GEOSS Interoperability Guidance on DEM data

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Draft v1 (21 March 2008)
Updated V1.1 (7 April 2008)
Updated V1.2 (6 May 2008)
Updated V2 (15 August 2008)

Abstract
The GEO 2007 Work Plan specified a data management task (DA-07-01) on Global DEM Interoperability. This has the objective of facilitating interoperability among Digital Elevation Model (DEM) data sets with the goal of producing a global, coordinated and integrated DEM. This DEM database should be embedded into a consistent, high accuracy, and long term stable geodetic reference frame for Earth observation. This activity also includes coastal zone bathymetric maps in shallow waters (~30-40 m), DEMs of DTED1-class for the generation of topographic maps and land use/land cover maps at scale 1/50,000 or 1/100,000. Based on input from system operators and data users (GEO members or participating organizations) regarding their experience on interoperability, a list has been compiled of current DEM data sources and their specification. This report also includes guidelines regarding interoperability including the proposed use of common formats, the proposed use of OGC protocols for data visualisation and small area dissemination, the standardisation of validation procedures, the web reporting of accuracies and known issues and different scenarios for the creation of a global integrated DEM. A draft plan is outlined on how these goals may be met. The report's contents has been open to peer review by the GEO task team (listed in Appendix 1) and recommendations will be debated at the proposed July workshop taking place on the first day of the ISPRS Congress in Beijing, China.

1. Context

The GEO 10-year Implementation Plan[1] lists 9 societal benefit areas (SBAs) which were identified for international collaboration on the shared application of space and *in situ* assets for the common public good. One of the main triggers for GEOSS was the appalling human tragedy of hundreds of thousands of lives lost following the so-called Boxing Day (December 26, 2004) tsunami off the coast of Banda Aceh in the Indonesian archipeligo. Lessons learnt from this tragedy included the fact that not only was there a

[1] www.earthobservations.org/docs/10-Year%20Implementation%20Plan.pdf

lack of ability to identify and track tsunami waves caused by the paucity of EO and *in situ* data but also the inbility to deliver warnings to local populations around the Indian ocean due to the lack of any coherent organisation to monitor, report and disseminate such hazards. Less well-known is the fact that although there are several existing models for tsunamis, they cannot provide very accurate forecasts of the details of wave-breaking onshore due to the fact that there is very poor knowledge of the bathymmetry of the continental shelf regions and near-shore topography (see Muller, J.-P., 2005). Hence the need for a global consistent DEM of both coastal areas, continental-shelf bathymetry and inshore areas is vitally important to ensure that early warning systems for tsunami (and other natural hazards) have the geospatial data they require to make accurate predictions once the initial hazard has been identified and tracked.

In addition to the needs of the disasters' SBA, all the other 8 SBAs have varying requirements for global DEM data. However, much of the remotely-sensed data, especially from SAR (due to its sideways look) and all of the other EO data of resolution more than ≈10km requires DEM data to correct for terrain relief distortions for more than half of the Earth's land surface (Muller, J.-P. and Eales, P., 1990). Global DEM data is required both for geometric correction (i.e. orthorectification) and for radiometric calibration/correction (e.g. vicarious calibration needs atmospheric correction and/or atmospheric characterisation which requires an altitude for the location) of all EO data needed for all the SBAs.

Accuracy requirements for different SBA application areas have not yet been articulated by the relevant SBA activity. These are required to be produced by the relevant SBAs in the future.

For geometric terrain relief correction (i.e. orthorectification), a rule of thumb is that the process requires a DEM of grid-spacing some 3 times the pixel size. However, quantitative justification for this and how this varies as a function of different types of landforms does not appear to have been studied to date. Konecny (2000) evaluated what accuracy you would need for different mapping scales of orthoimage and what mapping scale could different resolution DEMs be used to create. Table 1 is a summary of the heighting requirements and a summary of what different satellite images could be used for what map-scale/orthoimage resolution.

Map Scale	Example EO orthoimage	GSD	Standard deviation of point height	Contour Interval
1:5 000	IKONOS	1m	±0.3±0.6m	1-2m
1:10 000	KVR1000	2m	±1.5m	5m
1:25 000	IRS-1C	6m	±3m	10m
1:50 000	SPOT-HRV	10m	±6m	20m
1:100 000	Landsat	30m	±12m	40m
1:250 000	CBERS-IRMSS	80m	±30m	100m

Table 1. Heighting requirements for different equivalent orthoimagemap scales (after Konecny, 2000)

2. Status of Spaceborne and Cartographic DEMs for regional to global application

2.1 Global Spaceborne DEMs

The NASA-NGA-DLR Shuttle Radar Topography Mission (SRTM) mission Farr et al (2007) flew in February 2000 and acquired nearly complete coverage of the Earth's land surface from 60ºN – 56ºS. The NASA C-band SRTM was processed by JPL into 1º x 1º tiles at 1 arc-second (30m) elevation data. These data were then processed by NGA (US DoD National Geospatial- Intelligence Agency) contractors into the so-called finished 1-arc-second DTED®2 and sub-sampled 3-arc-second DTED®1 Slater et al. (2006). This processing including gap-filling where there were 16 or less contiguous missing pixels and defining all coastline and inland water bodies with the aid of ancillary datasets (loc. cit.). This finishing process was extensive and traceable but extremely expensive in terms of effort required. These data are distributed via USGS EROS Data Center (referred to as USGS-EDC hereafter). For all US territory, all cells are available at 1 arc-second (≈30m). For non-US areas, only 3 arc-second (≈90m) data are publicly available. Gaps still remain in a significant fraction of the total DTED®2 cells and are summarised by continent in Table 2. They can also be visualised as bright red areas for the original (what ICEDS refers to as SRTM V1) and turquoise areas in finished (what ICEDS calls SRTM V2) SRTM using the web-GIS ICEDS (Integrated European Data Server) at http://iceds.ge.ucl.ac.uk

	North and South America		Eurasia		Australia		Africa		Total	
Percent Full	No. of Cells	Cumul. % of Total	No. of Cells	Cumul. % of Total	No. of Cells	Cumul. % of Total	No. of Cells	Cumul. % of Total	No. of Cells	Cumul. % of Total
100	1,174	28.7	1,846	32.2	380	35.8	527	16.2	3,927	27.8
99	2,666	93.7	3,531	93.8	677	99.7	2,288	86.6	9,162	92.6
98	84	95.8	102	95.6	2	99.9	117	90.2	305	94.8
95–97	108	98.4	117	97.7	1	100.0	123	94.0	349	97.2
90–94	44	99.5	67	98.8	0		81	96.5	192	98.6
85–89	7	99.7	27	99.3	0		29	97.4	63	99.0
80–84	2	99.7	16	99.6	0		22	98.1	40	99.3
70–79	5	99.8	19	99.1	0		33	99.1	57	99.7
50–69	4	99.9	5	100.0	0		20	99.7	29	99.9
<50	3	100.0	0		0		9	100.0	12	100.0
Total	4,097		5,730		1,060		3,249		14,136	

Table 2. Gap (void) statistics for finished SRTM DTED®2 by region (excluding islands). Taken from Slater et al. (2006)

An extensive validation programme was undertaken much of which is described in some 40 oral and 20 poster presentations available from a USGS-NGA-NASA-CEOS-ISPRS workshop (http://eros.usgs.gov/conferences/SRTM/) co-organised by representatives of USGS (D. Gesch), NGA (J. Slater), NASA-JPL (T. Farr) and CEOS/ISPRS (the author) and a subsequent March 2006 Special Issue of Photogrammetric Engineering and Remote Sensing, co-edited by the same group (Gesch et al, 2006).

SRTM DEMs have been analysed using kinematic GPS data and appear to vary in RMS accuracy between 3.4-5.5m as shown in Table 2 taken from Farr et al. (2007) and a very comprehensive report summarised in Rodriguez et al. (2006). However, a number of authors (e.g. Guth, 2006) have pointed out that these figures are really best error estimates as they showed that the error does vary both as a function of slope and of land cover. The cited author also provided convincing evidence that although 1 arc-second

(≈30m) DEMs are available publicly for the conterminous USA, they only really have an equivalent of 2 arc-second (60m) intrinsic resolution when examined alongside a US National Elevation Dataset (NED) at 30m.

	Africa	Australia	Eurasia	Islands	North America	South America
Absolute geolocation error	7.2	4.4	5.3	5.5	7.6	5.5
Absolute height error	3.4	3.6	3.8	4.8	5.5	3.8
Relative height error	5.9	2.8	5.3	3.8	4.2	3.3
Long-wavelength height error	1.9	3.6	1.6	2.2	2.4	3.0

Table 3. SRTM height accuracy (RMS converted from 90% LE by dividing by 1.65) taken from Farr et al. (2007)

These validation results suggest that SRTM have better accuracy than the 10m across-track SPOT-HRV (1-4). Unfortunately, there is no comparable workshop or dedicated special issue journal on SPOT validation as across-track SPOT stereo was not a dedicated DEM production system from SPOT-1 launch in 1986 until the SPOT-5 along-track stereo system in 2002. One of the first attempts to validate SPOT-1 was described in Day, T. and Muller, J., 1988 who showed that SPOT-DEM accuracy appeared to be limited by the pixel IFoV (Zrms≈10m) when comparing different stereo matching algorithms with an unique DEM generated manually at the canopy-tops.

More recent attempts (Cuartero et al., 2005) have generated large numbers of DEMs (91 SPOT) using different commercial packages and then assessed the accuracy against just 315 points for DEMs containing millions of gridded points. They indicated that in such special circumstances that Zrmse=7.5m could be achieved which is slightly worse than SRTM (see Table 3).

Since 2002, SPOT Image have been generating a systematic **commercial** so-called "Reference-3D" 20m DEM product from the along-track 5m SPOT-5 HRS/HRG sensors. Between 2002 and 2004, they organised an international inter-comparison amongst worldwide groups and held a special session at the ISPRS Congress in 2004. An example paper Kornus et al. (2004) which is one of the most thoroughly studied, showed that standard deviations better than 5 m (1σ) could be achieved in flat and moderate terrain and better than 10 m (1σ) in mountainous using dense photogrammetrically-derived airborne DEMs. Figure 1 shows the status of SPOT5 coverage as of 15 May 2007 which indicates that SPOT5 could be used to generate a fairly comprehensive global DEM of most regions outside of North America, Greenland and Antarctica given sufficient resources.

An alternative source of global DEMs is from the NASA-JAXA ASTER along-track stereo sensor onboard the NASA Terra satellite in operation since March 2000. This 15m

IFov system has acquired some 1.4 million scenes over the 150 M Sq.km. of the Earth's land surface with each scene covering 60 x 60km.

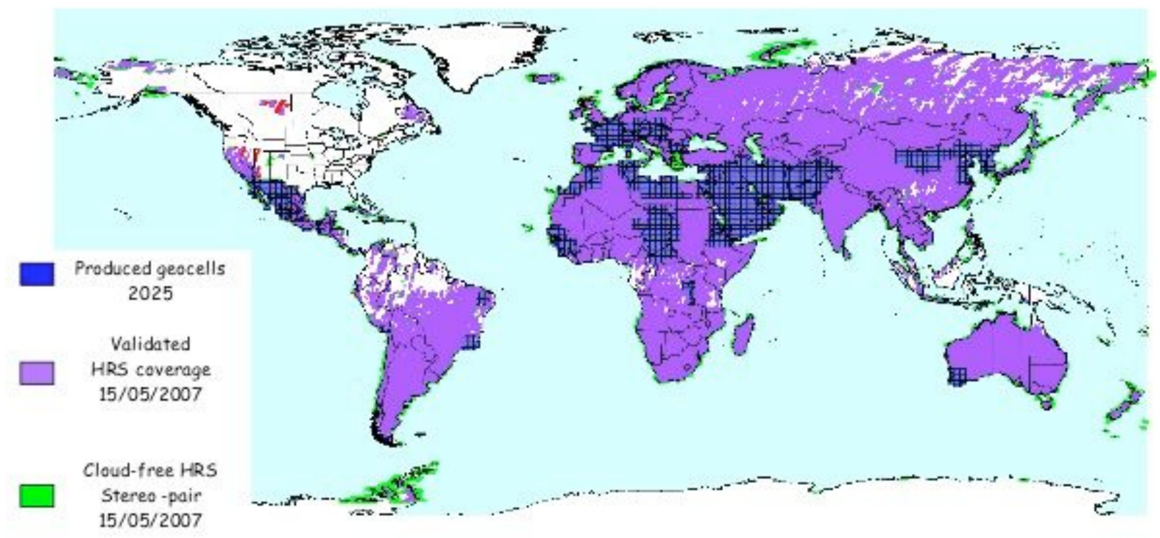

Figure 1. SPOT5 Reference-3D® 20m DEMs: status of production and acquisition of cloud-free HRS stereo-pairs suitable for Reference-3D® production as of 15/5/07

On 4 October 2007, updated on 21 February 2008, Bryan Bailey (Principal Remote Sensing Scientist, USGS, EDC) reported and I quote
"The National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade and Industry (METI), in cooperation with the U.S. Geological Survey (USGS) and METI's Earth Resources Data Analysis Center (ERSDAC), have announced plans to produce a global digital elevation model (DEM) from stereo data acquired during the past 8 years by Japan's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) that flies on the U.S. Terra spacecraft.

The ASTER Global DEM (GDEM) will have 30m postings, and it will cover land surfaces between 83ºN and 83ºS with estimated accuracies of 20 m at 95 % confidence for vertical data (elevation) and 30 m at 95% confidence[2] for horizontal data (geolocation).

METI and NASA have accepted an invitation from the Group on Earth Observations (GEO) to contribute the ASTER GDEM to the Global Earth Observing System of Systems (GEOSS), and it will be available at no cost to users from around the world.

At the GEO Summit in Cape Town, South Africa, in November 2007, US Secretary Kempthorne and Japanese Minister Tokai announced the two countries' plans to produce the ASTER GDEM and contribute it to GEOSS. That announcement was well received."

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[2] equivalent to Zrms=12.12m

This $3M project will fund a small private company based in Japan (led by Dr Fujisada) to process all 1.4M scenes into DEMs after screening each for cloud cover and then stack and average together all the remaining grid-points. No GCPs will be used but instead a dead reckoning georeferencing system. The global 30m DEM covering the region from ±83º of latitude is due to be publicly released in May 2009. The global DEM will be released in geotiff format via FTP in 22,895 1º x 1º tiles (each 3,600 x 3,600 2-byte integer grids) representing some 594 TB of DEM data. The current status (21/2/08) is that around 350,000 scenes have already been processed into DEMs.

Individual ASTER DEMs have been validated using the selective GCP check-point method with a Zrms= 13m described above for SPOT Cuartero et al. (2005) and using some 35 points from DGPS as well as lower quality DEMs generated from map products Hirano, A., Welch, R., and Lang, H., 2003 with Zrmse=7-15m. More recently, Fujisada et al. (2005) has shown that for 13 out of 14 ASTER DEM areas that Zrms≈3.88m can be achieved without the use of DEM scene averaging. An independent quantitative assessment of the achievable accuracy with averaged ASTER DEMs is given in a separate report by the author[3]

Other DEM sources include 1 arc-second SRTM-X Hoffmann, J. and Walter, D., 2006 and in future 0.3 arc-seconds (≈10m) DTED3® products from TANDEM-X (Irena Hajnsek, DLR, private communication, 2008). Both sources are **commercial** at present.

Two research systems could also play a useful role for validation or gap-filling in the future: ISRO CartoSat on IRS5P Radhika et al. (2007) with 2.5m IFoV along-track 2-view stereo and the JAXA ALOS-PRISM with similar 2.5m trioscopic along-track stereo Tadono et al. (2007); Takaku et al. (2007). These systems are too new for any published data on their accuracy although there were short reports and/or posters at the IGARSS 2007 meeting. Suffice it to say, their grid-spacing is around 0.3 arc-seconds (≈10m) with a predicted accuracy around 2.5m. Takaku et al. (2007) showed that the Zrmse can range from 2.85-12.5m depending on the nature of the land cover. Currently there is no published plan to create global DEMs from either CartoSat or ALOS-PRISM.

One attempt, which is available in the public domain, has been made to create a gap-filled SRTM product at 3 arc-seconds (≈90m) by the CGIAR Consortium for Geospatial Information, called the CGIAR SRTM DEM[4]. This process created vector contours from the original SRTM "finished" DEM, and the re-interpolation of these derived contours back into a raster DEM. These interpolated DEM values were then used to fill in the original no-data holes within the SRTM data. Although there is a quality assessment report online at the web-site, no assessment has been made of the accuracy the gap-filled pixels.

2.2 Regional to Global Cartographic and blended Spaceborne-Cartographic DEMs

[3] Muller, J-P (2008) "Trade Studies on best source and best fusion method for global DTED2". BNSC-Qinetiq contract report.
[4] http://srtm.csi.cgiar.org/

At the global level, there are 3 global datasets (and variants thereof) which are heavily employed for existing SBA applications and the georadiometric correction of medium resolution (250m-10km) satellite datasets of the Earth's land surface.

The GLOBE project Hastings et al. (1998), initiated by G. Schreier (DLR) and J.-P. Muller (UCL) in 1992 as part of a CEOS-WGISS Task Team on Global datasets resulted in the first ever fused DEM at 30 arc-seconds (≈1km). The project was initiated as a direct result of the availability of global digital contours from the DoD-DMA (Defense Mapping Agency) as part of the Digital Chart of the World (Danko, 1992). By the time of the release of GLOBE as a direct result of a Presidential Executive Order in 1995 to start releasing geospatial datasets initiated by US Vice-President Gore, previously restricted DMA DTED® (Digital Terrain Elevation Data) level 1 at 3 arc-seconds down-sampled to 30 arc-seconds were released in 1996. This is called DTED0 and forms over 50% of both GLOBE and another dataset which was produced around the same time at USGS-EDC called GTOPO30[5] Sources of the GTOPO30 and GLOBE are provided in Table 4. Unfortunately, ARCinfo® shapefiles are not available for either dataset to determine the geographical distribution of each source for each dataset. It can be observed that much of GLOBE contains the same sources with the addition of AUSLIG copyrighted material for Australia and various national mapping datasets. The DEMs derived from gridpoint interpolation of digitised map contours are identical in the 2 datsets with GLOBE using the GTOPO30 heights. GTOPO30 is used for EOS correction.

DEM Source	GTOPO30 % coverage	GLOBEv1 % coverage
Digital Terrain Elevation Data Level 0 (DTED-0)	50	57.5
Digital Chart of the World (DCW)	29.9	22.6
Antarctic Digital Database	8.3	8.3
USGS 1-degree DEMs	6.7	
Australia © AUSLIG		5.2
International Map of the World 1:1,000,000- maps	3.7	
Brazil 1:1,000,000-scale maps		3.5
Army Map Service 1:1,000,000-scale maps	1.1	
AMS 1:1,000,000-scale maps		1.1
Greenland (Radar Altimetry)		1.1
Peru 1:1,000,000-scale map	0.1	0.05
Japan (Geophysical Survey Institute)		0.26
Italy (Servizio Geological Nazionale, TerrainBase)		0.21
New Zealand (Manaaki Whenua Landcare Research)	0.2	0.18

Table 4. Sources of 30 arc-second data used to create GTOPO30 and GLOBE[6]

A number of mixtures of GTOPO30 with other datasets have been created since the release of GTOPO30 in 1996. SRTM30[7] has been generated from SRTM "finished"

[5] http://edc.usgs.gov/products/elevation/gtopo30/README.html#h17 Gesch et al. (1999)
[6] http://www.ngdc.noaa.gov/mgg/topo/report/s5/s5A.html

(Version 2) and merged with GTOPO30 by Tom Farr and colleagues at JPL. Unfortunately, no global source statistics show how much of each DEM in the original GTOPO30 is still present. However, it is very likely that most of the contour-based map sources between 60ºN and 56ºS have been replaced by SRTM data.

SRTM30_plus[8] is a new dataset (18 December 2007) which includes multibeam-derived bathymetry at 1 arcminute (≈2km) merged with ICESAT-GLAS derived polar elevations generated by David Sandwell and colleagues at Scripps Institute of Oceanography.

ACE is an interesting variation of GLOBE and GTOPO30 which used ERS-1 geodetic mission and ENVISAT-RA data to offset GLOBE and GTOPO30 heights (Berry et al., 2007).Figure 2 shows the distribution of these different classes and Table 5 the percentage from each class calculated from the source reference.

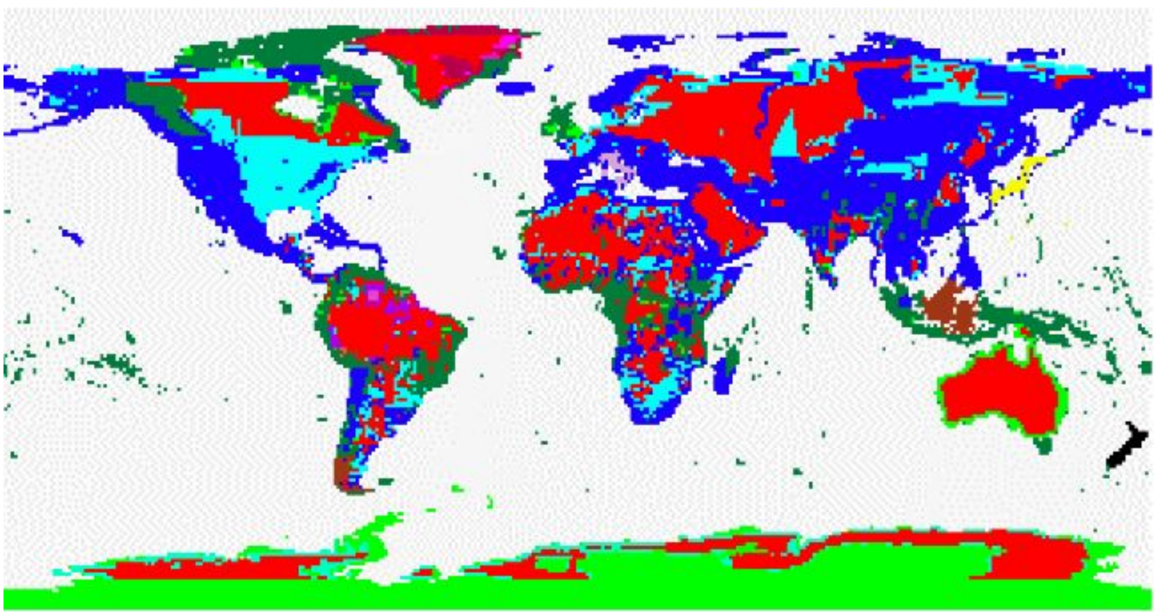

Figure 2. Source map of ACE-GDEM version 1[9] (colour key shown in Table 5)

Source	% coverage	Key colour
Altimeter derived DEM	26.38%	
DTED shifted	9.20%	
GLOBE/GTOPO30 SCAR Antarctica shifted	2.21%	
DCW GTOPO30 shifted	1.63%	
GLOBE Greenland DEM shifted	0.15%	
GTOPO30 Army Map Service shifted	0.01%	
GTOPO30 International Map of the World 1:1M shifted	0.04%	
DTED non-shifted	27.84%	

[7] http://icesat.gsfc.nasa.gov/tools/SRTM30_Documentation.html
[8] http://topex.ucsd.edu/WWW_html/srtm30_plus.html
[9] http://www.cse.dmu.ac.uk/EAPRS/products_ace_documentation.html

GLOBE/GTOPO30 SCAR Antarctica non-shifted	17.92%	
DCW GTOPO30 non-shifted	11.77%	
GLOBE Japan DEM non-shifted	0.29%	
GLOBE Italy DEM	0.19%	
GLOBE New Zealand DEM	0.24%	
GLOBE Greenland DEM non-shifted	0.82%	
GTOPO30 Army Map Service non-shifted	0.91%	
GTOPO30 International Map of the World 1:1M non-shifted	0.37%	
GTOPO30 Peru 1:1M non-shifted	0.02%	

Table 5. Statistics and colour key in Figure 2 of the ACE GDEM (see footnote 8 for details)

percentage change in each class. RA appears to have replaced around 26% and shifted some 14% of the total land pixels. RA is acquired at Ku band which tends to penetrate through dense vegetation (Muller et al., 1999) to either water or bare earth underneath. Berry et al., (2007) exploited the RA dataset to evaluate the accuracy of the SRTM-DTED1® and the overall results are shown in Table 6. The authors explain that some of this difference is due to the fact that the RA penetrates through forest canopies, part of this is due to the effect of steep within-footprint slopes and part due to gaps in the SRTM. Unfortunately, no statistics are given on the percentage of each.

Continent for SRTM-RA	Bias in m	Standard Deviation in m
Africa	1.86	15.62
Australia	1.09	11.49
Eurasia	2.54	16.09
North America	3.15	15.18
South America	12.22	18.51
Global	3.6	16.16

Table 6. Overall statistics for SRTM-RA showing effects of landscape objects, especially trees on the overall bias.

The authors have recently started the ACE2 project[10] to provide SRTM heights corrected for vegetation cover using the RA dataset supplemented with the latest RA data.

A further blend of ACE is contained with the GETASSE30[11] (Global Earth Topography and Sea Surface Elevation at 30 arc second resolution) which is employed by ESA for all georadiometric processing of medium resolution data. A recent release (11-Mar-08) includes SRTM30 version 2 and ACE.

Starting in 2007, a project to replace of the GTOPO30 is underway (Gesch, EDC, private communication, 2008) which will replace the existing 30" DEMs with a 3-resolution dataset (7.5", 15" and 30") utilising NGA void-filled SRTM 3" DTED®1, ICESAT-GLAS DEMs over Antarctica and University of Bristol (UK) Greenland data and national

[10] http://www.cse.dmu.ac.uk/EAPRS/projects_ace2.html
[11] http://141.4.215.13/doc/help/visat/GETASSE30ElevationModel.html

DEMs from Canada, the US (see later) and Australia. This is due to be completed in mid 2009.

All of the above global DEMs use the EGM96 geoid datum and WGS84 ellipsoid co-ordinates with the height value expressed at the centre of each gridpoint. They are available in a variety of different formats. There is no one location (such as a DEM portal) where the datasets can be easily compared with each other, other than ICEDS.

There are 3 well-publicised major regional DEM projects underway utilising a variety of different data sources, primarily cartographic, photogrammetric and some lidar and interferometric SAR. It is known that both India and China have major terrain mapping projects underway. However, the author has not been able to find any public domain sources detailing these projects.

The US National Elevation Dataset, NED[12] (Gesch et al, 2002) has created a uniform set of DEMs in lat,lon projection covering the conterminous US mainly derived from the digitisation of 1:24,000 scale maps. Most of the US is now covered with DEMs at 1/3rd arc-second (≈10m) resolution as shown in the screen-shot in Figure 3 but with some areas now filled at 1/9th arc-second (≈3m) derived from lidar altimetry (see Figure 4).

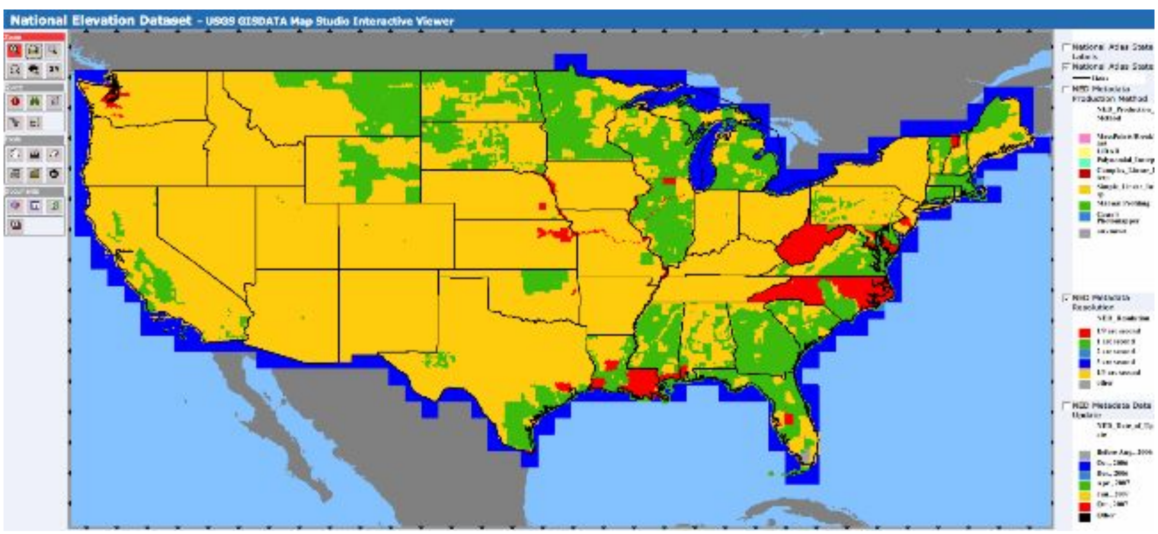

Figure 3. Grid resolution of NED showing US mainly dominated by 1/3rd arc-second (yellow), old 1 arc-second (green) and increasing amounts of 1/9th arc-second (red).

[12] http://ned.usgs.gov/

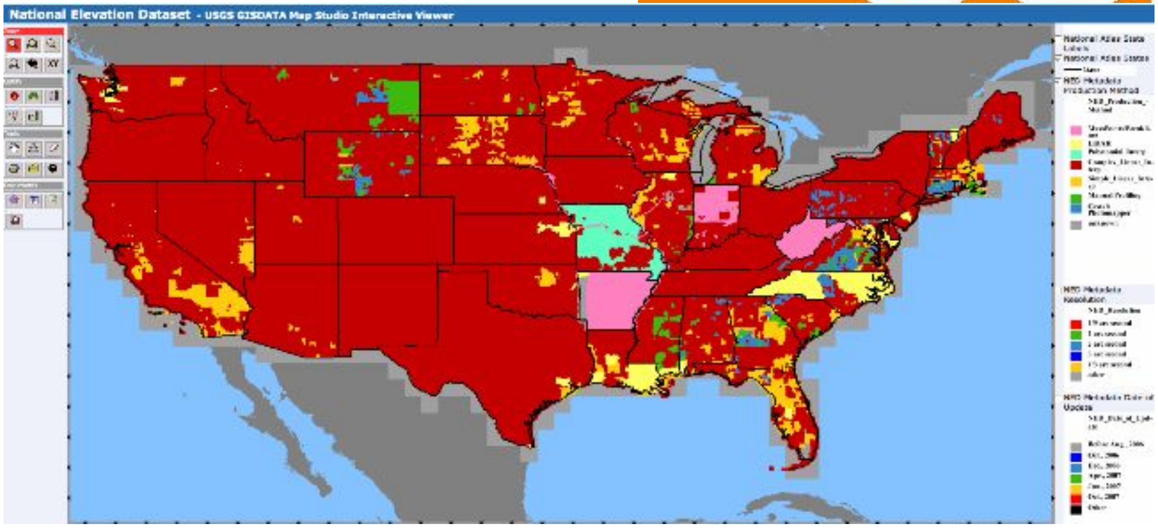

Figure 4. Source of DEMs and method of interpolation form input sources. Red areas indicate complex line vector interpolation whilst yellow indicate lidar.

Canada has created the GeoBase[13] product of DEMs derived from 1:50,000 (11,500 out of 13,500 maps) and complete coverage at 1:250,000. A coverage map for 1:250,000 is shown in Figure 5 and that at 1:50,000 is shown in Figure 6.

Figure 5. GeoBase shows complete 100% coverage of 1:250,000 derived DEM data

[13] http://www.geobase.ca/geobase/en/index.html

Figure 6. Geobase coverage at 1:50,000 (≈85% complete)

A consortium of European National Mapping and Cadastral Surveys called EuroGeographics have recently announced the 2 arc-second EuroDEM[14]. The EuroDEM has a grid of 2 arc seconds (approximately 60m at the equator, E/W dimensions vary according to the latitude) with a vertical accuracy of 8 to 10 metres. SRTM data (derived from CIGIAR, see above) were used for Baden Wurttemberg and Sachsen in Germany, Bosnia & Herzegovina, Serbia except Kosovo, Montenegro, FYR Macedonia, Albania and the Kaliningrad area. Only limited information is available at this time regards access and pricing. The countries included are shown in Figure 7.

[14] http://www.eurogeographics.org/eng/EuroDEM.asp

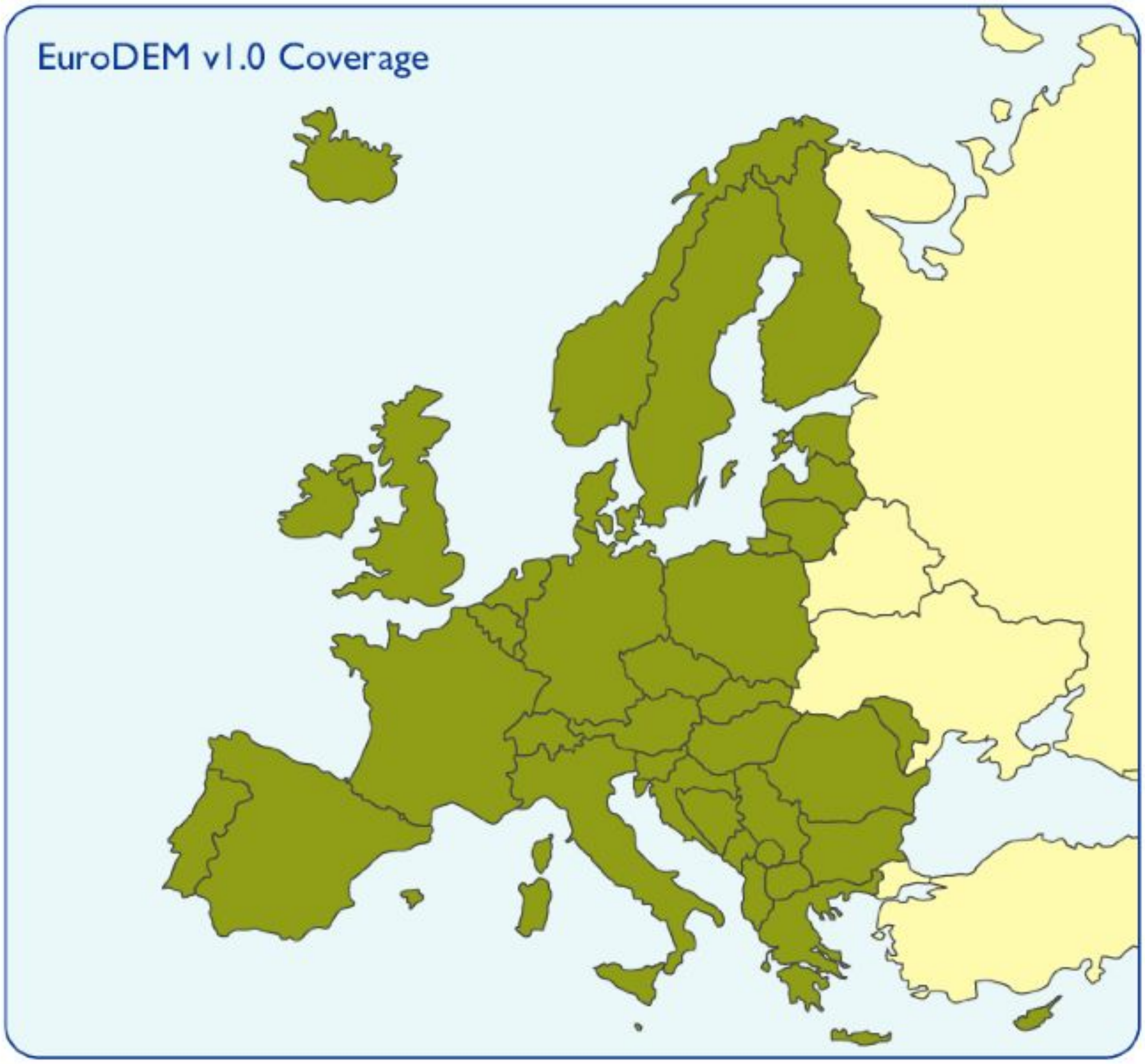

Figure 7. EuroDEM coverage of 2 arc-second DEM derived from various sources.

3. Status of Bathymmetric DEMs for regional to global application

The status of global continental shelf bathymetry (usually defined as those regions which have a depth from mean sea-level of around -100 m) is much poorer than the corresponding situation for land topography. There are three global bathymetric datasets currently available: Estimated global bathymetry, GEBCO global bathymetry and ETOPO2v2 global relief model, though some regional DEMs also exist. Recently Hall (2006) reviewed the status of the very long and winding road towards completion of a globally consistent global bathymetric dataset.

The latest version, 9.1[15], of global estimated seafloor bathymetry derived from sea-surface satellite altimetry measurements was released in August, 2007. This DEM spans -80.738 to 80.738° latitude at 1 arc-minute (~2 km) resolution, in Mercator projection. Land topography is derived from the SRTM30_plus DEM.

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[15] http://topex.ucsd.edu/WWW_html/mar_topo.html

A different global bathymetric DEM has been produced by GEBCO[16] (General Bathymetric Chart of the Oceans). It is also at 1 arc-minute (~2 km) resolution, though its bathymetric values are derived entirely from measured ship soundings and hand-drawn, interpolated contours. Significant near-coastal soundings were obtained from international sources in development of this DEM. In marine areas with sparse bathymetric soundings, seafloor depths were determined by interpolation. Land topography is derived from GLOBE.

NOAA's National Geophysical Data Center (NGDC) has developed the ETOPO2v2[17] two(2) arc-minute global relief model, derived from an earlier version of the estimated seafloor topography DEM, along with regional compilations. Land topography is derived from GLOBE. A one arc-minute DEM suitable for ocean circulation modelling will be developed in the summer of 2008.

A revised, regional, integrated bathymetric–topographic DEM of the Arctic Ocean, IBCAO v. 2.23, has been created (Jakobsson et al., 2008) and is available through NGDC[18]. This DEM is in polar stereographic projection, with 2 km cell size. Original datasets used in IBCAO v. 1 were re-evaluated to correct for systemic sound velocity errors, and augmented with recent high-resolution multibeam swath sonar surveys.

The coastal regions of the US are covered with the 3 arc-second Coastal Relief Model[19], that integrates coastal hydrographic soundings with land topography that predates SRTM. Soundings were extracted from the U.S. NOS Hydrographic Survey database[20] available thorough NGDC. These surveys were conducted in support of nautical charting and safe navigation. As such, they are highly reliable, with the exception that some of the surveys are quite old (dating back to the late 19th century) and thus subsequent morphologic change (natural and/or man-made) has reduced their accuracy in some places. Gaps between soundings were infilled using kriging interpolation. This means that much topographic detail is missing and input map scales can vary from 1:5,000 (harbours) to 1:80,000 (open sea) with the majority of regions being mapped at 1:20,000 (loc. cit.). The average depth accuracy is around 1m but this is along the transect soundings (loc. cit.). It should also be noted that the Coastal Relief Model has no adjustments for vertical datum differences among the hydrographic surveys and between the land and the bathymetry (Gesch, private communication, 2008).

NGDC is also building high-resolution, integrated bathymetric–topographic DEMs for select U.S. coastal communities in support of NOAA tsunami forecasting, warning and

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16 http://www.bodc.ac.uk/data/online_delivery/gebco/.
17 http://www.ngdc.noaa.gov/mgg/global/global.html
18 http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html
19 Divins, D.L., and D. Metzger, NGDC Coastal Relief Model, Retrieved date goes here, http://www.ngdc.noaa.gov/mgg/coastal/coastal.html
20 http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html

modelling efforts[21]. These DEMs are typically at 1/3 arc-second resolution and are seamless at the coast. Source datasets are converted to common horizontal and vertical datums, and common file format for evaluation, processing and DEM development. Land datasets are processed to "bare earth" to remove vegetation and building effects in the DEM and subsequent tsunami modeling. NGDC writes detailed reports for each DEM, documenting data sources, methodology, problems encountered and recommendations for future DEM improvement. There is also another source on merging topographic and bathymetric data[22] including a document that has a good discussion of the approaches to and issues involved with producing merged topographic-bathymetric DEMs.

For the UK, the Hydrographic Offce have generated a 20m gridded bathymetric DEM of the continental shelf with an accuracy of Zrms≈20 cm (Gupta et al., 2007). However, currently this is only available commercially or within the British academic system under a restricted license. It is unknown what other countries are doing with regards to higher resolution bathymetric data and searches on the Internet have not yielded any other sources. It appears that some 50 nations have performed soundings in their claimed territorial limits to back up their claims on this territory as part of the "Law of the Sea" under the auspices of the UN. These will be made public once the claims are agreed. However, this could take decades to establish (L. Czaran, private communication, 2008)

The GOMaP (Global Ocean Mapping Project)[23] was launched as a conceptual rallying call project in June 2000. It aims to provide bathymetry (nearshore at 1m, deep ocean at 100m) by leveraging worldwide multibeam sonar. However, it is only the US and the UK that appear to have sunk sufficient resources into creating 100% coverage of continental shelf regions. Although there is extensive multi-beam sonar[24], governments appear to be reluctant to share even metadata on what has been collected, let alone detailed bathymetry. Here is an excellent opportunity for remote sensing, either from aircraft or even from space.

Guenther, et al., (2000) have shown how airborne lidar bathymetry (ALB) can be employed to map the depths of near-shore bathymetry down to depths of 50m at much lower costs than the equivalent multibeam sonar. Global maps of ocean colour may be able to be utilised to determine which area could be best used and what time of year for such surveys. It may also be possible to transition some of this technology to a spaceborne platform to enable such measurements to be acquired worldwide.

4. Status of formats, visualisation and distribution of regional to global DEMs

Global DEMs come in one of 3 formats : geotiff, ascii and flat-field binary. To save disk-space and bandwidth they are usually encoded as 16-bit Integer (Big Endian) even though the global medium resolution DEMs would probably be best served using floating-point to preserve precision. Table 7 lists each global dataset (prospective DEMs

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[21] http://www.ngdc.noaa.gov/mgg/inundation/
[22] http://www.csc.noaa.gov/topobathy/
[23] http://mp-www.nrl.navy.mil/marine_physics_branch/gomap.php
[24] http://map.ngdc.noaa.gov/website/mgg/multibeam/viewer.htm

in the case of GTOPO30v2 and ASTER), together with URL to download, grid-spacing, tile-size, format and whether it can be downloaded using FTP-get or CD.

Source	URL for access or ordering (if known)	Grid	Tile-size	Format	FTP
GLOBE	http://www.ngdc.noaa.gov/mgg/topo/gltiles.html	30" (≈1km)	40° x 90°	binary	ftp
GTOPO30	ftp://edcftp.cr.usgs.gov/pub/data/gtopo30/global or http://seamless.usgs.gov/	30"	50° x 40°/30° x 60°	binary	ftp
SRTM30plus	ftp://topex.ucsd.edu/pub/srtm30_plus	30"	50° x 40°	binary	
GETASSE v2	ftp://ftp.estec.esa.int/ftp/pub/wipsftp/GETASSE_V2	30"	24° x 12°	binary	ftp
ACE	http://www.cse.dmu.ac.uk/EAPRS/iag/ace.html	30"	1°x1°	binary	CD?
GTOPO30 v2	Not yet known (NyK)	7.5", 15",30"	NyK	binary	ftp
SRTM V1* (USGS)	ftp://e0srp01u.ecs.nasa.gov/srtm	3" (≈90m)	1°x1°	binary	ftp
SRTM V1* (ICEDS)	http://iceds.ge.ucl.ac.uk	3"	N/A	geotiff	WCS
SRTM V2* (USGS)	ftp://e0srp01u.ecs.nasa.gov/srtm	3"	1°x1°	binary	ftp
SRTM V2*[25] (CGIAR)	http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp	3"	1°x1°	geotiff or Arc ascii	ftp
ASTER	Not yet known	1"	1°x1°	geotiff	ftp
SPOT-5 Reference 3D®	http://www.gisat.cz/content/en/products/digital-elevation-model/spot-3d	20m or 1"	1°x1°	geotiff	CD
ALOS-PRISM	Cannot find any for level-1a data or DSM ordering	2.5m	N/A	binary	CD?
Carto-DEM	Cannot find any for level-1a data or DSM ordering	2.5m	N/A	NyK	CD?
US NED	http://seamless.usgs.gov/	1/3",1", 1/9"	N/A	Geotiff or ascii	ftp
CN GeoBase	http://www.geobase.ca/geobase/en/download.do?produit=cded&items=official/cded1/&protocol=ftp	0.75-3" 3-12"	N/A	ascii	ftp
EuroDEM	http://www.eurogeographics.org/eng/EuroDEM.asp	2"	N/A	NyK	CD?

[25] V1 refers to the NASA original DEM and V2 to the NASA released finished DM

Table 7. List of global DEM sources, URL, grid-spacing, tile-size, format and FTP/CD

Aside from ICEDS (http://iceds.ge.ucl.ac.uk), there is no current source of OGC-compliant, global online visualisation of DEM data using WMS which at the same time provides WCS access to the underlying geotiff data (albeit only to V1 SRTM data at present). ICEDS is limited to a maximum of 20MB for any area download from a web-browser. The USGS seamless server is based on a proprietary web-GIS, ESRI® ArcIMS® combined visualisation and ordering system which generates FTP-get batch job commands. The CGIAR system allows you to order by specified area or via a map-based interface.

NOAA-NGDC land surface relief and bathymetric DEMs can be accessed and downloaded from individual dataset web pages[26], or by using the ESRI® ArcIMS® web-GIS 'DEM Discovery Portal'[27], a geospatiallly enabled tile-based system for locating web-published DEMs. NGDC has also developed the "Design-A-Grid" tool [28] that allows users to extract only that part of a bathymetric DEM in a user's region of interest, rather than entire DEMs. "Design-A-Grid" can also output the DEMs in multiple formats and resolutions. For land topography, GLOBE DEMs for each tile can be downloaded, along with data source maps[29] . Other non-DEM bathymetric source datasets, accessible using similar ArcIMS® geospatial viewers, include: global, international ship-mounted multibeam swath sonar surveys[30]; global, international marine trackline geophysics[31]; and U.S. NOS hydrographic surveys[32]. The ArcIMS viewers show ship tracklines or data coverage polygons and permit direct data download.

4. Global DEM Interoperability Guidelines

It should be noted that almost all DEMs generated from spaceborne sources whether stereo-optical or SAR-interferometric refer to the top-of-the-observable canopy. Most cartographically-derived DEMs refer to the bare earth except in topographically complex regions with dense forest where bare earth estimation is likely to be in error.

These "bare earth" DEMs are usually referred to as DTMs (Digital Terrain Models). This suggests that when merging DEMs derived from spaceborne DEMs and DTMs, that compensation needs to be made for the canopy height. Unfortunately, the mapping literature also includes the term DSM (Digital Surface Models) which can lead to confusion as a stereo-DSM at one particular resolution is likely to be at a different height to a SAR interferometric one at different wavelengths. The only spaceborne sensors capable of penetrating through dense vegetation are lidars and radar altimeters with the

[26] http://www.ngdc.noaa.gov/ngdc.html
[27] http://map.ngdc.noaa.gov/website/mgg/dem/
[28] http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html
[29] http://www.ngdc.noaa.gov/cgi-bin/mgg/ff/nph-newform.pl/mgg/topo/customdatacd
[30] http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
[31] http://www.ngdc.noaa.gov/mgg/geodas/trackline.html
[32] http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html

former being capable of achieving 70m footprints and the latter 350m footprints on flat ground.

Most end users require a DTM whether for hydrological (e.g. river routing) or geological (e.g. 3D block diagrams) or geophysical (e.g. seismic surveys) applications. Most space agency users who wish to perform georadiometric corrections require top of canopy DEMs, preferably tuned to the particular wavelength of the sensors they are trying to terrain correct.

In addition to different user communities requiring different types of elevation datasets, the sensor and DEM extraction technique used will also introduce their own noise characteristic when merging DEMs. In particular, stereo-matched DEMs suffer from pits which are due to floating precision round-off errors when noise is present whilst InSAR DEMs show a characteristic speckle noise due to being the result of a coherent radiation source. Therefore when stereo DEMs are merged with InSAR DEMs each source will require pre-filtering to reduce and/or remove system noise before data fusion.

Buckley, S. J. and Mitchell, H. L., 2004 have recently provided a review of different methods of merging DEMs, in their case from different sources (airborne lidar scanning and stereo) at different resolutions. The authors point out that often due to the inherent characteristics of each data collection process (e.g. crossing strips may be offset from each other due to accumulated INS and GPS errors), it may be necessary to ensure that individual DEMs have biases removed (both planimetric and vertical) before using surface fitting to merge the datasets together. If DEMs are collected at different epochs and changes have taken place (e.g. open-cast mining or construction), this will need to be taken into account also.

The authors propose the following steps (which the author has modified to take into account the different nature of DEMs being used here for Global DEM):

1. Perform an initial inter-comparison between the 2 input DEMs taking into account previous validation information and any visual inter-comparison (e.g. colourised hill-shaded DEMs flickered to search for any shifts in plan or height
2. Filter the DEMs to remove systematic noise (e.g. speckle in InSAR DEMs)
3. Remove land surface cover, if necessary, and if feasible
4. Surface match the 2 or more DEMs to recover systematic errors
5. Merge DEMs and ensure that differences are removed
6. Optimise the point density and distribution of the merged surface

One of the DEM surfaces will need to be assumed to be “correct” based on it’s a prior validation when performing such merger and criteria such as the DEM with the highest precision, best coverage or most recent acquisition will then need to be taken into account.

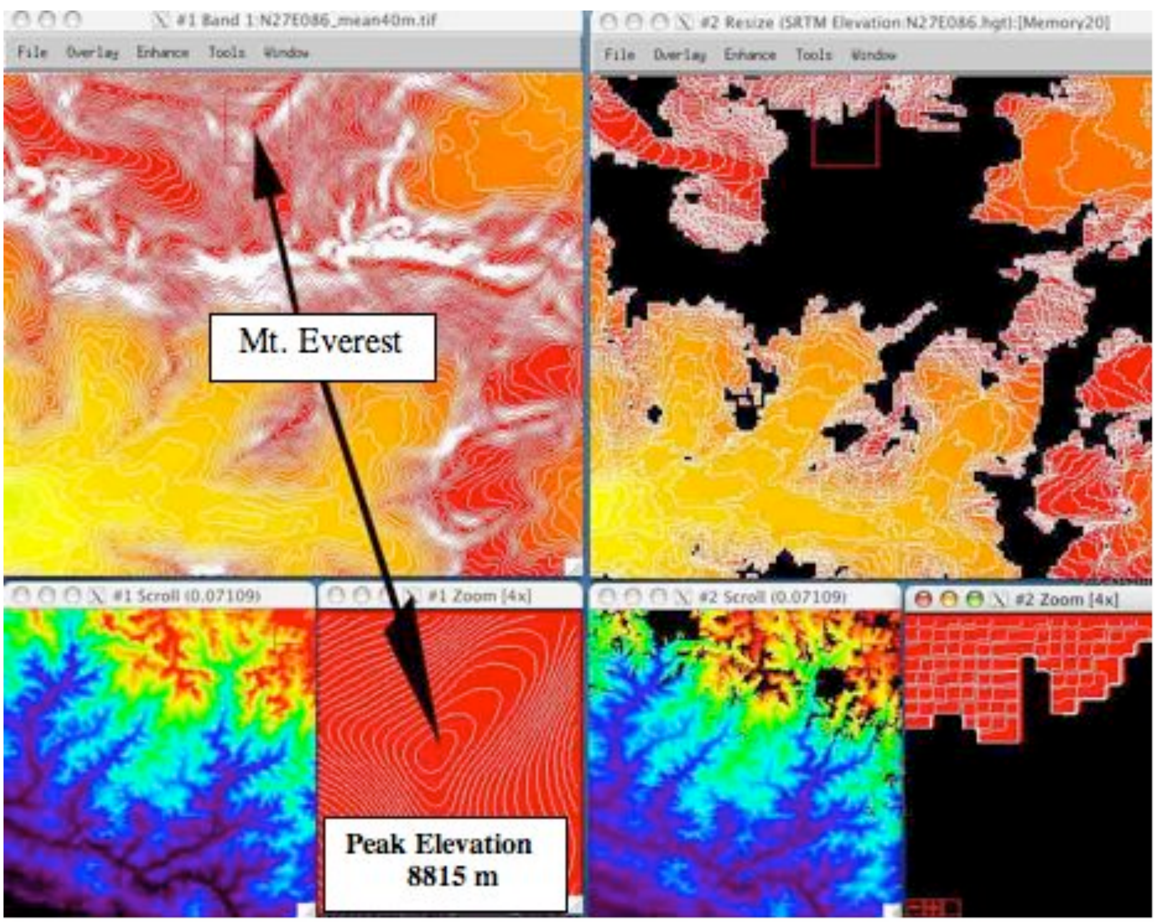
It should be noted that different DEMs may have different datums, grid-spacing and artefacts as well as different error effects. For example, InSAR often chops off the brow of tall hills and lowers the slope in steep slope areas. Blind fusion will only lead to the usual problem of “garbage in = garbage out”.

This merging process implies that filling in voids through the merger of 2 or more datasets will require that there is significant redundancy in coverage between the two so that the process outlined above can be realised.

It is likely that a near global ASTER DEM (1") will contain voids in areas of persistent cloudiness or poor image contrast. SRTM and TANDEM-X DEMs will be speckle noise and lower resolution (3") whereas SPOT-5 DEMs will have higher resolution (20m).

During the inter-comparison process and the evaluation of new DEMs, it will be important to ensure that each DEM is presented in an uniform manner This implies using the same solar elevation and azimuth as well as surface BRDF when hill-shading the same colour LUT. All of the colour LUTs used by each of the agencies displaying DEM elevations are non-standard and so the elevations cannot be easily compared. There is a need to develop an internationally agreed colour key, for example the ocean colour community have done this for all derived products from different ocean colour sensors[33]

An example of an inter-comparison of SRTM and ASTER DEMS over Mt Everest was kindly provided by B. Bailey (USGS) and is shown here in Figure 8



[33] http://www.globcolour.info/CDR_Docs/GlobCOLOUR_PUG.pdf

Figure 8. Prototype ASTER GDEM produced for the 1°x 1° area of Mt. Everest from 203 ASTER scene stereo pairs, compared with 90m SRTM DEM resampled to 30m. Measured elevation of Mt. Everest is 8,848 metres. White areas in the larger images are areas where contours are very close together. Black areas in the SRTM images are failed areas (gaps). Courtesy of B. Bailey (USGS-EDC)

In this particular case the injection of ancillary information (e.g. spot heights for the peak of Mt Everest) would suggest that the ASTER DEM would be the "truth" dataset in this case that the SRTM should be fitted to.

Interoperability of Global DEMs also implies that DEMs should be either held in the same format or that there are tools available for conversion between different formats. Although the DEM field has not suffered from the vast proliferation of formats which bedevils the image area, there are 3 generally accepted transfer formats: (a) geotiff (Ritter and Ruth, 1997); (b) flat binary (big endian); (c) ascii. The last two formats require metadata and here the problems begin. Firstly, these metadata header files can easily lose their association with the DEM file. Secondly, some agencies use binary format for these metadata files without providing a portable reading programme and just provide a format specification so that one is unable to import them without considerable effort. Thirdly, the metadata information included is different from different sources. In addition, there are many other proprietary standards which are often more efficient in terms of storage and the time to load into a particular GIS or image processing system. These formats also include the ability to encode missing data which Geotiff sadly lacks. More recently the GMLJP2 standard (JPEG2000 including GML metadata) has been proposed as a substitute for Geotiff. However, the lack of current readers or standards make this unlikely to be useful as a transfer standard although it may be useful as a final global DEM format given its ability to hold multiple layers of data within the same format (e.g. source-file format, error estimate by pixel or for the whole tile), include GML (which can be read into OGC-compliant readers).

In addition to the issue of standardising DEM formats is the need to validate DEMs using consistent methods. The CEOS-WGCV Sub-group on "Terrain mapping from satellites" which is currently chaired by the author, have proposed a "best practice standard" for DEM assessment in 1995. This urgently needs updating if resources were to be made available as this is a non-trivial effort. As part of this process, there will be a need to include a mechanism for user feedback over the web. A kind of web-log combined with a wiki is needed, whereby users can post observations of artefacts that they have come across and the data producers can provide feedback to the users when errors are fixed or why the observations are not in fact artefacts at all. Once again, such an enterprise would require significant resources both for setting-up, maintaining but also to ensure that artefacts were investigated and acted upon as well as feedback provided to users.

To create a fused global DEM, which is the ultimate objective of this activity, will probably require either a single centre to perform the fusion process described above or a number of regional centres (e.g. by continent) to perform this process. A very significant amount of computer processing power and storage will be required to perform the surface matching and merging processes. This could possibly be supported by existing GRID services using high-speed telecommunications bandwidth such as the facilities at ESRIN and CERN.

Distribution of the multi-TB dataset will also require new approaches to data distribution as such a system using a single server (or set of servers) within one organisation is likely to suffer from single point failures due to telecommunications bandwidth and access issues. One possibility is the BitTorrent protocol[34] which has been proposed by the University of Maryland Global Land Cover test Facility for the distribution of multi-GB sized files around the network. Another possibility is the use of a WMS tile cache[35] as proposed by Schuyler Erle and colleagues. This is another area which could be greatly assisted by inputs from CEOS-WGISS and OGC colleagues.

The OGC standards have been set up to address the issue of maximising inter-operability, both for pictorial representations of DEMs (WMS or Web Map Services), the underlying data in a common uniform format (WCS or Web Coverage Services) and vector or polygonal datasets which might represent additional layers such as source files (WFS Web Feature Servers). There appears to be a certain reluctance by many DEM supplier agencies to consider setting up WMS and or WCS/WFS services. This is partly due to the oft cited issue of authentication so that denial of service attacks or just huge numbers of users do not bring down the computer systems. One possible way around this in the short term whilst OGC battles with formulating a standard method of authentication is to limit the download via a OGC-compliant system to a maximum amount and anything over this will automatically generate a FTP-get script to download the relevant sections from the underlying DEM tiles. Another method is to use bitTorrent technology as referred to above but integrated into WCS.

A second complaint often heard is what web client should be used given the reluctance of many government organisations to embrace open standards given issues of support. One possibility is to use ICEDS which is based on the Open standard UMMS web-GIS with one of the Open standard GUIs.

5. Outstanding Issues

Bathymetry of continental shelves is missing for most continental shelves at anything approaching the 30m required for tsunami models. A possible mitigation is the use of the 1 arc-minute (2km) bathymetric data within the SRTMplus.

Datums and Geoids are frequently different for different datasets and often there are major geodetic issues in converting one dataset on one datum or geoid into another.

GIS and image processing software use different co-ordinate referencing systems. For example ENVI (ITT Visual) use the top-left corner, one-relative whilst ARCinfo (ESRI) uses the bottom left, one-relative. Frequently this is not properly documented.

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[34] example and FAQs at http://visibleearth.nasa.gov/faq.php

[35] http://mappinghacks.com/projects/distributed-wms-cache.txt

Copyright issues become a major issue if any of the input datasets have copyright restrictions. Some National Mapping Agencies demand that any derivative products even if they only contain one point have vested within them copyright from the source agency. It is therefore recommended that NMCA data only be employed for validation and not be burned into any downstream global DEM product where it could come back and bite global DEM users.

For regional, continental and global DEMs, a global 3-dimensional earth-centered geodetic datum should preferably be used such as WGS 84, ITRF or SIRGAS. Likewise the vertical reference datum for a DEM should use a global geoid to approximate mean sea level or should be tied to a global geoid so that one can transform between the regional and global systems with known variance. This is crucial for intercontinental tidal monitoring and in general for merging datasets. Achieving such agreement worldwide will be very challenging.

Funding and support issues. Although GEO tasks such as the one here are primarily planning in nature, GEOSS is treated by many member agencies as voluntary. For example, at a recent GMES meeting sponsored by BNSC in London, representatives of both the European Commission and ESA stated in public that GEOSS activities played no role in their GMES activities as GEOSS was only voluntary. There appears to be a different perception within CEOS, that as governments have signed an international treaty to become members of GEOSS, that actions associated with the stated intentions and recommendations of the GEO 10-year implementation plan, such as the construction of a global DEM, should be mandated on member space agencies and other government departments. This message clearly has to get through to the relevant funding bodies before any progress on a global DEM can occur. Within Europe, there is some hope that the Glob* activities which are part of the ESA DUE programme could be a possible vehicle for future funding of such activities.

6. Recommendations and Actions

A number of recommendations and proposed actions have been drawn from the body of this reportm and an international workshop held at IRSA, Beijing, PR China on 2 July 2008.

Recommendations

Gap-Filling

1. Global DEM suppliers (both land and continental shelf bathymetry) should be strongly encouraged by CEOS and GEO to consider participating in a global 30m DEM project. Such a project would not only be for their mutual benefit but also to the benefit of all GEO societal benefit areas, particularly related to natural disaster mitigation
2. Before any void filling, voids need to be identified and the DEM statistics characterised
3. CEOS sponsoring agencies should ensure that resources are made available so that all published spaceborne DEM datasets can be re-processed if "Known

Product Issues" identify bad data and these cannot be replaced from another source

4. CEOS-WGISS should encourage the development of software and infrastructure to allow easy inter-comparison of different satellite-derived DEM datasets stored as WCS datasets including both publicly released versions and those stored in-house
5. CEOS and GEO member agencies should consider sponsoring the development of continental-shelf bathymmetry programme, especially those using remote sensing to provide 30m bathymmetry information on near-shore and on continental shelves.
6. CEOS member agencies should encourage their relevant national and international bodies to make publicly available their bathymmetry heights using the mechanisms proposed for land DEM or something consistent with these principles
7. There is a need for a common reference frame to merge land topography and bathymetry. There is need to update coastal + bathymetry at much higher temporal frequency. Both needs are urgently required for predicting the behaviour of tsunami-generated waves
8. CEOS-WGISS should help facilitate the filling in of gaps (or artifact identified regions) in ASTER GDEM from another dataset.
9. CEOS-WGCV should investigate how QC information is to be incorporated into the data fusion process. This procedure should be best incorporated within a Web Processing Service.

Validation

10. All global DEM products provided for use in GEOSS societal benefit areas must be validated.
11. Validation statistics must also be supplied with the products.
12. There is a need to update the "best practice standards" for DEM validation and reporting DEM validation statistics in the light of the requirement to create a global DEM at 30m. Funding support is required from the relevant space agencies to develop such a standards document
13. DEM suppliers (both over land and continental shelf bathymetry) should be strongly encouraged by CEOS-GEO to consider participating in a validation effort for the global 30m DEM project. This could include supply of validation statistics and/or DEM and/or control data for validation.
14. There is a need to create and agree on a global colour LUT and hill shading parameterisation (e.g. scale specific) for the representation of global DEM elevation so that each supplier can ensure that they represent their data fairly and to allow users to compare one dataset against another
15. CEOS member space agencies should liaise with their national and/or regional mapping and/or hydrographic agency to provide DEM test sites with publicly available "ground truth" data for assessment of global EO-derived DEMs.
16. If publicly available mapping and/or hydrographic data is not available, suitable licensing mechanisms should be developed for access to these data by validation scientists.

17. Or if data cannot be distributed, a point-of-contact within the national mapping agency should be nominated who can act as a clearinghouse for DEM validation and provide standardized validation results on (a) specific test sites(s).
18. CEOS should encourage each EO-DEM data supplier to provide web-GIS and/or wiki facilities for the reporting of "Known Product Issues" including the delineation of areas of "bad data" which can later be flagged as such and compared against and substituted by other datasets (e.g. locating DEM pixels via a shapefile which have been shown to be in error).
19. CEOS member agencies to provide funding support for a user support service, including a "wiki" and "web-GIS" and, above all, a moderator. An example of such a system developed for product quality assurance of MODIS land products can be viewed at http://modis-250m.nascom.nasa.gov/cgi-bin/QA_WWW/newPage.cgi?fileName=terra_issues
20. NASA to provide a Web Processing Service for ICESAT-GLAS data for validation of global EO-DEM data. This would first be applied and developed for SRTM and could later on be applied to ASTER GDEM and also be used by SPOT5, ALOS-PRISM, CARTOSAT and TANDEM-X
21. ESA to consider developing a comparable service for Radar Altimeter and gravity data for the same applications.
22. JAXA and other CEOS members to provide validated DEMs for sites on other continents (e.g. Africa, South America, Asia, Australasia, Antarctica). These test sites should be established over different land covers
23. CEOS-WGISS to allow easy inter-comparison of different satellite-derived DEM datasets served through WCS including both publicly released versions and those stored in-house
24. CEOS-WGISS member agencies to develop suitable computing facilities to allow standard QA procedures to be fully automated so that when new "ground truth" datasets become available, existing EO-derived DEMs can be easily and very quickly assessed.
25. CEOS member space agencies should be encouraged to fund activities to prepare validation and control data set including data derived from current and previous EO missions e.g. ICESat. This will provide globally consistent reference data.

Global DEM Dissemination and Interoperability

26. Global DEM suppliers should be encouraged to agree on a common format for data and metadata. CEOS member agencies should be encouraged to sponsor a study as to whether either Geotiff or the emerging GMLJP2 standard would be "fit for purpose" especially with regard to the storage of validation statistics and relevant metadata
27. CEOS member agencies should be encouraged to sponsor a study as to whether it would be better to use a single Global DEM distributor, mirrored DEM distributors or to employ new standards such as Peer-to-peer or WMS caches to ensure integrity and reliability for global DEM supplies in the future, especially when multi-TB datasets will be available.
28. Existing Global DEM distributors should be strongly encouraged to set up WMS/WCS data servers, preferably at the same time as ftp servers are set up,

with a view to making WMS the standard method to view the data and WCS the preferred method to deliver SMALL quantities of data (<100Mb?) with ftp being available for larger downloads. Pilot study or studies should be funded to investigate the best mechanisms.

29. CEOS member space agencies who are creating global EO-DEMs should consider making these DEMs or different DEM subsets (e.g. small groups of pixels identified in ASTER GDEM as missing) publicly available through OGC-compliant servers. JAXA and NASA have shown the way forward with the proposed global ASTER GDEM but encouragement needs to be provided by CEOS and GEO to SPOT Image (via CNES), DLR (for SRTM-X and TerraSAR-TANDEM-X) and ISRO (for CartoSAT) to participate in providing data subsets to this GEO task.
30. CEOS-WGISS is to ensure that all Global DEMs WMS/WCS server URLs are easily discoverable

A set of actions is required for which funding is needed from GEO member space agencies and their partners for the following:

1. Production of validation data including specific actions on NASA, ESA,JAXA
2. production and supply of VALIDATED DEM heights needed to (a) fill in gaps; (b) available for 200 worldwide sites (1 x 1º cells)
3. production and supply of BATHYMETRIC heights. Quality and metadata layers must be delivered with any global DEM
4. validation of the global ASTER DEM
5. production of a single global DEM by fusing multi-source data
6. validation of this final fused DEM
7. visualisation and browsing system for global DEM using web-GIS
8. DEM distribution over the Internet
9. Maintenance of moderated "Known Issues" pages and supported responses to repair and correct notified errors in the global DEM
10. Additional trade studies on
11. Best practices regarding validation
12. Common format for global DEM including reference system and data typing
13. Best method for product dissemination and education of potential users

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