

Geometry of vertical and oblique image combinations

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ABSTRACT: For city planning and security services the combination of vertical and oblique images like from Pictometry and Multivision recently became very popular. For larger cities a high number of such image combinations are even included in Microsoft Virtual Earth. The geo-reference of the image combinations usually is based on direct sensor orientation – the combination of GPS and inertial measurement units. The images are taken by camera systems like Track’Air MIDAS, equipped with 5 Canon EOS cameras, each with 4992 x 3328 pixels. The Canon EOS is not really a metric camera; it keeps the inner and the system orientation only stable during one photo flight. The images are also used for simple measurement purposes as well as the generation of 3D-city models. If object information without disturbing loss of accuracy against the direct sensor orientation is required, a system calibration during the day of the photo flight has to be done. The method of calibration and achieved accuracy is described as well as the characteristics and potential of the image combinations.

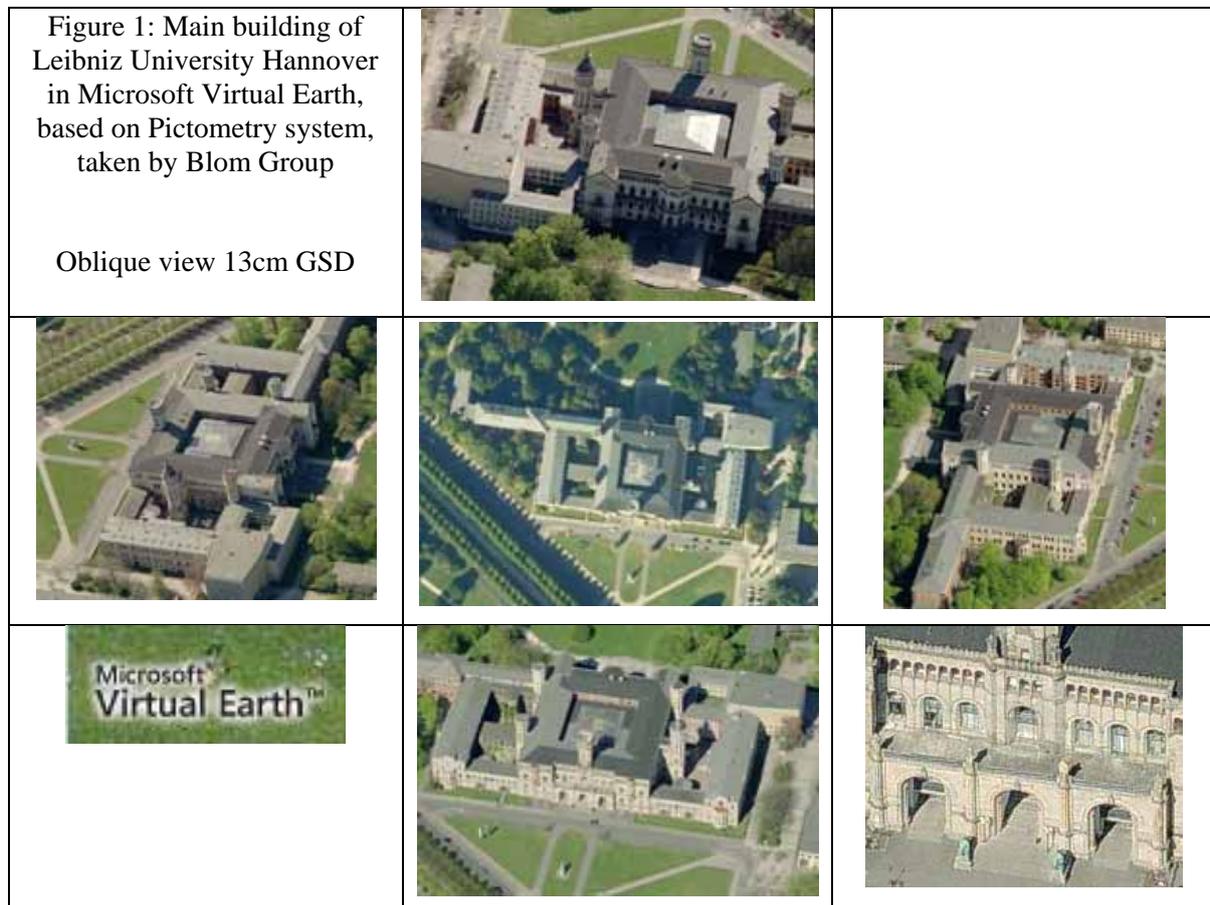
1 INTRODUCTION

The interpretation and understanding of vertical aerial or space images requires experience. For untrained persons the interpretation of terrestrial or oblique images is easy because they are closer to the standard experience in viewing to objects. In addition usually the facades are not or nearly not visible in vertical images. With the combination of vertical and oblique images totally new application for photogrammetry came.

Such images like from the Pictometry system using a camera system with one vertical and 4 oblique cameras are widely used by Microsoft Virtual Earth as “Bird’s Eye” (Figure 1). In Western Europe the Blom Group is imaging all cities with a population larger than 50000, that means approximately 900 cities with together approximately 100 000 km². 12 Pictometry camera systems are in use for this. The competitor MultiVision is using a similar system.

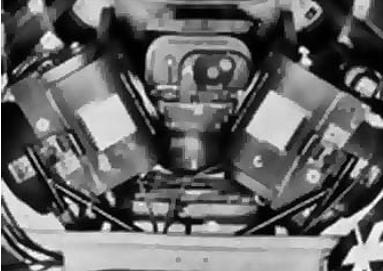
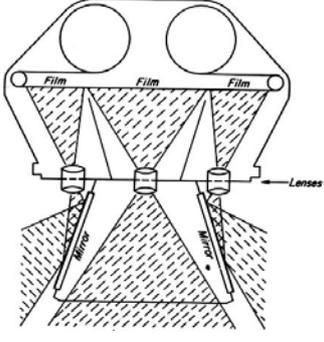
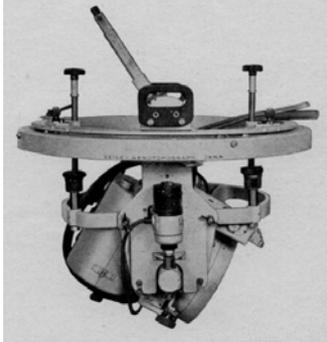
The commercial application of the combination of vertical with oblique images like generated by Pictometry and MultiVision systems is dominated by visual inspections and simple measurement of distances for public safety and planning purposes. The use together with geoinformation systems requires the knowledge of the exterior orientation of every image together with a digital elevation model (DEM). Block adjustments are too time-consuming and complex, so the exterior orientations are based on direct sensor orientation – the use of the combination of

inertial measurement units (IMU) together with relative cinematic GPS-positioning. In several countries networks of permanent GPS reference stations are available, but also with satellite based reference systems like OMNISTAR and different off-line reference systems, like JPL Final, the GPS reference is available in sub-meter accuracy. Especially for planning purposes not only the visualization is important, also some metric information is used. This requires a calibration of the imaging system and the relation to the IMU and the GPS-antenna.



The use of oblique aerial images or the combination of vertical and oblique images is not a new invention. Prior to 1938 in the USA, UK, Germany, France, Italy and Switzerland single and multiple lens cameras have been produced for oblique or combined configuration (Manual of Photogrammetry, 2nd edition) and Moffit 1967 (figure 2). Scheimflug invented an eight-lens camera in 1900, viewing oblique into 8 directions, Aschenbrenner developed in 1920 a 9-lens camera with 8 oblique and a nadir view, similar to the USGS 9 lens camera (figure 2).

In military reconnaissance oblique images are in use since long time. They combine the advantage of a view to facades and other vertical objects, together with imaging from distance. The orientation and calibration of such systems, partially with extreme long focal length, is known since longer time (Jacobsen 1988). The combination of a nadir, 2 low and 2 high oblique images taken by the Z/I Imaging KS-153 can be seen in figure 3. Today oblique images even can be taken by the very high resolution satellites like WorldView-1 (fig. 4).

		
		
		
<p>above: Aschenbrenner's 9-lens camera 1920 centre and below: USGS 9-lens camera</p>	<p>3 above figures: Trimetrogon below: Scheimpflug's 8-lens camera (1900)</p>	<p>Zeiss oblique camera arrangements</p>
<p>Figure 2: historic multiple lens and multiple camera arrangements for oblique aerial images</p>		

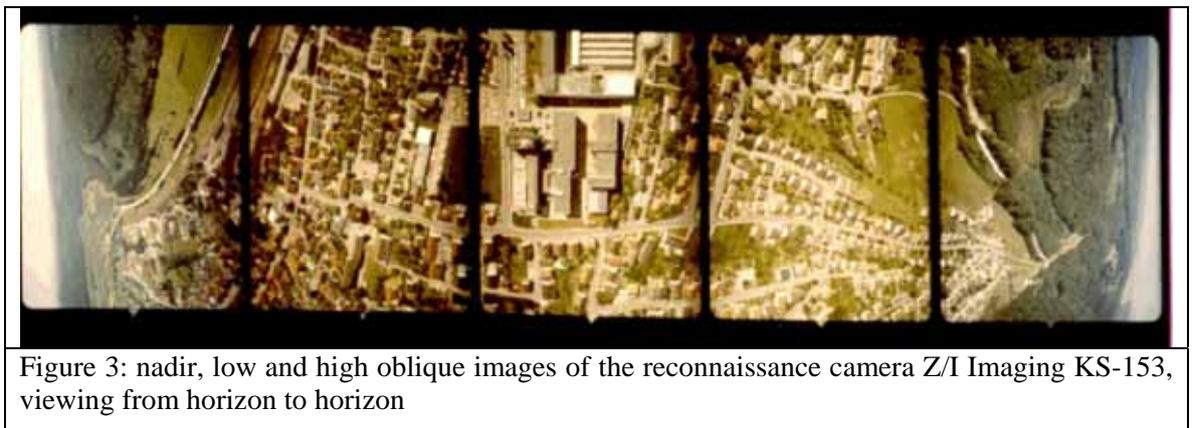




Figure 4: Dolmabahce palace, Istanbul in WorldView-1 image with 29.3° incidence angle

Today for the combination of nadir and oblique images dominating digital medium format cameras are used for civil application, allowing smaller systems which can fit to any standard aerial camera cone. Different camera combinations are in use. A typical camera system for such an application is the Track'Air (The Netherlands) MIDAS camera system. It has a combination of 5 of the shelf Canon EOS small format cameras with a focal length of 23.8mm for the nadir view and 51mm for the 4 oblique views (figure 5). The vertical camera has a field of view of 71.92° x 51.69° and the oblique cameras 38.8° x 26.4°, viewing approximately with 45° nadir angle, covering a nadir angle from 32° up to 58° (footprint arrangement – see figures 7 and 8). All 5 cameras have a CCD-array of 4992 x 3328 pixels with 7.2µm pixel size. The Canon EOS-cameras of the MIDAS system have a limited geometric stability, requiring more often a check of the calibration.



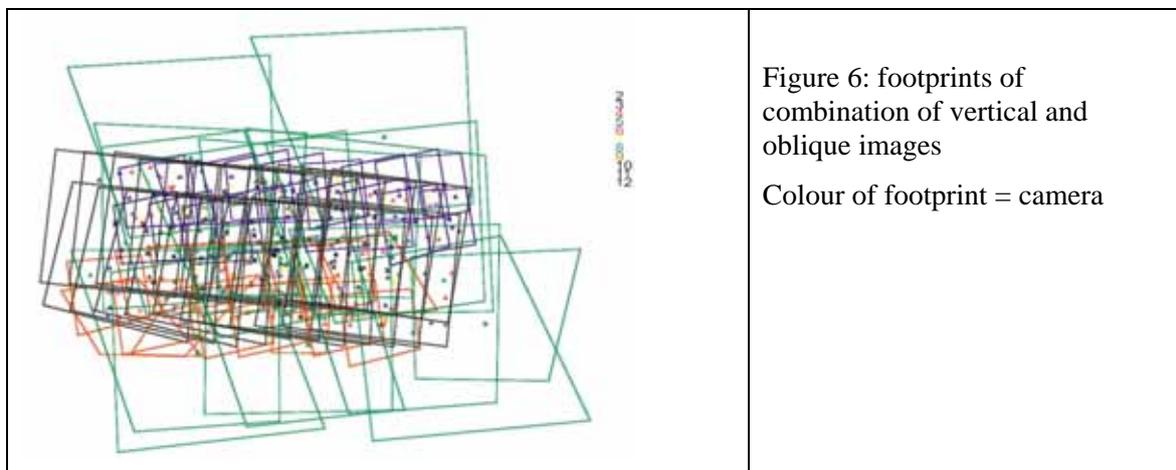
Figure 5: Track'Air MIDAS camera system – combination of 5 Canon EOS cameras

2 BUNDLE ORIENTATION OF VERTICAL AND OBLIQUE IMAGES

A data set with a combination of standard aerial wide angle photos (153mm focal length) and digital middle format images has been oriented by bundle block adjustment. The 3 different digital cameras have the same CCD-array like the Canon EOS, described above and focal length of 84.3mm, 169.5mm and 169.8mm. The oblique images have nadir angles in the range of 50°.

The image scale for the vertical images is approximately 1:4600 (9cm ground sampling distance (GSD) based on 20µm pixel size), for the centre of the oblique images 1:9400 (7cm GSD), 1:9900 (7cm GSD) and 1:26000 (19cm GSD). Because of the unusual arrangement and the different type

of images no automatic block adjustment was possible with standard commercial software for automatic image matching, so the tie points had to be measured manually. Only 13 ground control points and no direct sensor orientation has been used, but for such a block with an extreme number of ties, with up to 16 images per ground point, this is quite enough. The bundle block adjustment did not cause any problem, only the number of blunders was higher than usual; but this was expected because of the quite different image scale, different view directions and the combination of digitized analogue photos with digital images. The σ_0 value of $20\mu\text{m}$ was satisfying for the required purpose. At the ground control points for the horizontal component root mean square errors of 2cm and for the height 7cm have been reached. The orientation by traditional bundle adjustment is possible, but the manual measurement of tie points is time-consuming. That means for such an image configuration the direct sensor orientation (use of GPS + inertial measurement system (IMU)) is a must. Only for the calibration a manual measurement of the tie and control points of such a block is justified, but after the first initial calibration, the preceding calibration can be used for support of the measurement.



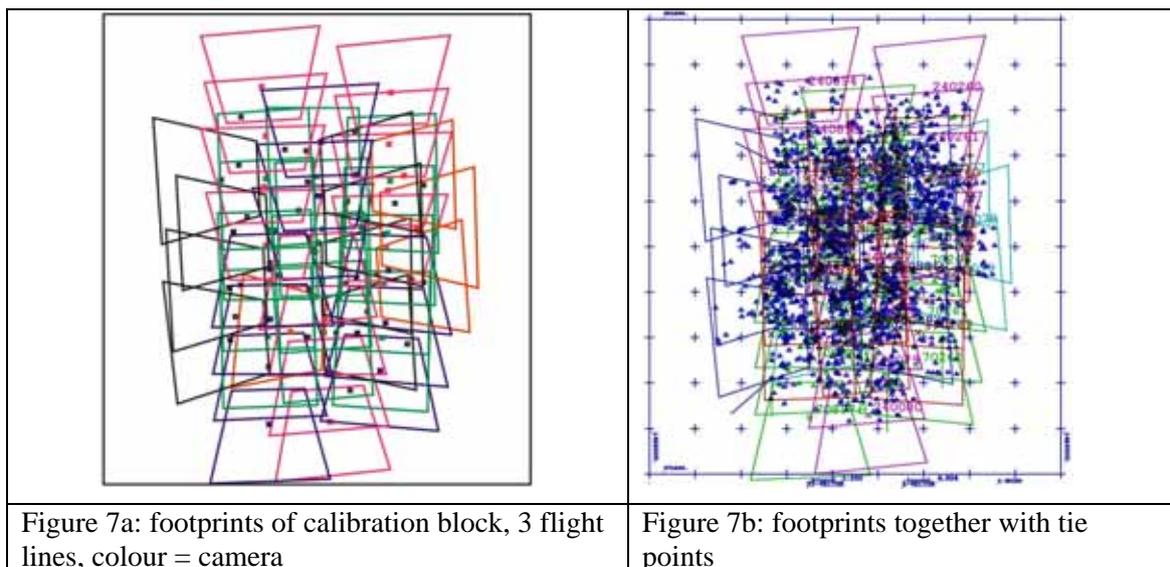
3 CALIBRATION OF TRACK' AIR MIDAS CAMERA SYSTEM

A larger area has been flown with the Track'Air MIDAS camera system, organized by MultiVision. The camera with the nadir view has a focal length of 23.8mm and the oblique cameras approximately 51mm. This corresponds for the vertical view to 17cm GSD and for the oblique images to 10cm x 11cm up to 15cm x 29cm. For oblique images the GSD in the view direction is the GSD across the view direction divided by the cosine of the nadir angle, so it is not a square size.

3 flight lines, each with 4 vertical images, and the corresponding oblique views have been used for the bundle block adjustment. This should lead to a configuration like shown in figure 8c, but some of the oblique images are not well connected with the block, so they are not supporting the calibration significantly. By this reason some of these images have not been used (figure 7a). The centre flight line has been flown from north to south, while the other both have been flown in the opposite direction, improving the calibration configuration.

The data acquisition was made with LPS. LPS had no problems to match the vertical images (figure 8a) and overlapping images in the image space, but for the oblique images the matching is limited to the connection of 2 neighboured images. An automatic image matching of the whole test block, even if it was supported by initial image orientation of the first bundle block adjustment, failed. LPS has not been developed for automatic aero triangulation of such a configuration,

starting with the problem of different focal length. So a combination between manual pointing and matching of 2 images was used. The automatic matching of overlapping different image combinations often leads to the extraction of corresponding object points. The used Hannover program system BLUH for bundle block adjustment is able to identify such points based on their similar object coordinates und can rename corresponding points to the same point names, leading to a better block tie. Some extension for program system BLUH was necessary, starting with the automatic exclusion of object points from the adjustment located only in images taken from the same projection centre. Such points do not allow the computation of object coordinates. As control information an orthoimage with 1m GSD and a DEM was used. For the vertical images this was leading to a σ_0 of $11\mu\text{m}$ and root mean square discrepancies at the control points of 16cm for X and Y and 1.6m for Z (table 1).

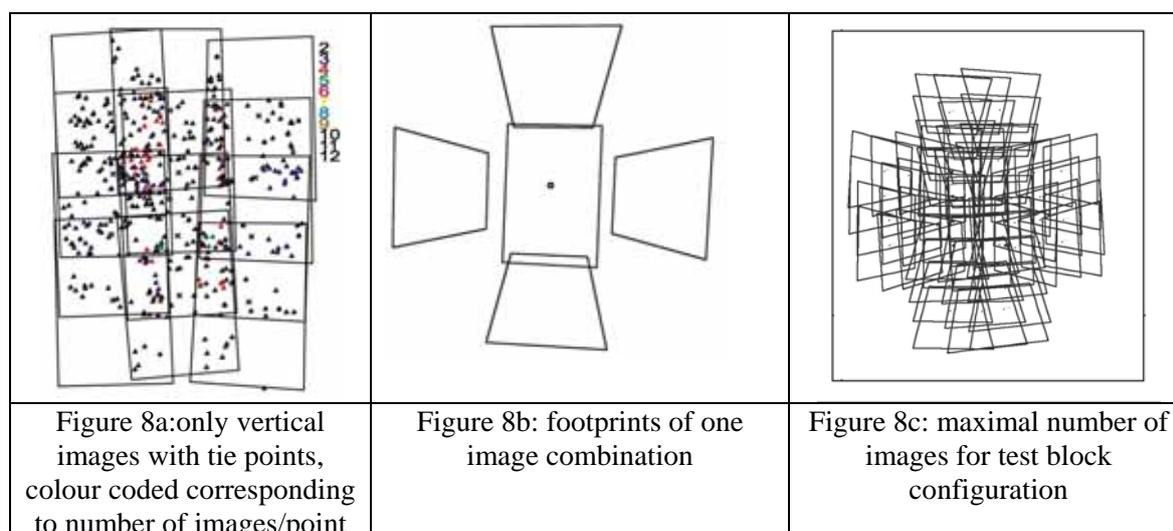


By the adjustment of all images of the test-block (figure 7) the system geometry and the camera geometry have been determined. The dominating systematic image errors are the radial symmetric components with values up to $100\mu\text{m}$. This is usual for the used optics. The radial symmetric distortions, as well as the overall systematic image errors, are similar for the oblique sub-cameras, using the same type of lens system. For the vertical sub-camera equipped with a different lens system it varies from the other. The systematic image errors, or in other words – the difference between the mathematical model of perspective geometry and the real image geometry, can be respected in the application software system for handling the vertical and oblique images, or it can be used for resampling the images to strict perspective geometry.

The σ_0 (accuracy of image coordinates) of the vertical images of $11\mu\text{m}$ corresponds to 1.4 pixels. With the average image scale of 1:11 000 it corresponds to 12cm on the ground, not far away from the reached root mean square discrepancies at the horizontal components of the control points. The larger discrepancies at the control point height only can be explained by the limited accuracy of the DEM used for the determination of the control point heights. In an adjustment of all images together the σ_0 is with $33\mu\text{m}$ larger, caused by the different view direction, but partially also by the limited accuracy of the control point heights (table 1).

Supported by relative cinematic GPS-positions of the projection centres, also the inner orientation has been improved. Of course there is a strong correlation between a shift of the GPS-positions, especially in Z-direction, and the inner orientation, but the block configuration together

with fixing the corresponding projection centres together, supports the determination of the inner orientation.



	sigma0	RMSX / RMSY control points	RMSZ control points
only 12 vertical images	11 μ m	15 cm	160 cm
all images	33 μ m	38 cm	122 cm

Table 1: accuracy of block adjustment of control-block 32 control points

Based on the improved inner orientation by combined block adjustment with GPS-coordinates of the projection centres, joining also the corresponding projection centres of the vertical and oblique images together, the relation of the oblique cameras to the vertical camera have to be determined (table 2). The image orientations taken from each projection centre have to be rotated by multiplying the rotation matrixes by the inverse rotation matrix of the vertical image. This leads to the rotation values for the nadir image of 0° for all 3 rotations. The averaged relative orientations of the oblique images in relation to the nadir view are identical to the internal system calibration.

Based on the orientation of the combined adjustment, the boresite calibration can be computed by comparing the orientation from the controlled bundle block adjustment with the inertial orientations. The boresite values are related to the roll, pitch and yaw-system, the required transformations are made within the Hannover program GPSCOR. The so computed boresite calibration values can be used in the same run or a separate run of GPSCOR for the correction of the inertial data. The corrected inertial data are corresponding to the orientation of the vertical camera. With the values of the internal system calibration (rotations of the oblique cameras in relation to the vertical camera – see table 2), with program ROTOR the exterior orientation of all images of a project can be computed. Of course the so computed orientations, within the calibration sub-block, should be close to the orientations from the controlled bundle clock adjustment.

The kappa-values of the orientation of the sub-cameras in relation to the vertical reference camera (table 2) show, that the sub-cameras are always oriented into the oblique view direction. The oblique angles vary from 49.1 grads up to 51.3 grads (44.2° to 46.2°). With orientation of the sub-cameras in relation to the nadir images, the orientations have been computed by ROTOR. With these orientations, object coordinates have been computed by combined intersection, resulting at the control points to RMSX=0.62m, RMSY=0.60m and RMSZ=1.63m, satisfying the expectation.

	phi [grads]	omega [grads]	kappa [grads]
sub-camera 5	-.0261	49.9609	-.3585
sub-camera 7	-49.1002	-.5065	-99.8977
sub-camera 8	1.7375	-51.1537	199.2017
sub-camera 19	51.3505	.4023	99.6800

Table 2: orientation of sub-cameras against nadir reference camera

4 CONCLUSION

The combined use of vertical and oblique cameras like in Track'Air MIDAS camera system requires an internal system calibration. The orientation of an image block, taken with such a combination leads to a strong overlap of images with up to 12 images per object point. Standard commercial programs are not able to handle such a block by automatic image matching and a manual measurement is very time consuming. So a direct sensor orientation with a combination of relative cinematic GPS-positioning together with an inertial measurement system is required. The direct sensor orientation together with the system calibration leads to the orientation of all sub-cameras.

With a sub-block of 3 flight lines and 4 vertical images in every flight line, with good connected oblique images, a complete system-calibration is possible. The used Canon EOS cameras have systematic image errors, dominated by the radial symmetric distortion, in the range up to 100 μ m or 14 pixels. The influence of the systematic image errors can be respected in a geo-coded interpretation and measurement system like from Pictometry or MultiVision by the application software or by generating perfect perspective images based on a resampling of the images using the systematic image errors.

The reached absolute accuracy within the calibration block of approximately 0.6m in X and Y is sufficient for the purposes of MultiVision applications. The relative accuracy is better than this. Of course it is depending upon the direct sensor orientation and the stability of the sub-cameras and the camera system including the misalignment. The camera geometry under usual conditions is stable within the block and the direct sensor orientation is dominated by the used hardware components. Images taken by MultiVision or Pictometry usually are only used as single images, allowing a geo-coding only by means of digital elevation models. These DEMs are an important limitation – because of the inclined views, the height errors of the DEMs are causing dislocations approximately in the same size like the height error.

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