METRIC CAMERA WITH FOCAL PLANE SHUTTER

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ABSTRACT:
As a matter of fact metric cameras always used central shutters. These shutters enabled an exposure which is done at the same time on all parts of the image. This means that the mid exposure time, and thus the projection center of images taken with a moving camera, is invariant in image space.
Unfortunately these central shutters are restricted in exposure time range. Under aerial imaging conditions, they should only be used in combination with forward motion compensation, which minimizes smear effects.
Focal plane shutters are able to produce short exposure times. So smear effect is minimized as good as possible. It gets especially important when Bayer arrays are used and no FMC is available. Also mid exposure time is no longer space invariant.
Focal plane shutters produce geometrical effects in the images and influence measuring accuracy.
We studied these effects and implemented a compensation method. In our paper we show the study results for the influences and our method to compensate the shutter effects.
The compensation was applied to test flight data. These results will be shown too.

1. INTRODUCTION, SITUATION AND BACKGROUND

Moving objects or moving cameras produce motion smear, depending on exposure time. This can be compensated by short exposure times or forward motion compensation (FMC) in case of aerial cameras.
A focal plane shutter introduces an additional movement. According to the position of the shutter the sections of the image are exposed at a different times.

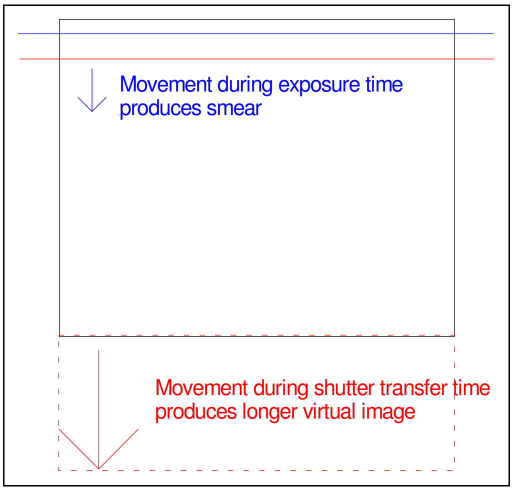

Figure 1: Principle of focal plane shutter.

The width of above shown shutter opening produces exposure time and is responsible for motion blur. The position and movement of the shutter opening itself produces a stretch or squeeze of the image, a linear geometrical distortion.
A Shutter running in flight direction produces a squeeze effect. A stretch is produced, when the shutter runs against flight direction
Shutter movement across flight direction produces shearing.
These influences are linear, as long as the shutter has a linear movement.
In photogrammetry influences like these can be handled by linear parameters in different camera models, called B1 and B2 for example in LPS and Orima.

The expansion factor can be easily derived from elementary geometry:

$$\rho = \frac{1}{1 - \frac{v}{w}} \approx 1 + \frac{v}{w} \qquad (1)$$

where v is the ground speed projected into the image plane, w = L / T is the speed of the shutter curtain, L is the length of the sensor in flight direction, and T is the time a curtain needs to transverse the sensor.

The following calculations are done for a 39Mpix sensor with 6.8 µm pixel size.

The operational parameters for which the system is designed are:

L = 36.8 mm
T = 8 ms
v = 40 mm/s (maximum)
w = 4600 mm/s

The largest absolute value of v/w differs by about 1 % from unity.
Therefore the approximation in the above equation is acceptable.
In above case shutter ran against flight direction.
In case of parallel shutter movement the image is compressed.

$$\rho = \frac{1}{1+\frac{v}{w}} \approx 1-\frac{v}{w} \qquad (2)$$

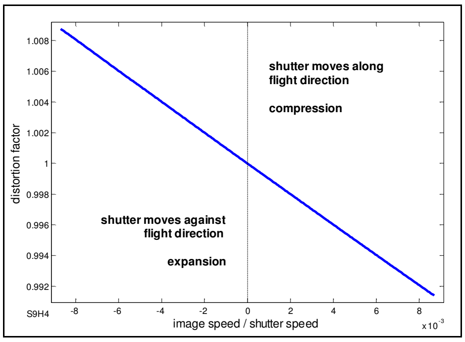

Figure 2: Relation between shutter speed, image speed and compression factor

The velocity v is the speed of the image in relation to the sensor, where the focal length c, the height over ground h and the ground speed if the airplane (Vap) have to be included.

$$v = Vap * c / h \qquad (3)$$

So the influence to the camera parameters gets dependant on flight project parameters and is not a constant parameter of the camera.

To determine the influence of this effect and its dependencies from speed and height following steps were done:

- Rough calculation of stretch or squeeze factor for constant conditions like height and speed.
- Calculation of influences, using artificial terrain
- Application of distortion and shutter influence correction on images.
- Measurement of rest errors by in flight calibration.

2. ESTIMATION OF VARIABLE INFLUENCE TO LINEAR FACTOR B1

In the following calculations a restriction to parallel or anti parallel movement is done.

For an example a 35 mm lens in and a 39 MPix sensor is used.
For different flying heights (h) and airplane speeds (Vap) the effect is calculated.
The sensor has 5400 Pixel in flight direction

h = 300 m			
Vap [kts]	78	156	233
Squeeze[Pixel]	5.5	11.0	16.5
h = 600 m			
Vap [kts]	78	156	233
Squeeze [Pixel]	2.7	5.5	8.2
h =1800 m			
Vap[kts]	78	156	233
Squeeze	0.9	1.8	2.7

This means, images from a flight in 300 m are squeezed by about 16 pixels. In the same direction the total number of pixels is 5400. So the relative factor is about 0.3 %.
As long such a factor is stable and constant within an image, compensation is no problem
But there are height variations within an image, produced by the landscape. So also the stretch factor varies.

Before correction software was produced and test with flight data were done, theoretical evaluation including all effects was made.

3. MODELLING OF HEIGHT DEPENDANT CAMERA PARAMETERS

As mentioned camera parameters spilt now into two parts

- Static parameters like distortion, influenced by lens and sensor only
- Dynamic parameters, varying with project conditions

Within this step these influences of the dynamic parameters were clarified:

- Influence of terrain height
- Influence of GPS / IMU data
- Influence of height accuracy

With an artificial terrain, shown in the next figure, imaging equations were used including and excluding focal shutter influence.
The influence was modeled using simplified equation (1,2).

Figure 3 shows a simple arrangement of object points in a terrain. The picture is a 3D plot of a Gauss Bell shaped terrain.

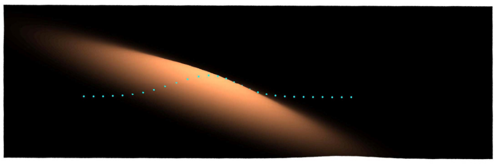

Figure 3: Terrain in the shape of a Gauss bell with a string of object points. The flight direction is from left to right.

Objects points on the artificial terrain are used to calculate their position in the image.
For this imaging position data if simulated flights and the time delay, caused by the shutter movement are included.
Then the theoretical deviation is calculated and the possible correction using equation (1) integrated in imaging process.

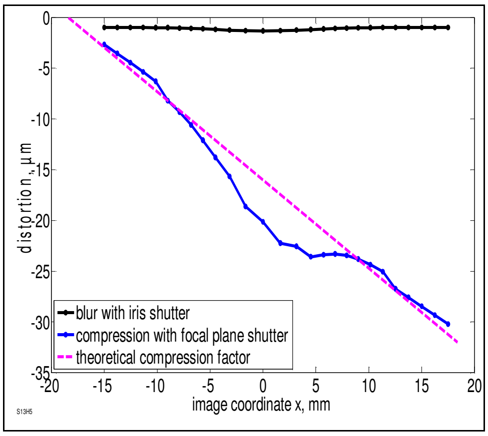

Figure 4: Image compression and possible correction by the action of a focal plane shutter.

The residual error is evidently reduced to less than 1.2 µm (using 6 µm pixels), which is about 1/5 of a pixel and much less than the blur caused by the finite exposure time.

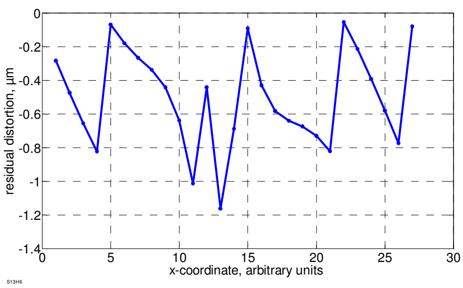

Figure 5: Residual errors after correcting for the shutter effect.

4. RESTRICTIONS FOR A POSSIBLE COMPENSATION

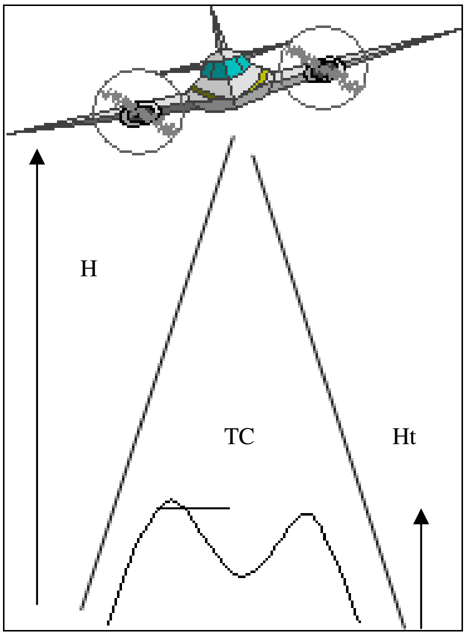

Figure 6: Flight situation

In above shown flight situation different 7influences can be seen.

- H means the flying height
- Ht is the terrain height
- TC is the size of a terrain cell (DTM)

After all calculation using various flight paths and terrains, it can be summarized

The influence of a focal plane shutter can not be eliminated totally.
It can be reduced by a factor of about 4, under realistic conditions.

For such a case we assumed.

- Ht <= 30% of H
- Height variation within one DTM cell is < +/- 20 % of cell size.

For example at 2000 m flying height 700 m terrain is allowed in an image. In a 100 m * 100 m DTM cell 40 m height differences are acceptable. This is a rather steep terrain, where also FMC produced residual errors.

These results show that a limited compensation is possible.

5. COMPENSATION SOFTWARE

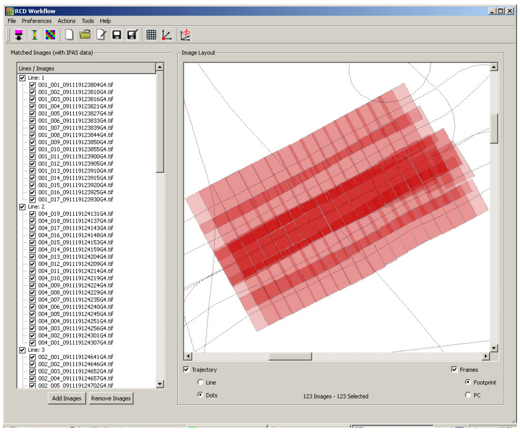

Figure 7: Start screen of compensation software

A resampling program was developed to compensate all distortion in the images, the static parts like lens distortion as well as dynamic part from shutter.

The output is a distortion free image

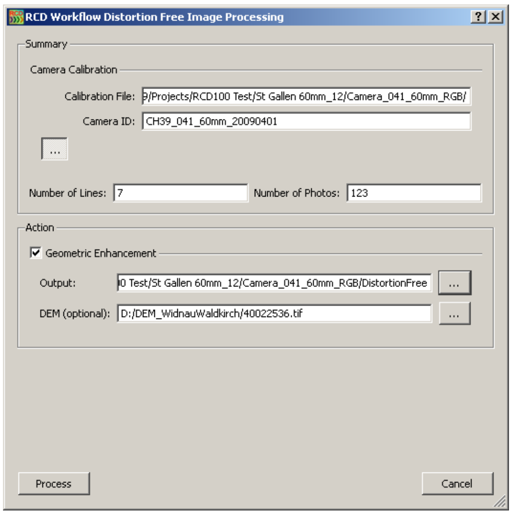

Figure 8. Input mask for compensation parameters

For the correction of images software needs

- GPS/ IMU data to calculate speed over ground and absolute flying height
- DTM to calculate height over ground
- Camera parameter file for distortion

6. FLIGHT TESTING WITH COMPENSATED AND UNCOMPENSATED IMAGES

The theory was tested with two different projects

- Calibration cross with two different flying heights, where residuals were determined for these two heights
- Block with height variations of the terrain and ground point measurements.

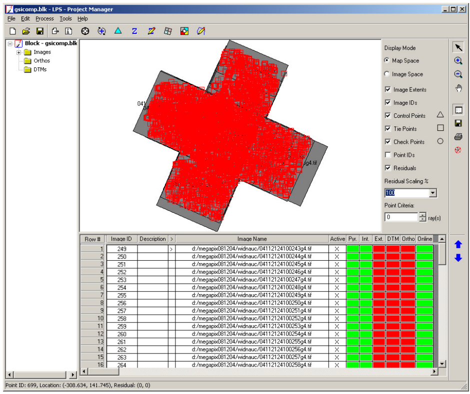

Figure 9: Calibration cross with two different flying heights.

Calibration cross was captured over a flat terrain, with 15 cm GSD and 25 cm GSD.
With these images in. flight calibration was calculated neglecting the dynamic stretch.

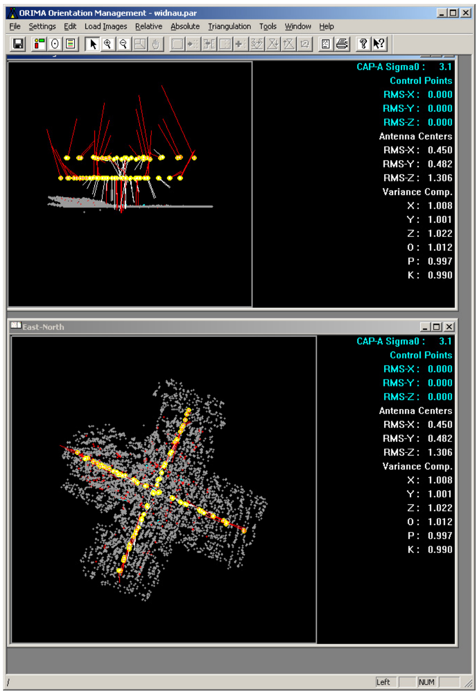

Figure 10: Triangulation Result with images, without shutter compensation

Here the result of an Orima calculation shows large systematic errors.
For all calculations original distorted images were used and distortion parameters were in input to ORIMA.

These systematic errors could be reduced, when a stretch parameter (B1) is included.
This is parameter a mean stretch value for the different heights: Residual errors show a strong dependency from the two flying heights.

Better compensation could be reached, when the stretch parameter was different for the two flying heights.

Best result could be obtained using corrected images, as shown in figure 11.

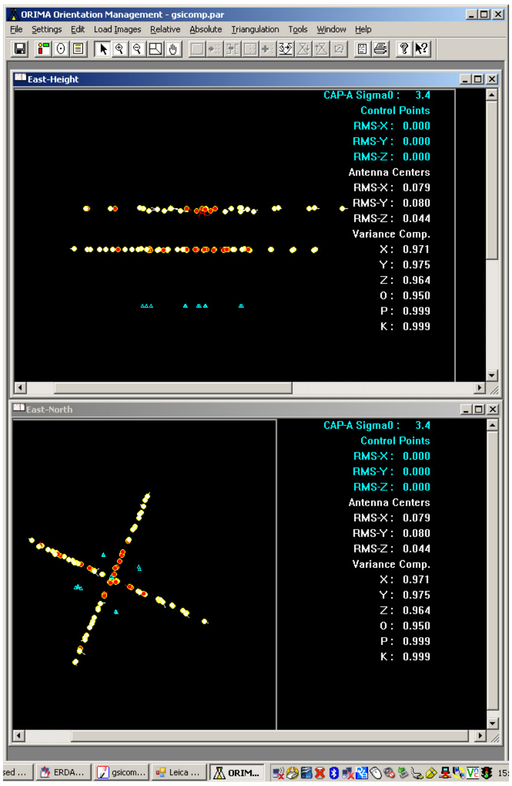

Figure 11: Result with shutter compensation

In last case distortion free images were used for calculations and all camera parameter were set to 0.

Only focal length was used as camera parameter.

In this case only flying height influences the correction, cause there is nearly no difference in terrain heights.

For a final measurements the total correction was applied to images of a photogrammetric block
Now hilly terrain was used to study influences of flying height and terrain height.

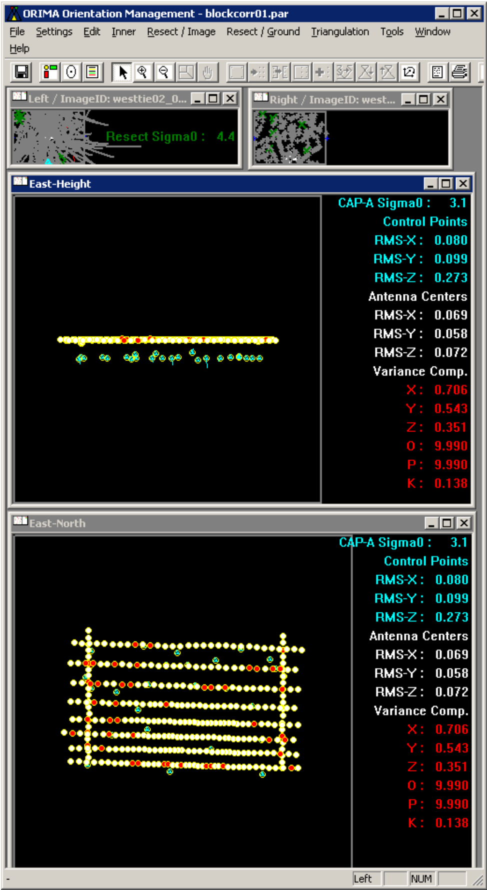

Figure 12: Photogrammetric block over hilly terrain.

After shutter correction good results on ground control measurements can be obtained. GSD here was 20 cm. So the accuracy was

- < ½ Pixel in X/Y
- ≈ 1 Pixel in Z

7. SUMMARY AND RESULTS

Focal plane shutters can be used for photogrammetric applications, when some restrictions are accepted.

- Good results for small GSD’s like 5 cm can only be expected for flat terrain
- For GSD’s > 15 cm also hilly terrain promise good results
- Terrain height within a image has to be restricted