DIGITAL ELEVATION MODELS: WHERE DO WE GO FROM HERE?

Ian Dowman
Department of Geomatic Engineering
University College London
Gower Street, London WC1E 6BT
United Kingdom
Tel: (44) 20 7679 7226 Fax: (44) 20 7380 0453E-mail: idowman@ge.ucl.ac.uk

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ABSTRACT

This papers examines the current status of DEM generation and discusses current research which may lead to better quality DEMs. Data from so many different sensors can now be used for DEM generation that it is necessary to set out their advantages and disadvantages. There are also many applications of DEMs, and ways of processing and presenting them, and new research is constantly extending and improving these. Some of these methods are discussed and these include improved stereomatching, better representation of the surface and the use of data fusion.

1. INTRODUCTION

Digital elevation models (DEMs) have become a major product from different types of remotely sensed data in recent years for a number of reasons: production has become easier with the use of digital images and automatic stereo-matching; new techniques such as interferometric SAR (IfSAR) and LIDAR have provided an accurate alternative source to stereo images; and many new applications have been developed, ranging from orthoimages through 3D city models and visualisation. However, with this upsurge in the production and use of DEMs have come a number of problems. The main problem is the reliability of a DEM produced by automatic matching. It has been shown many times that given suitable acquisition dates, and suitable land cover, accurate elevation data can be produced. However it is also well known that blunders can easily creep in due to mismatching, and that this becomes more common at larger scales in built up areas and on vegetated steep slopes. As much time can be spent editing a DEM as generating it is the first place. Similar problems apply to IfSAR, although in this case the coherence image gives an indication of the quality expected. LIDAR data does not have these problems but is mainly suitable for large scale work and generally, at present, does not produce an image. A summary of the characteristics of optical data is shown in table 1.

	Characteristics	**Problems**	**Comments**
Aerial photographs	2 Vertical images	Occlusions	Well established theory and method
Airborne 3 line scanners	Forward, nadir and aft views; require GPS/INS for position and orientation; multispectral data can be collected simultaneously	Intensive computation required for correction	HRSC successfully used for true orthoimage production
Medium resolution satellite images (SPOT, IRS, ASTER)	Pushbroom (line scanner systems) with varying configurations; orbit stable, but not well known.	For SPOT and IRS problem of obtaining stereo pairs in short time.	Now widely used. Much data now available from these sensors
High resolution satellite images (Ikonos, Quickbird)	<1m pixel size; highly manoeuvrable; high positional accuracy.	Cost, availability of stereo and exterior orientation data.	Not yet much used for DEM generation.
LIDAR	Direct determination of X, Y, Z co-ords.	Small swath width, high cost.	Good for some applications

Table 1. Characteristics of DEMs generated from optical data.

The availability of stereoscopic data from high resolution satellites such as Ikonos and Quickbird also has an impact on DEM generation. Images from these sensors may be acquired at very large incident angles: up to 45˚. Thus the degree of occlusion and correction needed is increased. Furthermore the accuracy of this data is dependent on the interior and exterior orientation data that may not be within the control of the user, being provided as rational polynomial co-efficients by the supplier.

As more data becomes available and techniques develop, there is a greater demand put on the DEMs. High quality is needed for terrain analysis in such areas as hydrology and terrain evolution for tectonic studies. It is therefore necessary that we examine the methods of generating DEMs and how we use them, asking a number of questions such as: is the matching method used the best for the application? Is the method of interpolation to a grid appropriate and is information lost in this process? Can we improve the DEM by using data fusion from two or more sources? This paper will discuss DEMs at medium to large scales and will consider DEMs generated from LIDAR only as supplementary data when high accuracy, over limited areas, is required. We will first review the methods of generating DEMs, not just the sensors used, but also the processes involved, and then look at ways in which the DEM might be improved and tailored to different applications.

2. GENERATION OF DIGITAL TERRAIN MODELS

2.1 Matching stereoimages

The principle method of generating DEMs from optical images is now automatic stereomatching. Software has been developed over many years and packages such as SOCET Set sold by Leica Geosystems and Match-T are now widely used. Editing software comes with the package and this has significant use, especially at large scales. The degree of automation in the editing routines in these packages is limited. Generally the software will handle aerial photographs and a range of satellite images, which is continually extending. This type of software is ideal for the generation of orthoimages, for which there is little editing required, limited to the removal of blunders. Surface features such as buildings and trees will be corrected only to the level of accuracy of the digital surface model (DSM) and at large scales this does not accurately model the surface features. 'True' orthoimages can be obtained from three line digital scanners using algorithms that use information from all three looks. Matching algorithms using only two images may be able to produce true orthoimages if breaklines can be utilised. This topic is discussed further below.

Automatic stereomatching produces a digital surface model (DSM) that is the first surface presented to the sensor, i.e. the tops of trees, buildings and other features. This is useful for some applications such as production of orthoimages and visualisations, and may be suitable for small scale applications, but at larger scales, a digital terrain model (DTM) will often be needed. This has let to the development of filtering algorithms to generate 'bare earth models'. These are more often used with LIDAR and IfSAR data.

2.2 Interferometric SAR

Interferometric SAR is used for generating DEMs from SAR images collected with a short base line from which phase differences can be determined and converted to elevation differences. The technique was proven with European ERS data and more recently used on the Shuttle Radar Topography Mission (SRTM) which collected data for the whole land surface of the Earth between 60˚ N and 54˚ S. ERS data is acquired with a time interval between images (repeat pass data) and has been used to create DEMs with regional coverage in countries such as Germany and UK. SRTM is single pass data and DEM data is now being released with 30m spacing in the USA and 100m spacing elsewhere. The vertical accuracy is generally around 8-10m. Airborne IfSAR systems are also in use now and are also used to collect regional DEMs with spacing typically 5m and with 1m vertical accuracy.

Prior to SRTM and airborne systems, which obtain 2 images simultaneously in a single pass mode, the major problem with IfSAR was lack of coherence between two images taken at different times. This led to gaps in the data that could be filled if multiple pass data was available. In the United Kingdom, for example, the Landmap project (Morley et al 2000) has created a DEM of the whole country using 4 near complete passes of ERS data. There is a very large archive of ERS data that can be used in this way.

Software for DEM generation from IfSAR is often developed for specific types of data nd is not generally available, although some vendors, such as PCI, sell software with image processing systems.

2.3 Discussion

We have shown that data is available to produce DEMs for most parts of the world with grid spacing of 30 metres or more using satellite data from sensors such as SPOT, IRS, ASTER and ERS. DEMs generated from SRTM IfSAR will shortly be available off the shelf. At higher resolutions airborne data is available from optical and radar sensors that can produce DEMs of small or large areas as required. High resolution optical sensors on satellites can also produce DEMs, but this data has not yet been much used for this purpose. Vertical accuracy is dependent on the sensor and the type of terrain and land cover, but also on the ability to obtain near simultaneous image pairs. The uses of this data are varied. A major use is to produce orthoimages and image maps. Sensors such as SPOT are particularly useful for this in areas where no up to date maps exist, and in remote areas where access is difficult and expensive. DEMs have also been extensively used in hydrological studies and for the prediction and management of disasters, such as flooding, landslides, volcanic eruptions and earthquakes. Differential interferometric SAR has been particularly useful in this latter application. In recent years DEMs have been in considerable demand for predicting flood prone areas for protection and insurance purposes. Airborne IfSAR has proved useful for large areas, supplemented by LIDAR for smaller areas.

3. IMPROVING THE QUALITY OF DEMs

3.1 Data acquisition

The main factors that affect the accuracy of a DEM that has been processed, edited and archived for use are:

- Accuracy of the source data and/or derived elevation;
- Terrain characteristics;
- Sampling method (grid [grid spacing], TIN]
- Interpolation method;
- Representation (raster, tessellation, contours…)

The relationship between accuracy and spacing is highly dependent on the nature of the terrain. The formula of Ackermann (1980) for optical data has widespread use:

$$\sigma_z^2 = (a \cdot d)^2 + b^2$$

where σ_z^2 variance of interpolated arbitrary points in the DEM
- d mean (representative) point interval between measurements (grid spacing)
- a proportionality factor depending on the type of terrain
- b measurement error.

Apart from the terrain, all of these variables are dependent on the sensor. A higher resolution will result in the ability to have smaller grid spacing and smaller measurement error. Better sensors will therefore give better accuracy. The best sensors at present are the high resolution optical sensors such as Ikonos and Quickbird, but, as discussed above, the data is expensive and is therefore not used for DEMs over large areas. Stereo optical sensors such as ASTER are making the data available to more people but the accuracy of the DEMs generated is not as high as from existing data such as SPOT and IRS because of a larger pixel size. Better resolution will come from the Japanese ALOS mission and the PRISM sensor that has 3 line stereo data with a pixel size of 2.5m. One of the aims of this mission is to create regional DEMs and the specification for PRISM DEMs are 10m spacing with 5m vertical accuracy. The accuracy is related to the cost and Figure 1 gives comparison between the cost of data with the vertical accuracy.

In the area of IfSAR, SRTM will be a valuable data set because of its near global coverage, the accuracy however is no better than SPOT. ENVISAT, RADARSAT 2 and ALOS PALSAR are potentially useful sources of IfSAR DEMs. It has also been demonstrated that airborne IfSAR can produce regional DEMs economically. Complete coverage of England Scotland and Wales has recently been completed by Intermap with a 5m spacing and 1m vertical accuracy (0.5m in some places).

Table 2 summarises the characteristics of data acquisition and DEM generation.

3.3 Improved representation of the terrain

The size of feature that can be shown is ultimately limited by the pixel size of the imagery. However the size of the window used for matching, which can be changed, is also important. Strategies within matching software can be changed to influence the detail obtained. The method if interpolation, however, is often fixed.

Scientists from the Earth sciences have made their own investigation into methods of surface fitting and have proposed the use of techniques such as dynamic modelling, geostatistics and fuzzy classification, (Wilson et al, 2002). Use of these tools could lead to techniques for handling uncertainty, identification of scale dependent filters and handling of sub-grid scale variability. Hutchinson (2002) discusses a locally adaptive approach to the interpolation of DEMs and indicates the importance of not loosing information when interpolating from an irregular network to a grid representation.

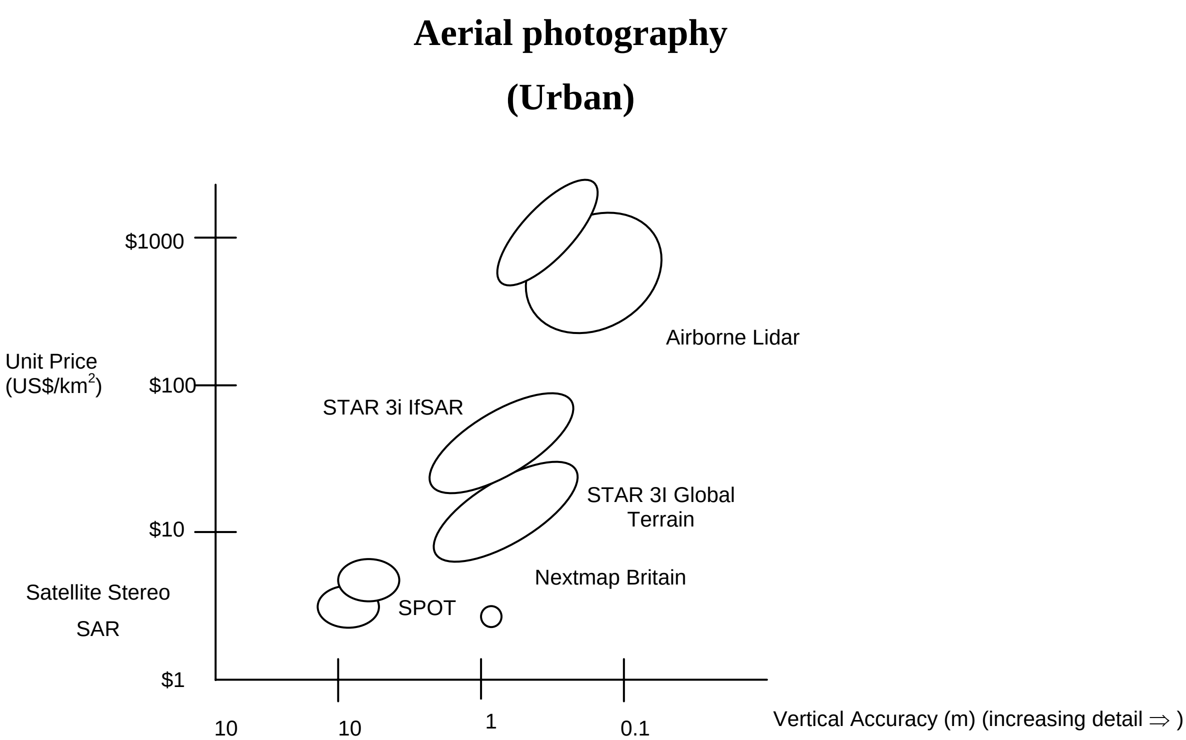

Figure 1. Relative costs of DEM production compared to vertical accuracy (after Mercer, Intermap)

Platform/Sensor	Grid spacing	Vertical accuracy	Comment
Medium resolution satellite images (SPOT, IRS, ASTER)	**30m**	**10m**	**Reliable data and software. Subject to gaps due to cloud, occlusions and decorrelation.**
High resolution satellite images (Ikonos, Quickbird)	**5m**	**2m**	**High accuracy, narrow swath and high cost.**
SPOT 5		**<10m**	**Continuations of SPOT 1-4 with improved resolution and revisit capability, and along track stereo**
ALOS PRISM	**10m**	**5m**	**Good potential for regional DEMs**
ERS IfSAR	**30m**	**10m**	**Can produce good results if multiple passes, but can be problem due to decorrelation, occlusions and layover.**
SRTM	**30m**	**10m**	**Good global coverage. Only 100m data available outside USA**
Airborne IfSAR	**5m**	**0.5m**	**High quality data for regional cover.**

Table 2. Summary of data acquisition

3.2 Improving stereomatching

Algorithms for stereomatching have been developed over many years and comprise highly complex code, there is therefore clearly an inertia to be overcome. New techniques such as the wavelet transform has been applied to image matching and suggestions have been made to use adaptive strategies, these are summarised in table 3. More use could also be made of breaklines, and to define these by automatic or iterative methods.

Technique	**Examples**	**Comment**
Use of breaklines	(Sohn and Dowman, 2001) concludes that the introduction of 3D breaklines improves the DEM which can be generated. Paparoditis et al (1998) and Cord and Declercq (1999)	Software available but not fully used. Methods developed for building extraction. Problem in defining breaklines by manual measurement or from maps
Wavelets	He-Ping Pan, (1996), Tsay (1998)	Not widely used
New strategies	Data fusion (Honikel, 2002) **Failure Warning Model (Fox and Gooch, 2001)** Adaptive strategies	Most promising approach, can be built on existing algorithms, but may require additional data.
Multipoint matching	Rosenholm, (1987)	Gives good results but also requires extra data.

Table 3. Techniques for improving stereomatching.

3.4 Data fusion

The opportunities for data fusion are greatly increased as more sensors are launched and data becomes more easily available and often less costly. If more than one data set is available then solutions have been proposed for exploiting any synergy that is present. (Honikel, 2002, Hahn and Samadzadegan 1999). Fox and Gooch (2001) have proposed generating 2 DEMs from the same data to improve the result.

A useful discussion of the topic is given by Honikel (2002) who recommends three steps:

1. Data **alignment** during which all data is transformed to the same reference system in the same units.
2. Data **association** during which data is grouped and edited so that common points are merged and erroneous points are removed;
3. **Estimation** during which a final DEM is created which best fits to the multiple observations.

Honikel is concerned with fusing ERS IfSAR data with a DEM from SPOT and demonstrates how the synergy of these two data sets can be exploited to make use of the strengths of both sets of data to give a DEM that is better than either of the initial sets of data. In his case the SPOT DEM is used to improve the phase unwrapping and to remove systematic trends; associated data is used to remove blunders and get a better estimate for points to which more than one observation refer, and by working in the frequency domain the strengths of both data sets can be combined. From this we can propose some generic techniques:

- Fusion of data with different spacing (quasi or true grid) to get a better estimate of individual points.
  Examples: Hahn and Samadzadegan (1999) use wavelets to combine DEMs of different resolution and accuracy.
- Fusion of data that has different qualities.
  Examples: IfSAR can be very accurate where coherence is high and SPOT can be accurate where correlation is high, either can perform better on particular types of feature depending on aspect, time difference etc. Stereo SAR might be used with SPOT for similar reasons.
  LIDAR data might give an indication of where buildings or trees occur, which could control matching of optical data.
- Fusion in a coarse to fine strategy.
  Examples: A coarse DEM can be sufficient to give initial values to generate a fine DEM and to indicate areas where problems might occur.
  A coarse DEM can assist with phase unwrapping of IfSAR data and remove trends due to atmospheric effects or base line errors. (Honikel 2002)
- Fusion of different types of data.
  Examples: Use of rivers, spot heights, lakes, breaklines etc. within the matching process.

Two general questions remain to be answered in respect to data fusion:at what stage should fusion take place? And how to exploit the full information from an irregular network?

3.5 Interferometric processing

Research is ongoing in the area of processing IfSAR data. It has been shown recently that data fusion (Honikel 2002, see above), and multiple passes (Landmap, Morley et al, 2000) can be used. SRTM and airborne IfSAR have shown that intensive processing from single pass data can provide reliable and accurate data.

4. FUTURE DIRECTIONS

Better sensors should produce better DEMs and this has been demonstrated by SRTM, IKONOS and airborne IfSAR. In the future ALOS PRISM and PALSAR and ENVISAT may also produce widely available improved data. The use of data fusion techniques can also produce better DEMs, but at the expense of having more than one data sets and more processing. This may not be a major disadvantage in the future if data such as SRTM become widely available at low cost, and Data from ERS continues to be available. However we also need more efficient production, that is lower cost and more automation. This is the area where most research is needed: to make more use of breaklines and adaptive strategies for DEM production.

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Prof. Dr. Martien Molenaar

Rector
International Institute for Geo-information and Earth Observation (ITC)
The Netherlands

Oral Presentation

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