ADS40 SYSTEM WITH NEW SENSOR HEADS – KEY TO THE SIMPLIFIED MODEL FOR SELF-CALIBRATION AND EXTENDED USER BENEFITS

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ABSTRACT

The new ADS40 sensor heads SH51 and SH52 are designed around a unique beamsplitter device which closely co-registers four spectral bands. Together with an increased signal to noise ratio, this opens new applications in remote sensing and photogrammetry, especially with the in-track four-band stereo imaging of the SH52. Other benefits of the new design are a higher geometric stability and largely reduced irregular distortions. This allows a new camera model for self-calibration by bundle adjustment, which could be directly derived from the optical properties of the system.

Besides the excellent image quality and geometric characteristics, the ADS40 system makes use of the innovative sensor orientation techniques as Precise Point Positioning (PPP).

This paper summarizes properties of the sensor system, gives an overview of the new camera model as implemented in the ORIMA bundle adjustment and presents practical results from flight missions using the PPP technique.

1. INTRODUCTION

The rapid development of digital electronics together with the requirements from the user side has paved the path for launching ADS40 with new sensor heads, SH51 and SH52.

The real technological driver for a new sensor head design was the micro-structured filter. At the same time, the mechanical structure was reworked to an even higher stability, using the new alloy for the focal plate structure and providing space for larger IMU (Inertial Measurement Unit) systems. The electronics re-design was done to improve signal quality, provide advanced functionality and reliability. It also allowed a much more compact sensor design.

An interesting side effect of the new optical design is a largely reduced amount of local distortions. This allows a much simpler camera model for the bundle adjustment and a straightforward approach to self-calibration of the sensor head.

All the above mentioned enhancements have contributed for expanding the ADS40 application range. The high efficiency of ADS40 for covering vast areas is already well-known. In the practical results the paper focuses on two fields, which this new technology has made available for the sensor user today. Firstly, covering the areas with 5 cm Ground Sample Distance (GSD) images and, secondly, achieving the required high accuracy orientation for the images without the need of the Global Navigation Satellite System (GNSS) reference stations.

2. HARDWARE IMPROVEMENTS OF THE SH51 AND SH52

The two main goals of the SH51/52 development were to make the system a far better remote sensing tool and to enable it to work at shorter integration times. The step towards a better remote sensing tool became possible by a micro-optical filter device in front of the CCD lines in combination with a new beamsplitter design. The advantage of this "Tetrachroid" design (Fig. 1) over the SH40 "Trichroid" is that it co-registers also the NIR (near infrared) CCD line to the RGB lines.

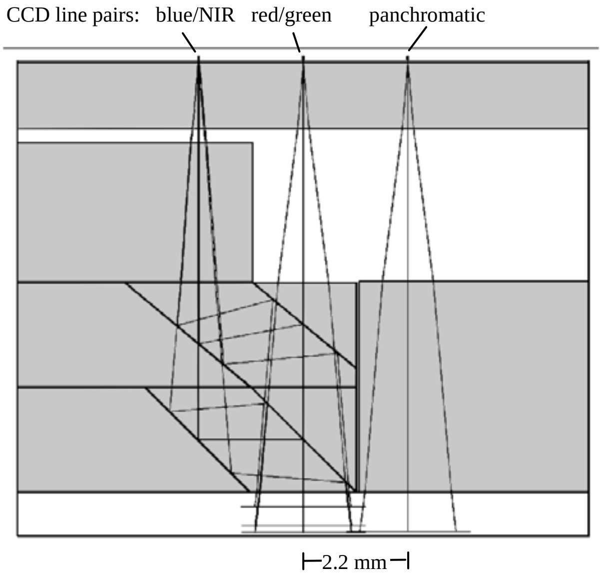


Figure 1: The Tetrachroid, glass shown in grey

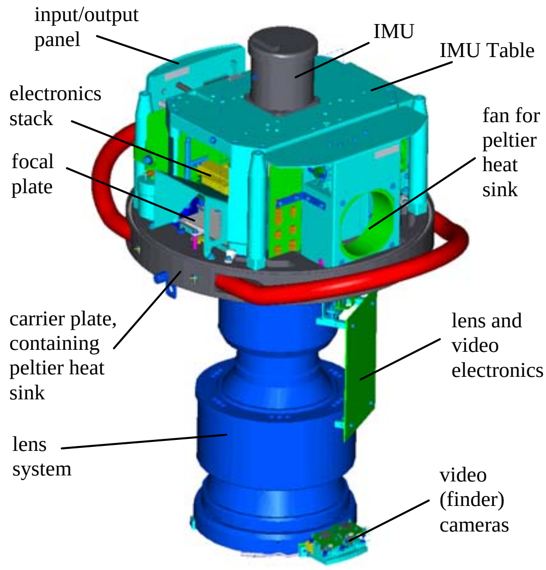


Figure 2: 3-D Model of a SH51/52

Tetrachroid offers as closely co-registered image bands with the same rectangular spectral shape as the SH40 Trichroid - but now simultaneously for true colour, false colour or four-band images. Each image has the full 12k pixel resolution across the swath (Fig. 3).

Figure 3: Ortho-rectified RGB and FCIR images, captured at and rectified to 5 cm GSD

Another advantage of the new design is the replacement of the 0.4 mm separate filter sheets that were cemented to the Trichroid. These filters had been a source of line-specific distortions that were difficult to model during calibration. All filters of the Tetrachroid are now on plane-parallel glass blocks. This, along with the telecentric lens design, ensures that no additional distortion, besides the lens distortion, is introduced.

The mechanical design of the SH40 was good, regarding the relative stability of the lens system, focal plate and the IMU. However, it was limited to small IMU systems and required space for a large focal plate cooler and a complex focal plate structure.

In the new SH51/52 (Fig. 2) the IMU sits on a table above the focal plate and the electronics, exactly on the optical axis and directly connected to the focal plate and lens interconnection ring. The table is designed to introduce no thermal rotations and withstands all practically possible shocks without significant deflexion. It can carry large IMUs, up to the size and weight of the highly precise Honeywell μIRS and allows IMU exchange by the user.

The fast development of digital electronics, especially FPGAs (Field Programmable Gate Arrays), allowed replacing the electronics rack by a small stack (Fig. 2) of only four boards (A/D conversion, digital signal processing, power, IMU interface), while providing even greater functionality.

The most important advantage, from the user's point of view, is the largely reduced noise level. SH51/52 images contain little more than the white noise of the CCD line. Patterned noise, visible in dark parts of SH40 images, is removed. Together with the slightly higher transmission of the Tetrachroid, the sensitivity (i.e. SNR) of the SH51/52 colour lines is more than two times better than that of the SH40. Subjectively, the ratio is even better, as the patterned noise was more disturbing. An analysis of images flown under different light conditions indicates that the same visual quality of orthophotos can be obtained at a quarter of the SH40 integration time.

The SH51/52 allows capture of good colour images at integration times down to 1.25 ms, even under winter light conditions. Images with down to 4 cm GSD can be taken.

3. GEOMETRIC CALIBRATION OF THE ADS40 SENSOR HEADS

3.1 Calibration parameters

In order to be open to any kind of distortion model, the mathematical model of the ADS40 ground processing uses the view angle for each pixel, encoded into a pair of virtual focal plate coordinates with fixed principal distance. Besides the view angles, the IMU misalignment also belongs to the calibration data.

The SH40 calibration process used a combined approach of self-calibration in bundle adjustment and a polynomial fit on the residuals of each sensor line. The polynomial fit was necessary, because the "Brown" parameter set could not model the relative shift of more than three CCD lines (Brown, 1976). Earlier attempts with the further described new parameter set failed due to the higher order line specific distortions from the Trichroid filters.

The situation changed with the SH51/52. The parameter set now has to cover only the basic opto-mechanical properties of the components. These are the principal distance, the radial-symmetric distortion and the position and the orientation of the individual CCD lines in the focal plane. A subset of these parameters should also be suitable for self-calibration on-the-job to compensate for effects such as abnormal atmospheric refraction.

Estimation of ADS calibration parameters in ORIMA is always done relative to an existing input "calibration". ORIMA uses the ADS sensor model library to convert tie and control point measurements into "calibrated" focal plane coordinates. On the output side, ORIMA applies the effects of the estimated calibration parameters to the input calibration and writes out a new calibration data set.

3.2 Geometric sensor parameters

The following parameters are used to describe the inner geometry of the sensor:

- Principal distance
- Coordinates of principal point
- Symmetry point offset for radial lens distortion
- Radial symmetric lens distortion
- Offset and rotation of each sensor line
- Misalignment between IMU and camera axes (three angles)

These sensor parameters are determined within the calibration process using bundle adjustment with self-calibration technology, described in detail in (Tempelmann, Hinsken 2007).

There is no significant difference in the final results between the "old style" calibration and the "new style", although the old method takes twice the number of iterations and requires an additional polynomial fit to the residuals. A calibration check or a re-calibration is now just a single iteration, based on an existing calibration. It can easily be performed by the user.

3.3 A new automatic weighting process for additional observations

A new automatic weighting process for additional observations has been introduced into the ORIMA software to assist the sensor calibration.

The sensor parameters described above cannot be determined as free parameters within bundle adjustment – this would cause ill-conditioned normal equation systems. The true values of the parameters have to be known in a certain tolerance, described by the standard deviation a priori and participating as additional observations.

An iterative method is used where the standard deviation a priori of the additional observations is adjusted based on the local redundancy value.

The advantage of this automatic process is that the solution is not dependent on the knowledge and experience of the user. Without this automatic process the user would have to set the standard deviation for the additional observations, requiring very special knowledge.

4. PRACTICAL RESULTS WITH ADS40 SH52

4.1 Expectations towards the PPP technology

Precise direct sensor orientation based on differential GNSS technology together with inertial measurement unit has been used successfully in the airborne mapping industry for a number of years. However, the dense coverage of reference stations is not common in all mission areas. In these cases Precise Point Positioning (PPP), a post-processing technique allowing high accuracy position and velocity determination using data from a single airborne GNSS receiver, would help. The technology benefits from using the precise GNSS satellite orbit and clock information during the post processing.

It is generally known that the positional accuracy, which can be achieved from this technology, is about 10-15 cm for horizontal components and 15-25 cm for height.

The method of comparing the flight trajectories processed with PPP against the differential GNSS processing is commonly used for getting an idea about the PPP accuracy. However, it is definitely worth performing accuracy assessments as well two steps further down the mapping workflow, after the PPP trajectory has been blended with the IMU data and been used for the adjusted image orientation through the aerial triangulation process.

4.2 Results from the Romanshorn test area

Romanshorn test area, near the Bodensee in Switzerland, has two polygons. The larger polygon, ca 100 km^2, has been covered by 4 flight lines of 20 GSD images. The smaller urban area, ca 4 km^2, had room for 2 and 3 flight lines for 10 cm and 5 cm GSD images respectively (Fig. 4).

Although the ground control, 50 points in the area, has not been signalized, the land features have been selected with special care and allow accurate measurement on images. 8 of the points, 2 in each corner, have been used as GCPs. The rest of the points participated in the bundle adjustments as Check Points (CHPs), by introducing them with a high sigma a priori (99 m). For the other half of the bundle adjustment runs, marked on the figures below as “BA w/o GCPs”, all the points have been used as CHPs.

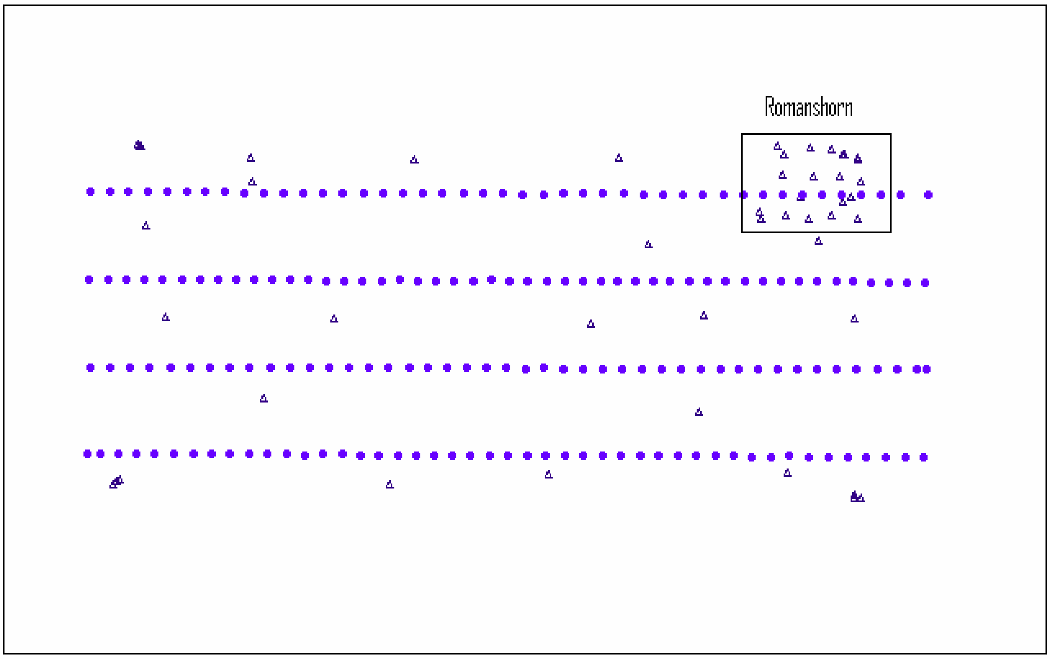


Figure 4: Romanshorn test area

It is important to note that the GNSS constellation during the test missions was good - PDOP was between 1.2 and 3.0 and the number of the tracked GPS satellites was from 6 to 11. The distance from the project area to the reference station was 20 km, giving the excellent solution for the Differential GNSS processing.

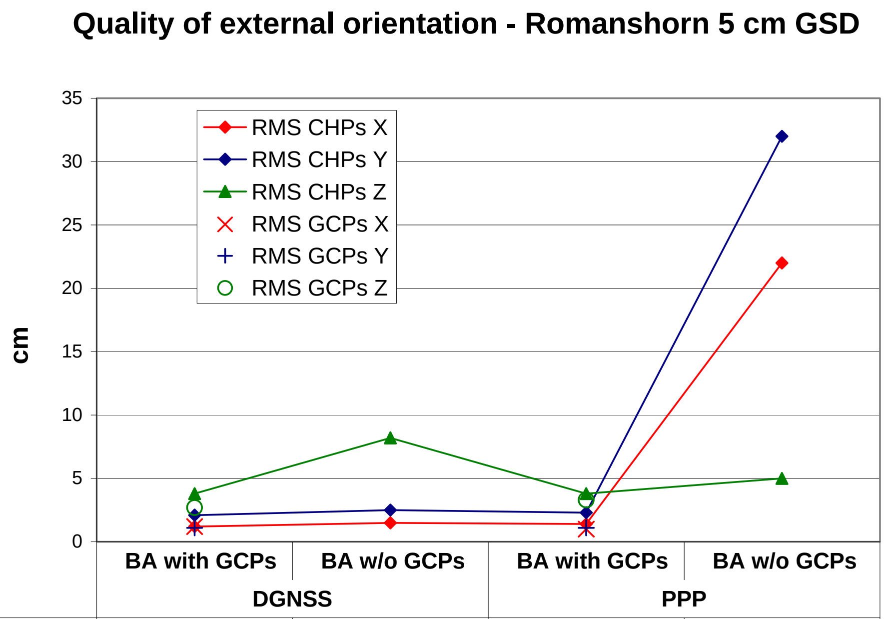
The three flights for 5, 10 and 20 cm GSD images have been executed as separate data captures. The time for recording the GNSS data has been 52, 45 and 70 minutes respectively.

Figures 5 to 7 below show the test results after the bundle adjustment with ORIMA. The only sensor parameter switched on for the self-calibration in these triangulation runs has been the misalignment between the IMU and the camera axes. This is also in accordance with the general recommendation we give for the production workflows – to use IMU misalignment estimation whenever the block configuration allows it.

Another recommendation would be to use ground control in bundle adjustment, to be able to eliminate potential datum deficiencies. Although the differential GNSS processed trajectory gave us very good results, inside the 1 GSD range, with or without the datum estimation, we saw clearly that the PPP processing without ground control did not lead to the best accuracy.

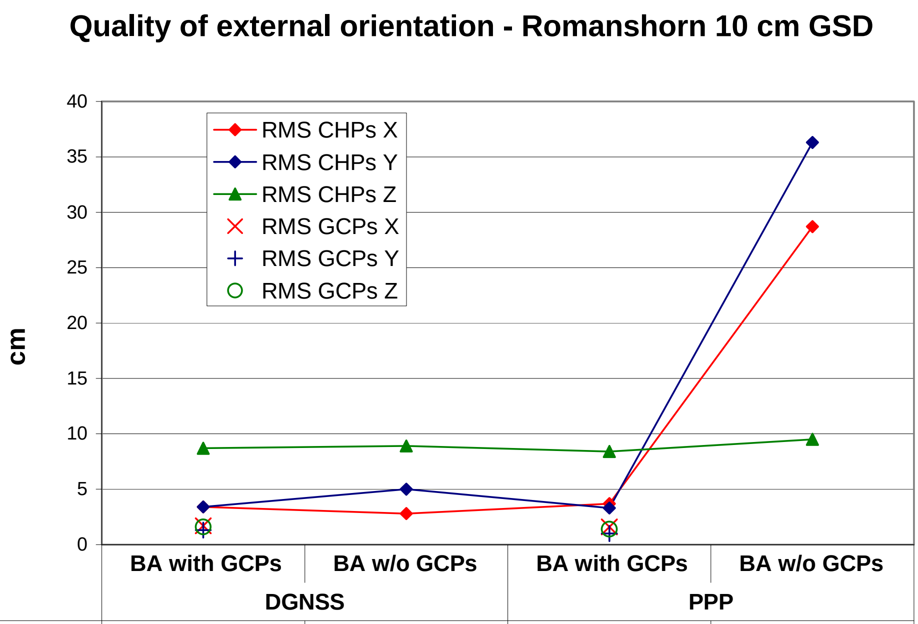
Still, in case ground control was used, the PPP solution gave identical results compared to the DGNSS one.

The behaviour has been similar with the images from all the 3 flying heights.



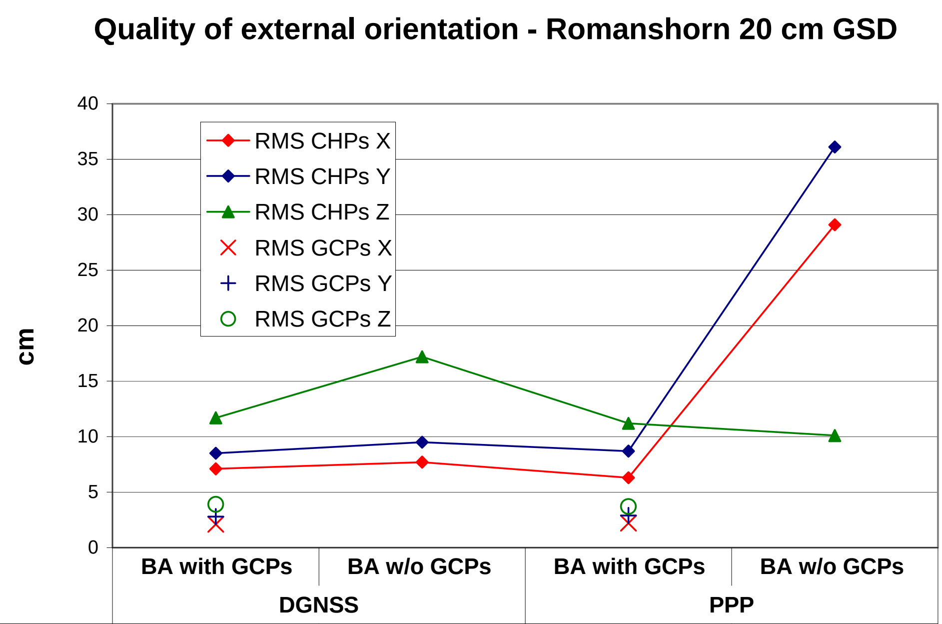
	DGNSS BA with GCPs	DGNSS BA w/o GCPs	PPP BA with GCPs	PPP BA w/o GCPs
RMS CHPs X	1.2	1.5	1.4	22.0
RMS CHPs Y	2.1	2.5	2.3	32.0
RMS CHPs Z	3.8	8.2	3.8	5.0
RMS GCPs X	1.2		1.0	
RMS GCPs Y	1.1		1.1	
RMS GCPs Z	2.7		3.3	

Figure 5: Quality of external orientation - Romanshorn 5 cm GSD



	DGNSS		PPP	
	BA with GCPs	BA w/o GCPs	BA with GCPs	BA w/o GCPs
RMS CHPs X	3.4	2.8	3.7	28.7
RMS CHPs Y	3.4	5.0	3.3	36.3
RMS CHPs Z	8.7	8.9	8.4	9.5
RMS GCPs X	1.7		1.6	
RMS GCPs Y	1.3		1.0	
RMS GCPs Z	1.6		1.4	

Figure 6: Quality of external orientation - Romanshorn 10 cm GSD



	DGNSS		PPP	
	BA with GCPs	BA w/o GCPs	BA with GCPs	BA w/o GCPs
RMS CHPs X	7.1	7.7	6.3	29.1
RMS CHPs Y	8.5	9.5	8.7	36.1
RMS CHPs Z	11.7	17.2	11.2	10.1
RMS GCPs X	2.1		2.2	
RMS GCPs Y	2.8		2.9	
RMS GCPs Z	3.9		3.7	

Figure 7: Quality of external orientation - Romanshorn 20 cm GSD

4.2 Results of comparing multiple PPP trajectories

We have seen, from the test results above, PPP being very promising for cases when a datum deficiency could be eliminated with help of GCPs. On the same time we observed that there was some room left for improvement in the terms of absolute accuracy with PPP.

PPP is highly session duration dependent – the GNSS observation data should be continuously collected for a long enough period. The recommended minimum observation period is 60 minutes, while the recording time of 4 hours could be considered as optimal.

The Romanshorn tests, being all close to 1 hour sessions, cannot be considered as typical in this respect.

We have performed another test with a 5 cm GSD ADS40 SH52 data set on a different area and in different conditions.

A good GNSS constellation was observed: PDOP from 1.5 to 2.7 and the number of the tracked GPS satellites from 7 to 8. Flight duration and GNSS data capturing session was 1 hour and 50 minutes. A distance from the project area to the reference station of 20 km provided a good DGNSS solution with fixed ambiguities.

The ground control in the area, 50 points, has been not signalized and therefore not been perfectly identifiable, but would still describe the typical map production conditions.

In this test we observed how using different precise observation and clock data for PPP processing impacts the image orientation quality.

International GNSS Service (IGS) offers two products, namely precise orbit data and precise clock correction data, to the GNSS community for better position and navigation accuracy. The IGS provides different categories of products based on the product's availability latency. One category is the “Final” product, which has a latency of about 13 days after the GNSS observation. Another is the “Rapid” product, which has a latency of about 17 hours after the observation. “Final” category products have generally better accuracy and reliability than the “Rapid” ones.

Under the organization of International GNSS Service, there are several data analysis centers, such as Jet Propulsion Laboratory (JPL), Center for Orbit Determination in Europe (CODE), National Geodetic Survey (NGS), etc. These analysis centers also generate their own precise orbit and precise clock corrections products. Unlike the IGS organization, the individual data analysis centers do not generate the “Rapid” category precise orbit and clock data files. They produce the corrections data only in the “Final” category.

In order to produce consistent solutions, the precise orbit and precise clock corrections used for the PPP data processing should come from the same agency.

In our test we have used “IGS Rapid”, “IGS Final” and “JPL Final” products for the calculation of the different PPP trajectories.

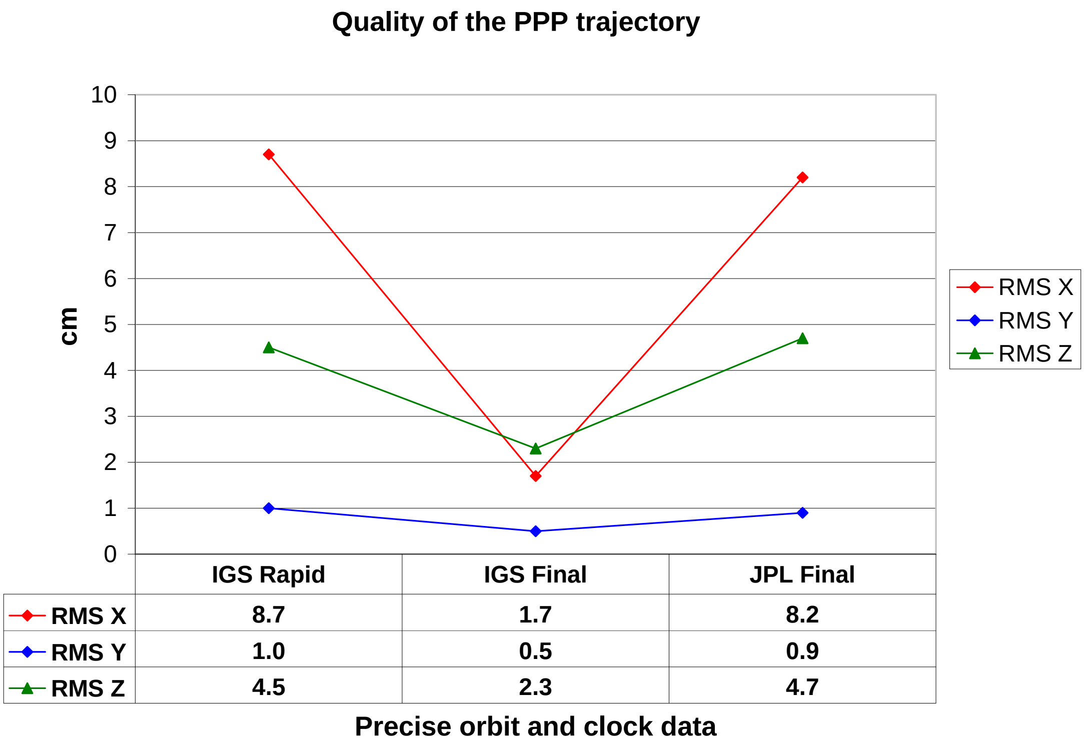


Figure 8: Quality of the PPP trajectory with different precise orbit and clock data

PPP processing software has quality control measures to check the accuracy and reliability of the solution based on several indicators. These include differences between 3D position from forward and backward processing, satellite geometry, residuals of the measurements and others. On Figure 8 an indication of the quality is given for the PPP trajectory based on the processing with different precise orbit and clock data.

The Figures 9 and 10 show the results of the image orientation accuracy, which is achieved after the bundle adjustment with ORIMA. The results based on the three different PPP trajectories are compared against the one based on the Differential GNSS.

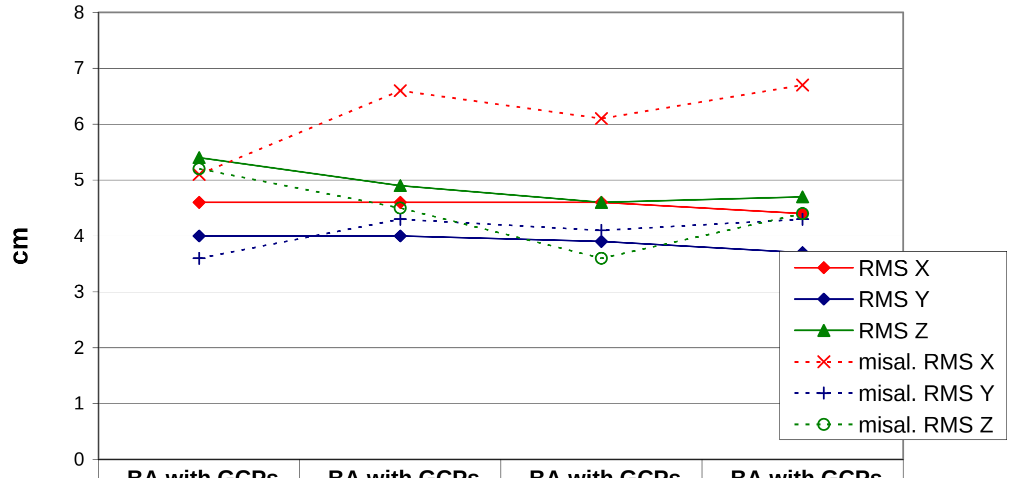
Figure 9 presents the results from the triangulation with 8 GCPs (2 in each corner of the block), while on Figure 10 the results show the orientation quality without the GCPs i.e. without datum estimation applied.

The misalignment between the IMU and the camera axes has been the only sensor parameter switched on for the estimation. On both figures the second set of CHPs residuals (“misal. RMS X, Y, Z” on Fig. 9 and 10) are from the processing without misalignment estimation.

The positive impact of using IMU misalignment estimation in the bundle adjustment is noticed.

All the processed PPP trajectories have lead to a very similar quality of the image orientation compared to the DGNSS one when the aerial triangulation was done using estimation of datum and IMU misalignment.

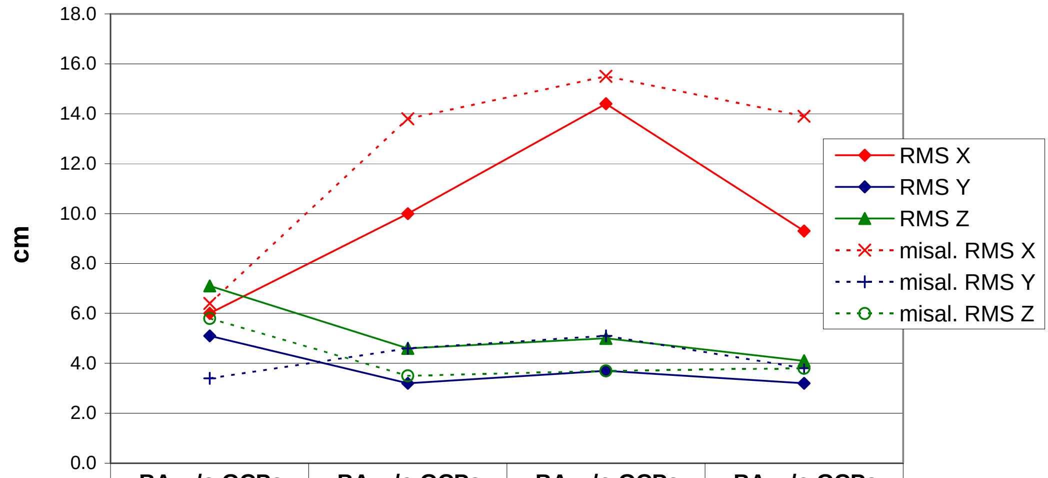
Quality of external orientation of Ground-Controlled data set - 5 cm GSD



	BA with GCPs DGNSS	BA with GCPs IGS Rapid	BA with GCPs IGS Final	BA with GCPs JPL Final
RMS X	4.6	4.6	4.6	4.4
RMS Y	4.0	4.0	3.9	3.7
RMS Z	5.4	4.9	4.6	4.7
misal. RMS X	5.1	6.6	6.1	6.7
misal. RMS Y	3.6	4.3	4.1	4.3
misal. RMS Z	5.2	4.5	3.6	4.4

Figure 9: Image orientation quality with different PPP trajectories when using GCP-s.

Quality of external orientation of Non-Ground-Controlled data set - 5 cm GSD



	BA w/o GCPs DGNSS	BA w/o GCPs IGS Rapid	BA w/o GCPs IGS Final	BA w/o GCPs JPL Final
RMS X	6.0	10.0	14.4	9.3
RMS Y	5.1	3.2	3.7	3.2
RMS Z	7.1	4.6	5.0	4.1
misal. RMS X	6.4	13.8	15.5	13.9
misal. RMS Y	3.4	4.6	5.1	3.8
misal. RMS Z	5.8	3.5	3.7	3.8

Figure 10: Image orientation quality with different PPP trajectories when not using GCP-s.

5. CONCLUSION

The SH51/52 sensor heads are a logical step forward in pushbroom sensor technology. It extends the range of applications into remote sensing and high-resolution photogrammetry. An interesting side effect of the new optical design is a largely reduced amount of local distortions. This allows a much simpler camera model for the bundle adjustment and a straightforward approach to self-calibration of the sensor head.

Bundle adjustment assures the external orientation for ADS40 images inside one pixel for all the different test sets when the Differential GNSS solution is used. This accuracy level of orientation is achieved with and without using Ground Control.
Adjustment with the PPP solution is giving the same high level of orientation accuracy of one pixel, when datum and IMU misalignment estimations are used in the aerial triangulation.

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