare-Earth DEM extracted from maps, the figures can be locally impacted by the sparse forest coverage, though the average does not show any bias versus ICESat. Therefore we computed the difference between GSI and Reference3D elevations, to detect the impact of vegetation.

As shown by Figure 4 below, the influence of different map sheet production lines or field campaigns clearly appears into GSI DTM. Homogeneity is another advantage of Reference3D, as compared to “historical” elevation datasets, frequently handicapped by such phenomena (a similar effect was noted in some regions of France years ago).

This historical interpretation is confirmed by the inspection of the “Reference3D minus SRTM” DEM, where this effect does not appear.

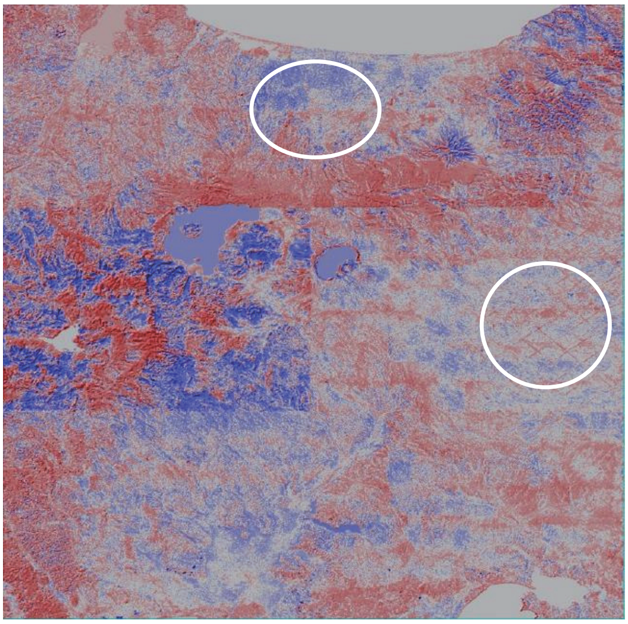

Figure 4: GSI DTM / Reference3D difference over N43E144. Blue / red colours show positive / negative differences. Delimitation of map-like frames is clearly visible. The white circles show the locations of the grid-pattern.

Furthermore, on the central East border of the geocell, a bizarre oblique grid pattern can be observed (Figure 4, white circle). A same pattern shows up in the Northern part of the geocell. The “lines” are 8 to 10m elevation difference along 200m-wide straight lines. Both places are similarly affected within the“Reference3D minus SRTM” DEM.

We suspected several mathematical flaws within the Reference3D process, and finally went to the field through the Reference3D orthoimage and… confirmed with Google Earth !

Figure 5 : Wide hedges within the Hokkaido landscape (as displayed through Google Earth)

Regularly spaced hedges are part of the agricultural landscape of Hokkaido Island. Their width, measured on Google Earth, is approximately 180m. Spacing is variable from one area to another. The grid pattern of the Reference3D DEM perfectly matches with the location of the edges, as seen on Reference3D orthoimage. The travellers' pictures available on Google Earth, confirmed the 8 to 10m order of magnitude of the trees.

Thus, these forest strips, perfectly portrayed within Reference3D, are neither described by the SRTM DEM, nor (not surprising) by the GSI DTM. While this is OK for use linked with water drainage or soil erosion, it can severely hinder the uses of these SRTM and GSI elevation datasets when it comes to applications such as flying objects or orthorectification of images for agricultural monitoring, automatic change detection, parcel surface measurement, …etc…

7. CONCLUSION

Over the Hokkaido region, Japan, the comparison of two 1° x 1° Reference3D geocells against ICESat data shows not more than 6 elevation differences larger than 10m, from a total of more than 800 measurements. This is fully compatible with the 6.7m LE90 absolute accuracy measured in 2008 against the highly accurate Japanese Triangulation Network.

Over this area, the cross comparison of different elevation datasets such as SRTM, GSI and Reference3D also allowed to enlighten the lack of homogeneity of GSI elevation data, probably due to "historical" reasons linked with different map production process or field campaigns. And also to pinpoint the extreme homogeneity and consistency of large global datasets such as SRTM or Reference3D (now covering more than 45 millions of sq.km).

Incidentally, it was discovered that Reference3D was the only dataset to portray the regular grid-shaped forest strips that rhythm Hokkaido's agricultural landscape, thus enabling its users to correctly orthorectify any image without undesired distortion.

Finally, the availability of ICESat data, with a perfectly known and mastered accuracy, stands as an important milestone in the history of global elevation DEM datasets, such as SRTM or Reference3D.

Indeed, the apparition of ICESat data sets provides NASA and other public US players another tool to evaluate and refine the SRTM DEMs and make them more robust and reliable. Same occurs for Reference3D, when ICESat data, available within the public domain, gives IGN and Spot Image the opportunity of providing the users with an unprecedented Vertical Accuracy Layer, consisting in an estimation of the error for each single elevation within the DTED2 Reference3D DEM.

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Acknowledgements

The authors would like to acknowledge T.Yoshino , H.Muraki , and Y.Yin from ImageONE Ltd (Tokyo), which work is recalled in section 3.3.