

CALIBRATION OF IMAGING SATELLITE SENSORS

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ABSTRACT:

Satellite cameras are calibrated in laboratory before launch, but the geometry may change by the strong acceleration of the launch and by thermal influence of the sun. CCD-line scan cameras have to be checked for the linearity of the CCD-line. Cameras with a larger swath width usually are equipped not only with one CCD-line, but with a combination which geometric relation has to be determined. Also the relation between colour CCD-lines and the panchromatic must be calibrated to allow the generation of pan-sharpened images without geometric problems. The in-flight calibration has to be made by means of control points. The required number of control points for the calibration can be reduced if a scene combination taken from neighboured orbits is combined in one adjustment. The not parallel orbits are causing a not parallel scene overlap, so one sub-image is supporting the connection of other sub-images.

Modern imaging satellites are equipped with direct sensor orientation based on gyros, star-sensors and positioning systems like GPS. Also the boresight misalignment of the components of direct sensor orientation to the camera has to be determined. The combination of the direct sensor orientation with the images allows also the calibration of the focal length. Because of the small view angle this cannot be done without the positioning system.

The geometry of CCD-array cameras is simpler because of the stable imaging geometry, but also the relation between the different cameras used for panchromatic and colour is required like the boresight misalignment. In addition the radial symmetric lens distortion has to be checked.

The calibration has to be based on a geometric reconstruction of the imaging geometry. Unknown parameters have to be calculated by means of additional parameters. The correlation of the unknowns and the determine ability has to be checked in the adjustment as well as remaining systematic image errors indicating not respected geometric problems. Remaining systematic effects can be checked by analysis of residuals of the adjustment and a covariance analysis of the discrepancies at the control points.

1. INTRODUCTION

In addition to the former perspective film cameras, some small satellites are equipped with CCD-arrays having also one perspective geometry for the whole image.

Very high resolution space cameras having a larger swath width are equipped with a combination of linear CCD-lines. The relation of the CCD-lines as well as their geometric linearity at least has to be verified after launch. The large acceleration during launch may change the exact position of the CCD-lines in the camera. In addition the location of the CCD-lines for multi-spectral images has to be known in relation to the panchromatic CCD-line combination. A calibration is possible by means of ground control points and overlapping scenes.

Modern high resolution space sensors are equipped with gyros, star sensors and a positioning system like GPS for getting a precise direct sensor orientation. This requires a system calibration of the imaging sensor in relation to the positioning components. The determination of the boresight misalignment of aerial photogrammetric systems requires a flight at least in opposite direction; this is not possible for satellites. But the very flexible satellites do have the possibility of a free rotation, so the calibration can be supported with different viewing arrangements.

Linear array systems do have perspective geometry only in the direction of the array. By theory neighboured scene

lines are independent, but the orientation is not changing very fast. For the classical satellites the view direction in relation to the orbit was nearly constant during imaging – this is different for the very flexible satellites. Images can be taken also by scanning against or across the movement in the orbit causing sometimes vibrations which have to be measured by means of the gyros. So a total separation of all effects is difficult, partially not possible. If effects cannot be separated, this is usually not influencing the final use of the calibration, so for example an error in the focal length may be compensated by the flying height.

The radiometric calibration can be based on artificial or natural test targets on the ground but also by means of sun light, it may change over the time. This will not be covered here like also the aspect of optimal focusing.

2. CCD-ARRAYS

Some small satellites are equipped with CCD-arrays or a combination of CCD-arrays. CCD arrays do have the advantage of a very stable inner geometry. There is no influence of the satellite orientation and change of orientation to the configuration of the lines. In addition the inner CCD-geometry is not changing during launch and in orbit, so it can be analysed without problems before launch. The inner accuracy of CCD-arrays is usually very high – better than 0.1 pixels and angular affinity not exists. Only in few cases the pixel size in row

direction is not identical the size in the column direction, but this can be checked before launch.

The inner orientation including the lens distortion may change during launch and in the orbit, so it has to be calibrated and validated from time to time. The location of the principle point in a perspective image having a small view angle is close to a linear dependency from the rotation angles phi and omega. By theory it can be checked in a mountainous area with control points in quite different height levels, but in reality the changes are so small that a correction usually is impossible or reverse, also not required.

The focal length is extremely correlated with the flying height, so a similar problem like with the principal point exists. But the available information about the exterior orientation can be used. The projection centre is usually known by GPS positioning and with this plus few ground control points, the focal length can be determined.

The radial symmetric and the tangential lens distortion may change in the orbit. A tangential lens distortion may be caused by a not centric location of some lenses of the optics. A radial symmetric lens distortion is caused by the optics itself and a change of the radial symmetric lens distortion may be caused by a deformation of the lenses.

The lens distortion can be determined by self calibration with additional parameters of a single image based on a sufficient number of ground control points or by bundle block adjustment of overlapping images with just few control points. The over-determination of a bundle block adjustment allows the determination of the systematic image errors – control points only have to be used for the geo-reference.

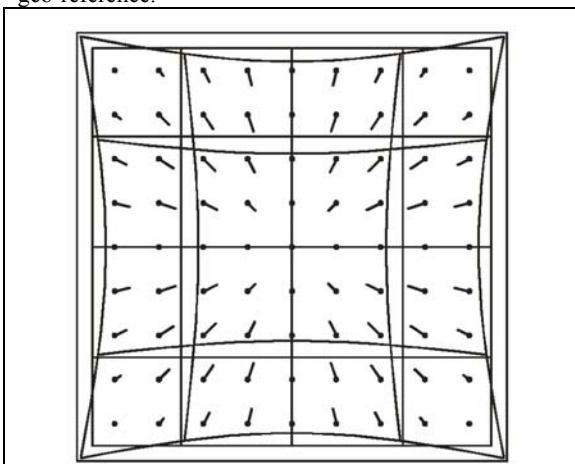


fig. 1: systematic image errors of perspective space camera KFA3000 determined by resection

The small satellites equipped with CCD-array cameras usually do have for every spectral band a separate camera. The cameras have to be related to each other. This can be done just by tie points and a similarity transformation.

The boresight misalignment – the relation of the star cameras, the gyros and the GPS-antenna to the camera – can be computed in relation to the exterior orientation based on control points. Because of the small view angle for a sufficient separation of the effects of the rotations phi and omega from the projection centre X_o and Y_o , control points in different height level should be used, but even in a mountainous area a strong correlation of between X_o , Y_o and phi and omega cannot be avoided.

So it is better to fix the location of the projection centre based on GPS-positioning and to reduce the boresight misalignment to the attitude. A correct time synchronisation between the imaging instant of the usual camera, the star camera and the GPS /gyro time frame is required.

2. CCD-LINE: INNER ORIENTATION

The inner orientation describes the relation between the pixel position in the CCD-line to the field angle – the angle between the view direction and the direction where the pixel is pointing. Under optimal conditions of a single straight CCD-line, located exactly in the focal plane and a system without distortion by the optics, the tangent of the field angle is identical to the relation of the distance from the principal position to the focal length. This will not be the case in reality. Due to the required characteristics, a combination of shorter CCD-lines is used instead of one longer CCD-line. The combination of the shorter CCD-lines may be located directly in the focal plane, this is only possible with a shift of the CCD-lines in the scan direction (figure 2) or they may be are combined by a system of prism – in this case they may fit directly together in a synthetic line. The offset of the CCD-combination in the focal plane, in the scan direction has to be determined and is respected by the generated synthetic image with a difference in time (figure 4). Also for the case of a combination of the smaller CCD-lines by means of a system of prism, the shift of the CCD-lines and the alignment has to be determined.

The multispectral CCD-lines in most cases do have a lower resolution, so in some cases one solid CCD-line is used for this, but for example IKONOS is also using a combination of 3 multispectral CCD-lines (figure 2), QuickBird even 6.

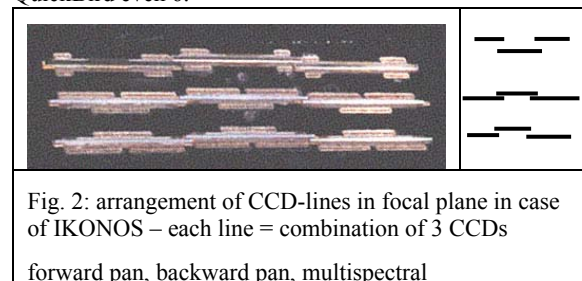


Fig. 2: arrangement of CCD-lines in focal plane in case of IKONOS – each line = combination of 3 CCDs

forward pan, backward pan, multispectral

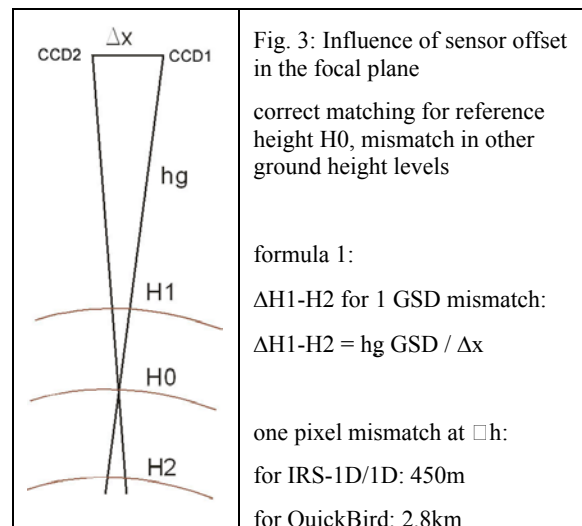


Fig. 3: Influence of sensor offset in the focal plane

correct matching for reference height H_0 , mismatch in other ground height levels

formula 1:

$\Delta H_1 - H_2$ for 1 GSD mismatch:

$$\Delta H_1 - H_2 = hg \text{ GSD} / \Delta x$$

one pixel mismatch at \square h:

for IRS-1D/1D: 450m

for QuickBird: 2.8km

The offset of the single CCD-lines in the scan direction is causing a different view direction (figures 3 and 4). For a chosen reference ground height, the individual images can be matched without discrepancy, but if a scene has a stronger variation of the ground height, a mismatch may be caused. For example in the case of IRS-1C/1D the difference in the focal plane corresponds to 8.6km difference in the corresponding projection centres, so with a location having 450m height difference against the reference plane, a mismatch of 1 pixel will be caused. For QuickBird the displacement corresponds only to approximately 100m and so 1 pixel mismatch is caused by a height difference of 2.8km. The mismatch of the multispectral CCD-lines is larger, but because of the lower resolution it is not so obvious in pan-sharpened images.

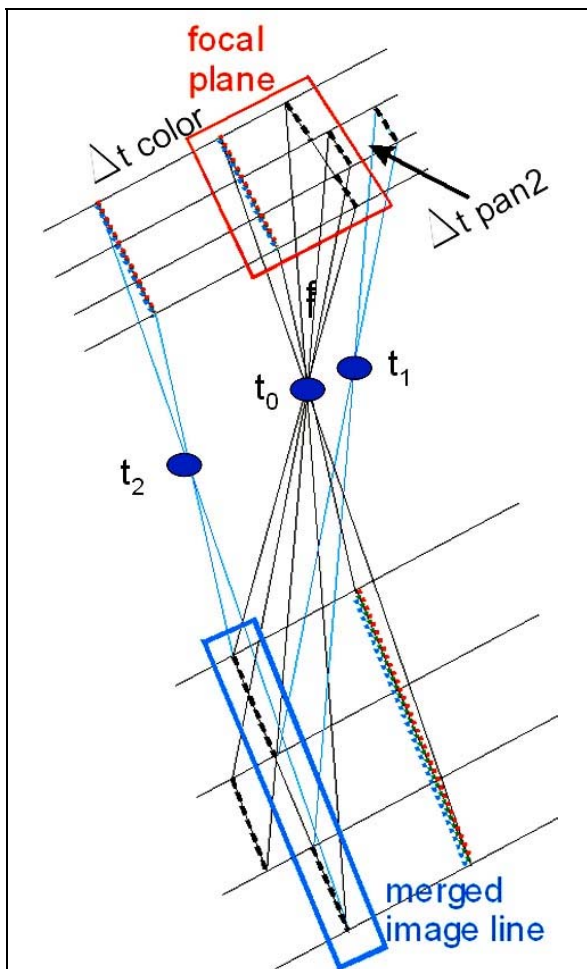


Fig. 4: combination of CCD-sensors with different location in the focal plane to a homogenous synthetic CCD-line

Only moving objects do show some effects. Because of the different imaging instant for colour and panchromatic in pan-sharpened images in the case of IKONOS the colour of fast moving cars is shown behind the grey value image and for QuickBird it is shown in front (figure 5). This effect can only be seen at fast moving objects; it is usually not disturbing and not affecting the objects important for mapping purposes.

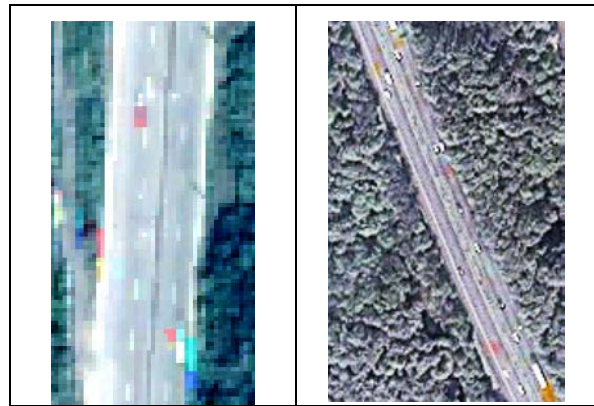


Fig. 5: difference in time for panchromatic against colour
left: QuickBird right: IKONOS

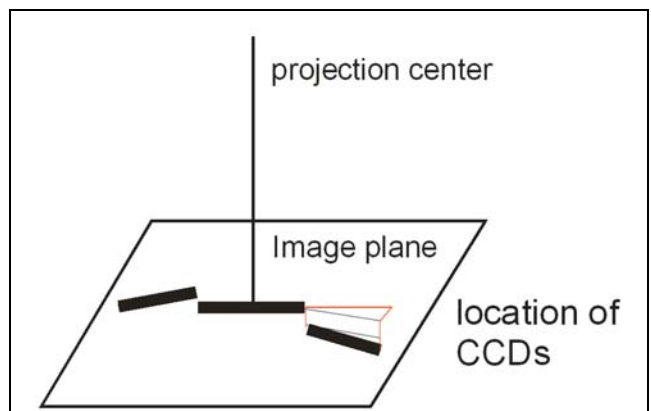


Fig. 6: location of CCDs in the focal plane – misalignment in the focal plane and vertical shift against the focal plane

The CCD-lines should be exactly aligned or at least parallel and located in the image plane. In reality this is not possible. The imaging system may be calibrated before launch, but in any case an in-orbit calibration is required. Thermal influence and drying out effects may change the geometry within the orbit, so from time to time the calibration has to be checked. The shift of the sub-images in and across orbit direction can be computed based on tie points in the overlapping part of the sub-images (figure 7). A rotation in and against the image plane as well as a different distance from the projection centre has to be determined by means of ground control and tie points.

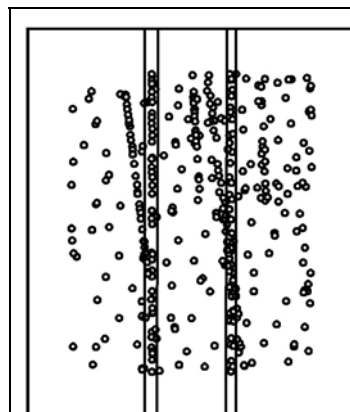


Fig. 7: overlap of IRS-1C sub-scenes with used tie points for matching of scenes and bundle orientation

The relation of the panchromatic to the multispectral CCD-lines belongs also to the inner orientation. It can be determined just with tie points, but for a general calibration the flying height above ground has to be respected. A transfer delay and integration (TDI= integration of the generated charge over some pixels, transfer corresponding to the forward motion speed – use of a small CCD-array instead of a CCD-line) has no influence to the geometry – the line shift is compensated by the different view direction.

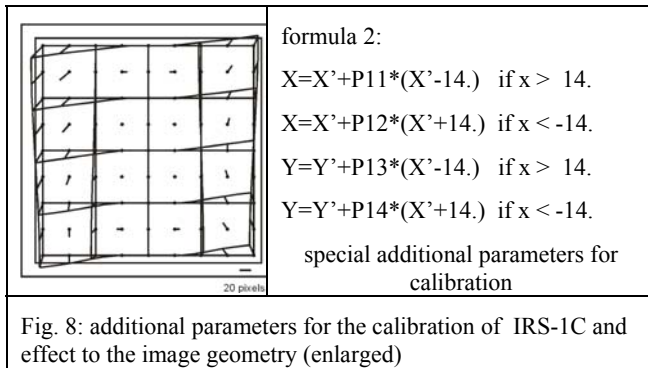


Fig. 8: additional parameters for the calibration of IRS-1C and effect to the image geometry (enlarged)

An IRS-1C sub-image configuration of 3 complete scenes taken within 3 days, with nadir angles of 18.7°, 0° and -20.6°, has been used for calibration (Jacobsen 1997) (figure 10). For the calibration 4 special additional parameters have been introduced into the Hannover program BLASPO (formula 2) with P11 up to P14 as unknowns, to be computed by adjustment. The constant values of 14mm are corresponding to the sub-scene size [mm]. A rotation in the focal plane can be determined and respected with the parameters 13 and 14. A different distance from the projection centre as well as a rotation against the image plane is handled by the parameters 11 and 12. In general statistical checks of the chosen additional parameters have to be made to avoid too high correlations and to check if the parameters can be determined and if the effect is available. In program BLASPO the individual correlation, the total correlation (value if the effect of one unknown can be fitted by the group of all other unknowns) and the Student test (with limit of 1.0) are used to avoid misinterpretations and over-parameterization. The residuals in the image and at the control points have to be analyzed for remaining systematic errors to allow an estimation of not respected systematic effects. For this the image residuals of all scenes and/or sub-scenes should be overlaid. A visual check is giving the first impression; this should be supported by a covariance analysis and the computation of the relative accuracy.

$$C_x = \frac{E(DX_i \cdot DX_j)}{n \cdot SX^2} \quad \text{formula 3: covariance}$$

$$RSX = \sqrt{\frac{E(DX_i - DX_j)^2}{2 \cdot n}}$$

formula 4: relative standard deviation

Both have to be calculated for distance groups – for example the longest available distance between points

can be divided by 20 and the computation will be made separately for the 20 distance groups like in figure 9.

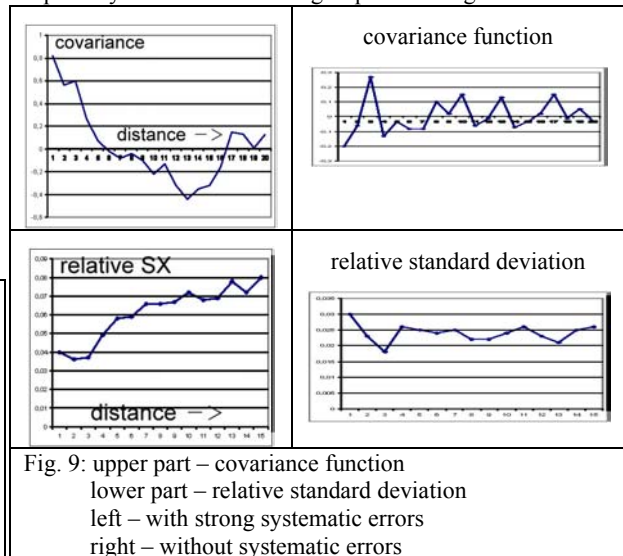


Fig. 9: upper part – covariance function
 lower part – relative standard deviation
 left – with strong systematic errors
 right – without systematic errors

As shown in figure 9 above left, neighbored points are strongly correlated if the mathematical solution has not respected all systematic errors and the correlation will be smaller for larger distances between points. If the systematic errors have been respected (above right), the correlation is small and nearly independent upon the distance; only some noise can be seen. The relative standard deviation shows smaller values for neighbored points and is increasing with the distance between points if remaining systematic effects are available (lower left). Without remaining systematic effects, the relative standard deviation is homogenous over all distance groups (lower right). For a better interpretation of the reason of remaining systematic effects, the residuals are analysed separately as function of X, Y and Z.

The analysis of the sensor geometry has to be based on ground control points and it can be supported by tie points in overlapping scenes (figures 7 and 10). One sub-scene is supporting the other. The arrangement should not be totally regular; if the scenes are taken with different angles across the orbit this will be the case automatically because of the satellite orbit if the area is not located at the equator – the scenes will be slightly rotated against each other. In addition the ground sampling distance (GSD, the distance of the projected pixel centres on the ground) is depending upon the nadir angle, so the covered area is different.

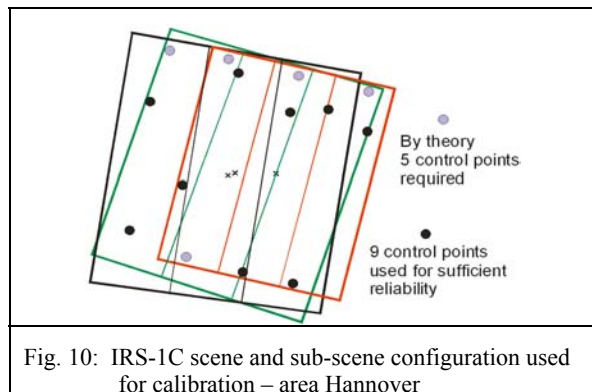


Fig. 10: IRS-1C scene and sub-scene configuration used for calibration – area Hannover

A typical geometric problem is the linearity of the CCD-lines. The distance within the CCDs will not be

influenced by the launch and usually is very precise, but it cannot be guaranteed that the CCD-line is totally straight. Results of CCD-line calibration are shown for MOMS02 and SPOT 5 (figures 11 and 12). This may also be influenced by systematic lens distortion which can be calibrated before launch, but may be influenced by the launch.

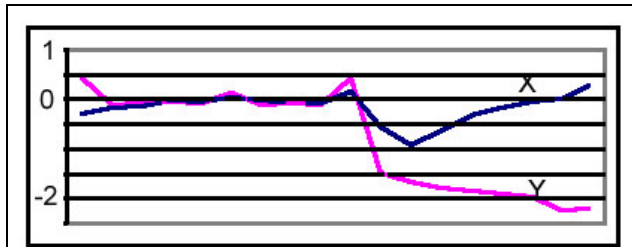


Fig. 11: post launch MOMS02 CCD-line calibration
X = in line, Y = across line [pixels] [Kornus et al 1998]

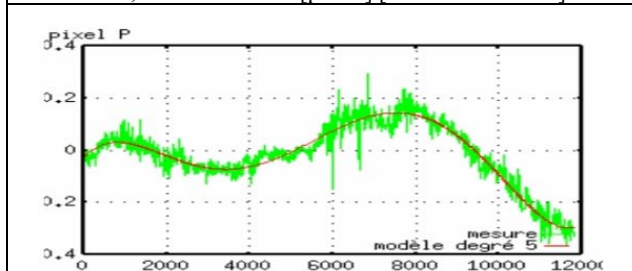


Fig. 12: in orbit calibration of CCD-line – discrepancies across orbit, SPOT 5 HRG [Valorge et al, 2003]

The user later will not see something about the individual effects of the inner orientation and the merging of the individual sub-images because not the original sub-images are distributed but synthetic images corrected by all mentioned effects.

3. CCD-LINE: EXTERIOR ORIENTATION

The focal length belongs to the interior orientation but caused by the very small view angle it cannot be calibrated accurate enough without information about the exterior orientation. This today can be determined precisely based on the combination of the satellite positioning by GPS or a similar system, gyros and star sensors. The gyros can determine the rotations, but they do have only good short time accuracy, so from time to time a support by star sensors is required. The relation between the imaging and the positioning system, named boresight misalignment, must be calibrated. The offset between the GPS antenna and the camera can be based on the satellite geometry, so the main problem is the angular relation and the time synchronization. The angular relation is required with higher frequency to avoid a loss of accuracy caused by satellite vibration. Based on the satellite position a calibration of the focal length is simple.

A complete exterior orientation can be computed by means of three-dimensional well distributed control points, but like the inner orientation it can be supported by overlapping scenes taken with different view direction. A separation of the unknowns can be simplified, if different scan directions are used. IKONOS, QuickBird and OrbView-3 can scan the ground also perpendicular to the orbit direction. IKONOS even is equipped with an additional CCD-line combination for a

scan against the orbit direction. A combination of a scan from one side and the opposite direction is improving the reliability of the calibration and so the number of required ground control points can be reduced.

IKONOS, QuickBird and OrbView-3 can determine the direct sensor orientation with a standard deviation of the ground coordinates in the range of 6m. But the complete precise geometric and radiometric calibration and the optimal focussing took approximately 6 month for each system. Such accuracy requires a sufficient knowledge of the datum of the used national coordinate system but today with the change of the classical ground survey to satellite positioning the datum is usually known, but sometimes not published. In addition also the geoid undulation should be known at least approximately to allow a transformation of the geocentric GPS-coordinates to geoid heights and reverse. The published world wide geoids with an accuracy better than 2m are sufficient because the nadir angle of the satellite images is usually limited and an error in the height has only an influence to the horizontal position with $\Delta P = \Delta h \cdot \tan \nu$ where ν is the incidence angle, the angle between the local vertical and the direction to the satellite.

The term accuracy today is causing sometimes confusion, because in addition to the traditional standard deviation the US expressions CE90 and LE90 are used. There is a fixed relation between these values. CE is the circular error; that means the square root sum of the horizontal X and Y discrepancies. 90 mean 90% probability level under the condition of normal distributed errors; while the standard deviation has 68% probability level. So to the standard deviation of the coordinate X (SX), also named 1 sigma, and CE90 have a fixed relation of 2.3 or CE95 a relation of 2.8. For the vertical accuracy the expression LE90 is used, having a relation of 1.65 to the vertical standard deviation or a factor 1.96 for LE95. Sometimes the standard deviation of the height is also named LE68.

The calibration requires a geometric reconstruction of the imaging geometry. Approximate solutions like the 3D-affine transformation, the direct linear transformation (DLT) or terrain dependent rational polynomial coefficients cannot be used even if they can lead for some sensors to sufficient orientation accuracy with a higher number and 3-dimensional well distributed control points (Jacobsen et al 2005).

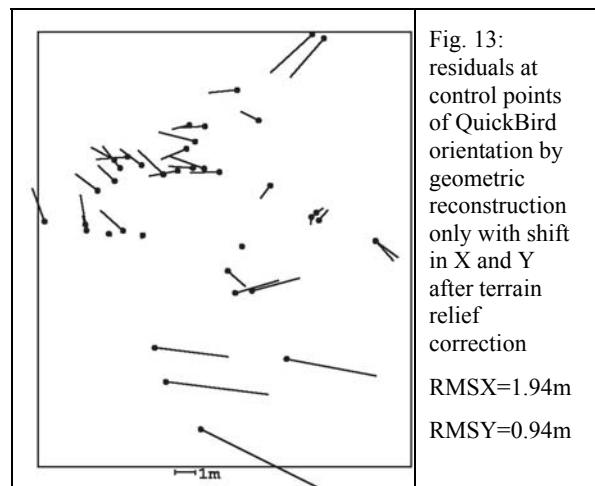
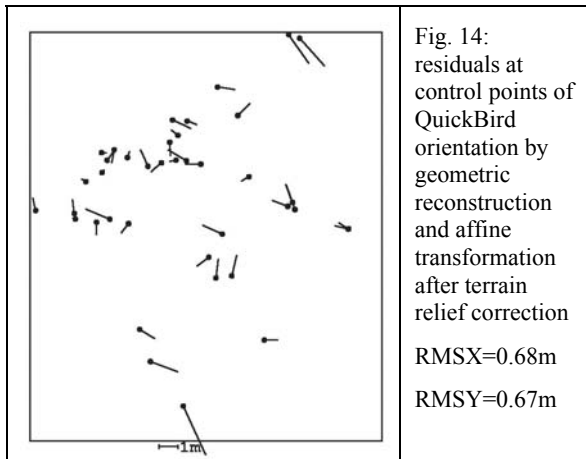
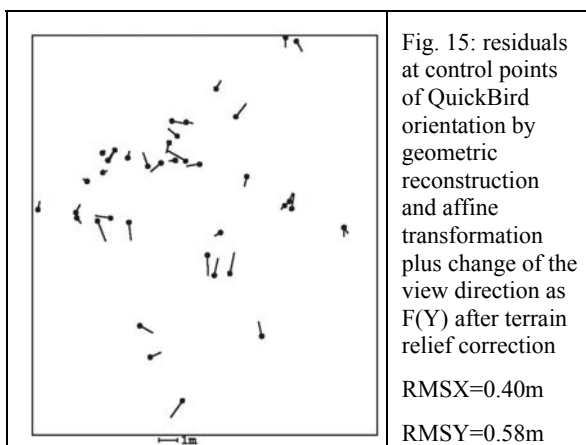


Fig. 13:
residuals at control points of QuickBird orientation by geometric reconstruction only with shift in X and Y after terrain relief correction
RMSX=1.94m
RMSY=0.94m

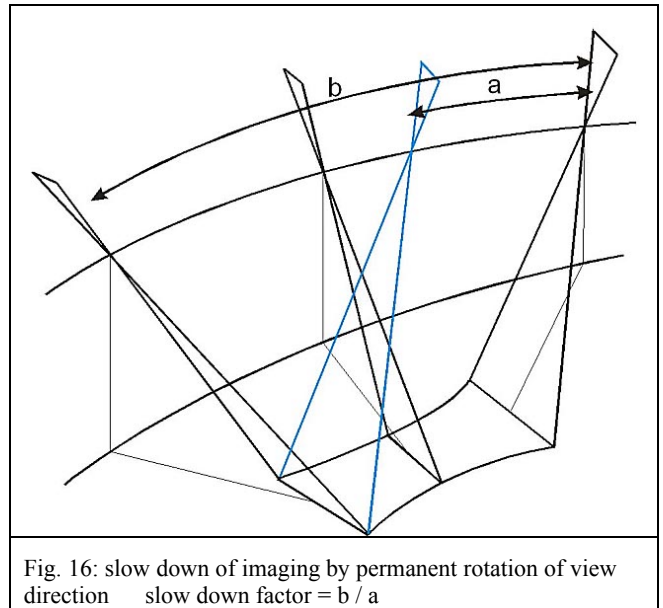
The exterior orientation can be used also for a verification of the calibration and a check of the quality of the direct sensor orientation. A QuickBird scene has been analysed in the area of Zonguldak by means of 39 control points determined by GPS ground survey. A geometric reconstruction of the scene with the Hannover program CORIKON with a simple shift in X and Y after terrain relief correction resulted in 1.5 up to 3 GSD (figure 13). This is a not satisfying result because with the same control points and corresponding handling, the orientation of 3 IKONOS scenes was leading to root mean square errors in the range of 0.9 GSD. As visible in figure 12, there are clear systematic discrepancies of the residuals.



An affine transformation of the scene coordinates after terrain relief correction (figure 14) reduced the residuals to 1.1 GSD. Because of the higher geometric resolution of QuickBird with 0.62m GSD, the absolute values are better like achieved with IKONOS images having 1m GSD. But nevertheless, the covariance analysis indicates remaining systematic effects. There is a clear dependency upon the Y- and the Z-coordinates. A detailed analysis indicated a change of the view direction as linear function of the Y-coordinate.



QuickBird has a sampling rate of 6500 lines/second. With the collected GSD of 0.618m this corresponds to a speed of 4017m/sec, but for the orbit height of 450km above ground, the footprint speed is 7134m/sec. The relation of $7134\text{m/sec} / 4017\text{m/sec} = 1.776$ has to be used as slow down factor – in relation to the orbit length used for the imaging of a scene with approximately the same view direction, the view direction is continuously changed to reach a 1.776 times longer length in the orbit (figure 16).



The verification of the QuickBird scene orientation showed a discrepancy of the slow down factor against the header and general information. By the additional parameter computing a difference in the slow down factor, sub-pixel accuracy has been reached. This problem of the slow down factor is not present if the orientation is verified by rational polynomial coefficients (RPC) distributed together with the QuickBird image. That means the problem is only caused by some not so accurate information used for the geometric reconstruction – it is not a problem of the calibration of the exterior orientation parameters. But also the verification of the orientation with the RPC required after the terrain relief correction an affine transformation to the control points. Corresponding results have been achieved also with other data sets. So the relative scene orientation of QuickBird without improvement is not accurate on the sub-pixel level. This is different for IKONOS not requiring the improvement by affine transformation. But without affine transformation the QuickBird orientation is reaching the same absolute accuracy like IKONOS, the difference is only caused by the smaller GSD of QuickBird, also allowing a higher accuracy.

4. CONCLUSION

The lens distortion of CCD-array cameras should be validated from time to time. For the direct sensor orientation also a correct boresight misalignment and time synchronisation is required which can be checked with ground control points.

The inner and exterior or system calibration of high resolution optical satellites requires a correct mathematical model reconstructing the imaging geometry. This has to include additional parameters for the calibration of the optical sensor as well as the positioning sensors. The determination of all parameters in one adjustment has the advantage of correct accuracy estimation and the determination of the dependencies. On the other hand, the imaging geometry like distortion and alignment of the CCD-lines can be split of, because of limited correlation. In general not only a single scene should be used, the common adjustment of a combination of overlapping scene improves the reliability and is reducing the number of required ground control points. The calibration has to be validated from time to time for

possible changes. In general a very high accuracy level of the imaging satellite geometry has been reached, allowing also the use of the direct sensor orientation in some cases.

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