DEM generation from satellite data

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ABSTRACT: Digital Elevation Models (DEMs) are required for several tasks like generation of orthoimages, flood planning, erosion control, agriculture, generation of contour lines, visibility check, 3D-views and others. Mainly in developed countries DEMs are available, but not in any case like required. DEMs can be generated by traditional photogrammetry based on aerial photos if they are available and not classified, but also very often more economic by means of space images. Another possibility is the use of airborne laser scanning – this will lead to very detailed and accurate information, but it is expensive. With Interferometric Synthetic Aperture Radar (InSAR) it is also possible to get the height information.
The achieved accuracy of DEMs based on space images is mainly depending upon the image resolution, the height-to-base-relation and the image contrast. In addition, systematic image errors of photographic products, but also a limited orientation quality may cause a difference between a relative and an absolute accuracy. Photographic data still do play an important role because of the up to now only a limited number of digital stereo pairs and the very often lower price. Following systems have been analyzed: Metric Camera, Large Format Camera, KFA-1000, MK4, KATE-200, TK-350, CORONA, SPOT, MOMS, IRS-1C/1D, ASTER, IKONOS, QuickBird and SRTM.
The manual measurement of DEMs is too time consuming, so most of the data acquisition has to be made by automatic image matching. This includes the disadvantage of a not selected point location. Instead of a DEM, a Digital Surface model (DSM) will be generated, with points located on the visible surface, including vegetation and buildings. The automatic elimination of points not located on the bare ground is possible; corresponding software has been developed and yields to satisfying results.
An analysis of DSMs based on InSAR of the SRTM-X-band showed in open areas a relative accuracy of 3m and an absolute accuracy in the range of 6m to 7m. With C-band data the NIMA reached a similar accuracy with the exception of mountainous areas.

1 INTRODUCTION

A digital elevation model (DEM) is based on a higher number of points with X-, Y- and Z-coordinates describing the bare soil. The DEM may be arranged in a raster or a random form. Instead of the expression DEM also the term digital height model (DHM) is used. The definition of a digital terrain model (DTM) is wider, it includes also the information about the location of objects.

With space and also other data, the DEM will not be determined directly, but points located on top the visible surface like on top of buildings and vegetation. Such a digital surface model (DSM) has to be reduced to a DEM by taking out all points not belonging to the bare soil.

Digital Elevation Models do play a fundamental role in mapping. The digital description of the three-dimensional surface is important for several applications. Today the most often used photogrammetric product are orthoimages generated by means of a single image and a DEM. The very high resolution space sensors are mainly operating in a single image mode; stereo pairs are not taken very often. A correct geo-referencing is only possible based on a DEM. But these DEMs have to be created. The existing and not classified world wide DEMs usually do not have a sufficient accuracy and reliability for more precise applications or they may be to expensive.

The height information can be generated by means of optical images, used in a stereo configuration but also with Interferometric Synthetic Aperture

Radar (InSAR). The optical images are dependent upon a cloud free view and sufficient light conditions, but they do have the advantage of a high resolution. Radar images are independent upon the cloud conditions, only heavy rainfall will cause an effect, but the object recognition is still poor and the geometric situation in mountainous areas is difficult.

Not only optimal results of the DEM generation are shown, also existing problems are explained to cause a realistic expectation.

2 BASIC INFORMATION

For the DEM generation with optical images we do need two or more images showing the same area (figure 1) from different directions. The projection centre has to be known in a specified object coordinate system in addition to the view direction for the correct determination of the ground point. If an orthoimages shall be generated, only one image is required in addition to the DEM (figure 2). If only an average height is available, discrepancies in the horizontal position dl are caused depending upon the discrepancy (figure 3, formula 1). The same relation we do have for discrepancies dh of a DEM.

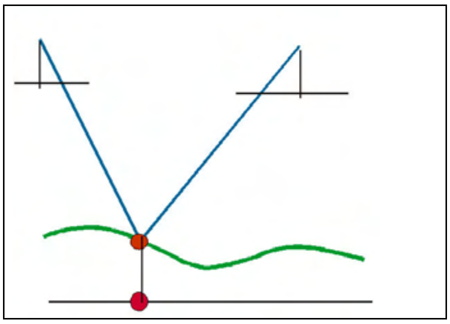

Figure 1. stereo condition of optical images

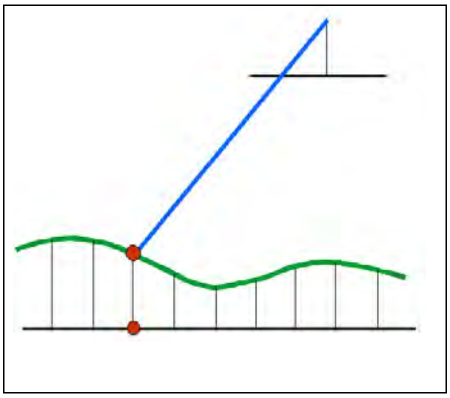

Figure 2. correct geo-location by means of 1 image and a DEM (orthoimage)

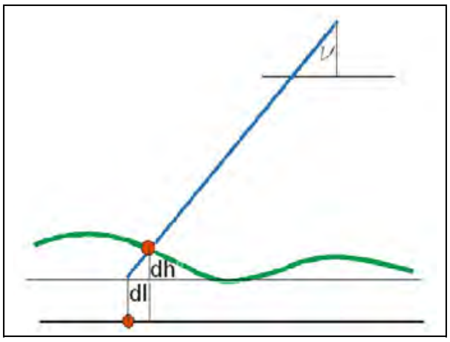

Figure 3. approximate geo-location by means of 1 image and height level of reference plane
Formula 1: position error: dl = dh * tan ν

If a DEM shall be used also for other purposes like a generation of orthoimages, orthographic heights are required which are related to the geoid. Space data are often available in WGS84 ellipsoidal heights which have to be corrected by the geoid undulation. Not in all areas of the world, the geoid undulations are known with a sufficient accuracy, so a local fit to vertical control points, defined with orthographic heights, is required in this case.

The geometric quality of a DEM is described by the accuracy. For the specification of the accuracy international the standard deviation is dominating, it is defined on a probability level of 68%. Especially in the USA also the circular error on the 90% probability level CE90 is used. It has a fixed relation of 2.1 to the standard deviation of the coordinates. Following the accuracy is used as standard deviation.

The accuracy of a height determined by the intersection of two imaging rays is depending upon the accuracy of the x-parallax Spx (px = difference of image coordinates x' – x") and the height to base relation of the imaging configuration.

SZ = image scale number • h / b • Spx
SZ = Spx' [pixel on ground] • a • h / b

Formula 2: vertical accuracy

For digital space images, the second line of formula 2 has to be used where "a" is a multiplication factor which is usually below 1. The accuracy of the x-parallax is depending upon the contrast and is usually below a pixel. The height to base relation is identical to inverse sum of the tangent of the nadir angles (1 / (tan ν_1 + tan ν_2)) in the base direction.

3 OPTICAL SPACE CAMERAS

The earth observation started with photographic cameras used for national security reason. The United States of America have had the Corona project, mainly used in a convergent arrangement creating a stereoscopic coverage in one orbit. The CORONA photos are available now just for a handling fee and still can be used for the generation of DEMs in areas without change of the surface. Most often, the CORONA was operated as KH-4B-version with 20 inch focal length, an image size of 2.2 inch * 30 inch, a ground resolution of 6 ft and a stereo angle of 30°. The Sowjet Union and today Russia is using the very high resolution camera KVR1000 together with the TK350 in the Komet class satellites with up to now more than 163 missions.

Table 1. technical data of Russian photographic space cameras usable for DEM generation

Sensor	KFA1000	MK4	TK350
f [mm]	1000	300	350
image size [mm]	300 x 300	180 x 180	300 x 450
Flying height [km]	220 / 350	220 / 350	220 / 350
covered area	66 / 105	132 / 210	200x300 310x470
ground resolution [m/lp]	5 - 10	10 -15	10 - 15
height-base-ratio	8.2	4.2	1.8

A higher number of digital optical space sensors are available; all these are CCD-line cameras. The main difference is the ground resolution and the view direction. The systems with the view across the orbit do have the disadvantage of a longer time interval between imaging the 2 scenes of a stereo model. The new, very high resolution systems IKONOS (US), QuickBird (US), EROS A (Israel) and TES (India) are equipped with reaction wheels, enabling a very fast change of the satellite orientation. So in the same orbit a stereo coverage is possible in changing the view direction.

Table 2. technical data of digital space sensors usable for DEM generation

	pixel size (nadir)	swath [km]	pointing in-track	pointing across
SPOT 1-4	10 20	60	-	+/-27°
SPOT 5	5 (2.5) 10	60	-	+/-27°
SPOT 5 HRS	5 x 10	120	+20°, -20°	-
MOMS-02 *MOMS-2P*	*5.8* *16.5*	*37* *78*	*-27.2, 0°, 27.2°*	-
IRS-1C IRS-1D	5.8m 23.5 / 70	70 142	-	+/-26°
ADEOS	*8 / 16*	*80*	-	+/-40°
CBERS-1	20	113	--	+/-32°
KOMPSAT	6.6	17	-	+/-45°
Terra ASTER	15 30 / 90	60	0°, 27.2°	-
IKONOS	0.82 –2.0 3.2-8	11.3	free viewing direction	
EROS A	1.8	12.6	free viewing direction	
QuickBird	0.61 2.44	16.4	free viewing direction	
TES	1	12	free viewing direction	

4 GEOMETRIC RELATIONS

Today only Russia is taking perspective photos in unmanned missions. Especially the TK350 used together with the panoramic camera KVR 1000, is important. They can lead to a more economic solution like more expensive line scanner systems. An advantage of the space photos is the high information contents. A TK350 photo corresponds to a size of approximately 31 000 x 64 000 pixels.

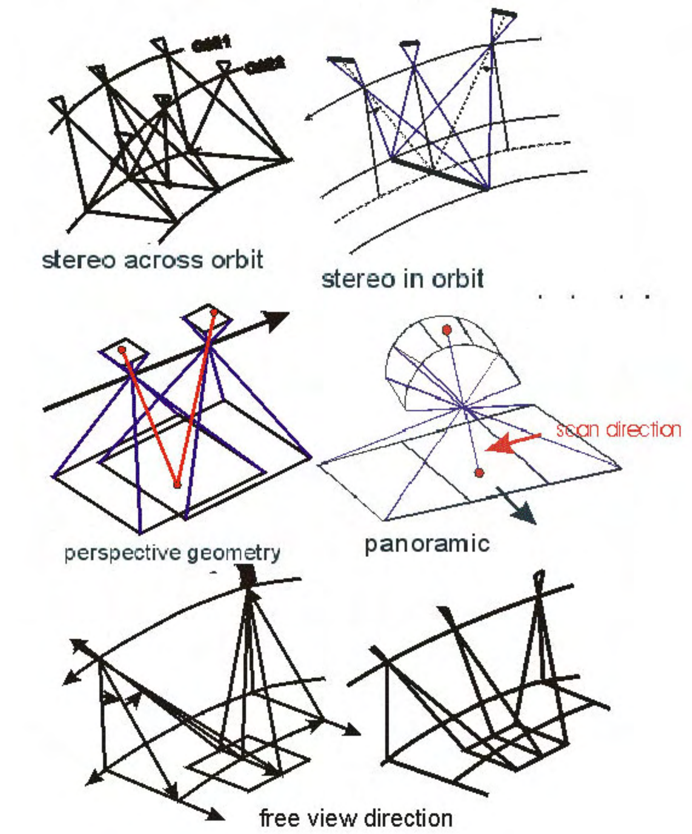

Figure 4. geometric relations of the different space images

The perspective images can be handled with the standard mathematical model used in photogrammetry. But the large format Russian photos often do show some systematic image errors which has to be handled by self calibration with additional parameters.

The handling of the panoramic photos from CORONA and KVR1000 must respect the special geometry. In the Hannover program system BLUH, the image coordinates are transformed to a tangential plane and the S-shaped deformation caused by the movement of the projection centre during imaging is determined by a special additional parameter.

Satellite line scanner images do have a geometric relation different to perspective photos. For each line we do have a different exterior orientation – the projection centre (X0, Y0, Z0) and also the attitude data (phi, omega, kappa) are changing from line to line. But the satellite orbit is very regular, allowing the determination of the relation of neighboured lines and also the whole scene based on the orbit information. In addition the attitude data are usually not changing in relation to the orbit. So the whole scene can be rotated three-dimensional and shifted to fit optimal to imaged control points. This mathematical model is the same for viewing across or in the view direction. The situation is a little different for the new systems with a free view direction. The Indian TES and the Israeli EROS A are not equipped with a transfer and delay integration (TDI) sensor like IKONOS and QuickBird. The TDI is not a single CCD-line, but a matrix where the reflected light intensity is accumulated over several CCD-elements. TES and EROS A do change the view direction during imaging to enlarge the time of imaging (figure 4, lower right).

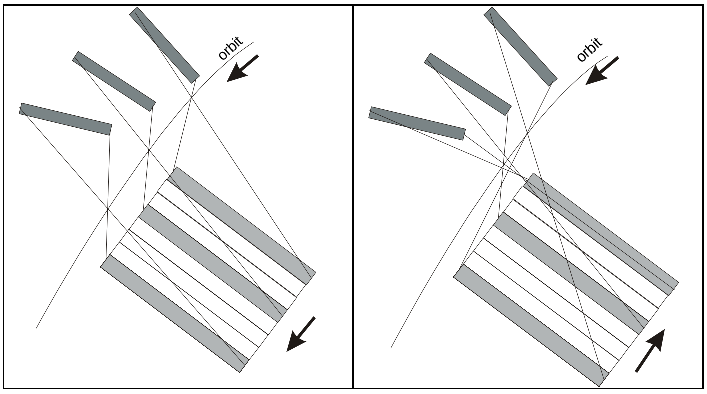

Figure 5. principle of imaging – sensors with flexible view direction
scan direction with orbit   scan direction against orbit

For all sensors with flexible view direction, the CCD-line orientation can be changed like shown in figure 5. A reverse scan direction like shown on the right hand side is also possible. Such a reverse scan will be made if from one orbit also a second scene east or west of the first scene is requested. This has to be respected in the mathematical model, but the influence is still limited because of the very long focal length.

SpaceImaging is not distributing the original images, only derived products are sold. With the CARTERRA “Geo”, “Reference”, “Pro”, “Precision” and “Precision Plus”, IKONOS image products with different geometry are available, reaching from a rectification without control points up to precise orthoimages. Caused by the extreme differences in the price usually only the CARTERRA “Geo” are used and upgraded to orthoimages. The Geo-product is a geo-referenced rectification to a plane with constant height (see figure 3). The geo-reference is based on the direct sensor orientation, using the satellite position and view direction for each line. Without the effect of the relief displacement by the height, the geo-reference is in the range of few meters.

The relation between image and 3D-ground points can be ordered together with the images from SpaceImaging as rational functions. The rational functions do describe the position in the scene (line, sample) as a relation of 2 polynomials depending upon the ground coordinates (see Grodecki 2001). 40 unknowns are used as rational polynomial coefficients (RPC’s) for the latitude and 40 for the longitude, so any type of geometry can be described. The RPC’s have to be calculated based on a strict mathematical model – an adjustment directly based on control points has to be avoided, it would hide errors of control points and it would have only a sufficient accuracy within the volume of the control points. The RPC's are determined by the direct sensor orientation of the IKONOS satellite. This has an accuracy of few meters on the ground and has to be improved by means of control points.

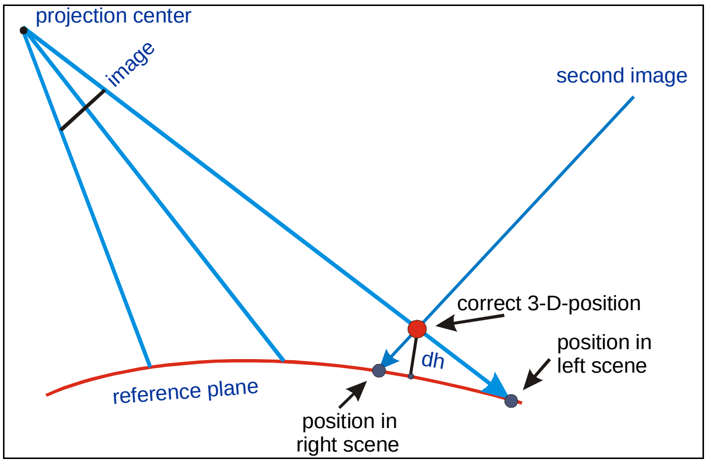

Figure 6. geometric relation between IKONOS Geo-images and the three-dimensional location of the imaged points

The handling of IKONOS-Geo-images with RPCs was leading to the same accuracy like a solution just based on the view direction, which is listed in the metadata-file together with some general orbit information. In few cases quite better results could be achieved with an additional adjustment of the view direction (Jacobsen, Passini 2003).

The computation of ground coordinates based on IKONOS Geo-images has to respect the geometric conditions of the Geo-scene (see figure 6).

Opposite to IKONOS, for QuickBird the so called "Basic Imagery" is available which is close to the original sensor image. The Basic Imagery is a sensor corrected merged image taken by the individual CCD-lines. It corresponds to the geometry taken by a unique CCD-line with 27552 elements without geometric distortion. The ephemeris and attitude data are delivered together with the images. Also other products like the "Standard Imagery", having a geometry similar to the CARTERRA Geo, are available. The Basic Imagery can be handled like standard satellite line scanner images.

5 RESULTS OF IMAGE ORIENTATION

The results of image orientations based on the different mathematical models and verified by independent check points are leading to information about the possible accuracy of ground points determined by a model of space images. This is usually to optimistic because only well defined points are used as control and check points, but it is showing the accuracy limit achievable under optimal conditions if the contrast of the reference points is very good.

Table 3. accuracy at check points achieved with space photos

	Sx'/y' [µm]	Spx [µm]	SX/Y [m]	SZ [m]
MC	10	10	8	20
LFC	9	8	7	9
KATE 200	21	19	30	39
MK4	25	15	22	29
KFA 1000	20	19	7	32
TK 350	12	12	8	15
CORONA	13	13	(4.3)	(7.8)

The image geometry of the photographic cameras KFA 1000, MK4 and KATE 200 is not very stable. Larger systematic errors with values up to 85µm have been seen. They only can be identified by means of self calibration with additional parameters based on control points. The systematic image errors are different from case to case and cannot be neglected. In a typical case of a KFA 1000-model (1m focal length, 30cm x 30cm image format, image scale 1:270 000, height to base relation 8.0), without self calibration based on 190 control points a sigma0 of 32µm, a horizontal accuracy of 15.1m and a vertical accuracy of 70.6m has been reached, with self calibration the sigma0 was reduced to 20µm and the accuracy in X and Y to 7.1m and for Z to 32m.

The accuracy in the image Sx'/y' and also the standard deviation of the x-parallax (Spx) reflects the geometric problems of some of the Russian space photos. The results achieved with the German Metric Camera (MC), the US Large Format Camera (LFC), the Russian TK350 and the US CORONA are clearly better and do correspond to the expectations. Based on this, the vertical accuracy SZ can be estimated with formula 2.

Table 4. accuracy achieved with satellite line scanner images * (Soo Jeong et al, 2001)

	SX/Y [m]	SZ [m]	Sx'/y' [pixel]	Spx [pixel]
SPOT H	4.6	13.4	0.5	0.5
SPOT G	8.4	4.1	0.8	0.4
IRS-1C	5.1	8.7	0.9	1.5
IKONOS	1.0	1.7	1.0	0.2
ASTER	10.8	14.6	0.7	0.5
QuickBird	1.0	5.1	1.6	0.7
KOMPSAT *	3.5	6.8	0.5	

The standard deviation of the image position Sx'/y' in digital images is in the range of one pixel or better. The larger values for QuickBird and IKONOS are caused by the control point accuracy and definition; with more precise control points, the results could be better. This is obvious at the accuracy of the x-parallax, which by simple theory should be larger than Sx'/y' by the factor of $\sqrt{2}$, but this is not the case, showing the better internal accuracy. Only the results achieved with a full IRS-1C-scene are a little larger, caused by the problem of fitting the individual CCD-lines together.

The listed vertical accuracy values SZ cannot be compared directly because they are dependent upon the intersection angle of the imaging rays (height to base relation) shown also at the example of the both results achieved with SPOT – in the case SPOT H, the height to base relation is 3.2, in the case of SPOT G it is 1.0. The shown accuracy of the x-parallax can be used in formula 2 for the estimation of the possible height accuracy under different conditions.

6 AUTOMATIC IMAGE MATCHING

The manual generation of a DEM by a human operator is extremely time consuming, by this reason it will be done usually by automatic image matching. The corresponding image positions of ground points have to be determined. The used methods of matching can be differentiated by the way in generating the approximate positions of corresponding points and the type of final matching. A higher number of programs are based on image pyramids – for the reduction of the problem of initial relation of one image to the other and in relation to the three-dimensional ground. The images are reduced in the size step by step and after getting the relations of the corresponding images in the highest pyramid level with the most reduced image pair, it will be improved step by step to the pyramid level with higher resolution. The initial relation may be feature or area based. In the case of feature based matching, well-defined corners are identified by different mathematical operators and the pattern of corresponding points in both images is compared. In general the identification of corresponding points (= homologue points) can be simplified if the exterior orientation and the image geometry is known. Corresponding image points are located together with the ground point on an epipolar plane, intersecting the images with the epipolar lines. So the homologue points only have to be searched on the epipolar lines. The region growing method is operating totally independent upon information about the exterior orientation and the image geometry. Starting from few corresponding points, which may come from the data acquisition for bundle adjustment, directly in the original images neighbored points are identified in any direction and starting from these again in any direction.

Based on the approximate position, the position of the homologue points may be identified by the correlation coefficient, an expression for the correspondence of small image matrixes in both images. A reference matrix of one image will be compared with a little larger search matrix of the other. For all possible combinations of the reference matrix with the search matrix, the correlation coefficient will be computed. If there is a clear maximum with a correlation coefficient exceeding a chosen threshold, this corresponds to the position of homologue points. The difference in size between reference and search matrix must be sufficient for fitting discrepancies of the approximate positions, but not too large to avoid a second maximum in the case of repeating objects. The correlation coefficient is the relation of the covariance to the standard deviation of the grey values of both images in the sub-matrixes; that means it is independent upon the level and range of the grey values – so a preceding change of the contrast and level of the grey values has no influence. The correlation coefficient is comparing sub-matrixes of the same size, this is only correct for images in the normal case and a horizontal area (figure 7 left). It is only an approximation if the ground is tilted (figure 7 right and figure 8). This problem can be solved by least squares matching, taking care about a tilt by an affinity transformation of one sub-matrix to the other and respecting a linear change of the gray values. The least squares matching has only a small radius of convergence, by this reason usually a preceding image correlation will be calculated.

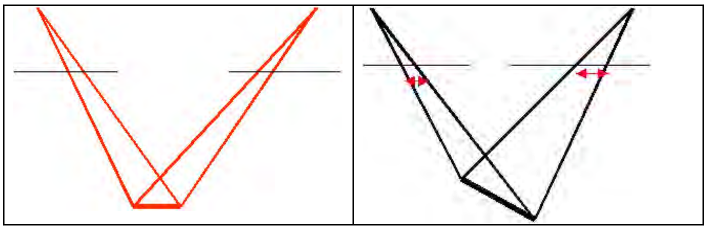

Figure 7. left: normal case, horizontal ground
right: inclined ground – different size in image

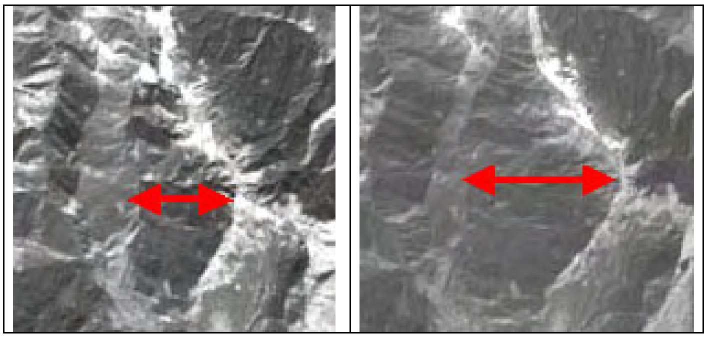

Figure 8. corresponding sub-images of IRS-1C in the Himalayan, the arrows are showing corresponding image points – same image scale in vertical direction

Similar functions like for the automatic image matching are used for the automatic aerial triangulation, but it is more dominated by feature extraction.

The automatic image matching has reached a high level of accuracy for the matched ground points; it corresponds to the accuracy of a human operator. The problem are the selected points. A human operator, measuring a grid of height points, is setting down the floating mark to the ground, even if the floating mark will be on top of a building. An automatic image matching will generate not a DEM; it will generate a digital surface model (DSM) with points located on top of the visual objects. A similar problem we do have with laser scanning and INSAR.

All methods of automatic image matching are depending upon corresponding, but not necessary identical grey value pattern in the conjugate image areas. Problems are caused by homogenous areas or repeating features. Especially in forest areas the contrast may be limited, causing problems of the matching. In snow covered parts a matching is not possible. Difficulties do exist with steep mountains – the view from one side may be quite different like the view from the other side.

7 DEM GENERATION

7.1 *SPOT*

For the generation of digital elevation models since longer time SPOT images have been used. The reached accuracy is depending upon the height to base ratio - the angle between the intersecting rays. Because of the not fixed view direction across the orbit, the base to height relation can reach the value 1.0. The simple theory of a linear dependence upon the height to base relation is justified if the matching accuracy in the image is independent upon the angle between the intersecting rays, but the matching is more precise for smaller parallax angles, where the image parts are more similar like for larger parallax angles with larger differences in the image parts. The optimal base to height relation is depending upon the area itself – for an open and flat area the relation 1.0 is optimal, for more undulated areas with buildings and vegetation the factor 1.6 may lead to better results (Börner et al 1997).

SPOT is viewing across the orbit. It takes at least few days for imaging the same area from a different orbit. If the weather conditions do not allow the imaging, the time interval may be larger. If the object is changing meanwhile, an image matching may be degraded or even impossible. In an example in the area of Hannover where the images of a model have been taken in June and August, even a human operator could not get a stereoscopic impression because of the complete change of the grey values in the agriculture area where the wheat was changing the colour from green to yellow. This is a general problem for all sensors viewing just across the orbit. If the object is not changing between the imaging periods, a vertical accuracy of 5 to 10m is possible in open and more flat areas with a sufficient height to base relation.

SPOT Image has respected the problem of time delay with the HRS-sensor at SPOT 5. The HRS-sensor is looking forward and backward, generating a stereo overlap in the orbit with a height to base relation of 1.2 with a pixel size in the orbit direction of 5m. SPOT Image is not distributing these images, only the matched results are sold.

7.2 *MOMS*

The MOMS-sensor was viewing forward, to the nadir and backward, so a DEM generation is possible with images taken with just few seconds time interval. The 3 view directions can be used together for a common intersection, improving not only the accuracy but also the reliability.

Table 4. Z-accuracy by matching of MOMS-images

	SZ	Spx
Urban area	7.9 m	0.36 pixel
Water	8.6 m	0.39 pixel
Open areas	10.1 m	0.46 pixel
forest	17.2 m	0.79 pixel

Kornus and Lehner (1999) have reached by automatic matching of MOMS-images in relation a reference of the German survey administration the vertical accuracy listed in table 4.

7.3 *IRS-1C / 1D*

The general configuration of IRS-1C / 1D is corresponding to SPOT, including the same problem of time delay in taking corresponding images. Because of satellite energy problems, not so many stereo models have been taken. The smaller pixel size on the ground has an accuracy advantage; on the other hand the radiometric quality is limited by the 6 bit grey values. Under optimal conditions a vertical accuracy of 7m is possible.

In the Himalaya the image matching has been analysed, showing the possibilities and limitations.

The very steep slopes are changing the image dimension in the view direction like visible in figure 8. In the higher regions snow fall between both imaging periods has changed the object – here no image matching was possible. Also in the dark forest areas the image matching failed caused by the limited grey value range of the panchromatic IRS-1C of only 6 bit. With just 64 different grey values the radiometric range from the snow to the dark forest cannot be expressed.

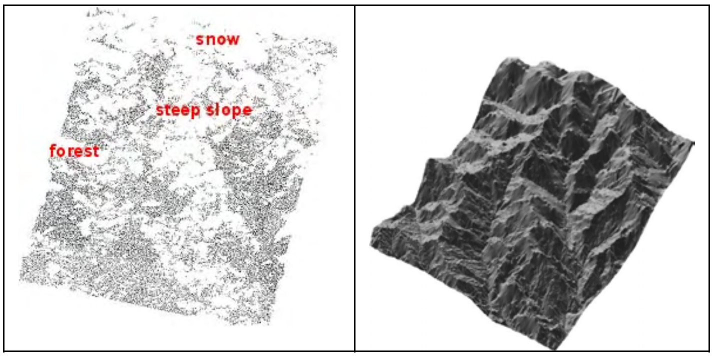

Figure 9. results of image matching with IRS-1C in the Himalayas, left: matched points, right: 3D-view of the generated DEM

7.4 *ASTER*

Like MOMS and SPOT HRS, Terra ASTER is generating the stereo model by a nadir and a backward view within a minute. The height to base relation of 2.0 simplifies the automatic image matching. The negligible time delay of imaging both scenes enables also an automatic image matching in forest areas. ASTER images are available in the Internet just for a handling fee.

An overview of matched points in the area of Zonguldak, Turkey (figure 10) shows only few gaps at locations of small clouds, lakes and slopes with forest in the shadow.

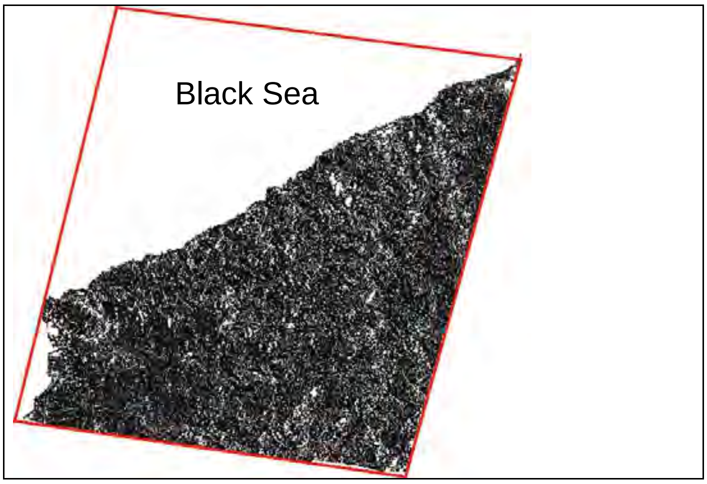

Figure 10. matched points of an ASTER model – mountainous area in Turkey with high percentage of forest, upper left = Black Sea

Between the control points and the ASTER-DEM a mean square height difference of just +/-6.6m corresponding to a standard deviation of the x-parallax of +/-0.22 pixel has been reached. This is not representative for the whole DEM because the control points are located only at positions with optimal image contrast. The achieved DEM has been compared with the Turkish DEM for the map scale 1:25000 which shall have an accuracy of approximately SZ=+/-5m. Approximately 50% of the mountainous area is covered by forest, by this reason the open area and the forest have been analysed separately. In the forest area a bias of 4.5m can be explained by the influence of the vegetation. In both parts a clear linear dependency of the discrepancy upon the terrain slope can be seen, so the accuracy has to be expressed as a function of the terrain inclination.

Table 5. accuracy of ASTER-DEM

Open area	SZ = 21.7m + 14.4•tanα
Forest	SZ = 27,6m + 17.5•tanα

In the average the vertical accuracy corresponds to a standard deviation of the x-parallax of 0.8 up to 1.0 pixel.

7.5 *TK350*

The Russian space film camera TK350 has imaged large parts of the world. The foot print of 200km times 300km offers an economic generation of a DEM over a large area. In the same area like the ASTER-data, a DEM has been generated by TK350-photos.

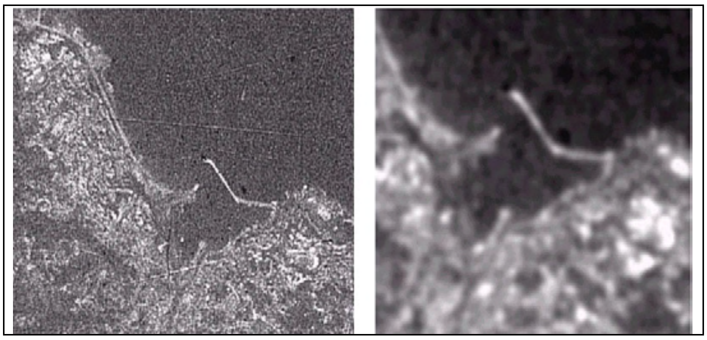

Figure 11. left: sub-area of original TK350-image
right: filtered sub-area of TK350-image

The TK350-photos have been scanned with a pixel size of 16µm. But even with this not very small pixel size the film grain is clearly visible. In addition the film contains several scratches. Without scratch removal and low pass filter the automatic image matching failed, but also after filtering problems occurred in the forest area. Larger parts could not be matched and several points have been removed because of exceeding a height difference of 150m.

Table 6. accuracy of TK350-DEM

Open area	SZ = 20.0m + 23.9•tanα
Forest	SZ = 53.9m + 11.4•tanα

In the open area approximately the same accuracy like with the ASTER-data has been reached, but the achieved results in the forest area cannot be accepted. The quite different results between the ASTER- and the TK350-data in the forest can be explained by the different spectral range. The stereo combination of ASTER is using the near infrared band with the advantage of a good contrast of the vegetation, while the TK350 is using panchromatic photos with limited contrast especially in the forest area.

7.6 *IKONOS*

Only few stereo scenes are taken by IKONOS. Corresponding to SpaceImaging the generation of stereo models is a "waste of capacity", nevertheless stereo models can be ordered. The flexible viewing of IKONOS enables also a stereo view with a base length of just 90km or 12 seconds time difference. The automatic matching of an IKONOS stereo model taken in the same orbit has not caused any problem. Even with the poor height to base relation of 7.5 an accuracy of building heights of SZ=+/-1.7m, corresponding to an accuracy of the x-parallax of just Spx=+/-0.2 pixel has been reached.

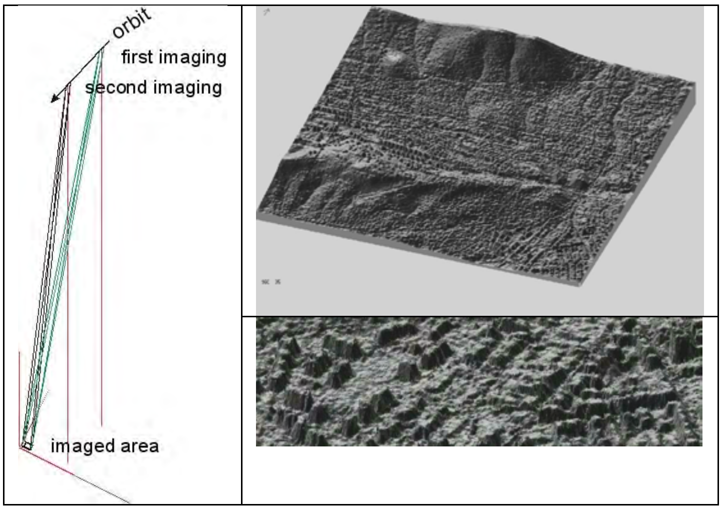

Figure 12. left: configuration of IKONOS stereo model right: generated DEM – lower part: detail in city area showing buildings in the DEM

Different results have been achieved with a combination of 2 scenes, one taken in July and the other in October. The change in the area, mainly caused by a quite different illumination, together with the very high resolution has caused large problems of the automatic image matching. Without smoothing of the images by a Gauss-filter the matching did not work. After this it was possible to match in the build up and open areas. In the forest areas the matching was limited (see figure 13). The matched points do have an accuracy of just +/-5.8m, corresponding to a standard deviation of the x-parallax of Spx=+/-1.5 pixel. The y-parallax of the matching has reached Spy=+/-2.2 pixel and 25% of the matched points have not been accepted.

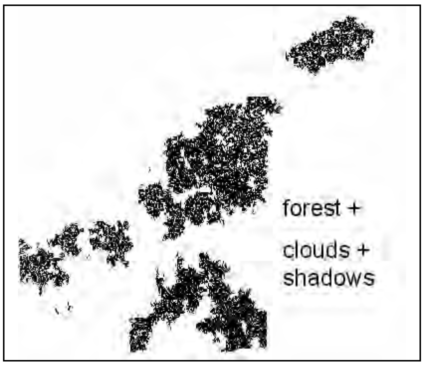

Figure 13. IKONOS DEM - matched points
same area like centre part of figure 9
1st image: July
2nd image: October
~ 33% of points matched

7.7 *QUICKBIRD*

QuickBird images are available as Basic imagery with a geometry similar to SPOT level 1A and as Standard imagery similar to IKONOS Geo. With the appropriate software both types can be handled. Two overlapping QuickBird images taken with 2 weeks time difference and a height to base relation of 1.6 have been matched. No larger changes at the vegetation could be seen and so no problems with the automated image matching appeared. Approximately 80% of the points have been matched successful. This is a satisfying result; the not matched points are located mainly at uniform areas like roads with the same grey value.

The accuracy of the y-parallax of the matched points is in the range of the orientation accuracy of 1m, dominated by the limited accuracy of the control points. As mean square Z-difference between the QuickBird-data and the not error free reference DEM of the USGS +/-4.8m, corresponding to spx=0.8 pixel has been reached.

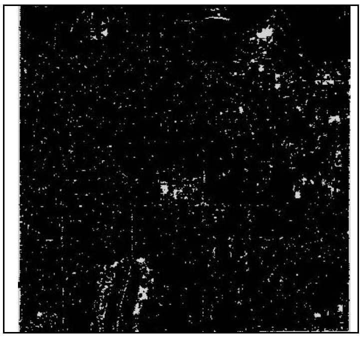

Figure 14. QuickBird model:
dark = matched points, bright = not matched

7.8 *CORONA*

The images taken by the former US spy satellites of the CORONA system have been released and are available just for a handling fee. Most often the KH-4B has been used. It has a combination of a forward and a backward looking panoramic film camera, creating a stereoscopic model with a height to base relation of 1.8. Of course these 30 to 40 year old images do not show the actual topographic features, but usually the ground surface is not changing, so the images can be used for the DEM generation. In areas of strong erosion, the old images can be used as reference for the changes (Schneider et al 2001).

The ground resolution of approximately 3m can lead to a relative vertical accuracy of +/-2m to +/-5m. The automatic image matching is usually without problems if the area is not to uniform, but the correct mathematical model has to be used for the solution of the panoramic images.

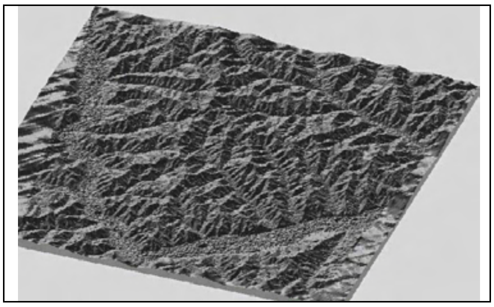

Figure 15. DEM generated by means of CORONA KH-4B - Loess Plateau China

7.9 *OTHER SPACE IMAGES*

The other Russian space images like KFA 1000, MK4 and KATE 200 or the old German Metric Camera do not play an important role for the DEM generation. The achievable accuracy is limited because of the small image scale or poor height to base relation.

With the US LFC-images reasonable results have been achieved, but only few images are available.

8 INTERFEROMETRIC SAR

Optical Images are depending upon a cloud free view and a sufficient clear atmosphere. In addition the sun angle should not be below approximately 25° to avoid long shadows. These conditions are not required for Radar images. A sufficient ground resolution is only possible by the method of Synthetic Aperture RADAR (SAR). The SAR is imaging the same ground point from different positions in the orbit. By means of the Doppler method the mixed signals can be separated and averaged corresponding to the signal from a theoretically very long antenna.

The identification of objects in SAR images like ERS, JERS, Radarsat or Envisat cannot be compared with the information contents of an optical image with the same pixel size. In addition to the general difficulty of object identification, a SAR-image is quite depending upon the view direction and we do have the geometric problems of foreshortening, layover and shadows in mountains. By these reasons SAR-images are only used for mapping in areas with more or less permanent cloud coverage and for special topics like determination of flooded areas. This situation may change with the very high resolution SAR-images like from TerraSAR-X and SAR-X Cosmo Skymed which shall be launched in 2005 and shall have a pixel size of 1m. Nevertheless also this pixel size should not be compared with a 1m-pixel-size from an optical sensor. The main advantage of SAR is more located in the generation of DEMs by interferometric SAR (INSAR).

Based on one active and 2 passive SAR-antennas digital elevation models can be generated by an interferometric method. This was done at first with the ERS-tandem mission. Very good conditions for INSAR have been given by the Shuttle Radar Topographic Mission (SRTM) in February 2000. During this mission a second passive antenna was available just beside the Space Shuttle.

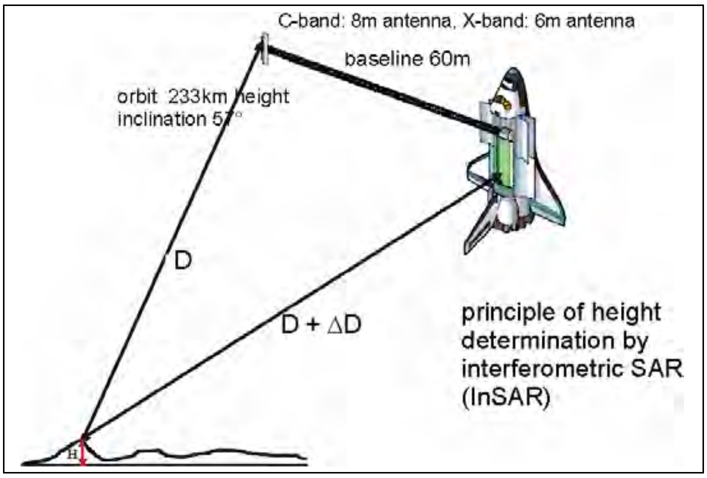

Figure 16. principle of INSAR during the SRTM-mission

Two different Radar-systems have been used – the X-band, organised by the German Aerospace Centre DLR together with Italy and the C-band organised by the NASA. The X-band is not covering the whole area, while the C-band, used in the scan-SAR-mode, has imaged the world from 58° south to 60° north. An analysis of some DEMs determined by the SRTM X-SAR resulted in mean square differences of +/-9.1m. This is larger than expected. A detailed analysis is showing the reason (Koch et al 2002).

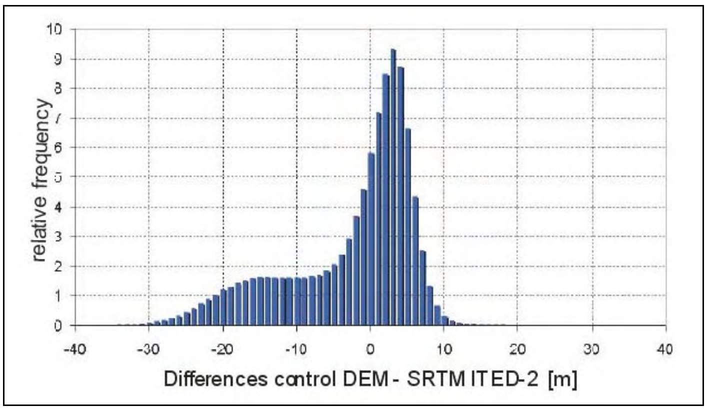

Figure 15. frequency distribution of the discrepancies in a SRTM X-band DEM

The frequency distribution of the differences between a SRTM X-band DEM and the German DEM-5, which has been used as reference, is showing an extension to the negative part. Especially with the X-band not the height of the bare ground will be determined, but the height of the visible surface – X-band Radar cannot penetrate the vegetation, while the longer C-band can penetrate at least partially. The cross-section through the DEM generated by the X-band (figure 16) demonstrates the problem – in open areas there is a height shift of –2.7m of the X-band-DEM. This can be explained by the limited orientation accuracy. In addition in the forest area the height values are clearly on top of the vegetation. If the shift of -2.7m in the open areas is respected, the root mean square is reduced to +/-3.4m. Such a correction is possible with control points.

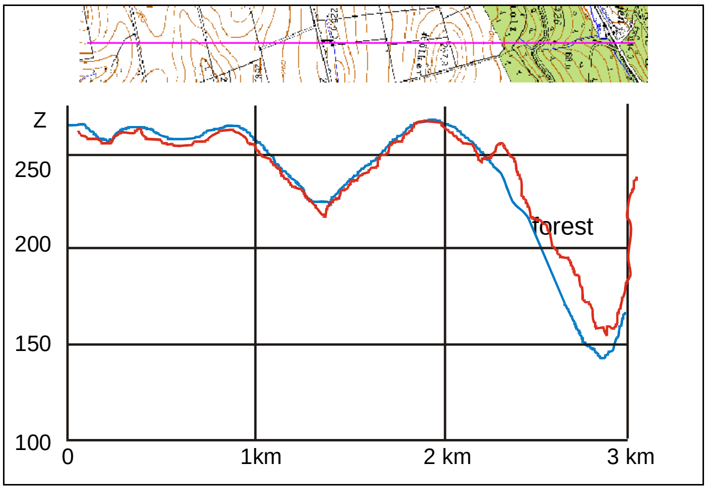

Figure 16. height profile through a DEM generated by SRTM-X-band and a corresponding DEM of the survey administration – upper part: topographic map

The NIMA has investigated the SRTM C-band in some test areas (Salamonowicz 2003). Caused by the good coverage by the C-band data most areas have been covered more than once and the final C-band DEM is based on averaged data.

Table 6. results achieved with SRTM C-band DEM (Salamonowicz 2003)

area	Elevation [m]	vegetation	bias [m]	SZ [m]
Guatemala	408 - 2432	heavy	-1.7	12.1
Venezuela	118 - 229	moderate	0.0	2.5
Stennis	0 – 52	heavy	0.5	2.6
Red River	252 – 293	light	2.6	1.5
San Diego	70 – 478	light	1.4	3.5
Panama	502 – 2153	heavy	-3.1	25.2
White Sands	1355 - 2066	scrub	2.4	3.2
Nevada TR	1433 - 1813	scrub	-1.5	3.1

In most of the test areas quite better results than estimated a priori have been achieved. The systematic differences are in the same range like with the X-band data and describe the accuracy of the absolute orientation which is changing from area to area, but it can be determined and respected by a group of control points. Not so good results are shown in the very mountainous areas Guatemala and Panama, so in similar areas also a reduced accuracy should be expected. It is not very clear in which extend the C-band is penetrating dense forest, some effects may be based on this, but it cannot be seen at the bias.

INSAR can be based also on the SAR satellites. Especially the tandem mission of ERS 1 and ERS 2 has been used for this.

9 DIFFERENTIAL INSAR

Changes of the digital elevation model can be determined very precise by differential interferometric synthetic aperture radar (DINSAR). The interferometric overlay of two INSAR data sets is leading to information about changes of the height with an accuracy of few millimetres if all required corrections have been handled in the correct manner. Very good results have been achieved in areas with limited vegetation shown in figure 17.

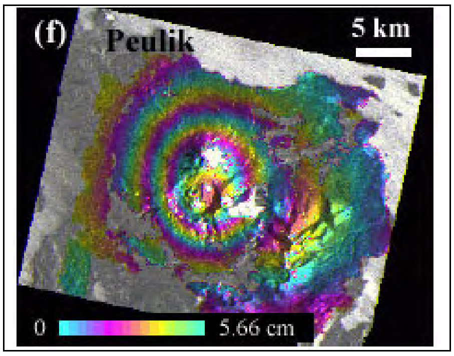

Figure 17. height changes of a volcano (Zhong et al 2002) determined by DINSAR based on ERS 1 and ERS 2

The very clear fringes do have a period of 5.66cm, so height changes of few millimetres can be detected. Quite more difficult is the application in areas covered by vegetation. The change of the vegetation from one imaging period to the other is causing a lot of noise.

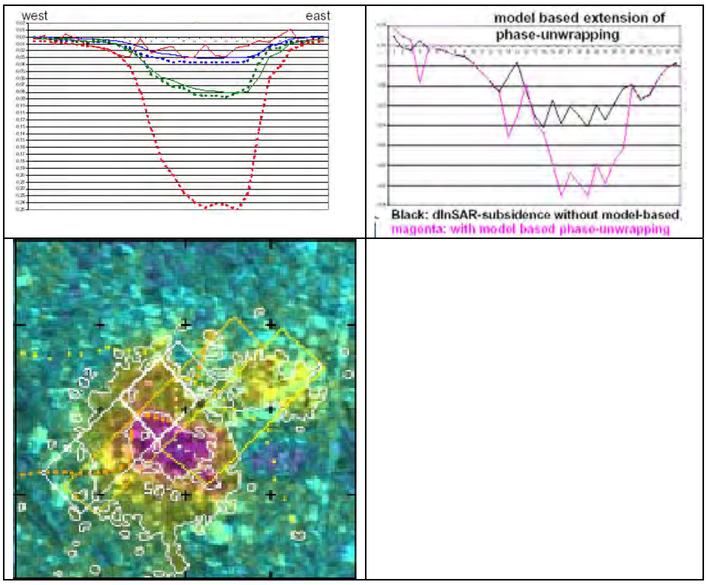

Figure 18. subsidence in coal mining area determined by DINSAR (Spreckels et al 2001)
upper left: lower red line = reference cross section upper right: cross section by DINSAR   left: interferogram

As shown in figure 18, the unwrapping of the fringes is very difficult in a German coal mining area with a dense vegetation. The upper right profile in figure 18 is demonstrating the problem of unwrapping the fringes – the individual fringes are disturbed by noise, causing errors with a multiple size of the period.

10 AUTOMATIC FILTERING OF DEMS

In general the result achieved by automatic image matching as well as INSAR is not a DEM with the height of the ground, it is a digital surface model (DSM) on top of the visible objects, including buildings and trees; in addition some mismatches cannot be avoided. The quality of the unfiltered result requires usually an improvement by outliers as well as the effects of buildings and trees. A simple filter should not be used for this, because it goes to the average height and not to the ground. The Hannover program RASCOR can improve a DSM based on a serious of tests. The following methods are combined: check for minimal and maximal height, height difference of a point in relation to the neighbored points in X- and Y-direction, linear or polynomial regression in X- and Y-direction, height difference against a moving rotated plane or polynomial surface and height difference against the surface of a prediction. The linear or polynomial regression and also the rotated plane or polynomial surfaces are combined with data snooping – it is necessary to use the redundancy numbers for isolated points. In addition for the identification of buildings, especially for LIDAR-data, sudden changes of the heights and in the same profile back changes are used. This function has usually no effect for automatic image matching, because such data usually do not show the buildings with a sudden height change, usually they are shown like small hills but not in a case like the small scale MOMS-images, where the Nyquist frequency does not allow the identification of single buildings in a DSM.

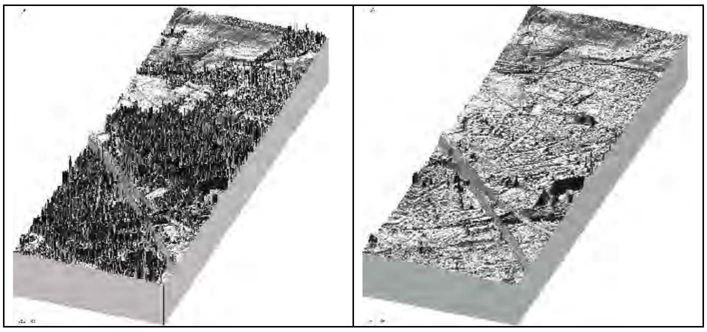

Figure 19. left: original DSM   right: DSM filtered by program RASCOR to a DEM

The settings of the required parameters are determined by an analysis of the data by the program. The program user only has to specify the main character of the area like smooth, undulated or very undulated and homogeneous or different. In addition usually a second iteration with the whole sequence of the tests should be used - the program is using automatically lower tolerance limits in the second iteration. After this, a smoothing of the results is possible by a local polynomial surface or tilted plane. Usually between 20 and 50% of the points are rejected. The advantage of such a filtering will not be seen only at the improved accuracy of the DEM, also the generated contour lines are much clearer like shown in figures 20 and 21.

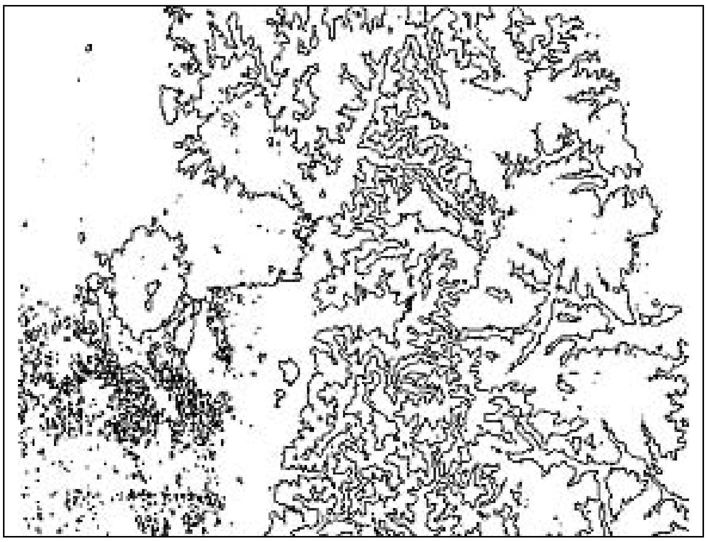

Figure 20. contour lines of a DEM determined by automatic matching of MOMS-images

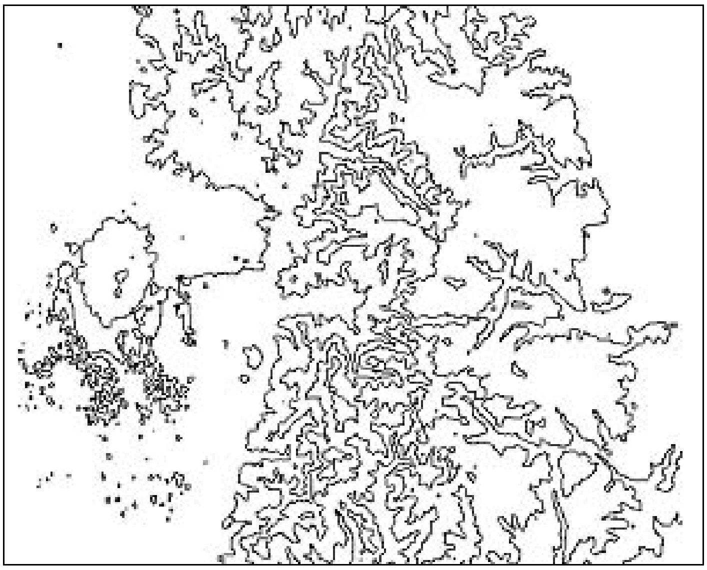

Figure 21. contour lines of the DEM after filtering with program RASCOR

CONCLUSION

With the raising number of high and very high resolution imaging satellites, with improved configurations and also by interferometric SAR, digital elevation models can be generated in any location with accuracy and with details which was not possible few years ago. For reaching satisfying results, images taken within the same orbit should be preferred. The generated digital surface models have to be reduced to digital elevation models. This can be without operator interaction by software. The highly automated processes are the base for the economic creation of orthoimages and line maps required for the optimal planning of resources, enabling a sustainable development especially in developing countries. But the now possible accuracy and details of the DEMs do optimise also the situation in developed countries.

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