AUTOMATIC MATCHING AND GENERATION OF ORTHOPHOTOS FROM AIRBORNE AND SPACEBORNE LINE SCANNER IMAGES

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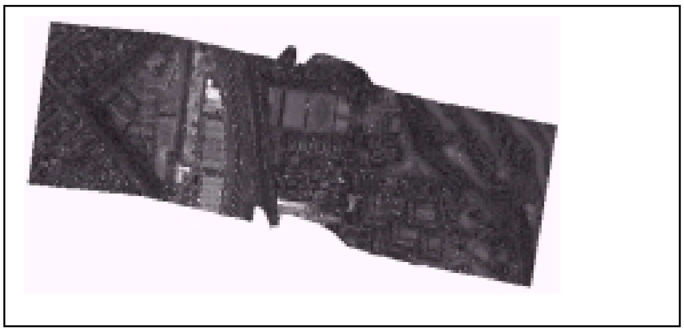
ABSTRACT

Caused by the turbulent atmosphere, the original airborne line scanner images are partially strongly deformed against normal case images and the ground coordinate system. An automatic matching requires a special program which can use the available orientation information from a combination of relative kinematic GPS-positioning and inertial measurement system (IMU). Another possibility is the rectification of the line scanner images to a chosen height level using the camera orientation for every single line. Such rectified images are displaced by the actual ground height and the view direction – especially in the case of inclined lines. The geometry is very close to the geometry of stereo orthophotos, also a stereo view is possible. With these rectified images an automatic image matching is possible by programs based on the region growing method like program DPCOR and with a special program the ground coordinates of digital elevation models (DEM) can be computed with the matched corresponding pixel positions of the rectification's and the sensor orientation. Exactly the same situation is given by the GEO-product of IKONOS-images. They are also rectified to a chosen height level. For the ortho-rectification of IKONOS GEO-products it is not necessary to use the full sensor orientation, the available nominal collection azimuth and elevation is totally sufficient. If control points in different height levels are available, also this information is not required for an optimal geometric correction shown at an example in a mountainous area.

A test block of HRSC-A-images has been rectified and the DEM's are achieved by automatic matching with DPCOR and computation of the ground coordinates by HRINT. Based on overlapping, independent flight strips an accuracy estimation was possible. The height accuracy corresponds to an accuracy of the x-parallax of 0.6 - 0.9 pixel.

1. HRSC – rectification

Original airborne line scanner images may be strongly deformed against the normal case of photogrammetry caused by the turbulent atmosphere, influencing every line in a different way. An automatic image matching in the object space requires the full information of the sensor orientation for every line, so a special software is required for this. An automatic image matching in the image space is usually not possible, but standard matching programs can be used for rectified images, they do have a geometry similar to stereo orthophotos.



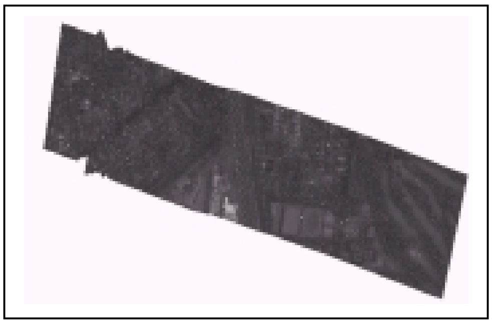


figure 1: rectified HRSC-images taken under turbulent conditions

The investigation of a data set taken with the aerial multiple line scanner sensor HRSC-A (high resolution stereo scanner) of the German Center for Aerial and Space Applications DLR was enabled by the Bundesamt für Kartographie (BKG), Frankfurt. With the program MSC of the BKG the original images have been rectified to a specified horizontal plane using the full sensor orientation, based on the Applanix combination of relative kinematic GPS and an inertial measurement unit (IMU), operating with 200 Hz. Two resulting rectification's are shown in figure 1 and 2. These extreme cases are demonstrating the impossible use of an automatic image matching in the original image space.

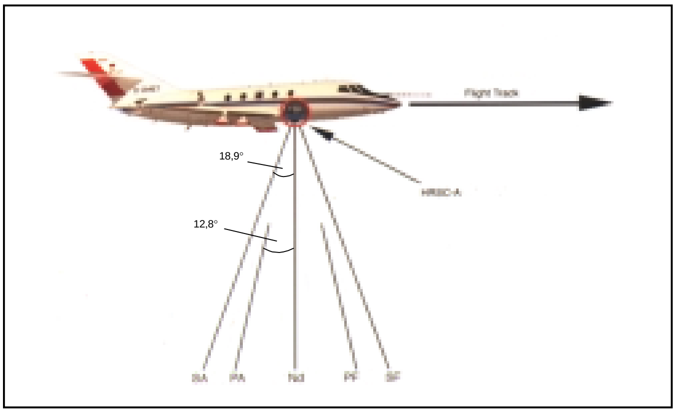


figure 2: geometric distribution of the HRSC-channels

The HRSC-sensor was originally developed by the DLR for mapping the Mars-surface. Based on this camera an airborne version has been constructed. From the available 9 CCD-lines, for the investigations only the nadir view and the most inclined panchromatic lines with a nadir angle of + 18.9° and –18.9° were used. With the flying height of approximately 2500m above ground, an original pixel size in the object space of 15cm has been reached.

The accuracy of the rectification's have been investigated by means of control points and the verification of long straight lines. Between 8 and 12 control points, determined by ground survey with GPS, having only limited differences in the height, are available for every scene. The mean square differences between the rectification's and the control points after affine transformation are shown in table 1. The affine transformation of the rectified HRSC images was necessary because of the limitation of the direct sensor orientation in this accuracy range.

Table 1: mean square differences between control points and affine transformed HRSC-A-rectification's

	flight strip 1		flight strip 2		flight strip 4		flight strip 5	
	SX	SY	SX	SY	SX	SY	SX	SY
nadir view	37mm	37mm	86mm	87mm	77mm	58mm	58mm	32mm
backward 18.9°	141mm	49mm	106mm	93mm	127mm	66mm	51mm	75mm
forward 18.9°	95mm	56mm	135mm	76mm	132mm	82mm	58mm	97mm

The mean square differences for X and Y for all flight strips was for the nadir view +/-72mm, for the backward view +/-109mm and for the forward view +/-110mm. This indicates an influence of the not respected ground height against the height level of the rectification of 83mm, corresponding to a height variation of 24cm for the control points – what is approximately the real height variation of the control points. With the exception of the influence of the height, no other special or systematic errors can be seen at the used control points. The excellent mean square differences of +/-72mm (0.5 pixel) for the nadir view, after fitting by affine transformation to control points, shows the high level of the relative accuracy of the direct sensor orientation.

Another possibility for a geometric evaluation is the analysis of straight lines in the object space. Such straight lines should be also straight lines in the rectification's. This enables the investigation also of possible local influences of a turbulent atmosphere, which may not be represented by the inertial data, operated with 200 Hz, corresponding to an image progress of approximately 2 pixel. Straight lines have been analysed especially in the centre part of the nadir view, where the influence of the limited height variation can be neglected.

Figure 3 shows the deformation of a straight line in the object space, represented in the rectification. This is an extreme case of the flight strip 2 (figure 1, left hand rectification) where the strong lateral acceleration could not completely be covered by the IMU. This is also visible in the image quality showing not sharp parts. In this case, the problem was caused by a rapid change of the yaw (kappa = flight direction) which can be seen in figure 4. The changes of the other rotations and especially the positions have not reached the same size. A similar problem is available in flight strip 4 (figure 2, right hand rectification). Also here the deviations against a straight line have reached the size of 30cm, corresponding to 2 pixel and again it is caused by a rapid change of the yaw.

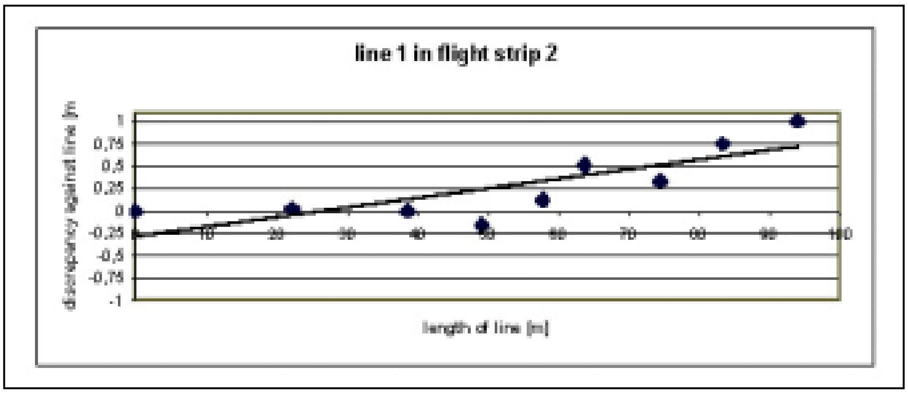


figure 3: deformation of a straight line in flight strip 2

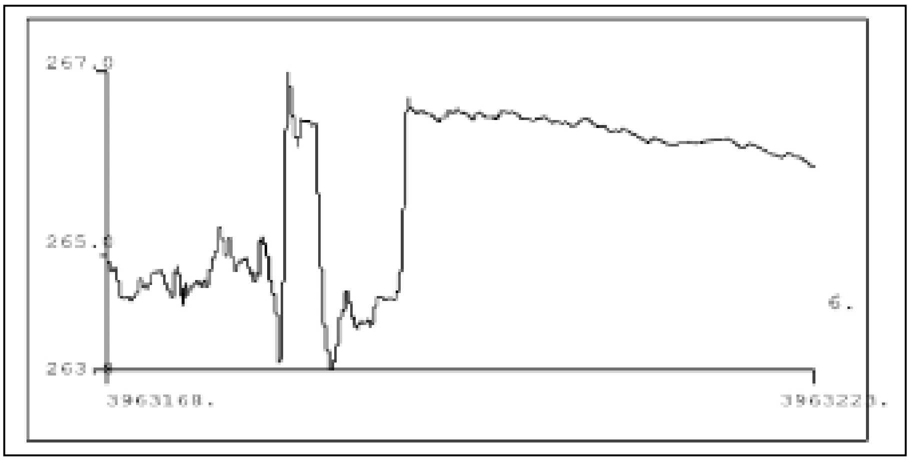


figure 4: change of yaw [°] in flight strip 2

In relation to the accuracy determined with control points of +/-72mm (0.5 pixel), the both extreme deviations in the range of 0.3m (2 pixel) can be accepted.

2. HRSC – automatic image matching

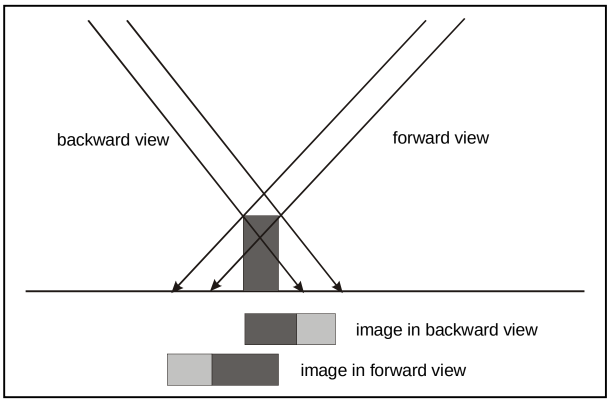


figure 5: geometric situation of rectified HRSC-images

Based on the HRSC rectification's, automatic image matching have been computed by program DPCOR. It is based on the region growing method, using the pixel positions of manual measured control and tie points as start values. The corresponding points are determined by a combination of image correlation and least squares matching. The image matching is handled in the image space. Starting from known corresponding points, other homologue points are identified in the neighbourhood and from these again other points are identified up to the covering of the whole model. This method has the advantage that it is not necessary to modify the matching program for the special image geometry. With the corresponding points, object coordinates have been computed by intersection with the special program HRINT of the University of Hannover using the HRSC rectification's, the direct sensor orientation and control points. Of course a program like HRINT, using the correct geometric model, is required for the determination of object coordinates, but this geometric model is separated from the image matching, so the image matching program DPCOR can be used without changes for several quite different applications like for aerial photos, IKONOS Geo-products and others. The geometric situation of the HRSC-rectification's can be seen in figure 5. The geometry is very close to the stereo-partner of a stereo-orthophoto where we do have exactly the same view direction. In the case of the HRSC, the view direction is changing only slightly corresponding to the recorded attitude data.

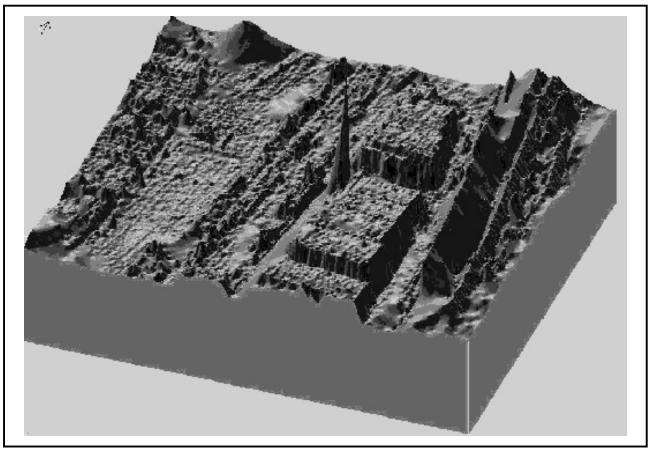


figure 6: sub-area of HRSC-rectification figure 7: generated DEM

In figure 6 a sub-area of a HRSC-rectification is shown and in figure 7 the DEM of the same area as a 3D-view generated by LISA-Basic. This area has been covered by 4 HRSC-flight-strips. With the combination of backward, nadir and forward view, several DEM can be generated from the same area. Mainly the combination of one inclined view and the nadir view have been used for the automatic image matching because of the fast height variation in this urban area. The combination of the backward with the forward view has caused larger gaps in the DEM. But some gaps can be seen also in the generated 3D-view (figure 7).

The region growing method, used in program DPCOR, is starting from corresponding points like the used control points and it is correlating the neighboured pixel. After correlation a least squares matching will be computed. In the case of a sudden change of the height like at a building, the procedure may not find some corresponding image positions in the neighboured positions. Also from other directions the identification of points located on top of the building may fail and so for example only the ground, but not the top of the buildings may be matched. In the upper left corner (see figure 6 and 7) the region growing method was not able to reach the top of the building and corresponding to this in the DEM there is only 1 point, leading to a 3D-view like a hill. In the region of the highway on the right hand side, the matching failed also because of not sufficient image contrast. In addition there is a mismatching in the centre, creating a steep peak in the 3D-view, but there is only one point causing this. DPCOR is creating only pairs of corresponding points. The object coordinates have been computed with program HRINT using also control points for an optimal location of the DEM.

Beside these problems, the elevations are presenting the area quite well. A lot of noise is caused by the vegetation, but also by parking cars. Finally not a DEM, but a digital surface model (DSM) has been generated, representing the visible surface and not the ground. Such a DSM is useful for several applications, but it can be reduced also to a DEM for example by the automatic method used by the Hannover program RASCOR (Jacobsen 2001). The same area has been matched with several different image combinations. After elimination of blunders, a standard deviation for Z between +/-24cm and +/-34cm has been reached. This corresponds to a standard deviation of the x-parallax between 8.2cm and 12.9cm or 0.6 up to 0.9 pixel. For the rough terrain this is a quite sufficient result.

3. IKONOS-products

Images taken by the space sensor IKONOS do have today the highest resolution available for civilian application. The original images of the line scanner camera are not distributed; only derived products can be bought as different CARTERRA versions. Caused by the lowest price, the CARTERRA Geo – a rectification to a surface with constant height – is mostly used. With the knowledge of the geometric relation it is possible to upgrade the Geo-product to an orthophoto or to determine ground positions with the possible highest accuracy of the mapping system. This requires an expensive stereo pair of images or a DEM. In general the Geo-product has a geometry which is very similar to the HRSC-rectification's.

The imaging system of IKONOS can produce panchromatic (pan) (black and white) with the very high or multispectral (ms) images with a four times lower pixel size. The original pixel size on the ground is depending upon the view direction (nadir angle) which can be changed in the orbit direction, but also across by +/-52°.

original pixel size on ground in view direction	$pv = 0.82m / \cos^2 \nu$	ν = nadir angle
original pixel size on ground across view direction	$pc = 0.82m / \cos \nu$	

formula 1: original pixel size on ground for panchromatic IKONOS images

nadir angle	0°	10°	20°	30°	40°	50°
pan across view direction	0.82	0.83	0.87	0.95	1.07	1.28
pan in view direction	0.82	0.85	0.93	1.09	1.40	1.98
ms across view direction	3.28	3.32	3.48	3.80	4.28	5.10
ms in view direction	3.28	3.38	3.71	4.37	5.59	7.94

table 2: original pixel size on ground [m] depending upon view direction

The pixel size across the view direction (= in orbit direction) is resulting in an oversampling. The oversampling is not changing the geometry; only the radiometric characteristic will be influenced by a low pass filter effect – that means the contrast will be reduced. A low contrast usually will be more than compensated by a contrast enhancement, named as "MTFC Applied: Yes" in the meta data, but of course the not available information cannot be brought back. Only derived products are available from the company Space Imaging, operating the satellite. The derived products are resampled with a square pixel format – for the pan-images with 1m x 1m and for the multispectral images with 4m x 4m. This is corresponding to a small loss of information for close to nadir images and for images exceeding a nadir angle of 25° the original information is below the used pixel size of 1m or 4m.

The imaging system of IKONOS, build by Kodak, is equipped with a Kodak linear array of 13 816 pixels for pan and 3454 pixels for multispectral, corresponding to a swath width of 11.329 km for a nadir view and up to 29.889km for a nadir angle across the orbit direction of 52°. The flying height varies between 678km and 682km (mean 681km) above mean sea level. The inclination of the satellite orbit against the equator is 98.2°, resulting in a sun-synchronous orbit – the satellite is imaging always at the same local time of the day at approximately 10:30.

CARTERRA -	horizontal accuracy	vertical accuracy	
Geo	50m	-	system corrected to earth ellipsoid and specified map projection
Reference	25m	22m	ortho rectified without control points (DEM with +/-22m required)
Map	12m	10m	ortho rectified without control points (DEM with +/-10m required)
Pro	10m	8m	ortho rectified without control points (DEM with +/-10m required)
Precision	4m	4m	ortho rectified with control points (DEM with +/-4m required)
Precision Plus	2m	3m	ortho rectified with control points (DEM with +/-3m required)

table 3: IKONOS- (CARTERRA-) products with accuracy claimed by Space Imaging

The satellite includes a GPS-receiver and star trackers, allowing a declared stand alone geo-location of +/-12m for X and Y and +/-8m for Z. Of course these are standard deviations which can be exceeded in the individual case and which do require a corresponding height accuracy coming from a stereo scene or an available DEM. The geo-location is present in the WGS84-system, which means, the relation of the national coordinate system to WGS84 (datum) must be known as well as the Geoid undulation. Based on control points, the CARTERRA Precision Plus shall reach a horizontal accuracy of +/-2m and a vertical accuracy of +/-3m.

4. IKONOS-geometry

Satellite line scanner images do have a geometry different from perspective photos. For each line we do have a different exterior orientation – the projection center (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.

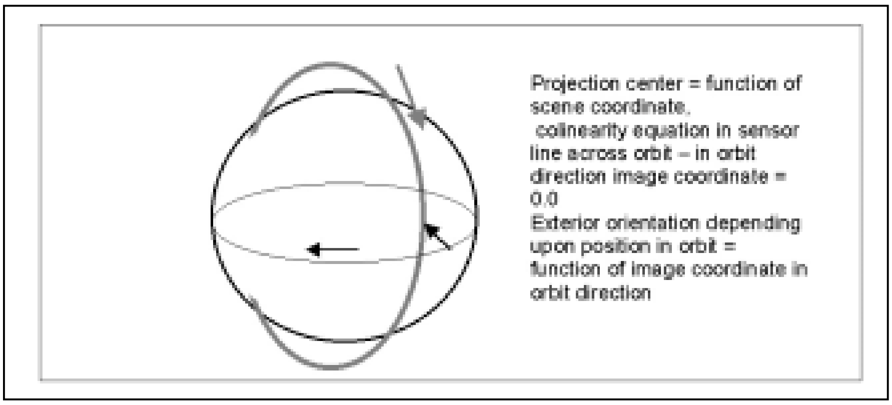


figure 8: geometric condition for satellite line scanner images

Based on a rough information about the satellite orbit, the geometric relation of such satellite line scanner images can be determined based on just 4 control points with the full possible accuracy for example with the Hannover program BLASPO. But like shown in table 3, Space Imaging is not distributing the raw images, only derived products are available. Of course from Space Imaging all the required products are available, but for a very high price and the control points together with the DEM have to be delivered to Space Imaging. If just the most often used CARTERRA Geo shall be upgraded to a higher accuracy level, a special mathematical solution is required.

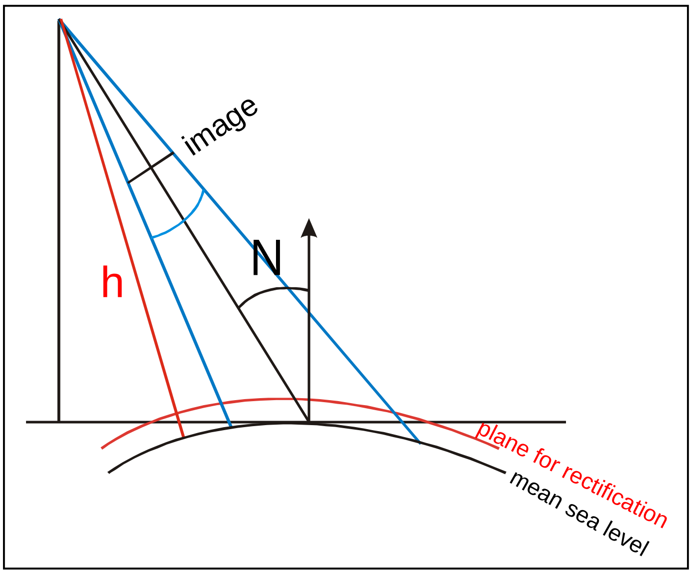


figure 9: : geometric situation of CARTERRA Geo-product

The Geo-product is rectified to a specified plane parallel to the earth ellipsoid. Beside the remaining errors of the image orientation, the geometry of such rectified images is influenced by the local height corresponding to figure 5, the geoid undulation and also the relation of the national coordinate system to WGS84 (datum).

The geometric situation of geo referenced CARTERRA Geo images has been analysed with the data set from the OEEPE-project "Topographic Mapping from High Resolution Space Sensors". A pan-scene with a displayed pixel size of 1m, located in Switzerland was given together with digital orthophotos and the Swiss DEM of the area as geo reference. The nominal collection elevation of 67.66476° (nadir angle 22.33°) corresponds to an original pixel size of 0,89m * 0.96m, which means the resampled scene includes only a small loss of information against the original image. The tangent of the nadir angle of 0.41 shows the relation between the height difference against the reference plane and the horizontal displacement.

The altitude in the mountainous region goes from 415m to 2197m above mean sea level. The DEM has a grid interval of 25m. The later required interpolation has been made bilinear because even a polynomial fitting of 2nd degree (6 unknowns) based on 3 x 3 points resulted in mean square discrepancies of 9.2m.

Control points have been measured in the available digital orthophotos and the IKONOS-Geo-scene. The available geo-reference of both allowed a direct handling of the coordinates of the IKONOS-scene in UTM (WGS84) and the Swiss orthophotos in the Swiss national coordinate system, an oblique Mercator system. Based on the X,Y-position in the orthophotos, the corresponding height has been interpolated in the DEM (Hannover program DEMINT). The three dimensional coordinates have been transformed from the Swiss national coordinate system to UTM (Hannover program BLTRA). In the UTM-coordinate system the control points determined in the IKONOS-scene could be compared with the transformed points from the orthophotos. Of course the positions directly determined with the CARTERRA-Geo-scene are depending upon the height against the reference plane and also a remaining scene orientation error. The square mean of the difference of in total 128 points reached: MSEX=+/-124.4m MSEY=+/-40.2m with maximal differences in X: -421m and Y: -77m (figure 11).

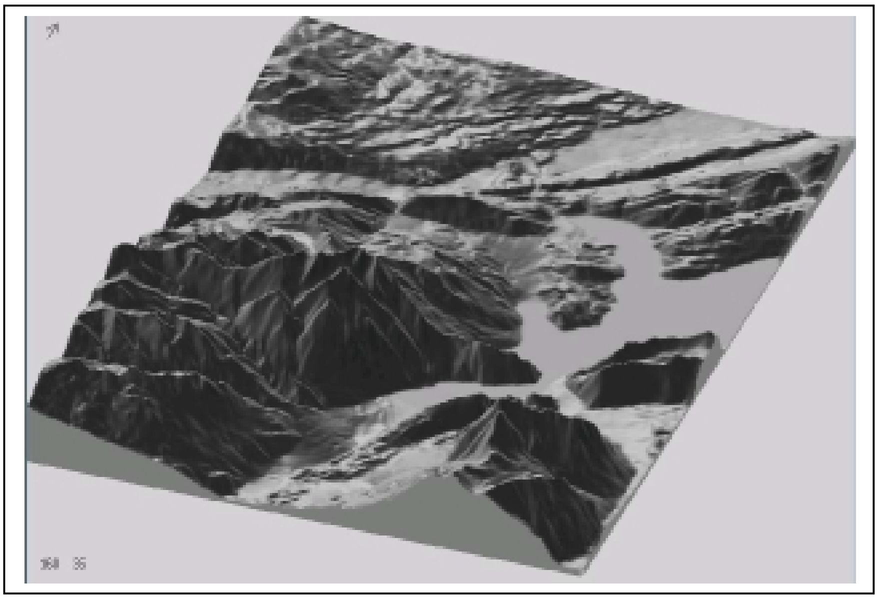


figure 10: DEM of the test area in Switzerland

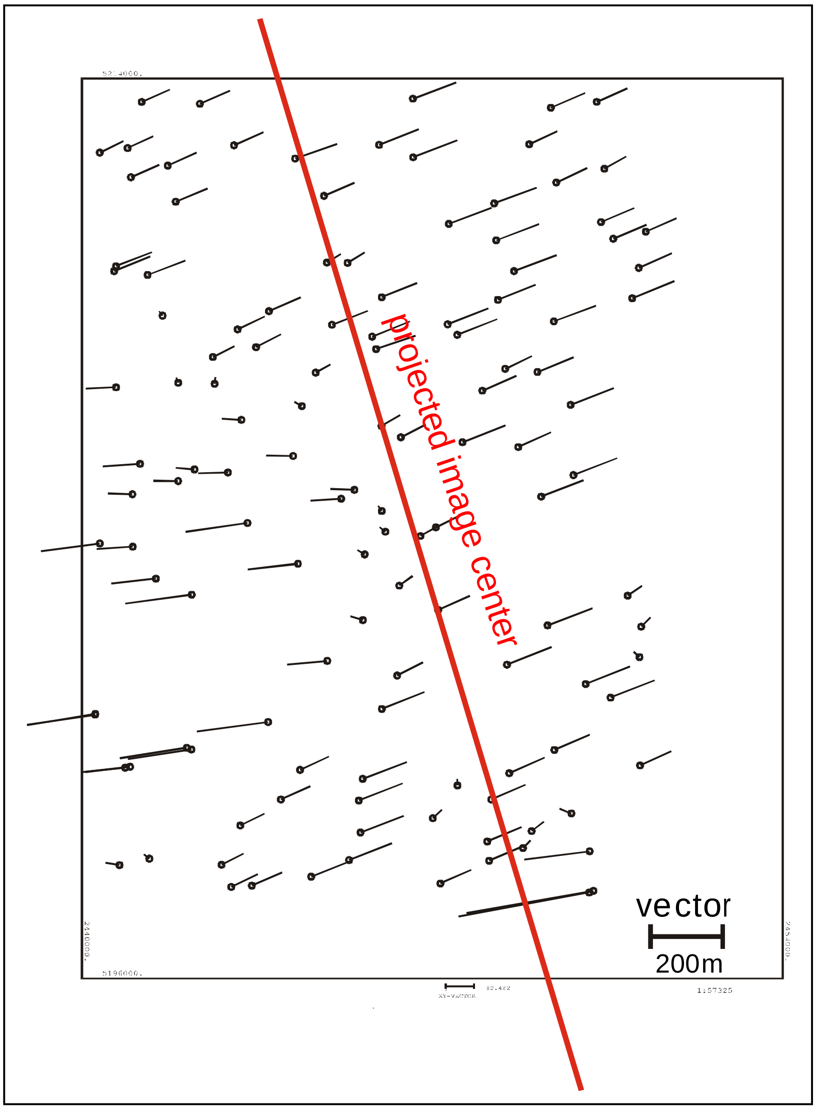
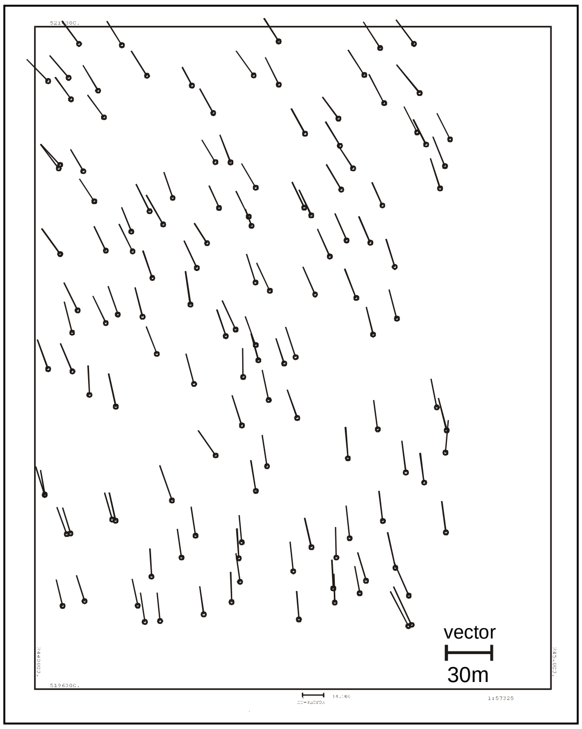


figure 11: geometric differences CARTERRA Geo against control points



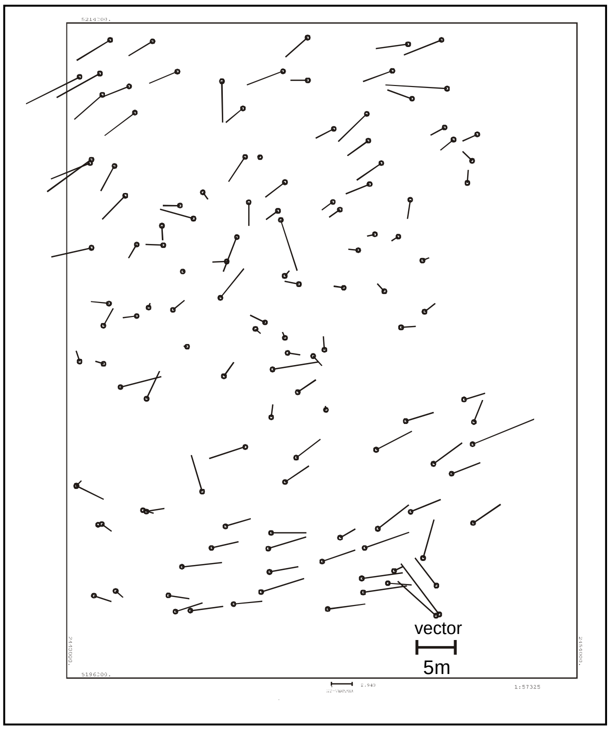
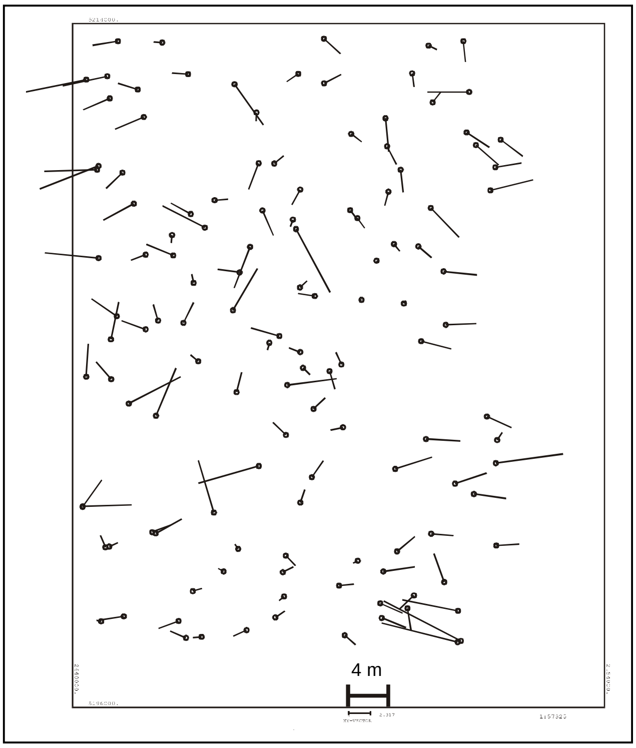


figure 12: differences after correction by the influence of height

figure 13: differences after correction by influence of height + shift in X and Y

The height level of the plane for rectification in this case is approximately 800m above mean sea level.



After correcting the influence of the height against the reference plane using the nominal collection elevation and azimuth together with the additionally required geometric model, the mean square differences have been reduced to MSE X=+/-7.5m and MSEY=+/-18.5m (figure 12). The again very obvious systematic errors can be explained by the accuracy of the geo-reference of the IKONOS-scenes without control points. A shift correction (in X: -6.8m, in Y: 18.3m) is reducing the mean square differences to MSE X=+/-3.5m and MSE Y = +/-2.3m. Again there are obvious systematic errors (figure 13) corresponding to a rotation of 0.4°, which means, a shift is not sufficient, a similarity transformation has to be used.

figure 14: differences after correcting the influence of height + affine transformation to control points

After height correction and similarity transformation to the control points the mean square differences are reduced to MSE X=+/-2.57m and MSE Y=+/-1.89m for 128 control points. These values are depending upon the used reference height for the rectification. If the reference height for the rectification has been used not corresponding to the definition used by Space Imaging, larger discrepancies could be seen. Usually the reference height for rectification is not known and has to be estimated. This problem can be solved also by an affine transformation instead of a similarity transformation after the height correction. Based on an affine transformation, the results are independent upon the reference height for transformation and in the case of the OEEPE-data set the mean square discrepancies are reduced to **MSE X=+/-2.52m** and **MSE Y=+/-1.72m** (see figure 14). Nevertheless there are local systematic effects shown by a covariance analysis, the relative accuracy of points neighboured up to a distance of 1km is only RMSEX=+/-1.76m and RMSEY=+/-1.23m. This can be explained by the accuracy of the control points itself, digitised from digital orthophotos – within the same orthophoto the accuracy is better than the absolute accuracy. In addition to this, a separate computation has been made only with control points which have been identified as good during the digitising procedure. For the 79 clearly visible control points the mean square differences are MSEX=+/-1.67m and MESY=+/-1.60m corresponding to approximately 1.6 pixels. Again here we do have an influence of the reference points from the orthophoto and the DEM, that means the final error component coming from the geometric improved IKONOS images is smaller, but here we are at the limit of the required accuracy. Corresponding to the rule of thumb, for mapping a pixel size of 0.05 up to 0.1mm in the map is required. This corresponds to a possible map scale for the panchromatic IKONOS images of 1 : 10 000 up to 1 : 20 000. For a map, the horizontal accuracy requirement is limited to +/-0.2mm or +/-2m for the map scale 1:10000. By this reason, no demand for a higher accuracy exists.

The shown results are based on the full number of control points used in the Hannover program CORIKON. If the nominal collection azimuth and the nominal collection elevation are available, the improvement of the Geo-scene can be made also with a small number of control points. Based on **4 control points**, at the 124 remaining points, root mean square differences of **RMSX = +/- 2.00m** and **RMSY = +/- 1.99m** have been reached – in the mean square of both components just 8% more than in the case of the use of all control points.

5. Conclusion

The geometric handling of rectified HRSC-images and IKONOS-Geo-products is very similar. Based on rectified images an automatic image matching is possible in the rectification's. With a DEM the points located in the rectification's can be transformed into the object space, using the view direction from the sensor to the plane of rectification, so the generation of orthophotos is possible. The geometry of CARTERRA Geo-products can be upgraded without knowledge of the full scene orientation to an accuracy corresponding to the CARTERRA Precision Plus. Only a limited number of control points are required if the nominal collection azimuth and the nominal collection elevation are available. If this is not the case, control points, covering the whole Z-range in the scene have to be used for the determination of these values.

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