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Oak Ridge National Laboratory Bundle Adjustment of Maxar WorldView and GeoEye Imagery

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ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
BA	Bundle adjustment
DEM	Digital Elevation Model
GCP	Ground control point
GE	GeoEye
GNSS	Global Navigation Satellite System
GSD	Ground sample distance
LiDAR	Light detection and ranging
ORB	Oriented Fast and Rotated Brief
ORNL	Oak Ridge National Laboratory
RANSAC	Random sample consensus
RFM	Rational function model
RMSE	Root mean square error
RSM	Rigorous sensor model
RPC	Rational polynomial coefficient
SIFT	Scale-Invariant Feature Transform
SURF	Speeded-Up Robust Features
WV	WorldView

ABSTRACT

Since the 1950s, bundle adjustment has been used to correct the geopositioning of imagery. With the increased availability of very high resolution satellite imagery, bundle adjustment has become an increasingly critical topic for both researchers and practitioners. Many studies have explored the bundle adjustment of satellite imagery from Maxar sensors, including the WorldView and GeoEye sensors. In this work, we review some of the recent and relevant literature pertaining to this topic.

1. INTRODUCTION

The least-squares analysis method is a mathematical technique used to compute the most-probable (best unbiased) parameters values in over-determined systems. Assuming that the only errors are mean-zero Gaussian (i.e., all blunders and systematic errors have been eliminated or removed) the most probably parameter values are those that minimize sum of the weighted squared residuals. Closed form solutions do not exist when the function being modeled is non-linear. Non-linear solution requires initial values that are iteratively refined. Alternatively, it is sometimes practical to adjust measurements instead of computing parameters (*e.g.*, adjusting the measurements of overlaping distances or closed loops of angles, or global navigation satellite system (GNSS) distance observations) Ghilani and Wolf [2017]. As evidenced, adjustment computations have a practical usefulness to many real-world applications. This work will specifically discuss the use of adjustments in relation to satellite imagery georeferencing, *i.e.*, the adjustment of sensor parameters and coordinates of ground features.

For maximum utility satellite imagery must accurately represent the surface of the Earth. That is, pixels within the satellite image must align to the precise location on the surface of the Earth they represent. Otherwise, the incorrect location of surface features would lead to systematic errors with satellite imagery analysis and usage. Initial georeferencing of satellite images is typically performed by the imagery provider prior to being delivered to the customer or end data user. The initial georeferencing uncertainty can vary from image to image because of a myriad of factors but may be may be acceptable for some applications. When it isn't adequate, they can be corrected using a non-linear least-squares adjustment of image position and pointing. This is typically called bundle adjustment or aerial triangulation.

In satellite image processing and photogrammetry bundle adjustment involves simultaneously refining the 3D coordinates of points observed in multiple images and the sensor models of the observing images. The bundles refer to collections of light rays that are projected from a given 3D point onto each corresponding image. The residuals minimized in the bundle adjustment are the differences between the measured and computed ground point projections. This minimization is a non-linear least-squares problem. Bundle adjustment was conceived in the 1950s [Brown, 1958], and it is still used in modern photogrammetry. Bundle adjustment requires images that overlap in their projection on the ground such that some areas are visible in both images. The first step of the adjustment is to match tie points on the ground in multiple images. This is an important step that measures features seen in both images to each other. These algorithms generally proceed by finding keypoints, often edge-like features of high contrast or notable texture, in each image, then calculating a descriptor of each keypoint in each image, and lastly attempting to match the keypoints in a given image to the keypoints in any other image. Many successful algorithms exist for this step, such as SIFT [Lowe, 1999], SURF [Bay et al., 2006], and ORB [Rublee et al., 2011]. The matched tie points create the constraints that are adjusted such that the minimization of the reprojection error is achieved. There must exist enough matched tie points in order to solve the system of equations that is generated. In practice, it is generally not an issue to achieve enough matched keypoints

Table 1. Maxar sensors of interest and their associated CE90 and LE90 values.

Sensor	Launch Date	GSD (m)	CE90 (m)	LE90 (m)	CE90/LE90 Product Specification (m)
WV01	2007	0.5	4.0	3.7	5.0
GE01	2008	0.5	3.0	None Given	5.0
WV02	2009	0.46	3.5	3.6	5.0
WV03	2014	0.3	3.5	None Given	5.0

between images to perform an adjustment, as satellite imagery tends to be quite large and contain many features that lend themselves to tie point matching. The sensor model parameters are generally non-linear whether these are from RPCs, physical camera parameters from a geometric sensor model, or some other warping or transformation of the images themselves.

Currently, there are many providers of satellite imagery from many different platforms and sensors. Of particular interest due to their high-resolution, high-revisit rate, and availability are the Maxar-owned WorldView (WV) and GeoEye-1 (GE01) sensors. WorldView-1 (WV01) is a panchromatic-only sensor launched in 2007 with a ground resolution of 0.5 m and an average revisit time of 1.7 days. GE01 launched in 2008 and has a panchromatic 0.5 m resolution imaging band with an average revisit rate of less than 3 days. WorldView-2 (WV02) is a panchromatic sensor that launched in 2009 with a ground resolution of 0.46 m and an average revisit time of 1.1 days. WV02 also has multispectral imaging capabilities at 1.84 m resolution. WorldView-3 (WV03) is the most recent WorldView sensor that is still active; it launched in 2014, has a panchromatic band resolution of 0.3 m, and has an average revisit time of less than 1 day. WV03 additionally has multispectral imaging capabilities at 1.24 m resolution. Taken together, these sensors create a plethora of high-resolution image data of the surface of the Earth that cover a large temporal span dating from 2007 to the present.

2. BUNDLE ADJUSTMENTS

Bundle adjustments of satellite imagery came about long before the WV or GE01 sensors were operating. Many works describe performing bundle adjustments on various preceding sensors, such as SPOT [Li, 1988], IKONOS [*e.g.,* Grodecki and Dial, 2003], and Quickbird [*e.g.,* Noguchi et al., 2004]. According to Ke [2005], with the launch of IKONOS in 1999 and it's 1-m spatial resolution, triangulation to improve georeferencing accuracy of images became a necessity. As with IKONOS, the Maxar sensor's initial georeferencing uncertainties are larger than GSD. WV and GE01 product specifications are horizontal CE90 of 5.0 m and vertical LE90 of 5.0 m [Maxar, 2021]. However, measured CE90 and LE90 from WV and GE01 sensors are slightly better than the product specifications. Table 1 shows more initial georeferencing uncertainty information for various Maxar senors [Maxar, 2020a,b, 2021].

Maxar level 1B imagery, an un-projected raw product, is delivered with rational polynomial coefficients (RPCs) and associated parameter estimations necessary to use the RPCs [Dolloff and Scientist, 2012] [Maxar, 2021]. Tao and Hu [2001] discussed and developed the rational polynomial model, to replace the more complicated physical model with a simpler model that has a precision similar to the reference model.

As stated, the raw geopositioning accuracy of the WV products has approximately 10 pixels of uncertainly at the 90% confidence level. CE90 is the circular error (horizontal error) at the 90th percentile, while LE90 is the linear error (vertical error) at the 90th percentile. This is inadequate for some applications, and many authors and researchers have achieved sub-pixel accuracy with bundle adjustments. The methods of those adjustments, however, can vary greatly from author to author or due to the availability of auxiliary data. We grouped the bundle adjustment methods as: single image, multi-image with ground control points (GCPs), and multi-image without GCPs. Research within each group is presented chronologically in the following sections.

2.1 SINGLE IMAGE

Bundle adjusting a single image requires GCPs. If the control data are accurate compared to the GSD, this technique can achieve good results.

Teo [2011] show that both WV01 and WV02 images, using GCPs, can be corrected using either a rigorous sensor model (RSM) adjustment or a rational function model (RFM) adjustment in either the orbital or image space. The bias corrections of the RSM was done both in orbital and image space. The bias correction of the RSM was only in image space [Teo, 2011]. The orbital space corrections adjusts the time dependent exterior orientation parameters. RSM and RFM image space bias corrections tested three different image space corrections: translational, conformal, and affine [Teo, 2011]. The authors stated that sub-pixel relative accuracies were achieved for all models tested except for a simple translation. An absolute accuracy of 0.36 m of 2D RMSE was achieved[Teo, 2011].

Aguilar et al. [2012] tested the improvements to GE01 georeferencing accuracy by using the RPC block adjustment schemes detailed by Grodecki and Dial [2003]. The authors tested image space corrections modeled as simple 2D shift, affine transformations, and 2^{nd}-order polynomials. The simple 2D translation achieved the best results, which were a relative accuracy RMSE 2D of 0.7 pixels and an absolute accuracy RMSE 2D of 0.46 m [Aguilar et al., 2012].

Aguilar et al. [2013] also tested the Aguilar et al. [2012], Grodecki and Dial [2003] adjustments on single WV02 images. The performed RPC-based bundle adjustments make use of a LiDAR derived DEM in addition to several GCPs. Using the mixed control sources they found that starting with ortho images rather than level 1B images provided better results. The simple 2D translation model performed best achieving sub-pixel accuracy and gives an accuracy RMSE 2D of 0.6 m for WV02 basic products and RMSE 2D of 0.44 m for WV02 ortho products [Aguilar et al., 2013].

Alkan et al. [2013] perform a similar assessment of WV01 images to improve topographic mapping accuracy of 1:5000 scale products. They adjusted single panchromatic images RPC using GCPs following the bundle procedures in Grodecki and Dial [2003]. As with previous work, they tested using either simple shifts or affine transformations. Absolute accuracy RMSE is 0.5 m in X and Y and this is ultimately good enough to produce topographic maps of a scale of 1:5000 [Alkan et al., 2013].

Barazzetti et al. [2016] perform similar RPC-based adjustments to a single WV03 image with different commercial, off-the-shelf software packages using several known GCPs. The authors test correction models of simple 2D shifts and affine transformations. The results give absolute accuracies of RMSE 0.7 m in the X and Y directions based on the simple shift models with no significant improvement generated from the use of the full affine model [Barazzetti et al., 2016].

2.2 STEREO/MULTI-VIEW WITH CONTROL

A number of authors have exploited stereo pair or multi-view Maxar imagery to improve geolocation accuracy of the imagery. These methods can use GCPs as control data within the adjustment in the same way as the single image bundle adjustments; however, the adjustments are applied to multiple images simultaneously.

Taylor et al. [2008] perform bundle adjustment with GCPs of a stereo pair of WV01 images using different combinations of parameters from a Replacement Sensor Model [Dolloff and Taylor, 2006] and the original sensor model. The authors compare results from each sensor model and show that absolute geopositioning accuracies of 1.9 CE90 m are achievable with either sensor model [Taylor et al., 2008].

Deltsidis and Ioannidis [2011] describe a novel geometric sensor model for pushbroom linear arrays based on collinearity equations. This model involves 24 parameters derived from the collinearity equations and the orbital and attitude data of the satellite; all 24 parameters have physical meaning [Deltsidis and Ioannidis, 2011]. More specifically, the model relates the Earth-centered fixed system to the camera's reference system. This is achieved through using rotational angles relating the Earth-centered fixed system and the Earth-centered inertial system, rotational angles defining the rotation of the satellite at the time of imaging, off-nadir viewing angles, and a scale correction for each object point between the two coordinate systems expressed as a 1^{st} or 2^{nd} order surface polynomial. Bundle adjustment of this model is performed on a WV02 stereo pair for various sets of parameters and numbers of GCPs and achieves sub-pixel accuracy in XY for minimum numbers of GCPs based on the number of unknown parameters [Deltsidis and Ioannidis, 2011]. Absolute geopositioning accuracy results approach RMS of 0.4 m in X, 0.28 m in Y, and 0.98 m in Z [Deltsidis and Ioannidis, 2011].

Xiao et al. [2014] examine the geopositioning accuracy of a WV01 stereo pair with RPC sensor models. The authors apply both a 2D translation and an affine image space corrections. It was shown that bundle adjusting the RPCs with a small amount of control points reduced systematic errors and improved the planar RMSE to 1.6 pixels or 0.9 m, irrespective of the correction model applied [Xiao et al., 2014].

Rupnik et al. [2018] applied the RPC bundle adjustment method presented by [Rupnik et al., 2016] to WV03 images. This bundle adjustment method used GCPs and applied a novel physical constraint to the global sensor rotation despite operating on RPCs. It was developed and tested on Pleiades imagery data. The bias compensation model involves two polynomial correction functions in image space. When Rupnik et al. [2018] used the process on WV03 imagery within a multi-view reconstruction pipeline, they reported absolute geolocation accuracy of 0.66 m, 0.90 m, and -0.77 m in XYZ[Rupnik et al., 2018].

Loghin et al. [2020] used an RPC-based affine transformation bundle adjustment, that included GCPs, to correct tri-stereo WV03 imagery. The objective was 3D reconstruction, but, as observed in other works, corrections to image orientations is a necessary step to remove systematic errors from the 3D reconstruction. The adjustment included 22 GCPs. The images space RMSE was 0.4 pixels. The absolute accuracy RMSE was 0.13 m in latitude and 0.12 m longitude and 0.28 m in elevation [Loghin et al., 2020].

Ling et al. [2020] perform bundle adjustment of six multi-view WV03 images collected over 6 months. Recognizing that bundle adjustment accuracy depends strongly on the tie point-matching accuracy they focused on an tie point matching refinement method. Previous works maked use of the random sample consensus (RANSAC) algorithm [Anzid et al., 2017, Fischler and Bolles, 1987] as a method of binary parsing of matches into inliers and outliers. Ling et al. [2020] introduced a matching confidence metric that rejects outliers and translates inlier confidence into weights within the BA. This methodology allows for accurate orientation results from the BA process even when a high percentage of mismatched tie points remain from the matching step [Ling et al., 2020]. They reported accuracy improvements when compared to other state-of-the-art BA procedures achieving RMSD of 0.55 m in plane and 0.3 m in elevation [Ling et al., 2020].

2.3 STEREO/MULTI-VIEW WITHOUT CONTROL

The adjustments discussed in the prior sections using known GCPs and/or high-accuracy DEMs are useful in specific instances, but such high-accuracy GCPs and/or elevation data are not necessarily available for any given location of interest. Furthermore, because the acquisition of such control data is a laborious time- and resource-consuming process, the need for GCP-independent methods is apparent. In this case, the bundle adjustment's absolute position information comes only from the sensor models. Due to the lack of GCPs, absolute accuracy of such adjustments is not generally reported. Relative accuracy, however, is improved and absolute accuracy will still improve owing to the redundancy gained through using multiple images.

Huang and Qin [2019] state that the CE90 of Maxar images is not satisfactory and propose large scale bundle adjustment as a method to correct images from these satellites prior to practical application. This study addresses the issues of bundle adjusting images using the RPC model from various satellite sensors together by obtaining robust tie points among different satellite images using a multi-view, multi-source tie point-matching strategy called multi-block census that is based on plane rectification and epipolar constraints [Huang and Qin, 2019]. The correction model used is a simple translational bias correction. However, since this cannot correct for nonlinear distortions, a plane rectification of all images is effected prior to the bias correction adjustment [Huang and Qin, 2019]. The methodology produces an average relative XY accuracy on five WV02 and WV03 images collected over a 100 km^2 area from 2015 to 2016 of 0.269 pixels [Huang and Qin, 2019]. The authors additionally note that image tie point mismatches still remained within their process and that additional work to reduce these mismatches would result in still better results [Huang and Qin, 2019].

Marí et al. [2019] explore multi-view RPC-based bundle adjustment of several multi-date WV03 images with respect to 3D reconstruction results. The images over the investigation sites were collected from 2014 to 2016 and contain sets of 47 and 26 images. The results showed that the RPC-based bundle adjustment methods to correct the geolocation of the results perform competitively to other state-of-the-art geometric digital surface model fusion methods that do not require bundle adjustment Marí et al. [2019]. Individual geolocation accuracies of the correction methods are not discussed; in contrast, comparative 3D reconstruction accuracies are. This work only applies two simple RPC-based bundle adjustments, separately, either simple translation corrections or rotational corrections. They make use of the SIFT algorithm [Lowe, 1999] for tie point matching [Marí et al., 2019]. It is interesting because it is one of the few works exploring multi-view over a longer temporal baseline and with multiple dozens of images. These images, however, were not spread across differing sensors.

Ling et al. [2021] combine the improved feature matching of [Ling et al., 2020] with the bundle adjustment step by formulating the union as the optimization of a global energy function. This constrains the solutions of the feature matching and the bundle adjustment to each other [Ling et al., 2021]. The methodology starts by ordering tie point matches through the confidence scores outlined in Ling et al. [2020]. Next, those matches are winnowed to remove outliers based on the confidence scores. A sparse bundle adjustment is applied using only the high-confidence matches, followed by re-weighting the tie points through confidence and geometric consistency, and least-squares matching with geometric consistency [Gruen, 1985, Hu and Wu, 2017] to refine the matches. The algorithm then iterates in over the loop of dense bundle adjustment, re-weighting of tie points, and redoing the least squares matching with the updated bundle geometry. the looping continues until the improvements become negligible [Ling et al., 2021]. According to Ling et al. [2021], when running on WV03 imagery, this method outperforms other state-of-the-art orientation techniques and achieves relative sub-pixel accuracy.

Pan et al. [2021] perform bundle adjustments of 47 multi-view WV03 images, spanning about 1.5 years, in order to compensate for attitude jitter, which, in the regime of very high resolution imagery, can introduce pixel-level distortions. A rigorous sensor model is used because the rational function model is too smooth to model jitter [Pan et al., 2021]. Additionally, a dense bundle adjustment is required because attitude jitter is a very high frequency distortion, *i.e.*, a sparse bundle adjustment scheme will likely miss the attitude jitter [Pan et al., 2021]. The bias compensation model used here contains 10 parameters and is a second-degree polynomial [Pan et al., 2021]. Ultimately, the authors show that the dense bundle adjustment of WV03 imagery using the rigorous sensor model eliminates systematic errors and achieves good relative results with RMSEs of approximately 0.4 pixels [Pan et al., 2021].

3. CONCLUSIONS

Bundle adjustment of satellite imagery is a well-established methodology that is used to improve the geolocation accuracy of a given set of sensors, including Maxar sensors. Since Maxar imagery is delivered with RPCs, bundle adjustment approaches that use them are predominant in the relevant literature. The methods reviewed here, when applied correctly, regularly give relative RMSEs of less than 1.0 pixel and absolute accuracies RMSE 2D of less than 1.0 m. Because bundle adjustment in its purest form is a solved problem, most current research in bundle adjustment methodology is actually centered on refining automatic tie points during the image tie point-matching stage due to the fact that bundle adjustment accuracy is intimately tied to the accuracy of this step.

Additional research does however pertain to how to efficiently solve bundle adjustment problems, *i.e.*, efficient use of computer memory and architecture or clever programming solutions to improve the speed or accuracy of the convergence, but these are generally within the realm of computer science. With geometric sensor models becoming more widely available for Maxar sensors such as WorldView, it will be interesting to explore the effects of performing such bundle adjustments on this model rather than the inherently generic RPC formulation. While RPCs do not have the ability to be attributed to real-world physical parameters of the model, these geometric sensor models do, as they are a straightforward representation of the physical parameters. Future work should investigate the ability to perform bundle adjustments using these geometric sensor models in order to model the correlations and covariances between physical parameters, such as sensor type, orbit, temporal revisit rates, etc. Using the geometric sensor models further allows for the adjustment of select exterior orientation parameters rather than the RPCs which are an inseparable aggregate of interior and exterior orientation parameters. The optimum parameterization of exterior orientation correction is a further area of research.

Another avenue of future research that appears to be lacking in the current literature is the use of multi-view images from differing sensors. While authors use multi-view images from the same sensors, *e.g.*, WV03 multi-date images used in Marí et al. [2019], not much work has explored using multi-view from multiple sensors. With the exception of the work of Huang and Qin [2019], which uses a single dataset of WV02 and WV03 images with a temporal baseline of approximately six months, multi-view work has not been extended to deep temporal stacks of imagery from multiple Maxar sensors. As stated, leveraging the additional temporal baseline given from pulling in images from additional Maxar sensors allows for many more images to be used and redundancy gained from such deep temporal stacks of imagery should improve absolute accuracy.

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