

Topographic Mapping with High Resolution Optical Space Images

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ABSTRACT

Topographic mapping traditionally was based on aerial images. With high and very high resolution optical space images now a competition to aerial images exists. The optical space images today are available without restrictions. Dominating criteria for mapping are the accuracy and the information content – what elements can be identified in the images. The accuracy is determined by the scene orientation and the relative accuracy within the stereo model. The direct sensor orientation reaches standard deviations up to 2m. If this is not satisfying or sensors with lower direct sensor orientation accuracy shall be used, ground control points or other methods for the scene orientation have to be used. The location accuracy of the SRTM height model or TerraSAR-X scenes for several applications is satisfying and SRTM can be used instead of control points. The relative accuracy within the stereo model is not the limiting factor for the possible map scale, this is the information contents or object identification. The information content is dominated by the ground sampling distance (GSD), but it may be influenced also by the image quality. The image quality can be analyzed by edge analysis.

INTRODUCTION

Very high resolution space images with up to 0.5m ground sampling distance (GSD) today are competing with digital aerial images for mapping purposes. The access to high resolution space images is simple and not restricted as it is in several countries the case for aerial images. The direct sensor orientation of optical satellites has reached standard deviations of the ground coordinates in the range of 2m, enabling mapping also without ground control points. With the radar satellites TerraSAR-X and TanDEM-X even a direct sensor orientation in the range of 0.1m is possible (Eineder et al. 2013). Such accuracy requires the information of the Earth tide and the continental drift. This allows accurate ground control information determined from radar images for the orientation of optical images. Nevertheless also classical ground control points may be used to improve the sensor orientation.

The image quality of the very high resolution space imagery is usually very good and can be compared with original digital aerial images, so the generation of topographic maps is not a problem. By the rule of thumb a GSD of 0.1mm in the image is required for topographic mapping, corresponding to a map scale of 1:5000 based on images with 0.5m GSD. As side condition the GSD above 5m is not useful for topographic mapping because it does not allow the identification of some objects important even for small map scales. Of course today maps are generated via Geo

Information Systems (GIS), but even if the information is directly connected with ground coordinates, the information details define a presentation scale corresponding to the former map scale.

VERY HIGH RESOLUTION OPTICAL SPACE SYSTEMS

The definition “very high resolution” varies depending upon the application. Here it is used for optical images with 1m GSD and better for the panchromatic channel. Only space systems from which images are available without restrictions are mentioned. The high number of military reconnaissance systems is not included here.

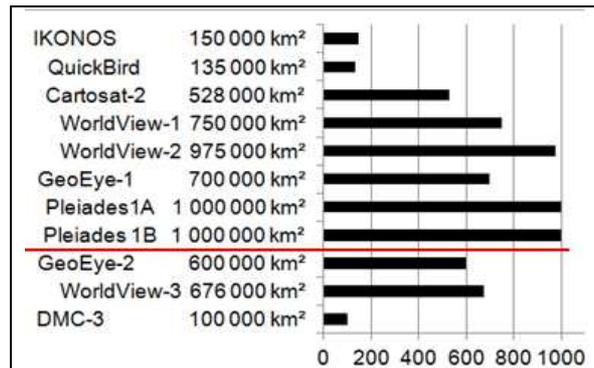


Figure 1: Theoretical daily imaging capacity

Sensor , launch	Altitude	GSD pan	Swath nadir	Pan/ms channels
IKONOS 2 1999	681 km	0.82m	11.3km	Pan, 4ms
QuickBird 2001	450 km	0.61m	16.5km	Pan, 4ms
EROS B 2006	508 km	0.7m	7 km	Pan
KOMPSAT-2 2006	685 km	1m	15km	Pan, 4ms
WorldView-1 2007	494 km	0.45m	17.6km	Pan
WorldView-2 2009	770 km	0.46m	16.4km	Pan, 8ms
GeoEye 1 2008	681 km	0.41m	15.2 km	Pan, 4ms
Cartosat-2, 2A, 2B, 2007-2010	631 km	0.82 m	9.6km	Pan
KOMPSAT-3, 2012	685 km	0.7 m	16.8 km	Pan, 4ms
Pleiades 1A, 1B 2011/2012	694 km	0.7 m	20km	Pan, 4ms

Table 1. Actual very high resolution optical satellites

The possibility to get actual images is strongly depending upon the imaging capacity (figure 1). Against the time before 2007 the today imaging capacity of the listed sensors is more as 20 times higher, enabling a quite improved access to actual data.

In table 1 only active satellite systems from which images are available without problems are included. Military reconnaissance satellites are not shown. Resurs-DK 1 is not listed because of restrictions with image resolution and the since 2010 reduced resolution to 1.3m GSD. OrbView-3 was only active from 2003 up to 2007.

Most systems have a very high resolution panchromatic channel and lower resolution multispectral channels. Usually there is a linear relation of 4.0 between the panchromatic and the multispectral resolution, requiring a pan-sharpening for very high resolution colour images. EROS-B, the Cartosat-2 series and KOMPSAT-3 are equipped with staggered arrays, that means with 2 CCDs shifted half a pixel against each other. So the physical pixel size is two times larger as the nominal size. For example Cartosat-2 has physically 1.64m GSD, but by the staggered arrays images with 0.82m GSD are generated. This is really improving the image quality, but not with the factor 2.0. Usually the effective pixel size of staggered systems is larger by approximately 20% (0.98m effective GSD instead of nominally 0.82m GSD) (see figure 6).

Pleiades 1A and 1B have 0.7m GSD, but the images are distributed with enlarged size with 0.5m GSD. Of course by this enlargement the image quality is not improved.

In 2013 GeoEye-2 with 0.34m GSD and in 2014 WorldView-3 with 0.31m GSD and Cartosat-3 with 0.33m GSD for the panchromatic channel shall be launched. Up to now it is not clear if GeoEye-2 and WorldView-3 images will be available with this resolution or if they will be reduced to 0.5m GSD because of legal restrictions in the USA. In addition a series of other very high resolution satellites is announced.

SCENE ORIENTATION

For data acquisition the relation between image and ground position is required. This relation is expressed via the scene orientation. From the two dimensions in the image it is not possible to determine three coordinate components in object space, so two images taken from different positions or the object height must be available. For perspective images the image orientation is expressed by the three coordinate components of the projection centre and three rotations. In general we have the same situation for CCD-line scanner images, but here the orientation is changing from CCD-line to CCD-line, so additional information about the relation of the projection centres and the changes of the rotations is required. For satellites the orbit location is not a problem, today this is known via GNSS-position with sub-meter accuracy, the limitation of the orientation information is caused by the attitudes. The modern optical satellites are taking the images in pre-planned orientations, mostly in North-South direction or in any other chosen direction. That means the satellite rotation is changing from line to line (figure 2).

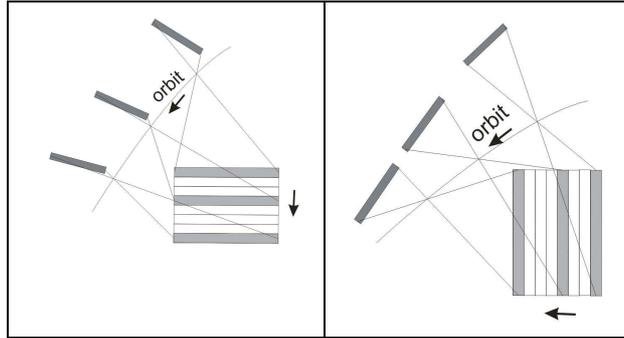


Figure 2: CCD-line orientation during imaging

The control and orientation of the individual CCD-line attitude is available based on inertial measurement units (IMU) with satisfying accuracy. Based on the header information delivered together with satellite images, the scene orientation can be reconstructed and improved by ground control points.

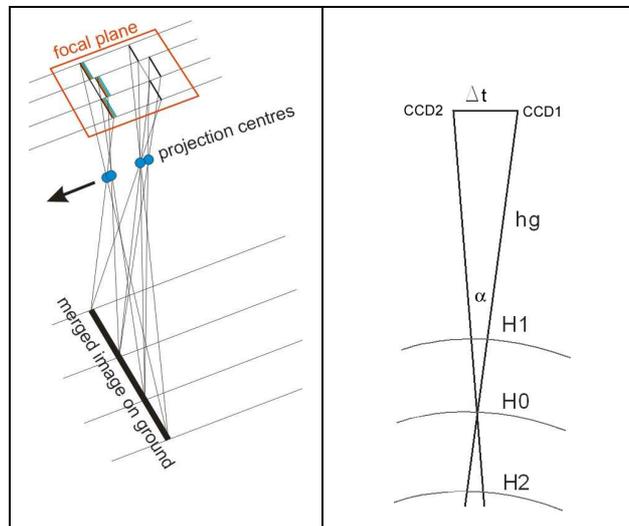


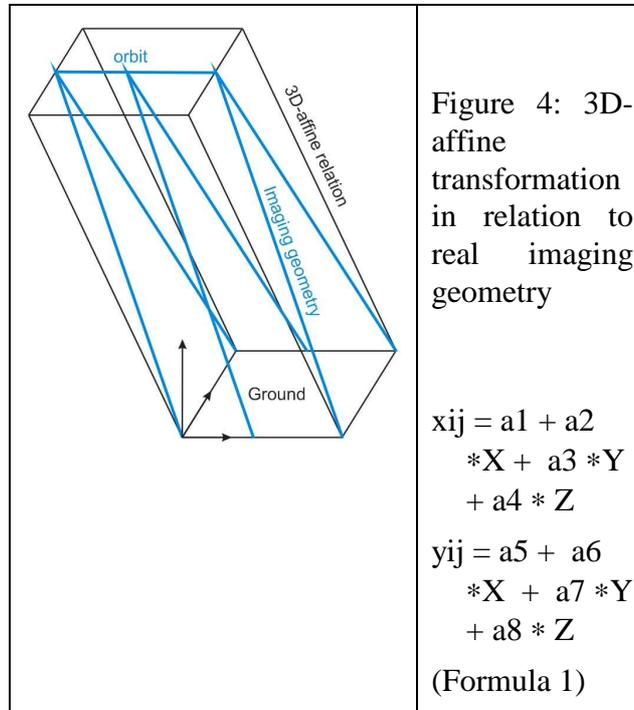
Figure 3: left: combination of CCD-lines to a homogenous line in object space right: mismatch of the sub-CCD-lines depending upon object height

Most very high resolution satellite images are based on a combination of CCD-lines (figure 3 left). The CCD-lines are usually connected to homogenous images, respecting the difference in time and also rotations of the individual CCD-lines. By theory such a combination of the individual CCD-lines is only possible for a fixed height of the terrain (figure 3 right), but in reality the misfit between neighbored CCD-lines in an area with strong height variation is quite below one pixel. In most cases today the images are projected to a plane with constant height (e.g. IKONOS/GeoEye Geo, OR Standard or SPOT level 1B), simplifying the scene orientation. At the beginning of the IKONOS imaging the former company Space Imaging did not like to publish the scene orientation, but based on the view direction of the image centre, the general orbit direction and the imaging time the imaging geometry could be reconstructed just based on one ground control point up to sub-pixel level (Jacobsen 2002).

Today most satellite images are delivered with Rational Polynomial Coefficients (RPC) expressing the image position by the relation of third order polynomials of X, Y, Z. They have the accuracy on the level of the direct sensor orientation. Several test with different types of satellite imagery

showed the same accuracy based on geometric reconstruction as with bias corrected RPCs (RPCs improved based on ground control points).

If no or not satisfying orientation information is available, by geometric reconstruction the image geometry can be determined by adjustment if a satisfying number of ground control points is available with satisfying three-dimensional distribution. Another possibility is the use of approximations as 3D-affine transformation (figure 4, formula 1).



$$x_{ij} = a_1 + a_2 * X + a_3 * Y + a_4 * Z + a_9 * X * Z + a_{10} * Y * Z + a_{13} * X * X$$

$$y_{ij} = a_5 + a_6 * X + a_7 * Y + a_8 * Z + a_{11} * X * Z + a_{12} * Y * Z + a_{14} * X * Y$$

Formula 2: extended 3D-affine transformation for original images

The 3D-affine transformation is only an approximate replacement of the correct geometric relation - it does not respect the perspective geometry in the CCD-line and no possible scan not in the flight direction (figure 2), in addition it requires more and three-dimensional well distributed ground control points. With a higher number of ground control points in rolling areas similar accuracy as with geometric reconstruction or bias corrected RPC-solution can be reached. With larger height differences in the object space the 3D affine transformation causes increased discrepancies. With an extended 3D-affine transformation (Jacobsen 2008, formula 2) the perspective condition in the CCD-line and a scanning not in the flight direction are respected. With a satisfying number of three-dimensional well distributed ground control points the same accuracy as with geometric reconstruction or bias corrected RPC-solution can be reached, but this is possible with a smaller number of ground control points by geometric reconstruction or bias corrected RPC solution.

Also the Direct Linear Transformation (DLT) sometimes is used for the orientation of optical satellite images. In general the DLT should not be used – it is based on the geometric model of perspective images what is not the case for today space images and it uses 11 unknowns which are strongly correlated in the case of the narrow angle optical space images. The extreme correlation of

	SX, SY [m]	SZ [m]	GSD	Spx [ground pixel]
SPOT -3	8.4	4.1	10 m	0.4
MOMS	3.5	4.5	4.5 m	0.4 / 0.13
Cartosat-1	1.5	2.5	2.5 m	0.7
IKONOS	1.0	1.7	1 m	0.2
ASTER	10.8	14.6	15 m	0.5
GeoEye-1	0.3	0.5	0.5 m	0.7
WorldView-2	0.5	0.3	0.5 m	0.2

Table 2: Root mean square differences at independent check points

the unknowns can cause large deviations in areas with lower number of ground control points or especially in areas outside the range of the control points which cannot be controlled by the discrepancies at the used control points.

Sensor orientation by geometric reconstruction or bias corrected RPC-solution is independent upon the type of images (original images or images projected to a plane with constant height). With both methods and both image products the same accuracy has been reached. In general standard deviations of the coordinate components of 1.0 GSD or better were reached as the examples in table 2 show. The limiting factor is the identification of the control points in the images – with better control point identification the accuracy is better. This explains why the results in the height are similar to the results for the horizontal coordinate components

An orientation accuracy of one GSD is totally satisfying for mapping purposes.

MAPPING

The generation of topographic maps is dominated by the image resolution – with better resolution the details can be identified and classified better and the geometry is improved. In figure 5 the identification of details in the GeoEye-1 image is quite better as in the IKONOS image. The scanned analogue aerial photo (figure 5 left hand side) is disturbed as usual by the photo grain and is not better as the IKONOS image with lower nominal resolution. The effective resolution of this aerial photo, determined by edge analysis with point spread function, with 0.74m is clearly below the nominal resolution of 0.63m (see image 6).

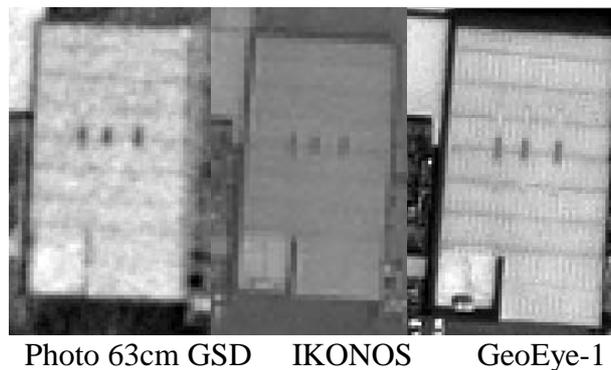


Figure 5: From left: building in aerial photo 63cm GSD, IKONOS (1m DSD) and GeoEye-1 (0.5m GSD)

An object with a sudden change of the brightness is imaged with a continuous change in the image (figure 6, upper part). The grey value profile, averaged over several pixels, shows the continuous grey value change in the image. A differentiation of this profile leads to the point spread function (figure 6, lower part). Half the width of the point spread function corresponds to the factor for the effective resolution; this multiplied with the nominal resolution is identical to the effective resolution, including the information for the identification of the objects.

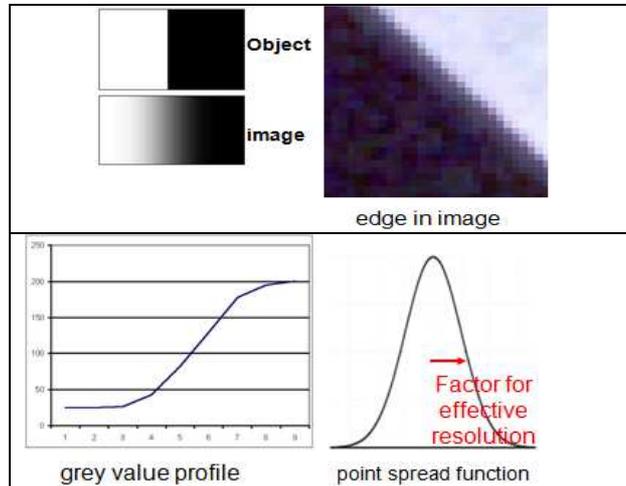


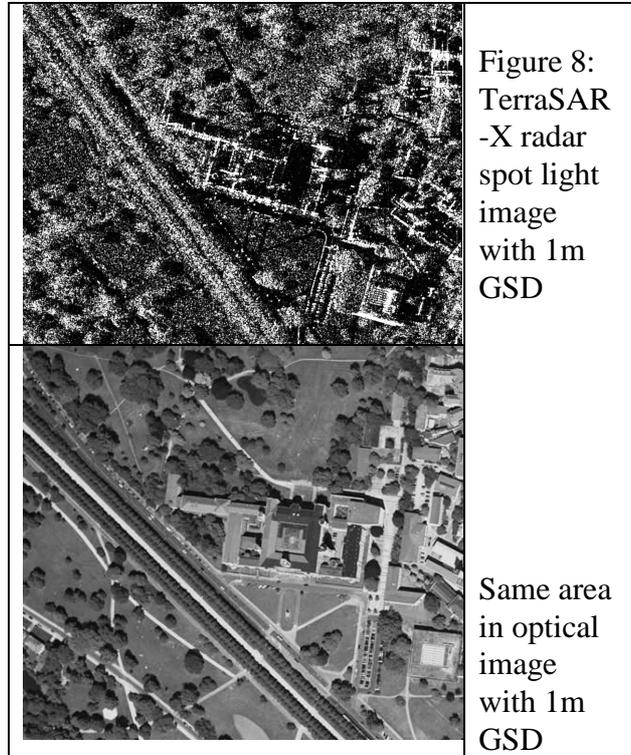
Figure 6: determination of effective image resolution by edge analysis

Mapping can be based on a stereo pair or by mono-plotting based on ortho images. A stereoscopic view has some advantages for the correct object recognition, so few errors of object identification can be avoided as the misidentification of an excavation as building in an image with 2m GSD, but the final influence to the map contents is usually limited.



Figure 7: comparison of object identification in panchromatic and colour image

The colour of pan-sharpened images simplifies and speeds up the object identification (figure 7) (Dowman et al. 2012). As demonstrated by figure 7 in an unplanned area with not regular arrangement of buildings the identification of the buildings is quite simpler in colour images. Nevertheless nearly no loss of objects occurred by mapping based on panchromatic images, but the mapping supported by image colour is more economic because of the faster mapping.



With German TerraSAR-X, TanDEM-X and the Italian CosmoSkymed radar satellites with up to 1m GSD are available for civilian application. Synthetic Aperture Radar (SAR) images also can be used for mapping purposes (Lohmann et al 2004). Radar has the advantage of penetrating clouds, so images can be taken at any time and because of the active imaging also during night. This is important for tropical regions with nearly permanent cloud coverage and for time critical disaster monitoring. In some tropical regions SAR images are the only possibility for mapping, but as the comparison of a TerraSAR-X image with an optical image in the same area (figure 8) demonstrates, is the mapping with SAR-images not as easy. For humans optical images are corresponding to the standard view of objects, so the interpretation is simple. The imaging principle of radar is different and requires some training and understanding of radar imaging for the correct interpretation. An intensive test of information extraction from optical and SAR images (Lohman et al. 2004) showed that even trained staff especial in urban areas could not extract the same amount of information from SAR as from optical images. In urban area the radar layover makes the mapping of objects complicate. In rural areas the image information is roughly the same. As a very rough rule of thumb can be stated, that with two times the resolution of SAR-images, similar information as in optical images can be extracted as for example 1m GSD from SAR corresponds to 2m GSD from optical images (figure 9).



Figure 9: above: optical image, followed by mapping with optical image, below: SAR image followed by mapping with SAR image (Lohmann et al 2004)

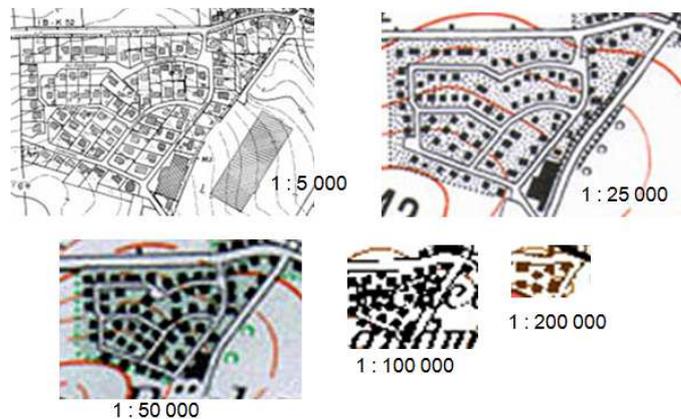


Figure 10: information contents of topographic maps with different scale

As figure 10 shows, depending upon the map scale different contents is required for topographic mapping. Starting with the presentation scale 1:25 000 map generalization starts – not all objects are shown, the information is grouped, partially replaced by symbols and not so important parts are eliminated. So in the map scale 1:25 000 all buildings and streets are included but not with the details included in the scale 1:5000. The map with scale 1:50 000 in the southern part instead of a sequence of 7 buildings includes just the symbol of 4 buildings and in the scale 1:100 000 the smaller roads are eliminated. Corresponding to this, for the generation of maps different details have to be extracted from the images that means a lower image resolution may be satisfying for topographic mapping.

Topographic mapping for civilian application started with SPOT-1, having 10m GSD for the panchromatic channel, in 1986. But a resolution of 10m was not really satisfying for any map scale because it did not allow the identification of all map details important for any scale, as for example railways and streets. For example a major road in Nigeria could not be identified in SPOT images because of overhanging trees from both sides. This became better with the former military satellite images as CORONA and KFA1000, but with the disadvantage that no actual images could be ordered. With IRS-1C in 1995 the resolution was improved to 5.8m GSD, but the effective resolution of the staggered CCDs was limited to effective approximately 7m GSD. The real breakthrough for topographic mapping came with IKONOS in 1999. The 1m GSD-images of IKONOS and later from the other very high resolution satellites have been intensively used for

topographic mapping, especially in areas where the access to aerial photos was restricted. Nevertheless also today country wide mapping mostly is less expensive with aerial images even if they may have the same resolution as the space images.

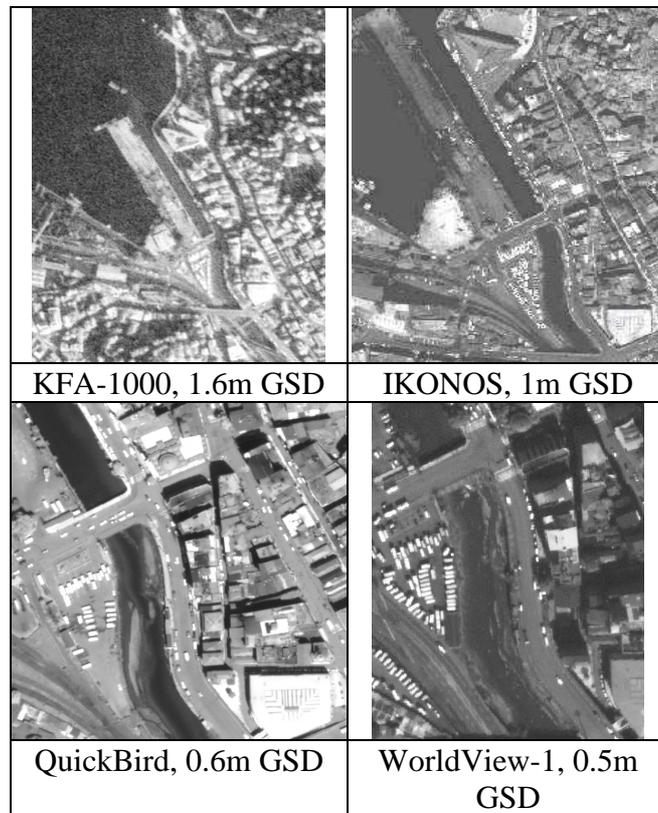


Figure 11: comparison of optical space images (not full resolution)



Figure 12: above GeoEye-1 image with 0.5m GSD, below samples from aerial photos with 0.7m GSD

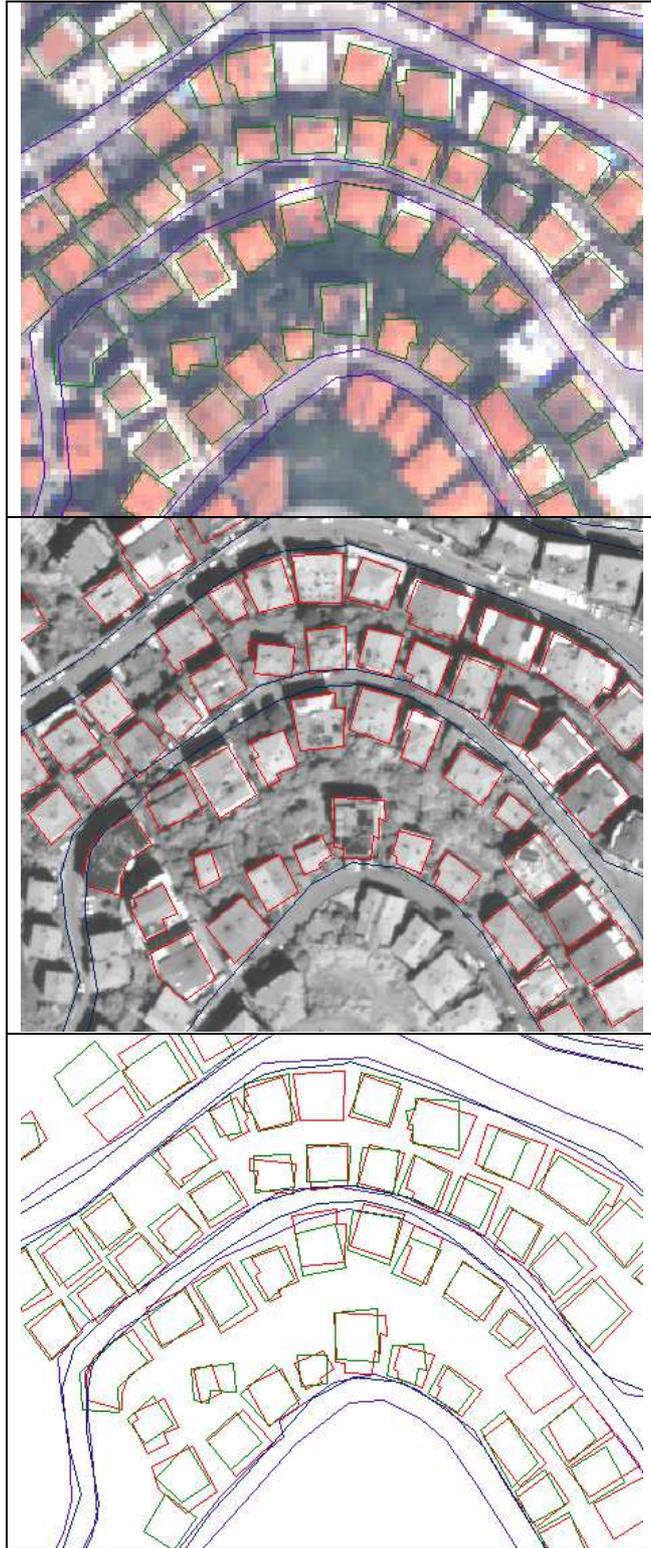


Figure 13: above: mapping with QuickBird colour image (2.4m GSD), Centre: mapping with QuickBird panchromatic image (0.6m GSD), below: overlay of generated vectors

The comparison of some space images in figure 11 demonstrates the differences. The scanned KFA-1000 photo with nominally 1.6m GSD has the typical influence of the image grain causing a

reduced effective resolution of approximately 2m. The contrast in original digital images is quite better and more details can be identified with higher resolution.

The GeoEye-1 image in figure 12 in a fast view cannot be separated from an original digital aerial image. The samples of scanned aerial photos with 0.7m GSD in figure 12 are not as good. So today it is not important if the image has been taken from space with 700km distance or from air with 5km distance if the ground resolution is the same.

The mapping test demonstrated in figure 13 shows that buildings can be mapped in images with 2.4m GSD – any building has been identified. But the details required for a larger map scale as 1:5000, including all building extensions can only be identified in the image with 0.6m GSD.

	required GSD
urban buildings	2m
foot path	1 - 2m
minor road network	5m
rail road	5m
fine hydrology	5m
major road network	10m
building blocks	10m

Table 3: required GSD for topographic mapping

As result of several mapping tests the required GSD for the identification of the different objects as listed in table 3 has been found. Of course as mentioned above there are differences in the object details depending upon the used GSD.

Based on several maps of different scale, generated with different space images, as rule of thumb we have the relation of approximately 0.05mm up to 0.1mm GSG in the map scale required for satisfying topographic maps. In addition we have the side condition that the GSD should not be smaller as 5m to guarantee the mapping required in any case independent upon the map scale. Figure 14 shows this relation in a graphical manner. It includes also the information that thematic maps sometimes have not the same requirement, so dependent upon the topic also larger scale thematic maps can be generated.

The above mentioned relation of image GSD and map scale is based on the identification of the objects; the accuracy has not been respected up to now. For topographic maps usually a standard deviation of 0.2mm up to 0.3mm is required. For the map scale 1:10 000 this corresponds to 2m up to 3m. For example with IKONOS-images having 1m GSD, which is required for such a map scale, under operational conditions well defined objects can be mapped with standard deviation of 1 GSG or 1m. That means the horizontal mapping accuracy can be reached without problems with images required for the identification of objects or reverse the limiting factor for the map scale is the image resolution and not the accuracy.

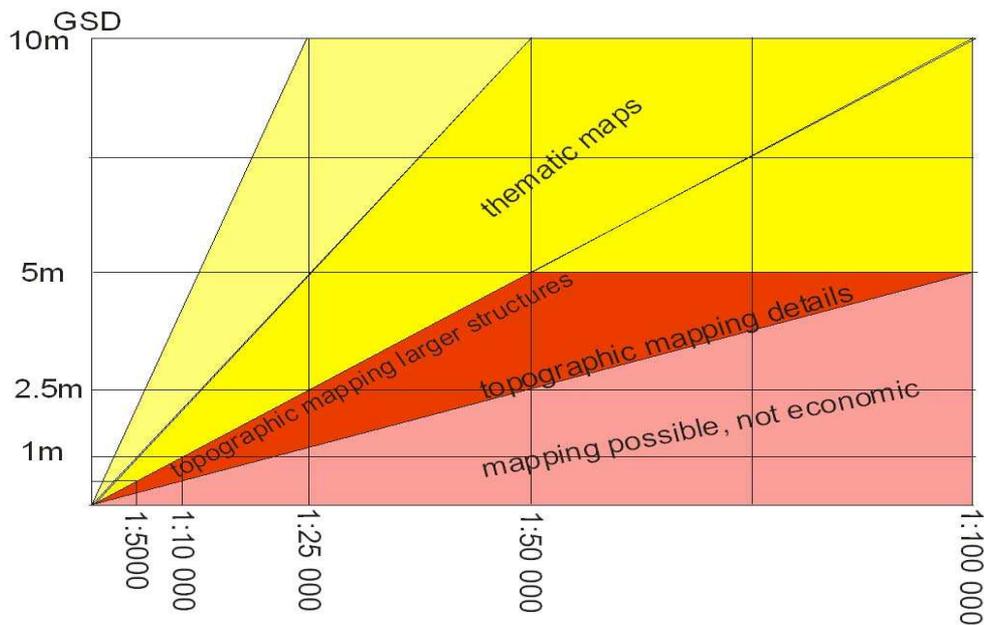


Figure 14: Required ground sampling distance for mapping

MAP UPDATE

Existing topographic maps must not be generated again, in most cases if not too much has been changed, a map update is more economic. Of course for map update the same relation of image GSD to map scale exists. Map update sometimes is very time consuming for identifying the changes. Very often some objects are not recognized. The update of buildings may be supported by a digital surface model.

For the update of a 3D-building model a digital surface model (DSM) based on an IKONOS stereo pair from May 2008 and a DSM based on a GeoEye-1 stereo pair from September 2009 has been generated (Alobeid et al. 2011). The differences of both DSM (figure 15) show the changes. All changed buildings have been identified including buildings where just one level has been added. Especially such changes just by one level are very difficult to be identified by manual inspection. In the whole suburb changes occurred and not just in new settlement areas.

CONCLUSION

Topographic maps today can be generated based on satellite imagery in the same manner as with aerial images. The resolution may be the same and the image quality shows no remarkable difference between optical space images and digital aerial images. Under special conditions maps are generated with SAR images, but this requires special training for the operators and causes especially in build up areas some problems, so it is usually limited to tropical areas and disaster mapping.

If the rule of thumb of approximately 0.1mm GSD in the map scale is respected, the map contents based on optical space images can be compared with contents based on aerial images. Today the availability of actual space images has strongly been improved caused by the higher number of optical satellites and the strongly extended imaging capacity. For limited areas it is simpler to organize mapping based on space images as to start a photo flight.

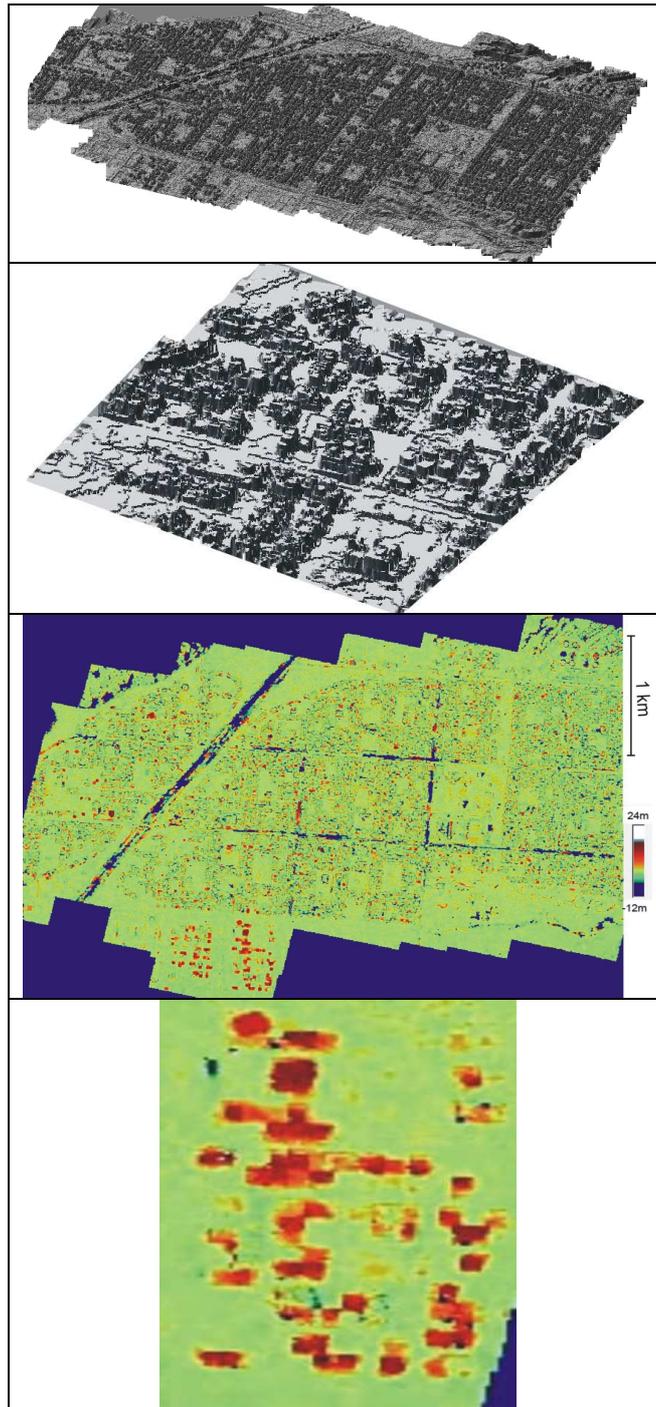


Figure 15: above: 3D-shaded view to IKONOS DSM (imaged in May 2008), centre above: sub-area GeoEye-1 (imaged in September 2009), centre below: difference of both height models, below: detail of a new settlement

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