GEOMETRIC MODELING AND VALIDATION OF ALOS/PRISM IMAGERY AND PRODUCTS

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ABSTRACT

PRISM is a panchromatic radiometer carried onboard of the new generation Japanese remote sensing satellite ALOS (Advanced Land Observing Satellite). It has three optical systems for forward, nadir and backward views with 2.5 meter spatial resolution. Multiple Linear Array CCD chips are located on the focal plane of each camera, along one across-track line. Three PRISM images per scene are acquired almost simultaneously in forward, nadir and backward viewing angles in along-track direction.The photogrammetric processing of PRISM imagery has special requirements due to the Linear Array CCD sensor structure. As a Member of the ALOS Calibration/Validation Team, we have implemented new algorithms for the geometric processing of the PRISM images, in particular for the interior orientation and self-calibration. In addition, we have refined our physical sensor model according to the multiple optical camera heads of the sensor. Our rigorous model for the PRISM sensor is based on a modified bundle adjustment algorithm with the possibility to use two different trajectory models: the Direct Georeferencing Model with Stochastic Exterior Orientation Elements (DGR) and the Piecewise Polynomial Model (PPM). The given trajectory values are used as stochastic unknowns (observed values) in both approaches in the adjustment. For the self-calibration of the PRISM imagery, we have initially defined 30 additional parameters for the 3 cameras. The parameters are described in accordance with the physical structure of the PRISM imaging sensors. In this paper, PRISM images acquired over three recently generated testfields are used for calibration and geometric validation purposes. We have tested our rigorous sensor model, both with the DGR model and the PPM, using self-calibration, in all testfields. In addition, we have evaluated the accuracies of the RPCs (Rational Polynomial Coefficients) provided by JAXA/RESTEC in two of the testfields, using three methods: the direct georeferencing (with forward intersection), 2D affine transformation with 6 parameters, and translational correction with 2 shift parameters.PRISM level 1B1 images are used in all tests. The rigorous model produces RMSE values, computed from check points, of about 1/2 pixel in planimetry and 1/3-1/2 pixel in height. Both trajectory models provide sub-pixel accuracy for georeferencing and point positioning in an optimal GCP configuration. However, the PPM requires a higher number of ground control points to obtain stable adjustment results. The direct georeferencing accuracy obtained from the given RPCs is fairly good, and results in 2.5 pixels RMSE in the worst case. The RPC triangulation results show differences between the testfields, requiring different bias-correction terms and GCP distributions for optimal results.

1. INTRODUCTION

High-resolution satellite images (HRSI) have been widely used in recent years to acquire panchromatic and multispectral images in pushbroom mode for photogrammetric and remote sensing applications. Most of these sensors use Linear Array CCD technology for image sensing and are equipped with high quality orbital position and attitude determination devices like GPS, IMU systems and/or star trackers. The recently launched high resolution satellite sensor ALOS/PRISM is also operating in the pushbroom mode, and has Linear Array CCD pixels with 2.5 meter ground resolution. It provides along-track quasi-simultaneous overlapping triplet imagery with three different viewing angles (forward, nadir and backward).

For the full exploitation of the potential of the Linear Array CCD sensors' data, the "classical" satellite image analysis methods must be extended in order to describe the imaging geometry correctly, which is characterized by nearly parallel projection in along-track direction and perspective projection in cross-track direction. In general the processing of this kind of images provides a challenge for algorithmic redesign and opens the possibility to reconsider and improve many photogrammetric processing components. In recent years, some amount of research has been devoted to efficiently utilize this high spatial resolution imagery data. Examples for sensor modelling and image orientation can be found in (Baltsavias et al., 2001; Jacobsen, 2003; Grodecki and Dial, 2003; Fraser et al., 2002; Fraser and Hanley, 2003; Gruen and Zhang, 2003; Poli, 2005; Eisenbeiss et al., 2004).

We have developed a full suite of new algorithms and the software package SAT-PP (Satellite Image Precision Processing) for the precision processing of HRSI data. The SAT-PP features mainly include: GCP measurements, image georeferencing with RPC approach and various other sensor models, DSM generation with advanced multi-image geometrically constrained Least-Squares matching for Linear Array and single frame sensors, ortho-image generation, feature extraction and others. The software can accommodate images from IKONOS, QuickBird, SPOT5 HRG/HRS, Cartosat-1 and sensors of similar type to be expected in the future. The functionality to accommodate ALOS/PRISM imagery has been added in the context of the work of the ALOS Calibration/Validation Team, organized by JAXA, Japan. Detailed information on the SAT-PP features can be found in Gruen et al. (2005). The image matcher is described in much detail in Zhang (2005).

For the georeferencing of aerial Linear Array sensor imagery, a modified bundle adjustment algorithm with the possibility of using three different trajectory models has been developed by Gruen and Zhang (2003). Two of those models, the Direct Georeferencing (DGR) Model with stochastic a priori external orientation constraints and the Piecewise Polynomial Model (PPM) have been modified for the special requirements of the PRISM sensor. Both models have been extended by additional parameters (APs) for self-calibration, to possibly improve the camera's interior orientation parameters and to model other systematic errors. The APs are defined in accordance with the physical structure of the PRISM cameras. The self-calibration model currently includes nominally a total of 30 APs for all three cameras.

Our methods of data processing and previous work on georeferencing of the ALOS/PRISM imagery are published in Gruen et al. (2007) and Kocaman and Gruen (2007a, 2007b). We have recently processed data of three new testfields (Zurich/Winterthur, Switzerland, Wellington, South Africa, and Sakurajima, Japan) and the results are presented in this paper.

In addition, the direct geolocation accuracy of the PRISM sensor is assessed using the RPCs of two testfields, Zurich/Winterthur and Sakurajima. The RPCs were generated by JAXA/RESTEC, using their rigorous sensor model. The data was provided by JAXA as a part of ALOS Cal/Val and Science (CVST) Team activities. The position and attitude data are measured by an onboard GPS and startracker. The camera calibration files are generated in the regular calibration process of JAXA. We have evaluated the given RPCs using three methods: the direct georeferencing (with forward intersection), 2D affine transformation with 6 parameters, and translational correction with 2 shift parameters. Different numbers of GCPs are used in the latter two methods.
Although the images have particular radiometric problems (Gruen et al., 2007), the sensor orientation results are in general at a good level of accuracy.

2. ALOS/PRISM SENSOR MODEL

The PRISM sensor features for each viewing angle one particular camera with a number of Linear Array CCD chips in the focal plane. Three PRISM images per scene are acquired almost simultaneously in forward, nadir and backward modes in along-track direction (Figure 1). The nominal viewing angles are (-23.8°, 0°, 23.8).

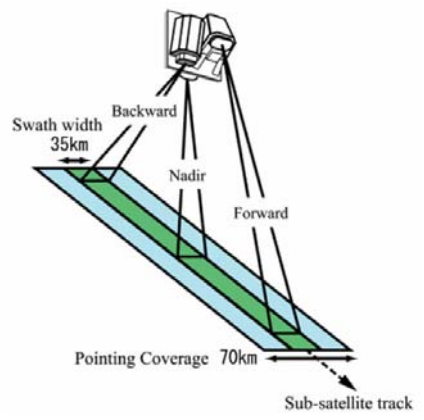


Figure 1. Observation geometry of the ALOS/PRISM triplet mode (Tadono et al., 2004).

The calibration data of the PRISM sensor is updated regularly at JAXA EORC. The absolute geolocation accuracies of the three PRISM cameras are given in Table 1.

	Pixel direction (cross-track)	Line direction (along-track)	Distance
Nadir (RMSE)	6.5 m	7.3 m	9.8 m
Forward (RMSE)	8.0 m	14.7 m	16.7 m
Backward (RMSE)	7.4 m	16.6 m	18.1 m

Table1. PRISM absolute geometric accuracy announced by JAXA EORC (as of 28 September 2007)

2.1 RIGOROUS SENSOR MODEL

Our rigorous model of the ALOS/PRISM sensor employs modified collinearity equations and uses of two optional trajectory models developed by Gruen and Zhang (2003). The specifications of the PRISM interior and exterior geometries have been taken into account in the models. In the DGR model, the given image trajectory (position and attitude) data are modelled using 9 systematic error correction parameters. In the PPM, the values of the exterior orientation parameters are written as polynomial functions of time. The bundle adjustment solution determines the polynomial coefficients instead of the exterior orientation parameters themselves. Due to the instability of the high-order polynomial models, the piecewise polynomial model is used, in which the full complex trajectory is divided into sections, with each section having its own set of low-order polynomials. Continuity constraints on the orientation parameters at the section boundaries ensure that the calculated positions and attitudes are continuous across the boundaries. The piecewise polynomial model is used to model the position and attitude errors with respect to time.

The sensor platform trajectory data, their a priori accuracy values, and sensor relative alignment parameters are provided in the image supplementary files. The attitude and position estimates are based on startracker and GPS receiver data (Iwata, 2003). The sensor alignment parameters are defined in relation to the satellite coordinate system. The knowledge of sensor relative alignment parameters is crucial to transform the platform position and orientation data into the camera coordinate system, which originates at the perspective centre. Although these parameters are provided in the image supplementary files, at the time of this writing, they are not fully employed in our sensor model. The given position values are accurate and used as stochastic unknowns (observed values) in the adjustment. The attitude values are also used as observations, but with smaller weights.

Self-calibration is an efficient and powerful technique used for the calibration of photogrammetric imaging systems. The method can use the laboratory calibration data as stochastic input into the adjustment. For the self-calibration of the PRISM imagery, we have initially defined 30 APs in total for the three cameras. The parameters are described in accordance with the physical structure of the PRISM imaging sensors. For more details on the PRISM interior geometry and the APs, please see Gruen et al. (2007) and Kocaman and Gruen (2007a, 2007b).

The camera calibration data provided by JAXA are used as input in the adjustment. The calibration data include the focal length values and the relative alignments of the CCD chips. The chip relative alignment values are obtained from in-flight calibration techniques using a large number of GCPs (ca. 700-

900) and multiple PRISM scenes (ca. 13-15, Tadono et al., 2007).

2.2 Rational Polynomial Functions

The Rational Function Models (RFMs) are special forms of polynomial functions. These models do not describe the physical imaging process but use a general polynomial transformation to describe the relationship between image and ground coordinates (Zhang, 2005). The Rational Polynomial Coefficients (RPCs) are often provided by the satellite operator, instead of (e.g. IKONOS) or together with (e.g. Cartosat-1) the rigorous sensor model parameters.

When the RPCs are generated from the rigorous sensor models (without use of GCPs), their absolute geolocation accuracies are usually not good enough to meet the requirements of many photogrammetric applications. Grodecki and Dial (2003) proposed a method to blockadjust the high-resolution satellite imagery described by the RFM camera models. With the externally supplied RPCs, the mathematical model used is:

$$\begin{aligned} x + \Delta x &= x + a_0 + a_1 x + a_2 y = RPC_x(\varphi, \lambda, h) \\ y + \Delta y &= y + b_0 + b_1 x + b_2 y = RPC_y(\varphi, \lambda, h) \end{aligned} \quad (1)$$

Where, a_0, a_1, a_2 and b_0, b_1, b_2 are the parameters of a 2D affine transformation for each image, and (x,y) and (φ,λ,h) are image and object coordinates of the points.

We have the possibility to post-correct given RPCs in SAT-PP using two different methods:

- RPC-2: Two shift parameters (a_0,b_0 of Eq. 1) are applied to correct the RPCs
- RPC-6: The full 2D affine transformation (Eq. 1) with 6 parameters is applied

In both cases we need a certain number of GCPs (at least one in the first and three in the second case) in order to determine the parameters.

We have evaluated the accuracies of the Zurich/Winterthur and Sakurajima RPCs provided by JAXA/RESTEC using these methods. In addition, we have performed a direct georeferencing (DG) test by computing the ground coordinates of each GCP using the given RPCs in a forward intersection with multiple rays procedure. Object space residuals, which are obtained from the comparison of computed coordinates with the given ones, are analyzed with statistical methods and also by visual checks.

3. EMPIRICAL TESTS

We have processed data over three testfields: Zurich/Winterthur, Switzerland, Sakurajima, Japan, and Wellington, South Africa. The DGR model has been tested in all testfields. The PPM with one segment and the RFM approach have been only applied to the Zurich/Winterthur and Sakurajima datasets. The empirical tests given in the following sections employ self-calibration with 2 APs per image, which are the scale parameter and the CCD line bending parameter (6 APs in total). For the accuracy assessment the RMSE values, which are computed from the differences between the given and the estimated coordinates of the check points, and the standard deviations, computed from the covariance matrix of unknowns, were used.

The results of four earlier datasets were presented before by Kocaman and Gruen (2007a, 2007b). The results show that the DGR is enough to model the PRISM trajectories. The PPM with larger number of segments causes instabilities and thus a larger number of GCPs are needed to correct for those. Therefore, only one segment per image trajectory has been chosen for the PPM in the tests presented here.

The image quality of the PRISM datasets used here is somewhat better than in previous cases. However, there are still some problems, such as jpeg compression artifacts, which cause problems in GCP image definition/measurement and in matching.

The given attitude values of the Zurich/Winterthur dataset were extracted and transformed precisely from the ECI (Earth Centered Inertial) coordinate system into the ECR (Earth Centered Rotating) coordinate system. However, due to partially missing sensor relative alignment values in the transformation, corrections in form of three attitude shift parameters per camera needed to be estimated in the adjustment. The a priori standard deviations used for the attitude shift and drift parameters in the tests were 0.07° per image and 6.25°×10-6 per 1000 lines, respectively. These values were computed from the results of previous adjustments of the Zurich/Winterthur dataset with all GCPs. The a priori standard deviations of the trajectory position values were the same for all datasets and 2 m in all three directions. The a priori standard deviations of the image measurements were assumed to be half a pixel.

The RPCs were evaluated in two testfields (Zurich/Winterthur and Sakurajima) with three different methods (DG, RPC-2, RPC-6). The results are presented in the following sections.

3.1 Zurich/Winterthur Testfield, Switzerland

The Zurich/Winterthur testfield has been established by the IGP, ETH Zurich in summer 2007 under an ESA-ESRIN contract. The PRISM image triplet has been acquired on 22 April 2007. During the GPS measurement campaign, the images were used to select the control points. A total of 99 GCPs were measured in the field and also in the PRISM images. In addition, 101 tie points were measured on the images. The point distribution in the PRISM nadir image is represented in Figure 2.

In the rigorous model, we used 1, 2, 4, and 9 GCP configurations with homogeneous distributions in planimetry. The a posteriori sigma naught values are equal to 0.3 pixels for all tests. When only 1 GCP is used, the RMSE values are equal to 1.3 and 3 pixels in planimetry and height, respectively. Already with only 2 GCPs, a sub-pixel accuracy level could be achieved with the DGR method (Figure 3). The PPM has been tested only in the 9 GCP configuration.

Comparing the 2, 4, and 9 GCP configurations we find that the planimetric accuracy is slightly worse in the 2 GCPs case compared to the other cases, while the height accuracy remains almost the same in all cases. The accuracy both in planimetry and height, as evidenced by RMSE(XY) and RMSE(Z), is below one pixel in all tests. The PPM results are the same as the DGR model results of the same 9 GCP configuration.

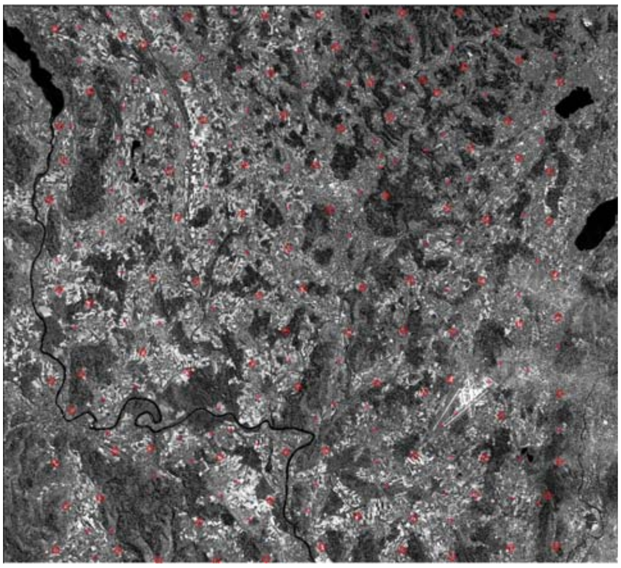


Figure 2. Point distribution in the Zurich/Winterthur testfield. The red circles represent the GCP locations.

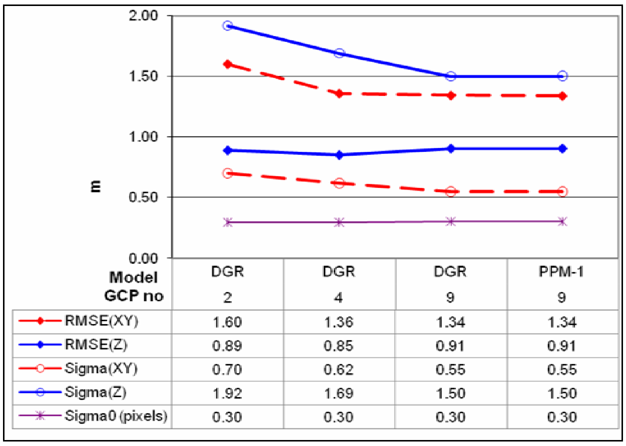


Figure 3. Accuracy results of the Zurich/Winterthur tests with rigorous sensor models

Considering the self-calibration, four of the additional parameters (scale parameters of the forward-nadir-backward images and the CCD line bending parameter of the nadir image) were statistically significant in the Zurich/Winterthur tests.
The DG accuracy values obtained from the RPCs provided by JAXA/RESTEC are presented in Table 2. The results are at sub-pixel level in planimetry and one pixel in height. There are local systematic effects in the residuals (Figure 4).

	X (m)	Y (m)	Z (m)
RMSE	1.7	1.7	2.5
Mean	0.6	0.9	-0.1
Max. residual	4.0	4.2	5.6

Table 2. DG accuracy values obtained from the RPCs provided by JAXA/RESTEC for the Zurich/Winterthur testfield

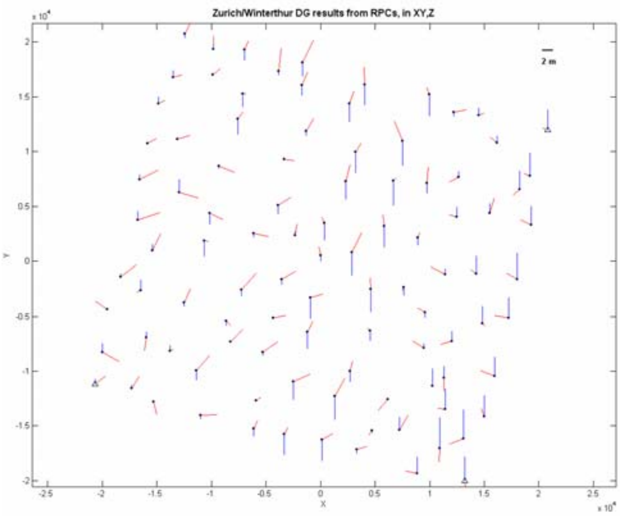


Figure 4. Object space residuals in the Zurich/Winterthur testfield obtained from the DG with the given RPCs.

The given RPCs were corrected using the RPC-2 and RPC-6 methods (Table 3) with three different GCP configurations. The three corner points depicted with triangles in Figure 4 were used as control points in the 3 GCP case. As can be seen from Table 3, the georeferencing accuracy was not improved in this case. Also, the systematic effects could not be removed from the residuals by this procedure.

Model	GCP	RMSE(XY)(m)	RMSE(Z)(m)	σ_0 (pixel)
RPC-6	All	1.3	2.3	0.63
RPC-2	All	1.5	2.5	0.73
RPC-6	6	1.4	2.4	0.41
RPC-2	6	1.6	2.5	0.51
RPC-6	3	1.4	3.3	0.39
RPC-2	3	1.6	3.9	0.49

Table 3. RPC correction results in the Zurich/Winterthur testfield

3.2 Sakurajima Testfield, Japan

The Sakurajima testfield was generated as a joint project of Kochi Institute of Technology and Kanazawa Institute of Technology. 31 GCPs, provided by the Japan Association of Remote Sensing (JARS), have a rather uneven distribution, caused in parts by the special topography (Figure 5). The PRISM image triplet was acquired on 8 November 2006. 60 tie points were measured on the images using semi-automated matching.

The rigorous model was tested using the DGR and the PPM with a single segment per image. The tests were performed using different numbers of GCPs and the results are provided in Figure 6.

The DG results in this testfield are presented in Table 4 and Figure 7. The systematic errors in the residuals could be removed using GCPs in the RPC correction adjustment (Table 5).

Figure 5. Overview of the GCP distribution in the PRISM nadir image of Sakurajima. The red circles represent the GCPs.

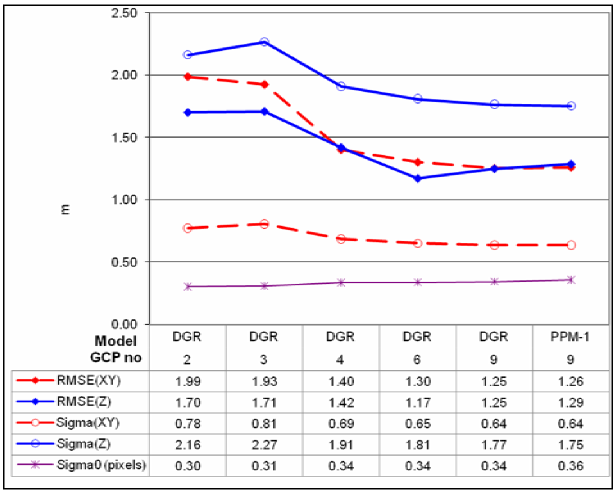


Figure 6. Rigorous sensor model results in the Sakurajima testfield

	X (m)	Y (m)	Z (m)
RMSE	1.6	4.9	6.4
Mean	1.1	-4.6	-6.1
Max. residual (absolute)	4.0	7.6	12.1

Table 4. DG accuracy values obtained from the RPCs provided by JAXA/RESTEC for the Sakurajima testfield

3.1 Wellington Testfield, South Africa

The Wellington testfield is located in the north-east of Cape Town, South Africa, in an area not so much affected by the clouds and occasional fog of Cape Town. The PRISM images over the Wellington testfield were acquired on 19 April 2007. The images were tested with the DGR model with self-calibration, using different subsets of GCPs.

67 ground control and 32 tie points were used in the triangulation tests (Figure 8). The GCPs were pre-selected on the PRISM images and surveyed by the Dept. of Architecture, Planning and Geomatics, University of Cape Town in September 2007. The averaged standard deviations of the GPS measurements are 3 cm in planimetry and height.

Model	GCP	RMSE(XY)(m)	RMSE(Z)(m)	σ_0 (pixel)
RPC-6	All	1.3	1.1	0.58
RPC-2	All	1.4	2.0	0.68
RPC-6	6	1.4	1.4	0.39
RPC-2	6	1.5	2.1	0.56
RPC-6	3	1.8	1.4	0.37
RPC-2	3	1.8	3.4	0.51

Table 5. RPC correction accuracy results for the Sakurajima testfield

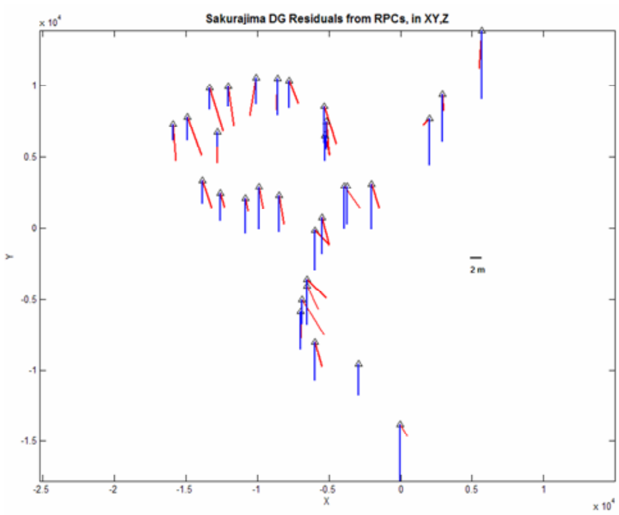


Figure 7. Object space residuals in the Sakurajima testfield obtained from the DG with the given RPCs.

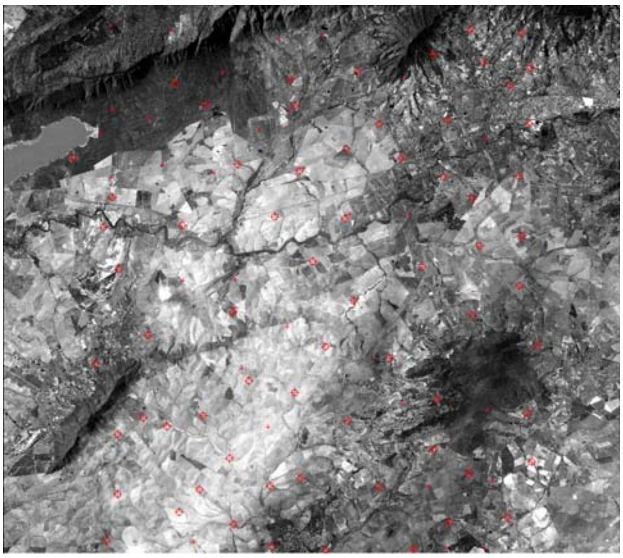
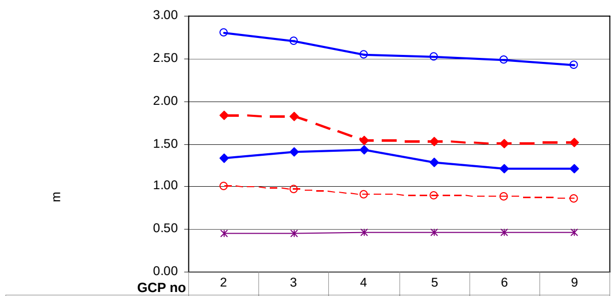


Figure 8. Overview of the control and tie point distribution on the PRISM nadir image. The red circles represent the GCP locations.

The results from the DGR model computations are presented in Figure 9. 4 GCPs are enough to reach the accuracy potential in planimetry. However, in height, there is still some improvement visible when going from 4 to 6 GCPs.



GCP no	2	3	4	5	6	9
RMSE(XY)	1.84	1.83	1.55	1.53	1.50	1.52
RMSE(Z)	1.34	1.41	1.44	1.29	1.21	1.21
Sigma(XY)	1.00	0.96	0.90	0.89	0.88	0.86
Sigma(Z)	2.80	2.71	2.55	2.53	2.48	2.43
Sigma0 (pixels)	0.45	0.45	0.46	0.46	0.46	0.47

Figure 9. DGR model results in the Wellington testfield

4. CONCLUSIONS

We have calibrated and validated ALOS/PRISM images over three testfields: Zurich/Winterthur, Switzerland, Sakurajima, Japan and Wellington, South Africa. For georeferencing we applied both our sensor/trajectory models DGR and PPM and found that DGR had the better performance in case of very few GCPs. In case of the Zurich/Winterthur and Sakurajima datasets, with correct a priori definition of the interior and exterior orientation elements, 2 GCPs were enough to achieve sub-pixel accuracy. Concerning the planimetric accuracy the theoretical expectations Sigma(XY) were usually significantly better than the empirical values RMSE(XY). However, we note that in many cases the empirical height accuracy values RMSE(Z) were even better than the corresponding theoretical precision values. This somewhat inconsistent behavior results from the fact that the height-related definition of the GCPs and check points in image space is better than the planimetric one.

Over all three testfields we achieved with our sensor model DGR quite consistent accuracy results. We stay in all cases in the sub-pixel domain, in the best cases we achieved about half a pixel planimetric accuracy and 1/3 pixel height accuracy. This relatively high accuracy is surprising, considering the fact that the image quality of PRISM has still much potential for improvement. On the other side one usually uses only well defined points as GCPs and check points, where the inferior image quality has not such a negative influence.

When using the supplied RPCs we achieved accuracies between 0.7 and 2.6 pixels. In these cases we noticed systematic effects in the check point residuals, which could partially be removed when using RPC correction terms together with GCPs. This also improved the georeferencing accuracy in parts quite substantially (up to a factor 4.6 in height). Yet, we do not have sufficiently broad experiences with the use of supplied RPCs. Their quality depends on the local navigation values. To be on the save side it is still advisable to use a few GCPs for RPC correction.

Self-calibration is a very powerful method for sensor model refinement. However, the most appropriate additional parameter functions have not yet been fully explored for PRISM imagery. In any case, self-calibration should be used with great care and not blindly. The statistical testing of additional parameters for determinability is a crucial requirement for a successful use of this technique.

If we compare these georeferencing results with those which were obtained earlier with other satellite sensors of similar type (SPOT-5, IKONOS, QuickBird) we note that the accuracy (expressed in pixels) is about the same as with these other sensors.

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