CALIBRATION OF OPTICAL SATELLITE SENSORS

KARSTEN JACOBSEN

University of Hannover
Institute of Photogrammetry and Geoinformation
Nienburger Str. 1, D-30167 Hannover, Germany
jacobsen@ipi.uni-hannover.de

KEY WORDS: satellite images, calibration, self calibration, mathematical model

ABSTRACT:

Satellite cameras are calibrated before launch in detail and in general, but it cannot be guaranteed that the geometry is not changing during launch and caused by thermal influences and drying out effects in the orbit. Modern satellite imaging systems are based on CCD-line sensors. Because of the required high sampling rate, the length of used CCD-lines is limited. For reaching a sufficient swath width, some CCD-lines are combined to a longer virtual CCD-line. The images generated by the individual CCD-lines do overlap slightly and so they can be shifted in x- and y-direction in relation to a chosen reference image just based on tie points. The geometry and geometric relation of the sub-scenes can be determined by a bundle orientation with a higher number of control points or a bundle block adjustment using a limited number of ground control points. Special additional parameters fitted to the image size are required for the calibration.

The resulting virtual image has only negligible errors in areas with very large difference in height caused by the difference in the location of the projection centres. Colour images can be related to the joint panchromatic scenes just based on tie points. Pan-sharpened images may show small colour shifts in very mountainous areas and for moving objects, but it is also possible to respect digital elevation models for the optimal fit of the sub-scenes.

The direct sensor orientation of the satellites has to be calibrated based on control points. Discrepancies in horizontal shift can only be separated from attitude discrepancies with a good three-dimensional control point distribution or with opposite scan directions. For such a calibration a program based on geometric reconstruction of the sensor orientation is required. The approximations of the scene orientation by 3D-affine transformation or direct linear transformation (DLT) cannot be used. These methods do have also disadvantages for standard sensor orientation. The image orientation by geometric reconstruction can be improved by self calibration with additional parameters for the analysis and compensation of remaining systematic effects for example caused by a not linear CCD-line but also a continuous change of the view direction. The determined sensor geometry can be used for the generation of sensor oriented rational polynomial coefficients, describing the sensor geometry by relations of polynomials of the ground coordinates X, Y and Z.

1. INTRODUCTION

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. 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 1) 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 3). 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 QuickBird is also using a combination of 6 multispectral CCD-lines (figure 1).

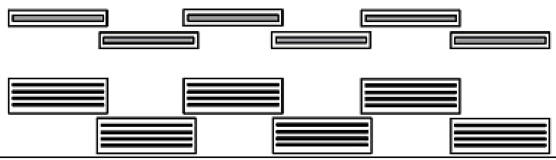


Fig. 1: arrangement of CCD-lines in focal plane of QuickBird

above: panchromatic, below: multispectral

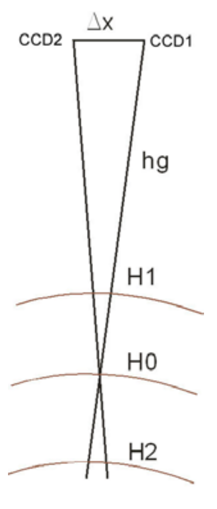


Fig. 2: Influence of sensor offset in the focal plane

correct matching for reference height H0, mismatch in other ground height levels

formula 1:

□H1-H2 for 1 GSD mismatch:

□H1-H2 = hg GSD / □x

one pixel mismatch at □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 2 and 3). 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.

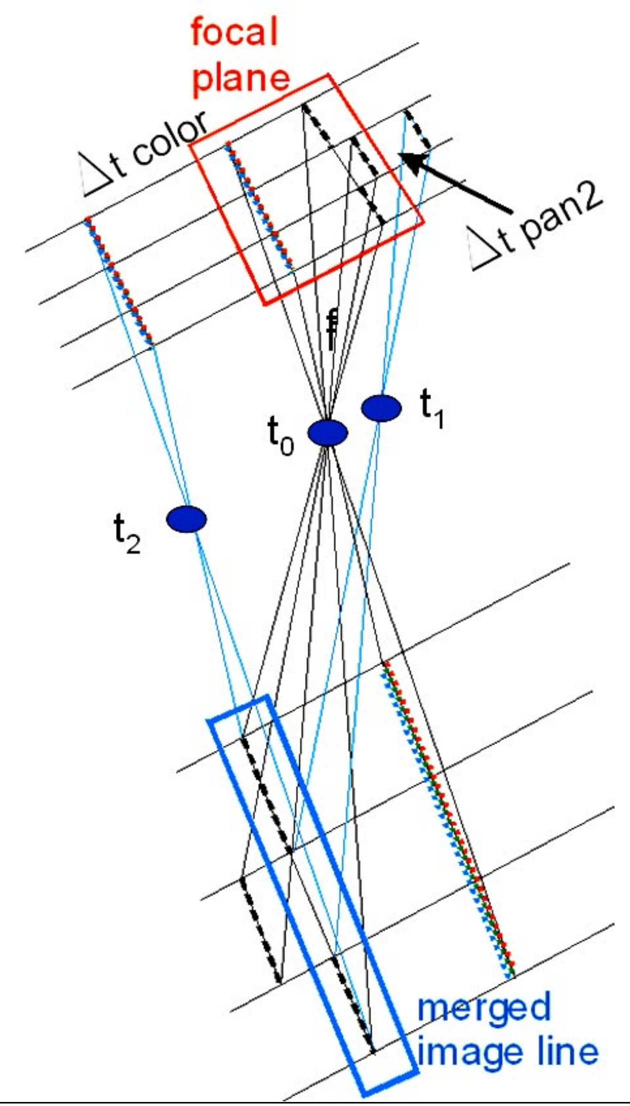


Fig. 3: combination of CCD-sensors with different location in the focal plane to a homogenous synthetic CCD-line

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 4). This effect can only be seen at fast moving objects; it is usually not disturbing and not affecting the objects important for mapping purposes.

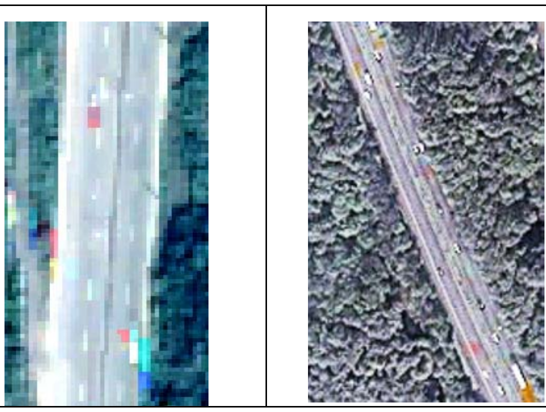


Fig. 4: difference in time for panchromatic against colour
left: QuickBird right: IKONOS

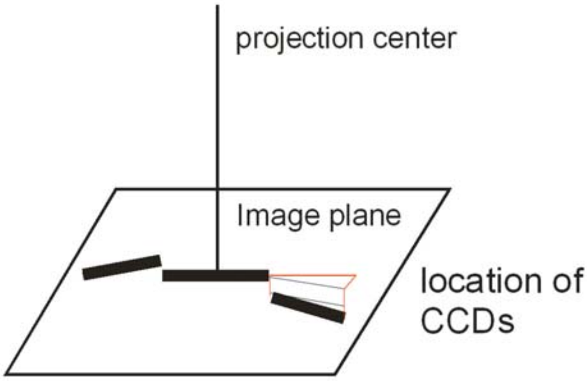


Fig. 5: location of CCDs in the focal plane – misalignment in the focal plane and vertical shift against the focal plane

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 6). 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.

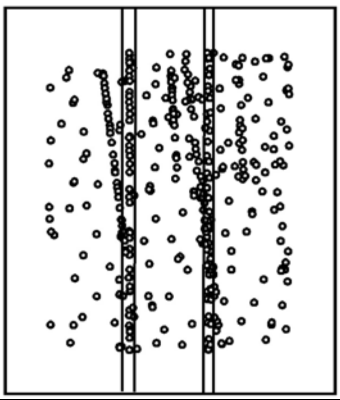
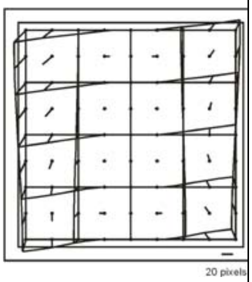


Fig. 6: overlap of IRS-1C sub-scenes with used tie points for matching of scenes and bundle orientation

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.



formula 2:

X=X'+P11*(X'-14.) if x > 14.

X=X'+P12*(X'+14.) if x < -14.

Y=Y'+P13*(X'-14.) if x > 14.

Y=Y'+P14*(X'+14.) if x < -14.

special additional parameters for calibration

Fig. 7: 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 9). 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.

$$Cx = \frac{E(DXi \bullet Dxj)}{n \bullet SX^2}$$

formula 3: covariance

$$RSX = \sqrt{\frac{E(DXi - DXj)^2}{2 \bullet n}}$$

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 8.

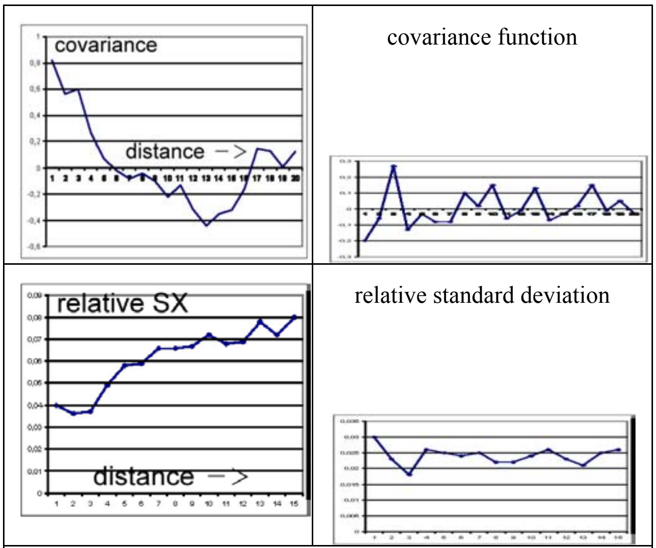


Fig. 8: upper part – covariance function
lower part – relative standard deviation
left – with strong systematic errors
right – without systematic errors

As shown in figure 8 above left, neighboured 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 neighboured 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 analyses 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 6 and 9). 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.

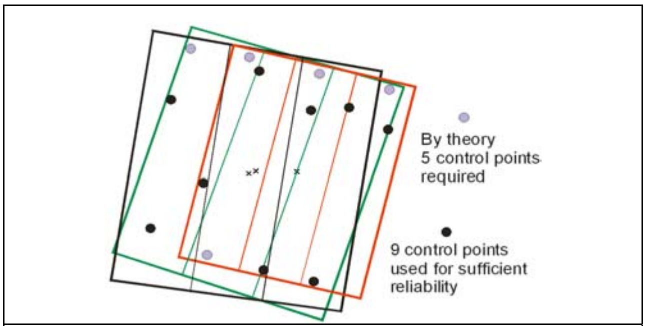


Fig. 9: IRS-1C scene and sub-scene configuration used for calibration – area Hannover

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 10 and 11). This may also be influenced by systematic lens distortion which can be calibrated before launch, but may be influenced by the launch.

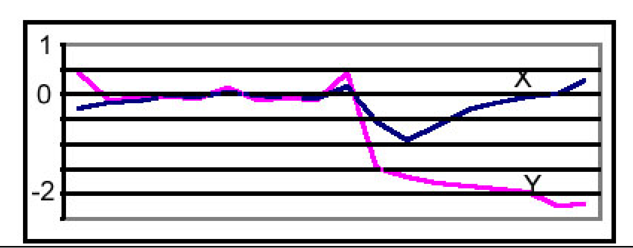


Fig. 10: post launch MOMS02 CCD-line calibration
X = in line, Y = across line [pixels] [Kornus et al 1998]

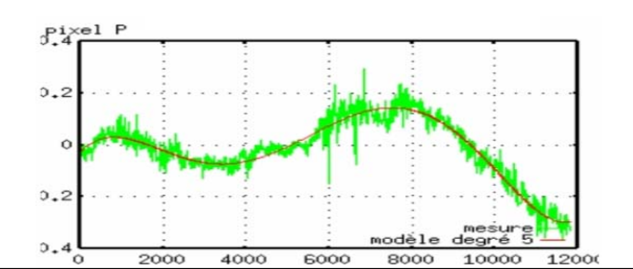


Fig. 11: in orbit calibration of CCD-line – discrepancies across orbit, SPOT 5 HRG [Valorge et al, 2003]

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. 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 $\Delta P=\Delta h*\tan\ \nu$ 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).

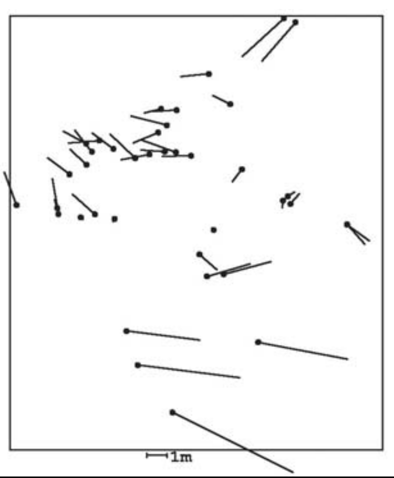


Fig. 12: residuals at control points of QuickBird orientation by geometric reconstruction only with shift in X and Y after terrain relief correction

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 12). 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.

Fig. 13: residuals at control points of QuickBird orientation by geometric reconstruction and affine transformation after terrain relief correction

RMSX=0.68m

RMSY=0.67m

An affine transformation of the scene coordinates after terrain relief correction (figure 13) 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.

Fig. 14: residuals at control points of QuickBird orientation by geometric reconstruction and affine transformation plus change of the view direction as F(Y) after terrain relief correction

RMSX=0.40m

RMSY=0.58m

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 7134m/sec / 4017m/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 15).

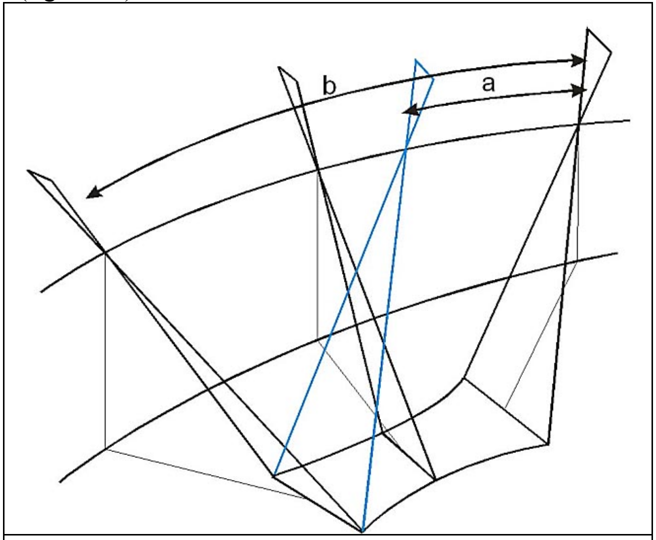


Fig. 15: slow down of imaging by permanent rotation of view direction   slow down factor = b / a

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 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.

REFERENCES

Dial, G., 2003: Test Ranges for Metric Calibration and Validation of Satellite Imaging Systems, Workshop on Radiometric and Geometric Calibration, Gulfport, 2003, on CD

Jacobsen, K., 1997: Calibration of IRS-1C PAN-camera, Joint Workshop „Sensors and Mapping from Space“, Hannover 1997

Jacobsen, K.: Issues and Method for In-Flight and On-Orbit Calibration, Workshop on Radiometric and Geometric Calibration, Gulfport, 2003, on CD

Jacobsen. K.*, Büyüksalih, G.**, Topan, H., 2005: Geometric Models for the Orientation of High Resolution Optical Satellite Sensors, Hannover Workshop 2005

Kornus, K., Lehner, M., Schroeder, M.: 1998, Geometric Inflight Calibration of the Stereoscopic CCD-Linescanner MOMS-2P, ISPRS Com I Symp., Bangalore 1998, IntArchPhRS. Vol XXXII-1, pp 148-155

Valorge, C., et al, 2003 : 40 years of experience with SPOT in-flight Calibration, Workshop on Radiometric and Geometric Calibration, Gulfport, 2003, on CD