COMBINED BUNDLE BLOCK ADJUSTMENT WITH ATTITUDE DATA

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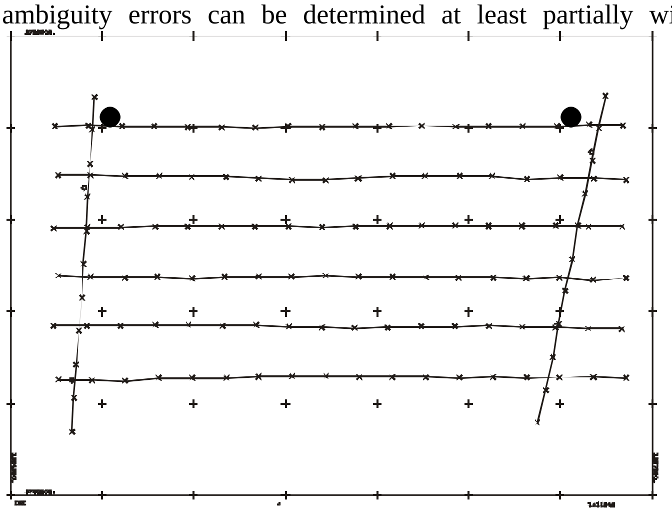
ABSTRACT

The combined block adjustment with coordinates of the projection centers, determined by kinematic GPS-positioning, has become a standard procedure. This method is operational and allows the reduction of the number of control points to a minimum, but it is limited to the handling of blocks. In the case of just one flight strip, the images can rotate around the flight line. With GPS-coordinates of the projection centers, the distance of the control points for such strips can be extended from 4 base length without GPS to 10 base length. If a longer distance shall be gapped, the block must be supported by attitude data. The attitude data determined by modern inertial measurement units (IMU) do have a rising quality, but they are still influenced by systematic errors, a drift (time depending systematic error) and also by problems in the connection to the camera, so a point determination in a model, not supported by a block adjustment, will not reach the usual accuracy. The Hannover program system BLUH has been extended for a combined bundle block adjustment with attitude data in addition to the projection centers determined by kinematic GPS-positioning. This method allows an extension of the distances of the control points for blocks with just one flight strip.

INTRODUCTION

With an exact data handling, combined block adjustments with projection centers determined by relative GPS-positioning are possible without control points (Jacobsen 1997). Such blocks are not accepted for usual production because of the missing reliability and the problems in handling the whole process, but nevertheless the number of control points can be reduced to a minimum and for special purposes block adjustments without control points are helpful. Such blocks should be supported by crossing flight strips. With a block, stabilized by crossing flight strips, systematic errors of the GPS positioning caused by ambiguity errors, changing from flight strip to flight strip, can be determined and respected if control points are available at the block corners. Without control points constant time errors and errors of the offset can be determined and respected if opposite flight directions are available. Constant time errors can be caused by the use of different types of GPS receivers at the reference station and in the aircraft. Other effects of ambiguity errors can be determined at least partially with such a block



configuration shown in fig. 1.

figure 1: typical block configuration for combined adjustment with GPS-data

Such a configuration should be the standard configuration for combined adjustment with GPS-data. It is not possible to get such bloc[...]se of linear projects like for the survey of roads and pipelines [...]nt strips are dominating. A single flight strip cannot be [...]th projection center coordinates and without control points - [...]e around the flight axis.

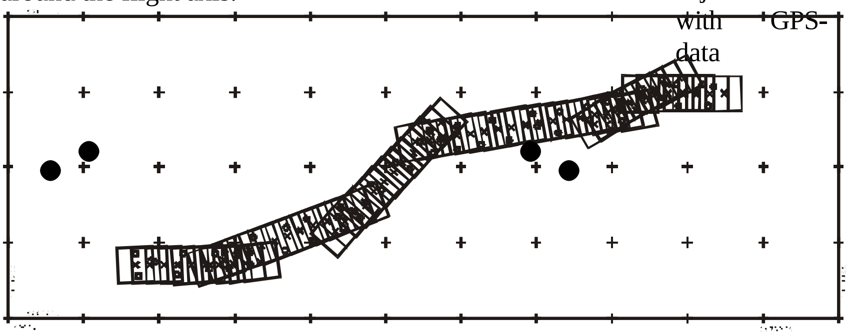


figure 2: typical block configuration for linear projects

Of course linear projects are usually not exactly linear, so a combination of single flight strips like shown in figure 2 are used. Such a block configuration can be handled just with GPS-data, but the accuracy in the coordinate

component across the main block direction is limited and the adjustment is not very robust. The same problem exists in the case of blocks with very long flight lines if the block is not stabilized with crossing flight lines or control points in the block center. In the center of such long flight lines the transversal tilt will not be very accurate.
Such block configurations can be handled without control points if the attitude data are available by means of inertial measurement units (IMU) – formerly named inertial navigation systems (INS), but not used for navigation.

CORRELATION AND ACCURACY OF ORIENTATION DATA

The projection center coordinates and the attitude data can be verified by a controlled bundle block adjustment. The standard deviations of the X- and Y-components of the projection centers are usually larger than the Z-component. This is opposite to the situation of the ground coordinates determined by photogrammetric methods. The reason for this fact are the correlation of the orientation data.

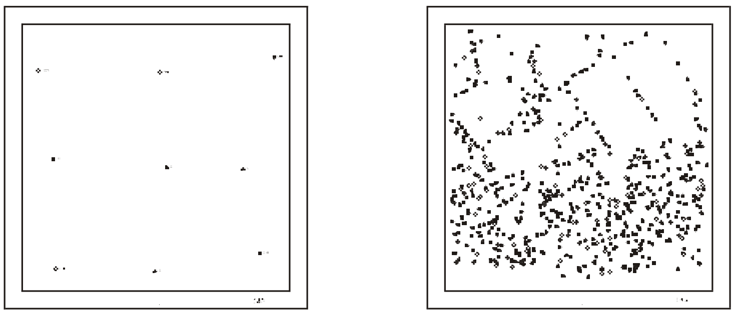


figure 3: point distribution in the images left: 9 points right: 615 points

	φ	ω	κ	X0	Y0	Z0		φ	ω	κ	X0	Y0	Z0
φ	1.00	-.17	.04	.98	.16	-.01		1.00	.05	-.03	.99	-.03	.34
ω	-.17	1.00	-.02	-.16	-.97	-.01		.05	1.00	.22	.03	-.98	.12
κ	.04	-.02	1.00	.04	.03	.00	**f=153**	-.03	.22	1.00	-.03	-.26	.01
X0	.98	-.16	.04	1.00	.15	.00	**mm**	.99	.03	-.03	1.00	-.02	.29
Y0	.16	-.97	.03	.15	1.00	.00		-.03	-.98	-.26	-.02	1.00	-.11
Z0	-.01	-.01	.00	.00	.00	1.00		.34	.12	.01	.29	-.11	1.00

	φ	ω	κ	X0	Y0	Z0		φ	ω	κ	X0	Y0	Z0
φ	1.00	-.22	-.01	1.00	.22	-.25		1.00	.04	-.04	1.00	-.04	.41
ω	-.22	1.00	.08	-.22	-1.00	.23		.04	1.00	.20	.04	-1.00	.11
κ	-.01	.08	1.00	-.01	-.08	.02	**f=305**	-.04	.20	1.00	-.04	-21	.00
X0	1.00	-.22	-.01	1.00	.22	-.25	**mm**	1.00	.04	-.04	1.00	-.03	.40
Y0	.22	-1.00	-.08	.22	1.00	-.23		-.04	-1.00	-.21	-.03	1.00	-.11
Z0	-.25	.23	.02	-.25	-.23	1.00		.41	.11	.00	.40	-.11	1.00

table 1: correlation matrixes of photo orientations

number of points	focal length	Sφ	Sω	Sκ	SX0	SY0	SZ0
615	153 mm	0.0013°	0.0011°	0.0005°	0.013m	0.012m	0.004m
615	305mm	0.0024°	0.0022°	0.0005°	0.047m	0.041m	0.009m
9	153mm	0.0023°	0.0023°	0.0010°	0.078m	0.075m	0.025m
9	305mm	0.0047°	0.0045°	0.0010°	0.261m	0.251m	0.052m

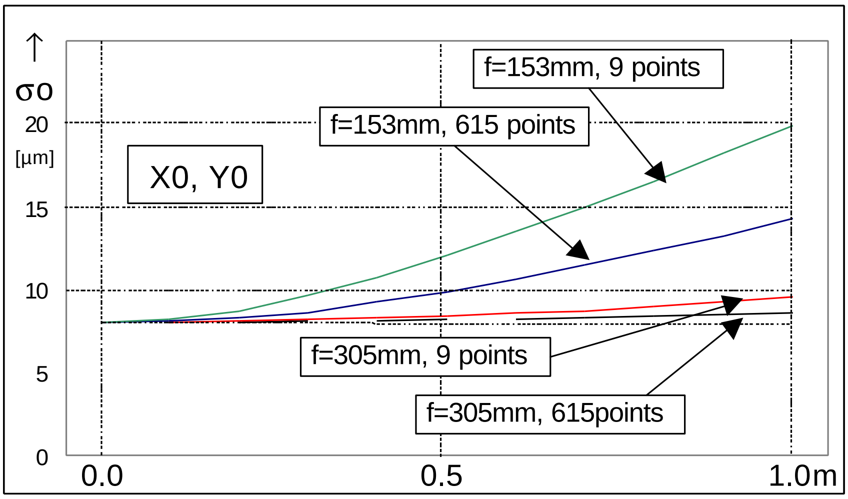
table 2: standard deviation of exterior orientation by resection
photo scale 1 : 10 000, σo = ± 5µm

The standard deviation of the exterior orientation, determined by resection, is depending upon the focal length, the number and distribution of the points, the photo scale and the standard deviation of the photo coordinates σo and/or the ground points. It is linear depending upon the scale and σo. In general the standard deviation of phi and omega is the same as well as SX0 corresponds to SY0, there is only a variation caused by the not equal point distribution. The standard deviation of the X- and Y-component is 3 times larger than for Z in the case of a wide angle camera and 5 times in the case of normal angle. For the ground points in a model, the relation is reverse by the factor of 1.6 and 3.2. This problem of the projection center position is caused by the strong correlation between phi and X0 and also omega to Y0, listed in table 1 as 0.98 up to 1.00 – that means up to larger than 0.995. This fact has to be respected for the combined bundle block adjustment. If the accuracy of the projection center coordinates in X0 and Y0, based on GPS, is limited, this fact will be compensated by the attitude data phi and omega. Such a compensation is not possible with Z0. That means, the height quality of the GPS-positions for the projection centers is more important for the block adjustment than the horizontal accuracy. This is corresponding to the requirement for the block structure – a support of the horizontal ground point accuracy is not so important like the support of the height.

number of points	focal length	influence of 1m in X0	influence of 1m in Y0	influence of 1m in Z0
615	153 mm	11.3 µm	12.2 µm	34.4 µm
615	305 mm	3.1 µm	3.5 µm	17.0 µm
9	153 mm	17.9 µm	18.5 µm	55.8 µm
9	305 mm	5.1 µm	5.4 µm	27.4 µm

table 3: influence of the change of the projection center to σo of a resection
photo scale 1 : 10 000

Table 3 shows the limited influence of the horizontal projection center position to the σo of a resection, that means, also the combined block adjustment. For normal angle images a not respected standard deviation of ±1m for X0gps and Y0gps (photo scale 1 : 10 000) is influencing the σo of the



block adjustment only by 3.3µm if the points are distributed in the whole photo. That means a general σo of ± 5µm is enlarged to ±6µm or ±10µm are enlarged to ±10.5µm. Such an effect is more or less negligible.

figure 4: influence of a change of the projection center coordinates in X0 or Y0 to σo of a resection, based on a σo = 8µm for the photo coordinates (image scale = 1 : 10 000)

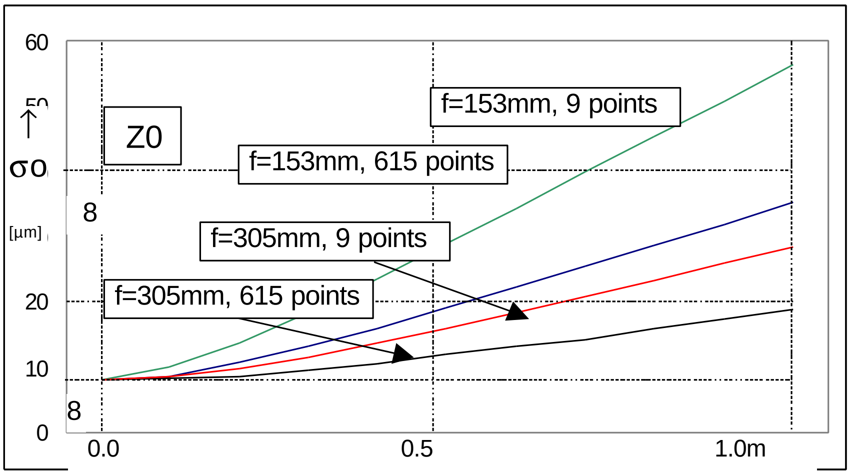
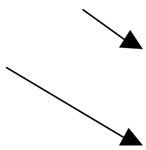


figure 5: influence of a change of the projection center coordinates in Z0 to σo of a resection, based on a σo = 8µm for the photo coordinates (image scale = 1 : 10 000)



As it also can be seen in figure 4 and 5, the influence of a change of the projection center position caused by the GPS-coordinates is influencing wide angle images much more than normal images and the a change in Z0 has a much stronger effect than a change of the X0 or Y0 component. This result of a resection can directly transferred to the standard deviation of a combined bundle block adjustment using projection center coordinates determined by GPS.

	X0, Y0 10%	X0, Y0 20%	Z0 10%	Z0 20%
f=153 mm, 615 points	0.32m	0.45m	0.11m	0.15m
f=153 mm, 9 points	0.20m	0.29m	0.05m	0.09m
f=305 mm, 615 points	1.05m	1.6 m	0.21m	0.31m
f=305 mm, 9 points	0.70m	1.0 m	0.13m	0.19m

table 4: size of the change of the projection center position causing a rise of the basic σo of ±8μm by 10% and 20%

A change of the σo of a bundle block adjustment by 10% or even 20% is not very obvious, that means, the accuracy of the GPS-observations X0 and Y0 is not so important for the block adjustment. This is not the case for Z0, especially for wide angle images. Of course this cannot be extended to systematic errors, but systematic errors have to be eliminated by the process of combined block adjustment.

The correlation of X0 and Y0 to phi and omega may cause problems for a combined block adjustment with projection center coordinates for very long flight strips. The lateral tilt in the center of the strips at the border may have a limited accuracy. By this reason, very long blocks should be stabilized by crossing flight strips every 20 to 30 images or control points (see figure 6).

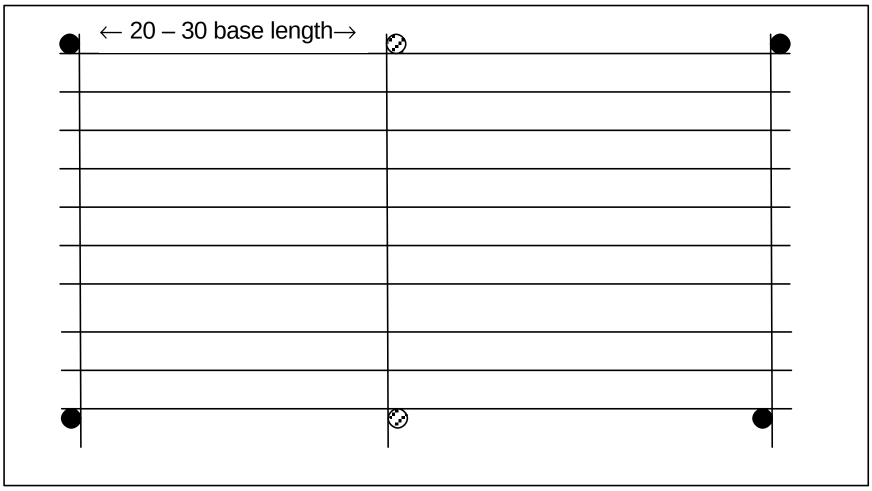


figure 6: block configuration – crossing flight strips every 20 – 30 base length or control points in the corresponding position

COMBINED BLOCK ADJUSTMENT WITH PROJECTION CENTER COORDINATES AND ATTITUDE DATA

As mentioned above, attitude data are not required for a combined block adjustment if a real block structure is present. This is not the case for linear projects. Of course also linear projects can be handled just with GPS-coordinates of the projection centers, if instead of one flight strip, two with different location are used (one flight axis beside or even above the other).

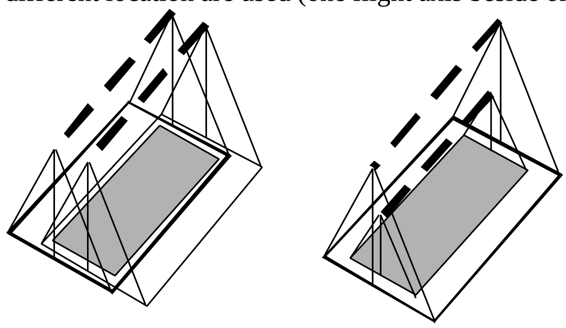


figure 7: block configuration of linear objects – without support of IMU-data

In the last years the quality of the IMU have been improved and the price has been reduced. In addition the size and weight became smaller. A major reason for this is the replacement of the rotating gyros by ring laser or fiber optic gyros.

Simple IMU can be used for the support of the GPS-positioning. Even with cheap systems, GPS-cycle slips can be detected and the antenna offset can be respected, but the full support requires a higher quality of the IMU-data. If the influence of the attitude information to the image coordinates shall not exceed 5µm, for wide angle cameras in the image center an accuracy for phi and omega of ± 0.0021° and for the corner position ±0.0013° are required. For normal angle cameras phi and omega should be available with ±0.0010° or ±0.0009°. For kappa the standard deviation must be only ±0.003°. Even if the IMU guarantees such a quality, it is not available for the photo orientations, caused by the mounting stability of the IMU to the cameras, which is limited to approximately ±0.003° by reasons of the camera construction and the vibration of the aircraft. Of course for the production of orthophotos, based on existing digital height models, such an accuracy is not required, but for the model handling, even if the accuracy is not important, the y-parallax should not exceed 20µm. By these reasons a combined block adjustment using also the photo information is required.

For a combined block adjustment together with GPS and attitude information, errors of the GPS-positions cannot be compensated by phi and omega because they are used as observations. That means also the antenna offset must be handled with more care and the same GPS-receivers should be used in the aircraft and on the reference station. A combination of different GPS-receivers often causes small errors in time, corresponding to systematic errors in the position. The IMU has to be combined with GPS to reduce the large drift of the IMU.

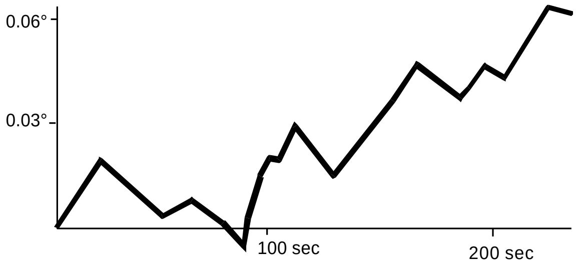


figure 8: drift of the LCR-88 – Z-giro not supported by GPS

With a combination of the IMU-information together with relative GPS-positioning by Kalman filter, the strong drift of the IMU-positions can be eliminated and the attitude drift can be reduced. The combination of both systems also includes the advantage of a better interpolation of the GPS-data which are available with a time interval of 0.6 up to 1 seconds corresponding to 37m – 62m for a speed of 120 kn. The IMU-data are taken with 50Hz or even a higher frequency, corresponding to a distance between the readings of 1.2m for a speed of 120 kn.
If the IMU is attached to the camera, it cannot directly support the reduction of the antenna offset because of the camera rotation against the aircraft for drift compensation. Only if the antenna is directly above the camera, this problem does not exist. This problem is enlarged if the camera together with the IMU are mounted on a gyro stabilized platform. The exact solution requires an additional IMU attached to the fuselage or readings of the camera rotation against the aircraft.
The IMU will give information about roll, pitch and yaw, this has to be transformed to the orientations phi, omega and kappa used in the block adjustment. Yaw is usually oriented to the true north and not the Y-axis of the national net coordinate system. The transformation does not include problems.

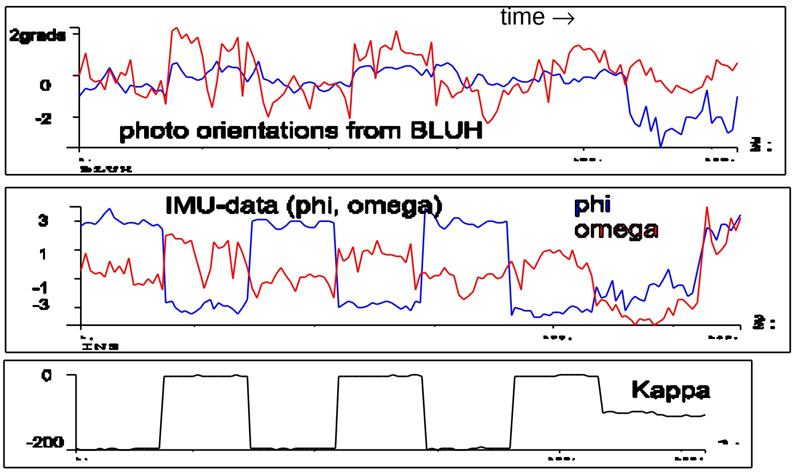


figure 9: top: photo orientations phi and omega from controlled block adjustment
center: photo orientations phi and omega from inertial system LCR-88
below: photo orientation kappa

A test block with 6 flight strips in east-west-direction and 2 crossing strips in north-south-direction has been flown, including in total 130 photos with a scale 1 : 2000. The inertial measurement unit Litef LCR-88 was mounted at the aircraft body and not at the camera. Corresponding to this, the relation between the camera and the IMU is changing from flight strip to flight strip as it can be seen in figure 8, caused by the camera rotation for the compensation of the aircraft drift. Above in figure 8 the photo orientations of a bundle block adjustment with program system BLUH using only control points are shown. At kappa the relation to the flight strips is obviously and it can be seen that the differences of the orientations between BLUH and IMU do have constant differences changing from flight strip to flight strip.

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SQUARE MEAN OF DIFFERENCES
Sphi = +/- 2.658°  Somega = +/- 1.241°  Skappa = +/- 4.535°

SQUARE MEAN OF DIFFERENCES WITHOUT SYSTEMATIC DIFFERENCES
Sphi = +/-  .060°  Somega = +/-  .085°  Skappa = +/-  .110°

SQUARE MEAN OF DIFFERENCES TO LINEAR FITTING
Sphi = +/-  .062°  Somega = +/-  .082°  Skappa = +/-  .108°

FITTING BY POLYNOM T*T
Sphi = +/-  .063°  Somega = +/-  .081°  Skappa = +/-  .107°
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SYSTEMATIC DIFFERENCES OF FLIGHT STRIPS

strip	dphi	domega	dkappa [°]
1	3.071	-.347	2.039
2	-2.871	-.152	-5.069
3	2.924	-.280	4.609
4	-2.827	-.425	-4.865
5	2.796	-.141	4.744
6	-2.964	-.425	-5.178
7	.203	-2.934	4.516
8	.491	-2.918	4.411

table 5: analysis of the discrepancies of the photo orientations determined by block adjustment and IMU, separately handled for each flight strips

The analysis of the IMU-attitude data shows systematic differences mainly depending upon the flight direction. After improving the rotations by the constant differences for each flight strip, no higher degree of systematic errors can be seen. There is no drift during the flight time of approximately 40 seconds for each strip, also a polynomial fitting is not improving the result. The mean square differences of ±0.060° for phi, ±0.085° for omega and ±0.110° for kappa do show the limited potential of the used IMU. It is just sufficient for orthophotos with a limited enlargement and a limited accuracy. A model handling with such an accuracy is not possible. But nevertheless it can be used as an observation within a combined bundle block adjustment if the high potential of the photogrammetric data for the relative accuracy will be respected.

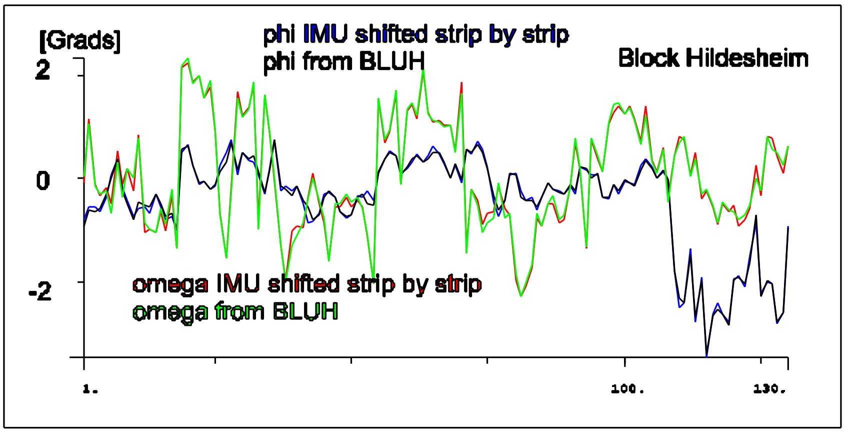
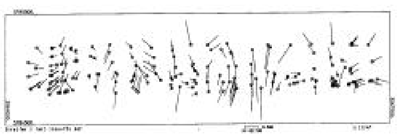


figure 10: overlay of the IMU-attitude data, shifted individually for every flight strip and orientations from bundle block adjustment

The accuracy characteristics of the IMU-data is similar to the situation of GPS-projection center coordinates. The attitude relation of one image to the neighbored image can be determined very accurate by means of photogrammetric tie points (~ relative orientation), but the photogrammetric error propagation within a longer flight strip is not advantageous – this has to be compensated by IMU-data. Of course the IMU-data should be more accurate than the results obtained with the Litef LCR-88. On the other hand, the absolute relation between the IMU-data and the camera has to be determined by means of control points. All this can be done together within a combined bundle block adjustment. In the Hannover program system for bundle block adjustment BLUH, the GPS- as well as the IMU-data can be filtered by a local polynomial fitting and the absolute relation, that means the systematic errors, can be determined by additional unknowns. This can also include the determination of time depending drift values – if required, separately for every flight strip.



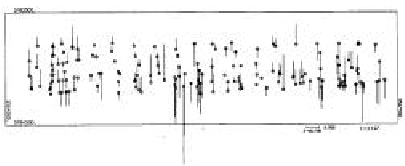


figure 11: discrepancies at check points of a block handled by combined block adjustment with GPS- and IMU-data
left: discrepancies in X and Y, right: discrepancies in Z

The handling of a test block flown with DGPS and IMU at an image scale 1 : 2000 was possible without control points – with an independent check following results have been achieved : SX=±0.12m, SY=± 0.17m and SZ=±0.19m. A single strip of this block was handled in a combined bundle block adjustment with one control point and the IMU-data. With the above mentioned limited accuracy of the IMU-data together with the GPS-data, SX=±0.22m, SY=± 0.40m and SZ=±0.62m have been reached. Of course this is not an optimal result, but based on the combined block adjustment, the relative orientation of one image to the neighbored, enables the handling of the resulting model.

CONCLUSION

The combined bundle block adjustment with coordinates of the projection centers, determined by relative kinematic GPS-positioning, of single flight strips is not possible without control points. Attitude information by means of IMU can solve this problem. In the case of a combined block adjustment with GPS- and IMU-data, the GPS-data must be more precise, because errors in the X- and Y-component cannot be compensated by the image rotations phi and omega. It is difficult to reach with IMU-data the accuracy of the attitude data which is required for a handling of models. The y-parallax should not reach the size of the floating mark. Even if the IMU attitude information is accurate enough, the physical connection of the IMU to the camera body is limited to approximately ±0.003°. So a combined bundle block adjustment is required – the tie points can connect the images together in a method which enables a model handling with the resulting photo orientations. At least one control point is required for the determination of the relation of the IMU to the camera.

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