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High Resolution Optical Satellite Images – from Scene Orientation to GIS-Data Acquisition

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ABSTRACT

Mapping today is a data acquisition for a Geo-Information System (GIS). For geometric qualified map product the sensor orientation should be based on strict orientation solutions. The information extraction can be made in a stereo model or an ortho-image by manual interpretation or partially an automatic object extraction. For the required digital elevation model (DEM) existing data can be used or by automatic image matching a digital surface model (DSM) can be generated, which has to be filtered to a DEM.

The scene orientation by geometric reconstruction, and sensor oriented rational polynomial coefficients (RPC) are described as well as the approximate solutions, not using any of the available sensor orientation information. The approximate sensor orientations partially can be used for scenes with a small field of view and if the control points are three-dimensional well distributed, but it requires quite more ground control points like the strict orientation solutions.

Based on the scene orientation with a stereo pair by automatic image matching height models have been generated. The image matching of scenes not from the same orbit often is difficult up to not successful; changed shadows, changing reflection, and changed objects especially in agriculture areas and moved cars on parking places caused matching problems. With the stereo satellites ASTER, SPOT-5 HRS, Cartosat-1 and ALOS-Prism the lack of stereo models has been solved. ASTER with its limited ground resolution of 15m cannot reach the same accuracy as the free of charge available SRTM height model. SPOT-5 HRS has in forest areas only a very limited range of grey values caused by the spectral range not including near infrared. This is quite better for Cartosat-1 and ALOS-Prism. By automatic image matching as well as by interferometric synthetic aperture radar (InSAR), using the C- or the X-band, the height of the visible surface is determined. If the DSM includes a sufficient number of ground points, a DEM with the height of the bare ground can be achieved by filtering the DSM. An accuracy analysis of the computed height models based on different satellite sensors is made. In build up areas with very high resolution satellite images the matching strategy has to be modified against the matching in rural areas because of large disparities of neighboured points.

The mapping of ortho-images by screen copy is quite simpler like a 3-D-data acquisition, but is not supported by the stereo view, simplifying the identification of some objects. Colour information, often used by merging high resolution panchromatic images with lower resolution multispectral images, is speeding up the interpretation of some objects. As rule of thumb for mapping 0.1mm ground sampling distance (GSD) in the map scale is required for the contents corresponding to a topographic maps e.g. with 1m GSD a map 1 : 10 000 can be generated. This rule of thumb depends upon the object itself and the contents in topographic maps which is different from country to country.

SCENE ORIENTATION

Any data acquisition with images requires a geo-reference based on a scene orientation, corresponding to the relation between scene and ground coordinates. The scene orientation partially is distributed together with the satellite images. Usually this is coming from the direct sensor orientation of the imaging satellites using a positioning system like GPS, gyros and star cameras.

The rough sensor orientation may be available as orbit points for a specified time interval together with attitude information, in a reduced form as scene centre position together with the view direction to the satellite (like nominal collection azimuth and elevation) or as a orientation replacement model by rational polynomial coefficients (RPCs). In any case the given orientation information is not precise enough for the accuracy potential of space images and has to be improved by ground control points (GCPs) even if the direct sensor information of IKONOS is in the range of a standard deviation of 4m on the ground and for WorldView-1 it is claimed as 2.5m similar like GeoEye-1 with 3m. The orientation using orbit points and attitude information is in use since SPOT-1, launched in 1986. For IKONOS at first SpaceImaging liked to handle the precise geo-reference themselves, but they distributed the location of the scene centres and the nominal collection azimuth and elevation. This is sufficient for the geometric reconstruction of the orientation of images projected to a plane with constant height like IKONOS Geo, QuickBird OR Standard or in general as level 1B like defined by SPOT Image. In the Hannover program CORIKON the vector from the projected scene centre to the orbit is intersected with the published orbit parameters, leading to the right ascension (figure 1). With the distance from the scene centre in the imaging direction and the relation between the distance B on the ground and the orbital distance A (figure 1), the projection centre for each scene line can be computed respecting the earth rotation. This orientation should be improved by GCPs. After the so called terrain relief correction (shift of position based on height difference to the reference plane and view direction) a two-dimensional transformation has to be done. For IKONOS-scenes a simple shift is sufficient, for the other satellites a 2D affine transformation is required if the full accuracy potential shall be used.

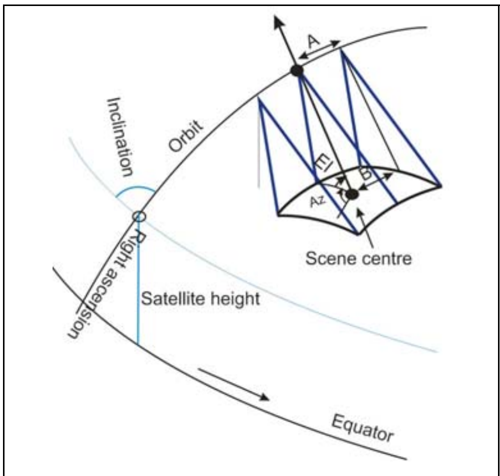


Fig. 1: orientation by geometric reconstruction

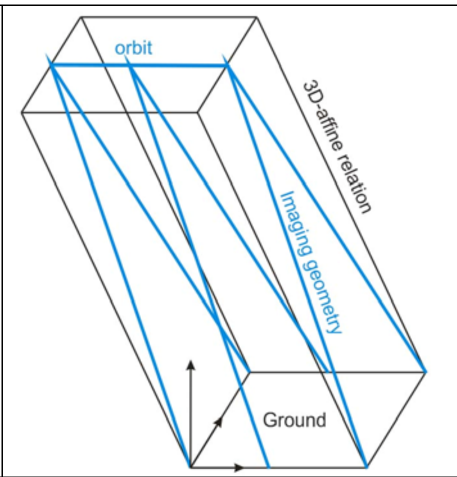


Fig. 2: 3D-affine transformation

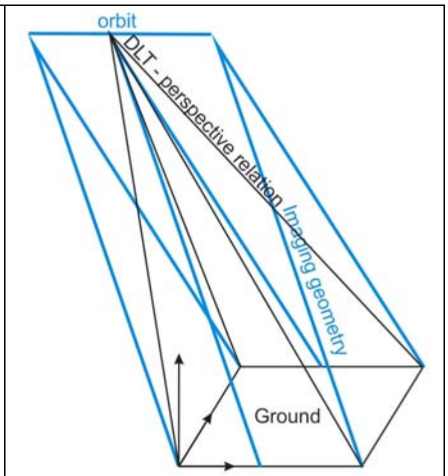


Fig. 3: direct linear transformation (DLT)

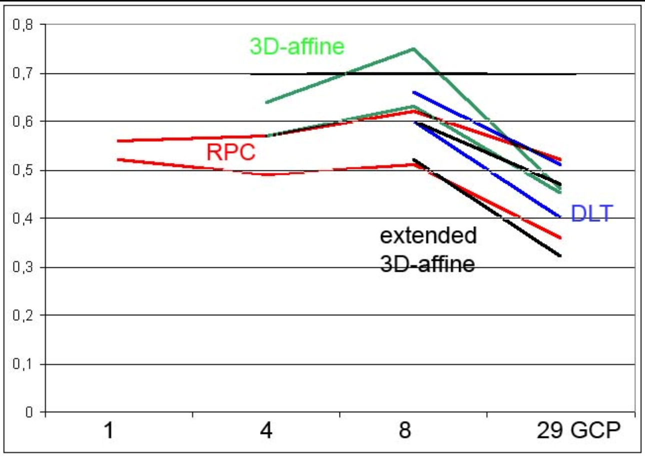
Instead of the exact geometric model, the relation between scene and ground coordinates can be replaced with RPCs, expressing the scene positions by the relation of two polynomial functions of the ground coordinates. Usually third order polynomials as F(longitude, latitude, height) are used, so with 2 x 40 coefficients the relation can be approximated in a sufficient manner (Jacobsen 2008). The RPC-solution has to be improved by control points like the geometric reconstruction, named as sensor oriented, bias corrected RPCs. The quality of the RPC-solution based on the direct sensor orientation of the satellites corresponds for usual scenes to the geometric reconstruction. Only for very large scenes a degradation of the accuracy can be seen. In some commercial software packages a limited number of polynomial coefficients are computed by means of control points, not using any of the available sensor orientation information. These “terrain dependent RPCs” are strongly dependent upon the three-dimensional control point distribution. The user is not getting any statistical information and cannot control the geometric quality with the commercial software packages and very large errors may occur in areas not well supported by control point. This terrain dependent RPC-solution should never be used, it is absolutely unserious.

Instead of the methods using information of the approximate satellite orientation, also some replacement models like 3D-affine transformation and direct linear transformation (DLT) are used. The standard 3D-affine transformation (terms a1 up to a8 in formula 1) is the mathematical model of a parallel projection (figure 2), while in fact we have perspective geometry in the sensor line. For scenes with a small field of view like IKONOS and limited Z-range in the object space, the 3D-affine transformation leads to acceptable results. For a larger field of view like in the case of QuickBird and larger Z-range in the object space, the achieved accuracy is degraded. Here an extension of the 3D-affine transformation up to term a12 may solve the lack of the mathematical model, but requires more control points. In any case more and three-dimensional well distributed control points are required. If original images (Basic or level 1A) have to be handled, the 3D-affine transformation needs a further extension up to whole formula 1.

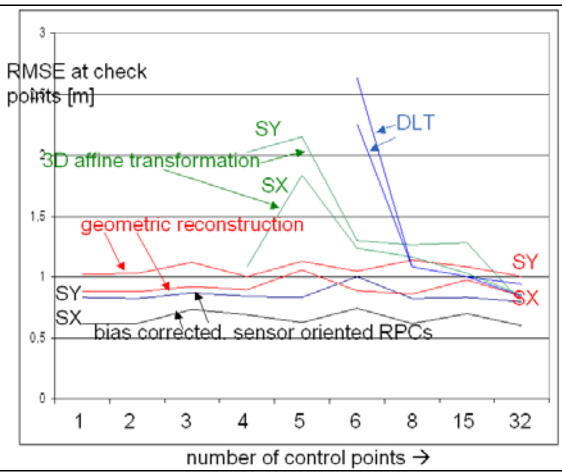
$$xij = a1 + a2*X + a3*Y + a4*Z + a9 *X*Z + a10*Y*Z + a13*X*X$$
$$yij = a5 + a6*X + a7*Y + a8*Z + a11*X*Z + a12*Y*Z + a14*X*Y$$

formula 1: extended 3D-affine transformation

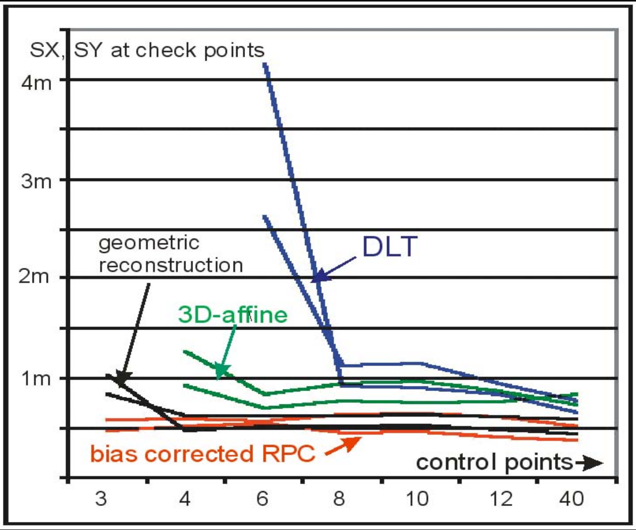
The mathematical model of the DLT is perspective geometry, determining inner and exterior orientation together. This model also does not fit to the satellite image geometry (figure 3). The DLT is still in use as a replacement model, not requiring any pre-information about the sensor orientation. For the 11 unknowns at least 6 three-dimensional well distributed control points are required. Beside the not strict geometry, the unknowns of the DLT are usually strongly correlated with correlation coefficients exceeding r=0.99. Such correlation may lead to geometric problems in regions not well supported by control points.



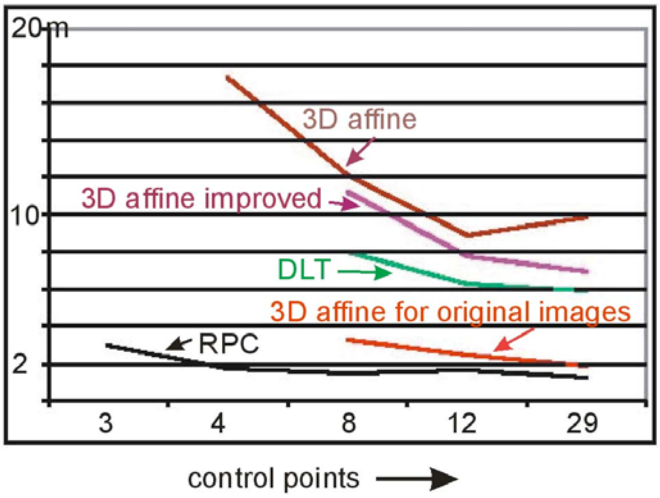
WorldView-1, Basic (0.5m GSD)



IKONOS Geo (1m GSD)



QuickBird, OR Standard (0.6m GSD)



OrbView-3, Basic (1m GSD)

Fig. 4: accuracy of the sensor orientation determined at independent check points (vertical [m]) depending upon the number of used control points (horizontal).

As shown in figure 4, the results based on the sensor oriented, bias corrected RPCs and the geometric reconstruction are approximately on the same level of 1 ground sampling distance (GSD) or better. Only with OrbView-3 this accuracy has not been reached, but OrbView-3 worked with over-sampled pixels, it had 1m GSD but 2m projected pixel size. For 3D-affine transformation and DLT quite more control points are required and not in any case a similar accuracy has been reached. Especially for the larger field of view of QuickBird and for the Basic imagery of OrbView-3 the extended 3D-affine transformation is required. In general it can be said, that the approximate solutions 3D-affine transformation, DLT and terrain dependent RPCs are not justified. A geometric reconstruction or the bias corrected, sensor oriented RPCs should be preferred.

GENERATION OF HEIGHT MODELS

Digital elevation models (DEMs) are required for several purposes; they are a basis component of a GIS. By automatic image matching of stereo pairs digital surface models (DSMs) with the height values of the visible objects can be generated. From a DSM a DEM with the height values of the bare ground can be achieved by filtering the objects not belonging to the bare ground if enough points on the ground are available in the DSM (Passini et al 2002). The DSM from the shuttle radar topography mission (SRTM) can be downloaded from the internet free of charge. It is available with 3 arcsec spacing, corresponding to 92m at the equator. The standard deviation of the height values (SZ) of the SRTM DSM depends upon the area. For open and flat terrain SZ is in the range of 4m, in rolling and mountainous areas it is in the range of $SZ = 5m + 8*\tan\alpha$, where α is the terrain inclination. In forest areas systematic height errors have to be expected (Passini, Jacobsen 2007). If the 3 arcsec spacing and the vertical accuracy of the SRTM DSM are not satisfying, the generation of height models from space image stereo pairs are justified. Especially the 3 arcsec spacing cannot be accepted in rolling and mountainous areas.

The classical arrangement of corresponding images taken from neighboured orbits is not optimal. The time period between imaging often is too large, so that changes of the object and changes of the sun elevation are causing problems for the automatic image matching. Modern high and very high resolution optical satellites are flexible and can change the orientation against the orbit very fast, allowing the generation of stereo pairs within approximately 1 minute. In addition with ASTER, SPOT5-HRS, Cartosat and ALOS-PRISM stereo satellites are available and also the old CORONA stereo pairs can be used.

Sensor	GSD [m]	height / base	area	SZ [m]	SZ F(slope) [m]	Spx [GSD] flat area
ASTER Zonguldak	15	1.7	open	25.0	$21.7+14.5*\tan\alpha$	0.8
			forest	31.2	$27.9+18.5*\tan\alpha$	1.1
			check points	12.7		0.5
KOMPSAT-1 Zonguldak	6.6	2.0	open	13.6	$11.3+11.5*\tan\alpha$	0.9
			forest	14.7	$14.1+12.1*\tan\alpha$	1.1
SPOT 5 Zonguldak	5	1.85	open	11.9	$8.4 + 6.3*\tan\alpha$	0.8
			forest	15.0	$9.8 + 5.3*\tan\alpha$	1.1
			check points	3.8	$3.5 + 0.9*\tan\alpha$	0.4
SPOT 5 HRS Bavaria	5*10	1.2	open	6.7	$6.4 + 4.9*\tan\alpha$	1.1
			forest	17.0	$16.4+ 2.2*\tan\alpha$	2.7
SPOT 5 HRS filtered Bavaria	5*10	1.2	open	4.4	$4.2 + 1.6*\tan\alpha$	0.7
			forest	12.3	$10.0 + 6.9*\tan\alpha$	1.7
IKONOS Maras	1	7.5	open	1.7	same orbit	0.2
IKONOS Zonguldak	1	3.8	open	5.8	Δt = 3 month	1.5
QuickBird Arizona	0.62	9.1	open	4.8	Δt = 10 days	0.8
OrbView-3 Zonguldak	1	1.4	open	8.5	$4.4 + 15.7*\tan\alpha$	3.1
Cartosat-1 Warsaw	2.5	1.4	open filtered	2.4	$2.39 + 8.8*\tan\alpha$	0.7

Table 1: overview - accuracy of DEMs based on different space images

By automatic image matching with least squares, height models with standard deviations against reference height models like shown in table 1 have been generated. In general the vertical accuracy cannot be expressed just with one figure. A detailed analysis showed an accuracy structure which can be expressed very well with SZ = A + B ∗ tan α, where α is the terrain inclination. Of course in open areas a better result than in the forest can be reached. Results achieved at check points cannot express the DEM / DSM accuracy. Check points are located usually in flat terrain at locations with good contrast. So the accuracy determined at check points usually is better by the factor 2 than the accuracy determined by a comparison against a reference height model. Before the comparison against a reference height model a horizontal shift of the height models has to be checked and respected by adjustment. A shift of the reference height model often has been seen, mainly caused by datum problems. A filtering for elements not belonging to the bare ground is strongly improving the accuracy, as it can be seen at the examples of SPOT-5 HRS and Cartosat-1. Only in forest areas a filtering does not help because of missing points on the bare ground. SPOT-5 and SPOT-5 HRS stereo models are not optimal in forest areas, where gaps in the DSM cannot be avoided. SPOT-5 and SPOT-5 HRS are sensitive mainly for the visible range from 0.48 – 0.70µm wavelength. In this spectral range forest may be very dark causing a poor grey value range. IKONOS, QuickBird and OrbView-3 are sensitive for the spectral range from 0.5 up to 0.9µm wavelength, similar to Cartosat-1 with 0.50 up to 0.85µm. With these sensors no problems of matching in forest areas exist. In an extreme case of mountainous forest in Turkey, SPOT-5 HRS failed nearly completely, while with Cartosat-1 good results have been reached (Büyüksalih et al 2008). The standard deviation of the height SZ can be expressed as SZ = h/b * Spx, where h/b is the height to base relation of the stereo model and Spx is the standard deviation of the x-parallax in [GSD]. As it can be seen in table 1, in open and flat areas usually a standard deviation of the x-parallax of one GSD or better can be reached. In the case of IKONOS in Zonguldak there was a time difference of 3 month between the images causing large gaps in the DSM and a lower accuracy. For OrbView-3 not a precise reference height model was available.

In build up areas the automatic image matching of high resolution images is difficult. The difference in the view direction is causing differences in corresponding image parts – in one image the roof and one façade, in the other image the roof and the opposite façade may be seen. Here a smaller convergence angle (larger height to base relation) may lead to better results than the usual h/b of 1.4 up to 1.6. In addition the matching window causes a rounding of the objects. At the location of a building edge, 50% of the matching window is located on the roof, while 50% may include parts of the façade or the ground. In a 3D-representation the DSM is showing buildings as hills and not with sharp edges. Here a different method of matching like dynamic programming may be helpful. The required epipolar images can be ordered from some of the satellite image distributors or they have to be generated. In the case of dynamic programming one epipolar line is compared with the other, allowing the determination of building edges and the occlusions (Alobeid, Jacobsen 2008).

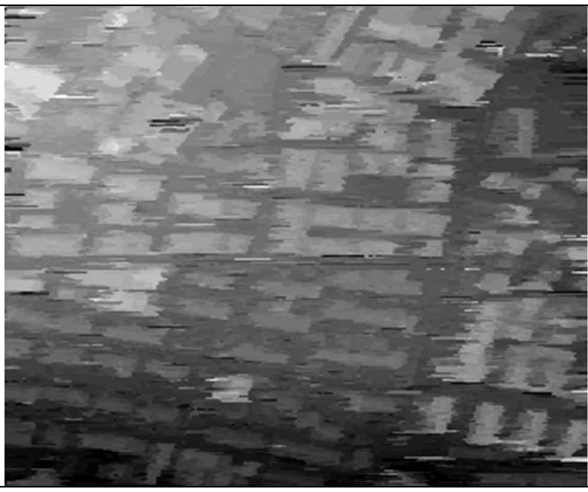


Fig. 5a: disparity matrix from dynamic programming – IKONOS, Istanbul city

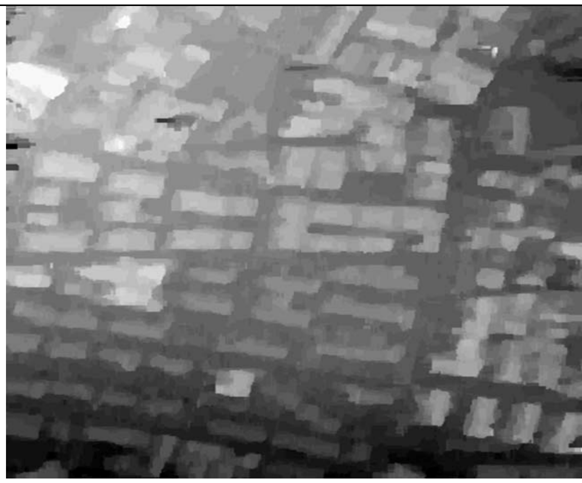


Fig. 5b: disparity matrix median filtered in y-direction

Figure 5a shows the disparity matrix (x-parallax for every pixel) of a part of an IKONOS epipolar image pair in the densely build up Istanbul city area. The buildings are well detected, but caused by the fact, that dynamic programming uses only one line, noise cannot be avoided. By median filter in the vector perpendicular to the epipolar line, the noise can be eliminated and the buildings came out very clear with sharp edges (figure 5b).

MAPPING

With most of the images listed in table 1, line maps have been generated. The data acquisition is possible three-dimensional in a stereo model or as on-screen digitizing of orthoimages. By economic reasons – only one space image is required for an orthoimage – and because of simpler handling, in most cases the on-screen digitizing is preferred. Some tests showed only a loss of few details by on-screen digitizing against stereo mapping. Nevertheless the object identification is simpler in the stereo model. Colour is simplifying the object classification, but there was only a negligible loss of elements in the case of panchromatic images. Even if today the data acquisition is made in a GIS directly in the object coordinate system, the details of data acquisition are corresponding to a presentation scale, also today named as map scale. A map shall have an accuracy of approximately 0.2mm up to 0.3mm in the map scale and it shall show the object details corresponding to this presentation scale. The accuracy is usually not the limiting factor; 1 GSD can be reached without problems. The limiting factor is the details which can be identified. Intensive tests (Jacobsen, Büyüksalih 2008) showed; images with 0.1mm GSD in the map scale are required. So for a map 1 : 10 000 a GSD of at least 1m has to be used. In addition the GSD should not be larger than 5m because also in a smaller map scale elements have to be included which have to be shown independent upon the map scale.

CONCLUSION

Space images today are competing with aerial images for mapping including the generation of DEMs. The method of orientation has been solved, approximate solution should be avoided, they require more control points, so they are not economic. The automatic image matching became a standard for digital elevation models. Stereo pairs from the same orbit should be used, the high resolution stereo satellites, sensitive up to the near infrared, have some advantages. For the generation of 3D-city models other methods are required like for open areas. In general, the use of high and very high resolution optical satellite became a standard for mapping.

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