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USE OF VERY HIGH RESOLUTION SATELLITE IMAGERY

1. Introduction

Satellite imagery is available for civilian applications since the launch of the first Landsat satellite, named at first ERTS, in 1972. The main application of this type of satellites has been the classification of the imaged objects, so a good spectral, but not a high geometric resolution was required. With SPOT 1, launched in 1986, the first civilian satellite for mapping purposes was designed. In the following only the civilian systems usable for mapping purposed are taken into account. The specification "very high resolution" is not fixed and it is used with different values. I will not use it not for the spectral resolution but only for the geometric resolution, that means the ground pixel size or more exact, the distance of the centres of projected neighboured pixels, the ground sampling distance (GSD). Only the systems usable for mapping applications are respected. Because of the development also SPOT will be included even if it is belonging to the high, but not to the very high resolution systems.

2. Imaging satellites

The imaging satellites can be classified into satellites for global information like weather satellites delivering information at least once per day with a very course resolution. The next group are the land satellites with the main purpose of classification, they do have a high spectral, but only a limited geometric resolution. The satellites for mapping applications do have a high up to very high geometric resolution, a limited spectral resolution up to only panchromatic and they do have the possibility of generating stereoscopic image pairs by changing the view direction or by a combination of different fixed view directions. The mapping sensors do have usually a lower resolution for the multispectral bands in relation to the panchromatic band, requiring a pan-sharpening for the generation of colour images with the full resolution. This is sufficient because of the use for interpretation by a human operator. The human eye is not so sensitive for the colour information like for the grey values – there are more rods, sensible for the grey values, like cones, sensible for the colour information, in the human eyes. The used expression panchromatic is usually not precise – by the definition it describes the spectral range visible by the human eye, but the satellite sensors usually do include also the near infrared.

For a GSD below 5m the available imaging time below 0.7ms is not sufficient for the generation of an acceptable image quality if the sensor has a fixed orientation against the orbit. Some sensors like IKONOS, QuickBird and OrbView are equipped with time delay and integration sensors (TDI); they do have not only one CCD-line but a small array. The generated charge in the first CCD-elements is shifted with the speed of the image motion to the next CCD-elements and so the energy can be accumulated generating a sufficient quality. The other satellites like EROS A and TES do extend the imaging time by a permanent rotation of the satellite, so they are imaging the scene over a longer orbit path. This is generating a sufficient image quality, but it is reducing the capacity.

The MOMS and also the additional HRS-sensor at SPOT 5 do have more than one view direction in the orbit direction, generating a stereoscopic coverage with a short time interval. This will be the case also for the announced CARTOSAT-1 and ALOS. The sensors viewing only across the orbit do have the disadvantage of a larger time interval for the generation of a stereo pair from different paths.

Table 1

Successful launched imaging satellites

	launch	country	GSD pan	GSD [m]	swath	view direction
SPOT 1	1986	France	10 m	20 m	60 km	across
SPOT 2	1990	France	10 m	20 m	60 km	across
SPOT 3	1993	France	10 m	20 m	60 km	across
MOMS 02	1993	Germany	4.5 m	13.5 m	80 km	3 x orbit
IRS-1C	1995	India	5.8 m	23.5 m	70 km	across
MOMS-2P	1996	Germany	6 m	18 m	105 km	3 x orbit
ADEOS	1996	Japan	8 m	16 m	80 km	nadir
IRS-1D	1997	India	5.8 m	23.5 m	70 km	across
SPOT 4	1998	France	10 m	20 m	60 km	across
IKONOS 2	1999	USA	0.8 m	2.4 m	11 km	free
KITSAT 3	1999	S. Korea	15 m	15 m	50 km	-
UoSAT 12	1999	UK	10 m	30 m	10 km	-
Kompsat 1	1999	S. Korea	6.6 m	-	17 km	across
EROS A1	2001	Israel	1.8 m	-	12.6 km	free
QuickBird	2001	USA	0.6 m	2.4 m	16.8 km	free
TES	2001	India	1 m	-	8 km	free
SPOT 5	2002	France	5 (2.5) m	10 m	60 km	across
OrbView 3	2003	USA	1 m	4 m	8 km	free
Resourcesat	2003	India	5.8 m	5.8 m	70 km	across
BilSat	2003	Turkey	12 m	28 m	12 km	free
ROCSat	2004	RO China	2 m	4 m	24 km	free

Table 2

Announced imaging satellites

	launch	country	GSD pan	GSD ms	swath	view direction
Cartosat 1	2004	India	1 m	2.5 m	27 km	2 x orbit
Kompsat 2	2004	S. Korea	1 m	4 m	15 km	free
Topsat	2004	UK	2.5 m	5 m	15 km	free
ALOS	2005	Japan	2.5 m	10 m	70 km	3 x orbit
Resurs DK2	2005	Russia	1 m			
Cartosat 2	2005	India	0.8m	-	9.6 km	free
RazakSat	2005	Malaysia	2.5 m	5 m		free
China DMC+4	2005	PR China	4 m	32 m		free
EROS B	2006	Israel	0.7 m	-	7 km	free
WorldView	2006	USA	0.5 m	2 m	16.8 km	free
IKONOS Bl. II	2006	USA	0.4 m	1.6 m		free
OrbView 5	2007	USA	0.4 m	1.6 m		free
Pléiades HR	2007	France	0.7 m	2.8 m	21 km	free
THEOS 2	2007	Thailand	2 m	15 m	24 km	free
RapidEye	2007	Germany	6.5 m	6.5 m	80 km	free
EROS C	2009	Israel	0.7 m	2.8 m	11 km	free

The access to images taken by the existing imaging satellites is different. Of course the images taken by satellites owned by private companies like IKONOS, QuickBird and OrbView are well distributed. Also for SPOT, the Indian Satellites and EROS A a good distribution network is existing. The ROCSat images are distributed by SPOT Image, but for some other satellites the access is more complicate.
Several high and very high resolution systems are announced (table 2). The launch very often is delayed and also some systems do disappear by different reasons, opposite some additional will come. But obviously, in the near future we will have a larger group of very high resolution systems operated by a higher number of countries. The tendency goes to higher resolution, to more light weight satellites and to flexible view direction or stereo in orbit direction. Most systems are used for military and civilian applications; without military contracts the private companies could not survive.

Table 3

Announced very high resolution SAR-satellites

	country	launch	band	highest resolution
RADARSAT-2	Canada	2005	C-band	3 m
TerraSAR-X	Germany	2005	X-band	1 m
SAR-X Cosmo-Skymed	Italy, France	2005	X-band	1m

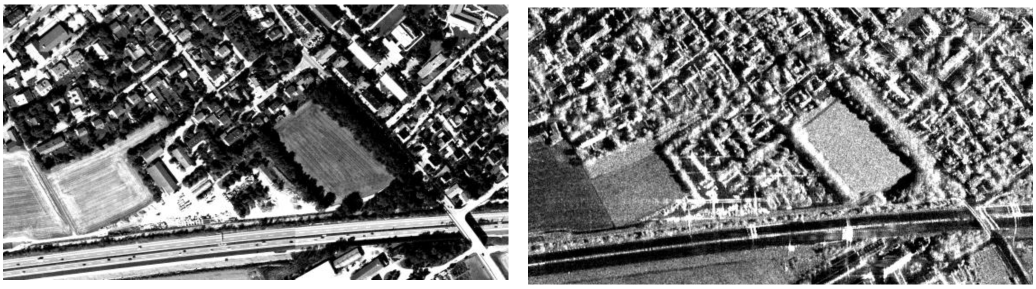


Fig. 1: optical image 1.5m GSD

Fig. 2: SAR-image 1.5m GSD

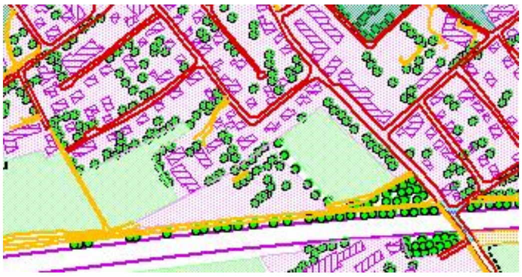


Fig. 3: mapping optical image

Fig. 4: mapping SAR-image

In addition to the optical sensors we will have in near future also very high resolution synthetic aperture radar (SAR) sensors. SAR has the advantage of being independent upon sun light, it can penetrate clouds, a large area can be covered in a short timed and in the interferometric mode it can be used for accurate determination of digital elevation models (DEM). But SAR-images do have the disadvantage of lower information contents like optical images with the same GSD (figures 1 up to 4). Only approximately 80% of the information contents of the optical images could be mapped with the SAR-images of the same pixel size (Lohmann et al, 2004). The SAR-images are disturbed by speckle and the displacement of objects in orthoimages located in another elevation like the used DEM is larger like for optical images (formula 1 + 2). In very steep areas where the terrain inclination exceeds the incidence angle, radar overlay is disturbing the image.

$$DL = DZ \bullet \tan(i)$$

formula 1: horizontal displacement in optical images

$$DL = \frac{DZ}{\tan(i)}$$

formula 2: horizontal displacement in SAR images

DL = horizontal displacement, DZ = difference in Z, i = incidence angle
Incidence angle = nadir angle of the view direction at the ground point

A possible alternative solution to satellites may come with the high altitude long endurance platforms (HALE), unmanned aerial vehicles (UAV) which may stay for long time in the air based on solar energy. The Belgian company Pegasus plans a HALE for 2007 which shall stay for 8 month in an altitude of 20km. It shall be equipped with a digital camera delivering a GSD of 20cm.

3. Mapping with space images

Mapping today is the data acquisition for geoinformation systems (GIS). Even if it is available with the national coordinate system, it is related to a representation scale. For mapping the aspect of accuracy and information contents have to be fulfilled. Under usual conditions an accuracy of 0.25mm up to 0.3mm in the map scale is required. The information contents have to correspond to the details which can be shown in the maps.

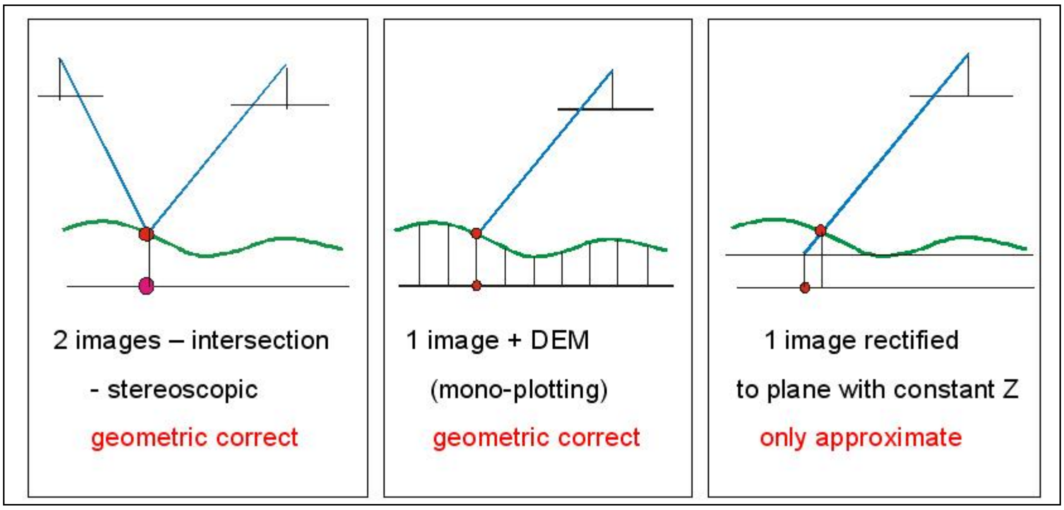


Figure 5. Geometric conditions for mapping

3.1 Geometric relation

The traditional satellite line scanners do take the images with a constant orientation in relation to the satellite orbit. Perspective geometry is only available in the line across the orbit. Every line has a different exterior orientation, but the smooth conditions in space does guarantee a predicted location of the projection centre and an unchanged orientation against the orbit. This is not the case for the agile very high resolution satellites, they can change the view direction permanently very accurate in a planned direction, so they can take images also directly related to the map projection (see figure 7). IKONOS even can take images against the direction of the movement of the satellite. Also SPOT 5 is changing the view directly for a so called yaw correction – this is eliminating the effect of the earth rotation to the covered area. The geometric model for the orientation based on original images (e.g. SPOT level 1A, QuickBird Basic) has to respect the change of the view direction. Today all the high resolution satellites are equipped with GPS or another positional system, giros and star sensors. So the exterior orientation of each line can be determined with a good accuracy without using control points.

Original IKONOS images are not distributed, only the CARTERRA Geo, a projection of the image to a plane with constant height (figure 6). This geometry is also available for SPOT and IRS as level 1B-images and as QuickBird OR Standard.

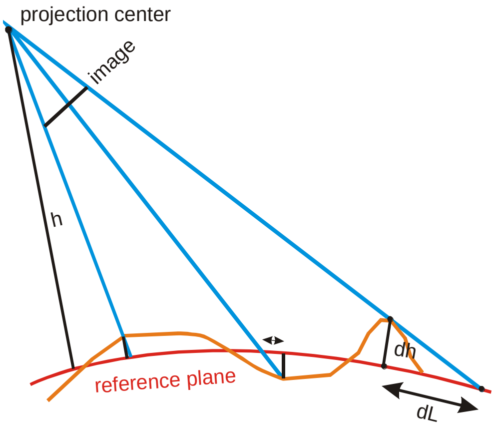


Figure 6: geometric condition for IKONOS Geo, QuickBird OR Standard and SPOT + IRS level 1B

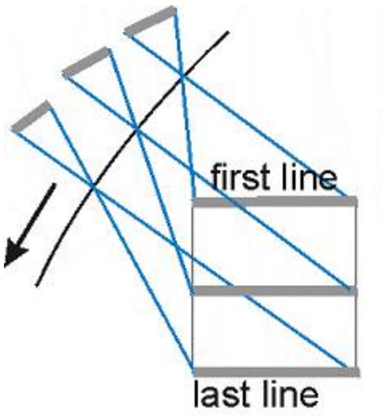


Figure 7: geometric condition of original images of satellites with flexible view direction (Basic imagery, level 1A)

For IKONOS images the sensor model is not published. Different solutions for the orientation of such images can be used:

1. Rational Polynomial Coefficients (RPCs) from the satellite image vendors – they do describe the image coordinates as a ration of a polynom as a function of the object coordinates (longitude, latitude, height) by another. Third order polynoms with 20 coefficients are used, so with 80 coefficients the relation of the image coordinates to the object coordinates can be described based on the direct sensor orientation of the satellites. The RPCs have to be improved based on control points, but often a simple shift is sufficient.
2. Reconstruction of imaging geometry: For the scene centre the direction to the satellite is available in the header data of the images. This direction can be intersected with the orbit of the satellite which is published with its Keppler elements. So the view direction from any ground point to the corresponding projection centre can be computed. This has to respect the actual distance in the orbit in relation to the distance on the ground. This method requires the same number of control points like the sensor oriented RPC-solution.
3. Three-dimensional affine transformation: This method is not using available sensor orientation parameters, the 8 unknowns have to be computed based on control points. At least 4 well distributed control points, not located in the same height level are required.
4. Direct Linear Transformation (DLT): The 11 unknowns do require at least 6 control points.

5. Terrain dependent RPCs: A limited number of polynomial coefficients are calculated based on control points.
The terrain dependent RPC-solution is very sensitive for the control point distribution. Outside the area of the control points the accuracy may be very poor (Büyüksalih et al 2003). The DLT does not lead to the same accuracy like the other methods and requires a high number of control points (Hanley 2003). With the first three methods similar accuracy has been achieved, but for the 3D-affine solution more control points are required.

Table 4:

Accuracy achieved with different space images

	SX / SY [m]	SZ [m]	Sx‘ / Sy‘ [ground pixel]	Spx [ground pixel]
SPOT Han. h/b = 2.6	4.6	13.4	0.5	0.5
SPOT Gren. h/b = 1.0	8.4	4.1	0.8	0.4
SPOT HRS h/b=1.2	5.9	3.9	0.9	0.6
IKONOS Geo h/b = 7.0	1.0	1.7	1.0 (0.7)	0.2
IRS-1C h/b=1.0	5.1	8.7	0.9	1.5
QuickBird	0.55	4.8	0.9 (0.6)	0.8
ASTER	10.8	14.6	0.7	0.5

The ground point accuracy achieved with the different space images mainly depends upon the pixel size; it can be expressed also as a function of the ground pixel size. For the vertical accuracy we do have the relation: $SZ = \frac{h}{b} spx$ (formula 3). The vertical accuracy is depending upon the height to base relation and the accuracy of the x-parallax (spx). Only the vertical component determined by IRS-1C is exceeding the size of one pixel, but this can be explained by a limited image quality caused by a very low sun angle of just 12°. So in general with all listed images sub-pixel accuracy is possible. In one case the same SPOT 5 images have been available as level 1A and as level 1B scenes. Nearly the same accuracy has been achieved with both, so with a correct handling, the type of used image product is unimportant.

3.2 Information contents

Maps with larger scale do show more details, so also more detailed object information is required. There is no mathematical relation between the GSD or ground pixel size and the scale of the map which shall be generated, but based on the experience the following relation can be used:

GSD = 0.05 up to 0.1mm in the map

That means for generating a map 1 : 50 000 a GSD of 0.05 * 50 000 = 2.5m up to 5m is required. The smaller value is valid for detailed maps in areas with a high number of details, while usually the higher value is sufficient.

Not in any case the nominal pixel size on the ground is corresponding to the effective information of the image. This can be investigated by an edge analysis. An edge is a sudden change of the grey values on the ground. In the image the change will not be so sharp like on the ground (Fig 9). A differentiation of the grey value profile leads to the point spread function, which shall be normal distributed. The width of the point spread function shows the effective ground sample distance. By this method especially the real resolution of the Russian KVR1000 space photos could be analysed. They have distributed with 1.6m GSD, but the effective resolution determined by edge detection was 2.2m. But also the IRS-1C has had an effective GSD of 7m instead of the nominal 5.8m. Of course the effective GSD is also influenced by the atmospheric condition, so it can differ from scene to scene.

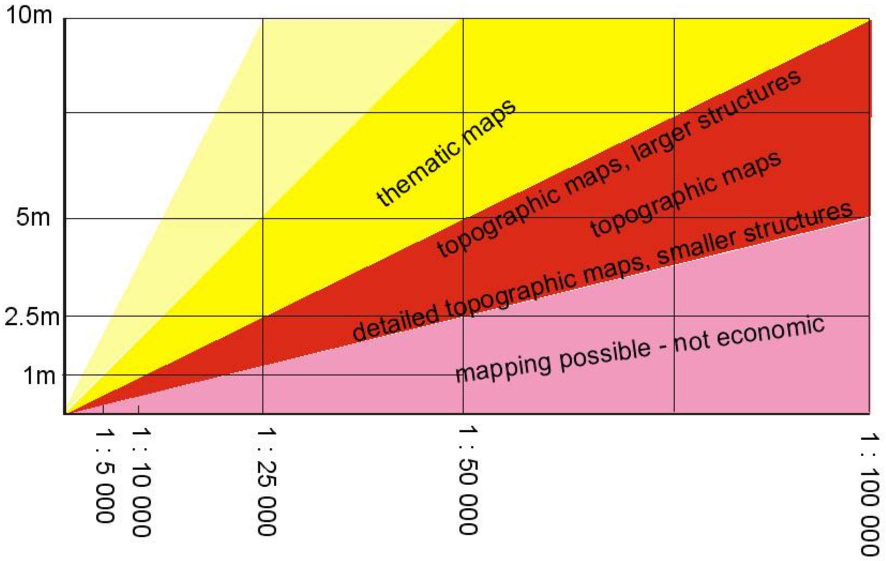


Figure 9. Relation GSD to possible map scale

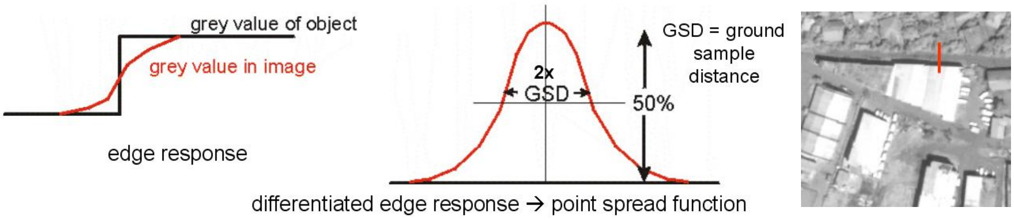


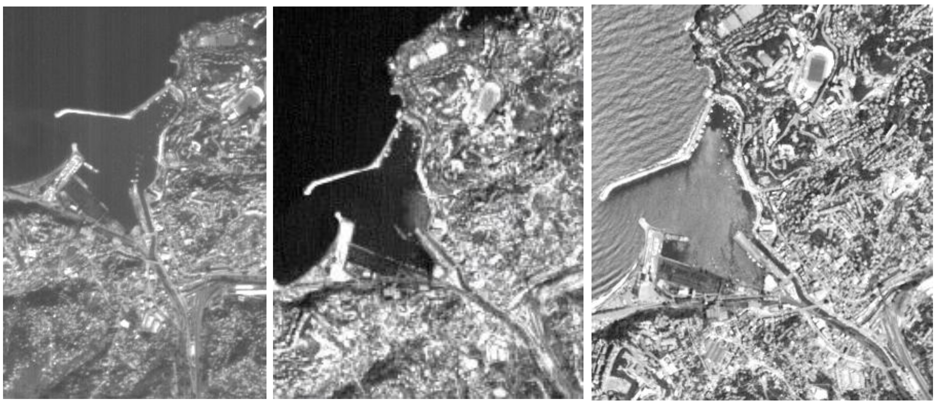
Figure 9. Edge analysis, right hand: edge in QuickBird image (dark shadow – bright building)

Different space images have been used for the generation of line maps. The contents which could be used for mapping was mainly depending upon the pixel size. Colour has some advantages for the object identification, so more details could be extracted from colour images like from panchromatic images with the same GSD. The colour is not influencing the accuracy. In dense city areas the sun elevation is important. So in one IKONOS-scene with lower sun elevation where the streets have been in the shadow, it was difficult to map the streets and not a street instead of the backyards. In the same area with an IKONOS image taken under higher sun elevation no problems occurred. In general the mentioned relation between the GSD and the possible map scale has been confirmed.

Corresponding to the requirement of 0.1mm GSD for the generation of line maps, for a map scale 1 : 10 000 a GSD of 1m should be used if the map should have the necessary details. An accuracy of approximately 0.25mm in the map should not be exceeded, corresponding to 2.5m for the scale of 1 : 10 000. That means, the accuracy should not exceed 2.5 pixels – this is absolutely not a problem. So the accuracy is not the limiting factor for mapping, the limitation is the information contents of the images.

4. Digital elevation models

Digital elevation models (DEM) are a basic part of the information about an area. They are required for the generation of orthoimages and a high percentage of planning purposes. The worldwide lack of qualified and accessible DEMs has been improved with the Shuttle Radar Topography Mission (SRTM) in February 2000. Based on Interferometric Synthetic Aperture Radar (InSAR) DEMs have been generated. The DEMs based on the US C-band are available free of charge in the internet (http://edcsgs9.cr.usgs.gov/pub/data/srtm/) with a spacing of 3”, corresponding to approximately 90m at the equator. Only for the USA the data with a spacing of 1” (~ 30m) are also in the WEB.



Kompsat 1, 6.6m GSD IRS-1C, 5.8m GSD SPOT 5, 5m GSD

IKONOS ms, GSD 4m QuickBird ms, GSD 2.4m

KVR 1000, (2.2m) GSD IKONOS, 1m GSD QuickBird, 0.6m GSD

Figure 10: Details visible in different space images

Table 5

Accuracy of SRTM C-band DEMs in open areas after filtering

	RMSZ [m]	Bias [m]	RMSZ F(slope)
Arizona	3.9	1.3	$2.9 + 22.5 * \tan \alpha$
Williamsburg NJ	4.7	-3.2	$4.7 + 2.4 * \tan \alpha$
Atlantic City	4.7	-3.6	$4.9 + 7.6 * \tan \alpha$
Bavaria, rolling	4.6	-1.1	$2.7 + 8.8 * \tan \alpha$
Bavaria mountainous	8.0	-2.4	$4.4 + 33.4 * \tan \alpha$

DEMs generated by automatic image matching with optical images as well as the DEMs based on InSAR with short wave length like the C-band are related to the visible surface, the top of trees and buildings – they are corresponding to a digital surface model (DSM). Usually a DEM showing the bare ground is required. It is possible to filter a DSM to a DEM if at least few points on the ground are available (Jacobsen 2001). In forest areas such a filtering has a limited effect. In table 5 the reached accuracy of the filtered SRTM-DEMs in open areas are shown. In any case there is a clear dependency upon the terrain inclination. The accuracy for the flat parts ($\alpha = 0.0$) are influenced by the systematic error (bias). Without the bias, which can be determined and respected by means of control points, the SRTM DEMs do have accuracy in the range of 3 to 4m – sufficient for several applications. But for mountainous areas the spacing of 3", corresponding to 92m at the equator, is causing a loss of details.

Table 6

Loss of accuracy by interpolation to the centre of the spacing

	spacing	mean slope	mean change of slope	SZ
Zonguldak	80m	0.27	0.32	12.0 m
Arizona	90m	0.17	0.09	4.8 m
New Jersey	60m	0.024	0.015	0.45 m
New Jersey	120m	0.024	0.015	1.12 m

In the extremely rough terrain of Zonguldak by the interpolation over 80m, against the available reference height in the centre of the spacing a root mean square difference of 12m appeared. In the more flat area of New Jersey, the loss of accuracy was limited in relation to the SRTM-DEM accuracy. By this reason there is still a justification for the generation of DEMs based on space images.

Table 7

DEM accuracy achieved by automatic image matching

Sensor	GSD [m]	height/ base	area / type	SZ [m]	SZ F(slope) [m]
TK 350	(10 /13)	2,0	open	23.3	20.0 + 23.9*tan α
			forest	51.3	49.0 + 11.4*tan α
			check points	6.6	4.7 + 2.2*tan α
ASTER	15	1,7	open	25.0	21.7 + 14.5*tan α
			forest	31.2	27.9 + 18.5*tan α
			check points	12.7	
SPOT 5	5	1,85	open	11.9	8.4 + 6.3*tan α
			forest	15.0	9.8 + 5.3*tan α
			check points	3.8	3.5 + 0.9*tan α
SPOT 5 HRS	5..10	1,2	open	6.7	6.4 + 4.9*tan α
			forest	17.0	16.4 + 2.2*tan α
SPOT 5 HRS filtered	5..10	1,2	open	4,4	4,2 + 1.6*tan α
			forest	12.3	10.0 + 6.9*tan α
IKONOS	1	7,5	Maras	1.7	same orbit
IKONOS	1	3,8	Zonguldak	5.8	Δt = 3 month
QuickBird	0,62	9,1	Arizona	4.8	Δt = 10 days

In all cases a clear dependency of the DEMs generated by automatic image matching upon the terrain inclination is available. For the forest the accuracy was not so good, caused by the fact in showing the elevation of the visible surface. In addition the contrast often was not so good in forest areas. The accuracies at check points have been quite better like the comparison with a reference DEM. The reference DEMs have not been free of error, but the major effect was caused by the clear description of the check points. Check points are located usually in flat areas having a good contrast and here the quality of the image matching is quite better like in areas, where the contrast may not be so good. So in general the DEM accuracy determined by means of check points instead of a reference DEM is too optimistic.

The image matching is difficult with images taken not under the same condition. For example the height determination with IKONOS in the area of Maras was excellent, but in the area of Zonguldak it failed for large parts and was not so good because of quite different sun elevation of the images causing large radiometric differences.

With SPOT HRS approximately the same accuracy has been achieved like with SRTM. For automatic image matching a spacing of 3 pixels is sufficient and required for getting nearly independent height values, so a spacing of 15m was possible based on the SPOT 5 data. This guarantees quite more detailed morphologic information like SRTM, but even with the not so precise ASTER data more morphologic details are available in mountainous areas.

5. Conclusion

The very high resolution space images are today in a competition with aerial images. Only the economic aspects and the availability of the images are influencing the decision in using the different image types. The tendency to space images with higher resolution (smaller GSD) is continuing and more satellites are announced. Line maps up to a scale 1 : 10 000 can be generated with images having a pixel size of 1m; with 61cm pixel size even a map scale 1:5000 is possible. The accuracy is not the limiting factor for mapping; the limitation comes from the interpretation of the objects. With the availability of the DEMs based on the SRTM InSAR a qualified, nearly a worldwide DEM can be used free of charge. If more morphologic details are required, DEMs can be generated by automatic image matching of optical space images. These DEMs should be filtered for objects not belonging to the bare ground.

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