TOWARDS A GLOBAL ELEVATION PRODUCT: COMBINATION OF MULTI-SOURCE DIGITAL ELEVATION MODELS

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ABSTRACT

Mapping and monitoring the Earth's surface is subject to various application fields. This three-dimensional problem is usually split into a two-dimensional planar description of the Earth's surface supplemented with the height information provided as separate digital elevation models. However, from the global point of view there is still a tremendous need for suitable height information at a resolution level of about 1 to 3 arc seconds. The Shuttle Radar Topography Mission (SRTM) will help to fill this gap by providing high quality digital elevation model (DEM). In order to provide terrain information for areas where either SRTM data will not be available or the corresponding resolution is not sufficient a combination with other sources will be required.

The German Remote Sensing Data Center (DFD) of DLR intends to implement such a global DEM service. All SRTM/X-SAR data will be processed to elevation data and will serve as the backbone as it provides a global net of homogenous elevation information. This net can be used for the absolute orientation of other DEMs as geometric reference, but also for the improvement of the height quality by integrating elevation data from a variety of other sources by DEM fusion and mosaicking techniques.

The paper describes the principles and corresponding accuracy of space borne missions for the derivation of DEMs. The main focus is on the DEM products of SRTM/X-SAR. Furthermore, the ERS-1/2 tandem configuration and the MOMS-2P mission are described. The technique to combine multi-source DEMs is outlined, which is based on the concept of height error maps. The method is illustrated by practical examples. Finally, an outlook is given on further investigations.

1 INTRODUCTION

Within the last years a growing need for high resolution elevation data with global coverage became clearly evident. Although in the meantime global elevation data, e.g. the 1 km resolution GLOBE data set (Hastings & Dunbar, 1998) became available, high quality elevation data at a resolution level of about 1 to 3 arc seconds are still lacking in many regions of the Earth and therefore are of high interest for a large number of applications worldwide.

However, several dedicated missions, that have been launched in the last years can contribute to a significant improvement of this situation in the near future. This is mainly due to the data acquired during the Shuttle Radar Topography Mission (SRTM). SRTM mapped the land surface within 56° southern and 60° northern latitudes covering 119 million km^2 (Pessagno, 2000) with NASA's C-band and approximately 58 million km^2 with DLR's X-band system. The data of both systems are currently processed using SAR interferometry.

The European Space Agency ESA built up an excellent global data basis operating it's ERS-1 and ERS-2 satellites in the tandem mode for interferometric DEM production, even providing multiple coverage. Moreover, e.g. the RADARSAT system provides elevation data based on SAR interferometric processing as well as SAR stereo processing.

Satellite systems based on optical stereo sensors as the SPOT system acquire data in different viewing angles for stereo image processing. The German stereo camera MOMS-2P was mounted on the PRIRODA module of the Russian space station MIR. It delivered approximately 65 million km^2 of high quality and high resolution imagery (Schroeder et al, 2000).

Each of those techniques and systems is able to provide high quality elevation information. However they are also restricted to their inherent limitations. The imaging geometry, the look direction and the look angle as well as illumination conditions are important parameters. Repeat pass acquisitions are affected by changes on ground and in the atmosphere reducing the precision of the final DEM product. Simultaneous operating single pass systems like SRTM and MOMS-2P provide optimized imaging conditions. The relative position of the imaging apertures is directly observed. However geometric limitations still exist and a total coverage of the earth's surface could still not be achieved.

In order to further improve this situation a technique for DEM fusion and mosaicking is required allowing to overcome the limitations and to provide a global DEM.

2 DEM SOURCES

In principle, a variety of space borne missions and sensor systems exist, which provide valuable data sources for the generation of DEMs. The techniques, that are currently used, can be grouped according to the sensor technology into SAR (interferometry and stereo) and optical stereo methods.

SAR interferometry utilizes the phase of SAR signals to measure differences between the distances from two radar antennas to the ground in an accuracy of a fraction of the wavelength. The acquisitions are either performed simultaneously (single pass interferometry) or at two different dates (repeat pass interferometry). The shuttle mission SRTM provides data for single pass interferometry, the satellite systems ERS-1/2, Radarsat and ENVISAT-ASAR provide data suitable for repeat pass interferometry. A detailed description can be found e.g. in (Bamler & Hartl, 1999).

SAR stereo (or radargrammetry) exploits the intensity of the back-scattered signals. Within SAR images the terrain slope mainly influences the brightness. Similar to the optical case parallaxes are measured within the image pair. The capability of using multiple incidence angles is realized in Radarsat and ENVISAT-ASAR. (Leberl, 1990) and (Toutin, 1999) describe in more detail the SAR stereo processing.

Optical stereo techniques from space are in general based on line scanner images, which are acquired either at two different satellite passes (dual pass stereo) or in a single pass e.g. by a three-line scanner system (single pass or along track stereo). For the dual pass configuration it is necessary that the sensor can be tilted to cover the same area at two different acquisition dates providing a suitable base/height ratio for DEM generation. For instance, the panchromatic sensors of SPOT satellites as well as of the IRS-1C/1D enable such capabilities. The first along track stereo scanner in space was the German MOMS-02 camera, which was flown as technological experiment on the second German shuttle mission (MOMS-02/D2) as well as on the Priroda module of MIR space station (semi-operational MOMS-2P, see Kornus et al, 1999). Within the next years several satellite missions will be launched, which will provide along-track stereo capabilities. These systems will offer stereo data at high resolution, e.g. SPOT-5 (10 m resolution), IRS Cartosat-1 (2.5m) and ALOS PRISM (2.5 m).

The following chapters will describe in more detail the three missions SRTM, ERS-tandem and MOMS-2P, which were used as data source for the practical investigations described in chapter 4.

2.1 SRTM / X-SAR

SRTM mapped the Earth's surface between February 11th–22nd, 2000. Within only eleven days approximately 80% of the land mass was covered being the home of 95% of the world's population. Two antenna pairs were operated during the mission working in two different frequencies - NASA's C-band-system and the German-Italian X-SAR. Due to the 230 km swath-width of the C-band a full coverage will be achieved. The X-band swath is only 50 km wide leading to a coverage net showing the biggest distance of approximately 150 km at the equator. The distance gets smaller with increasing latitudes until the scenes overlap at about 55° north and south (see figure 1). A benefit of the X-SAR system is the high frequency, which leads to a high elevation sensitivity.

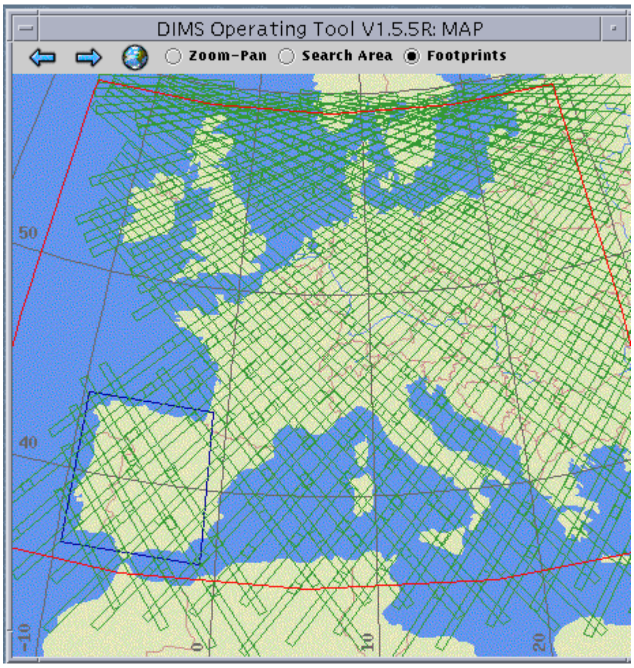

Figure 1. SRTM/X-SAR coverage Europe

SRTM provided the capability of single pass SAR interferometry for the first time in space. The active antennas sitting in the shuttle's cargo bay were supplemented by a second pair of antennas mounted on a boom that was deployed in space. Temporal de-correlation being the major limitation of repeat pass interferometry doesn't effect the DEM quality as the observations are performed simultaneously. Another benefit is the direct measurement of the baseline. Throughout the entire mission the shuttle-orbit and attitude, as well as the position of the outboard relative to the inboard antenna were observed from the Attitude and Orbit Determination Avionics (AODA) instruments.

Not only the land surface but also the ocean heights were measured by SRTM and therefore it is able to "see" the elevation reference itself. Utilizing this effect the processing of the image strips - the so called "data takes" - always starts at the coastal areas.

The direct observation of the baseline as well as the fixing of the elevation processing on the sea surface significantly improve the processing throughput as the time consuming and mainly interactive determination of ground control points is not required. Additionally this procedure enables a homogeneous product quality.

SRTM/X-SAR provides a backbone for global DEM production. This net can be used for the absolute orientation of other DEMs as geometric reference but also for the improvement of the height quality by integrating elevation data from a variety of other sources by DEM fusion and mosaicking techniques.

2.2 ERS Tandem

Interferometric DEM generation is also possible using ERS tandem data. The processing differs to SRTM in some details but the main steps are identical. A big advantage of ERS is the multiple coverage. Beside the radar frequency the baseline length mainly determines the height sensitivity. Optimal configurations can be selected and combined in order to improve the DEM precision. In particular for Europe the best image pairs can be selected from a huge archive. E.g. figure 2 shows the ERS-tandem coverage of Germany.

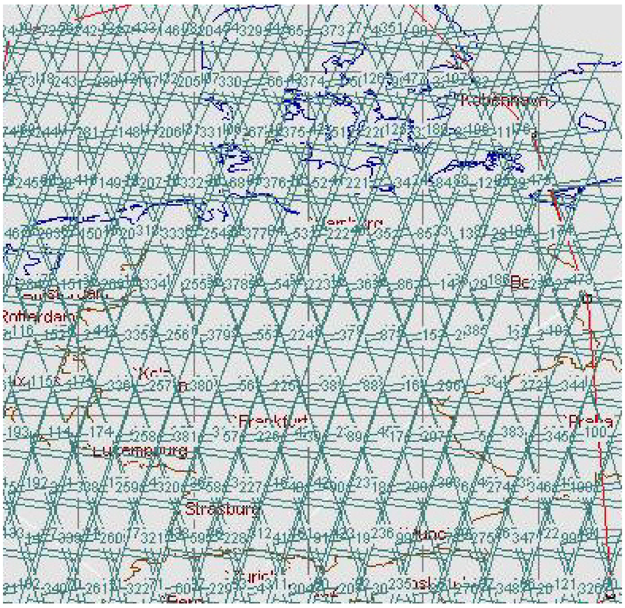

Figure 2. ERS tandem coverage of Germany

Limiting factors of ERS-tandem are the repeat pass conditions and the steep incidence angle. Temporal de-correlation is a significant limitation. Water bodies de-correlate within fractals of a Second. Dense vegetation and precipitation cause a loss of coherence, too. Whenever de-correlation appears the noise level in the interferogram increases. Atmospheric distortions additionally corrupt the phase information.

Common to all SAR systems is their side-looking geometry. SAR specific terrain distortions are foreshortening, layover and shadow. The derivation of extreme foreshortening, layover and shadow areas is not possible. ERS uses a relatively steep incidence angle of 23° that causes foreshortening and layover, but less shadow. Contrary SRTM / X-SAR has an incidence angle of 40°, which mainly causes shadow and less layover.

2.3 MOMS-2P

The MOMS-02 camera was flown on board the Priroda module of the Russian space station MIR during the mission MOMS-2P from 1996 to 1999. Approximately 65 million km^2 were imaged at an orbit inclination of 51.6° and from an altitude of 400 km, which resulted at a ground pixel size of 18 m and 6 m, respectively. The majority of all data takes was acquired in so-called mode D, that is a combination of two inclined stereo and two nadir looking multi-spectral channels with a swath width of approximately 100 km and a ground resolution of 18m. The stereo angle of 21.4° results in a base/height ratio of approximately 0.8, which results in a mean height accuracy of better than 10 m (Müller et al., 2001). Figure 3 shows a coverage map of MOMS-2P over Europe. Beside the along-track stereo capability a highly accurate navigation package (dual-antenna GPS receiver and gyros) was used for the first time in space with respect to civilian use.

The main limiting factor for DEM generation from MOMS-2P is, and this is of course true for all optical systems, the availability of cloud free images or images with low cloud coverage. Therefore, the resulting DEMs derived from these optical stereo data in most cases do not provide full coverage of large areas, e.g. whole countries or continents.

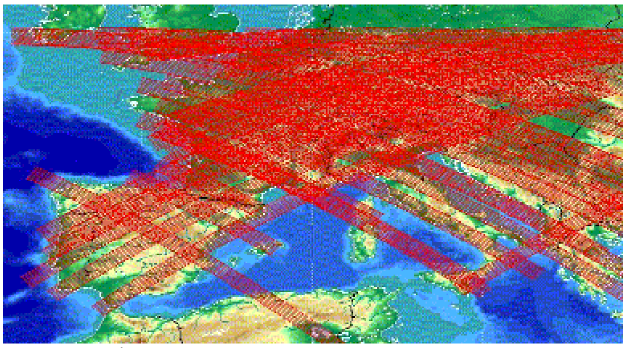
Figure 3. MOMS-2P coverage over Europe

3 DEM FUSION AND MOSAICKING

A line of processors was developed at DLR for interferometric DEM generation. It consists of four individual processing systems:

- The screener
- the SAR processor
- the interferometric processor (Genesis)
- the geocoding and mosaicking system (GeMoS).

Within the first two steps – the screening and the SAR processing – the corresponding images of the two antennas are individually prepared for the interferometric processing. This step comprises quality control, image formation and focussing of the SAR data. The output is the complex product which provides the amplitude/intensity and phase information.

The interferometric processor determines the interferogram of the differential phase, which is direct proportional to the difference of the distance between a ground position and the two antennas. The processing comprises spectral shift filtering, optional slope adaptive filtering, co-registration, multi-looking, coherence estimation, flat earth phase removal and the phase unwrapping (Eineder & Adam, 1997).

Finally the geocoding and mosaicking processor converts the phase into elevation information, geocodes the height values and compiles the individual DEMs to a large area data set (Roth et al, 1999).

For the paper at hand the mosaicking procedure is the most relevant part of the InSAR system. It compiles the individual DEMs to a large area data set. Overlapping areas from both crossing and adjacent scenes are utilized for cross-checking and an accuracy improvement. Multiple coverage reduces the height errors as several independent measurements can be combined. This procedure was developed for the generation of DEM mosaics from different sources, primarily based on interferometric SAR (Knöpfle et al, 1998). But it can also be used to incorporate DEMs provided by other sources and techniques, especially from optical stereo systems. The pre-condition is the availability of a height error description. The mosaicking and fusion algorithm takes into account the different prior accuracy of the DEMs and derives the quality of the resulting DEM.

3.1 Error sources

In general the quality of a DEM produced by SAR interferometry is determined by three different error sources (Bamler, 1997):

- the phase noise representing the measurement accuracy of the interferometric phase,
- the imaging geometry,
- possible atmospheric distortions in case of repeat pass interferometry.

A detailed description of the error sources and their functional dependency with the resulting height error is given in Knöpfle et al. (1998).

The accuracy of a DEM derived from optical stereo data is determined by the following groups of error sources:

- the measurement accuracy and density of tie points in the image space,
- the accuracy of control points in image and object space,
- the error budget of orbit and attitude determination and
- the overall imaging geometry (base to height ratio etc.).

The measurement accuracy of tie-points in the image space can generally be estimated from the matching procedure. For instance, if least squares matching is used, then the standard deviation of point determination can be derived within the estimation process for each point. This accuracy is mainly depending on the gray value gradients and the degree of correspondence of the homologous points. The overall accuracy including the influence of the imaging geometry can be determined from the inverse of the normal equation matrix for the determination of the exterior orientation parameters and the forward intersection for the computation of all ground points. Moreover, to take into account the subsequent interpolation process for the derivation of a regular grid DEM the density of points is also considered in the calculation of the resulting height error.

3.2 Height Error Map

The height error is calculated for each grid point in the raster DEM and is stored in a height error map. For each DEM a corresponding height error map with the same dimensions is generated, which is used as input for the following mosaicking procedure. The imaging geometry defines the scene specific level of accuracy, while the coherence (InSAR) or the correlation precision (optical stereo) are considered as local measure for each raster cell.

3.3 DEM Fusion and mosaicking

The mosaicking procedure creates large area DEMs from various input DEMs stored in the same coordinate system and pixel spacing. They need to be provided together with the corresponding co-registered height error map. This step also comprises the fusion of DEM data sets covering the same area. This is done by a weighted averaging of the individual height values within the overlap areas. Additionally a statistical outlier test is performed in order to identify and correct errors that cannot be detected in the individual models without a proper reference.

The height error map contains for each pixel an error estimate utilized as local weight during the averaging process. Whenever the elevation of the ground position is measured several times the result is statistically improved. The procedure allows the elimination of identified and labeled erroneous measurements in one of the single DEMs caused e.g. by disadvantageous imaging conditions like layover or shadow. In this case the low weight prevents from the consideration of the erroneous value.

4 PRACTICAL EXAMPLE

As test site an area in the south west of Germany was selected (figure 4). It covers approximately 110 km x 140 km of the Black Forest and the southern Rhine Valley. The area shows different types of terrain, the flat Rhine Valley up to the mountainous Black Forest and the Vogues in France. The heights are ranging from 140 m to 1500 m above mean sea level. The test site covers parts of Germany, France and Switzerland.

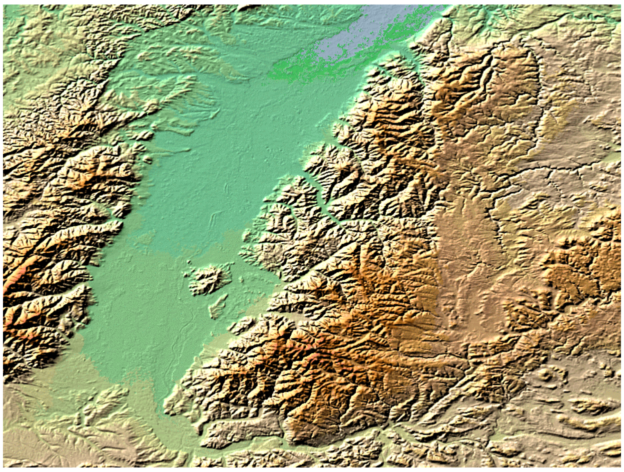

Figure 4. Fused DEM “Black Forest”

The test site is mostly covered by SRTM/X-SAR (60%), approximately 25% by MOMS-2P and 100% by ERS tandem. Figure 5 shows the resulting height error map. The blue area indicates an accuracy of 1-5 m that could be achieved due to the triple coverage and the complementary height improvement. The bigger errors in the image center occur because only ERS tandem is available. The densely forested area causes decorrelation. South of this area a sharp horizontal line appears where additionally MOMS-2P covers the test site.

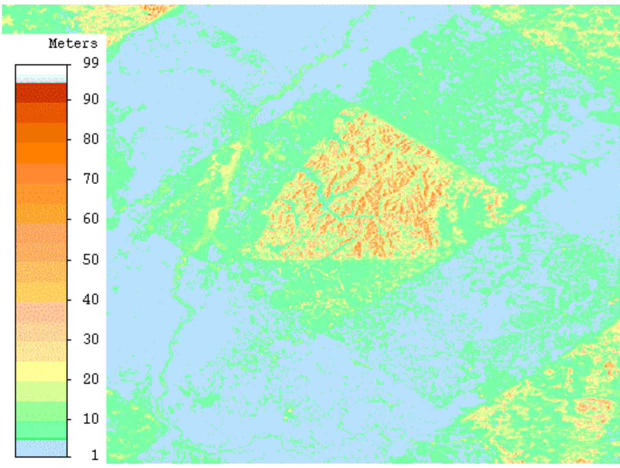

Figure 5. Fused Height Error Map

Comparing the color shaded DEM and the height error map it is obvious that the different DEMs could be seamlessly mosaicked. MOMS-2P and ERS tandem were adjusted to SRTM/X-SAR which refers to WGS84 as horizontal and vertical datum.

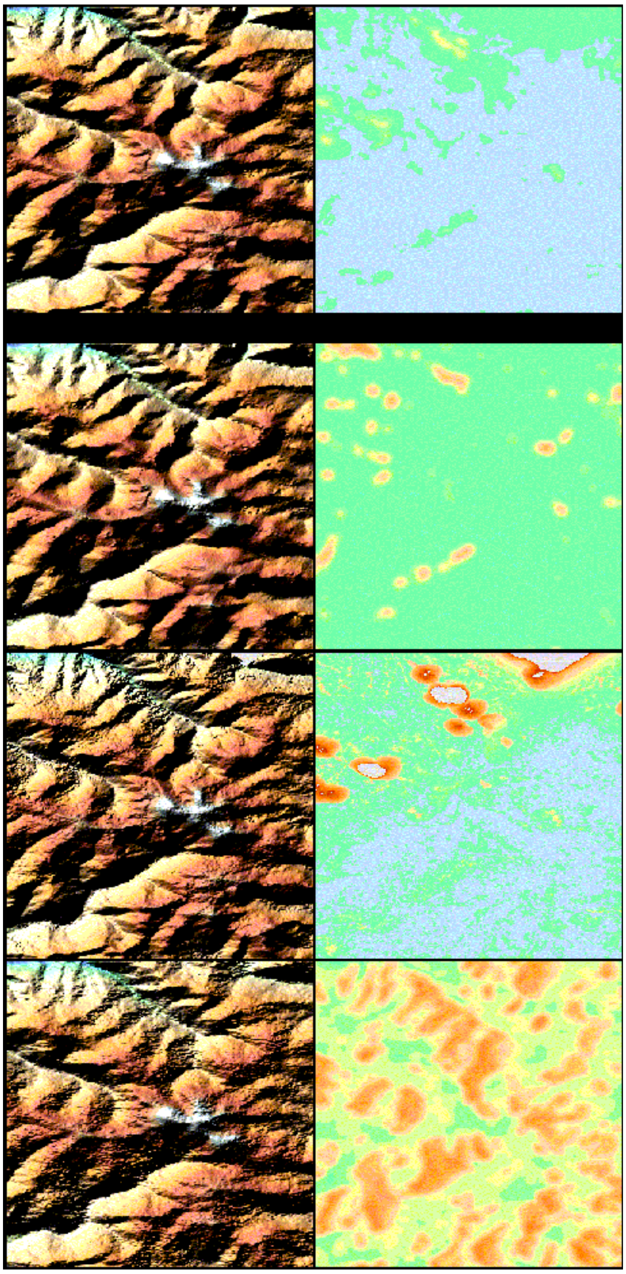

Figure 6. Detail of DEM and height error map
fused data set (top), MOMS-2P, SRTM / X-SAR, ERS-Tandem (bottom)

The DEM-detail in figure 6 demonstrates the quality improvement of the complementary fusion. It covers an area of approximately 10 km x 10 km around the “Feldberg”, the highest mountain of the Black Forest. It is surrounded by steep valleys. The two columns show the elevation model and the corresponding height error map (identical color bar as figure 5) of the fused data set, MOMS-2P, SRTM/X-SAR and ERS tandem.

The height error map of SRTM/X-SAR contains areas affected by radar shadow (brown to white) causing an increase of phase noise and a noisy appearance of the resulting DEM. However those areas were precisely mapped by MOMS-2P and the fusion DEM provides the best quality out of both.

5 CONCLUSIONS

Recent developments at DFD concerning the fusion and mosaicking of digital elevation models resulting from different sources have been described. The results show, that a seamless high quality elevation model is generated and the fusion considerably improves the quality of the DEM product. The tool is operated in the SRTM/X-SAR ground segment for the mosaicking of individual scenes to a large area DEM.
Further developments shall be performed regarding the utilization of the SRTM/X-SAR products as reference for the stereo processing of optical data. It shall be investigated whether tie- and control points can be derived from the X-SAR image.

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