PREPARATIONS FOR THE ON-ORBIT GEOMETRIC CALIBRATION OF THE ORBVIEW 3 AND 4 SATELLITES

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ABSTRACT

A new generation of commercial satellites offers 1 meter resolution, GPS orbit tracking with star tracker and gyro attitude determination. This powerful combination of sensors can be used to precisely locate positions on the Earth without the need of ground control points. However, this goal can only be realized after the sensor suite has been properly calibrated on-orbit.

A robust system for on-orbit geometric calibration is composed of several essential components: computer hardware and software, and geometric calibration range(s). This paper discusses a Geometric Calibration System to address these necessary tasks for the geometric calibration of the OrbView 3 and 4 satellites.

The OrbView on-orbit Geometric Calibration System is based on the mathematical modeling and estimation of calibration parameters incorporated into a rigorous and flexible self-calibration triangulation and Kalman filter software suite. Medium scale aerial imagery is used to form the basis of a geometric calibration range. To reduce the collection time and improve the quality of the calibration solution, the calibration range imagery is combined with powerful image correlation software techniques to automatically acquire tie points with the satellite imagery and to allow the assembly of an extremely dense collection of ground control points.

The components used in the OrbView Geometric Calibration System are easily modified to perform geometric calibrations of other satellite or aerial imaging systems.

1 BACKGROUND

Imaging satellites are subjected to several factors that may cause the value of the geometric calibration parameters to vary between the time of ground calibration and their use on-orbit. Some of these are: launch shock; loss of moisture due to vacuum; and gravity release. The ground calibration process is used to obtain the best a priori estimates of the on-orbit values of the calibration parameters. Generally, the satellite builder can perform mechanical analysis to estimate what range the critical calibration parameters are expected to vary between ground calibration and on-orbit use.

After calibration, the OrbView satellites will have the capability to position points on the Earth without need of ground control points. Determining positions without ground control points and by using only the satellite data is known as stand alone positioning. The accuracy of stand alone positioning relies heavily on the quality of the geometric calibration. An incorrect geometric calibration can result in unaccounted for systematic errors (biases). If unaccounted systematic errors are present after the geometric calibration, their effects may be driven down into the determination of object space positions. Furthermore since no ground control points were used, the results of the systematic errors may not be easily discovered leading to a possible false sense of accuracy of the stand alone positioning capability of the satellite system. If ground control points are available, they can be used with the OrbView

The geometric calibration plan for the OrbView 3 and 4 satellites calls for an initial geometric calibration during the satellite commissioning phase and a monthly geometric calibration there after. There is a significant effort associated with the initial calibration. However, the accumulated magnitude of effort involved with the periodic monthly geometric calibrations over the life of the satellite will surpass the one time initial effort. It is important that the on-orbit geometric calibration method be able to take advantage of autonomous methods as much as possible in order to drive down the effort and time required to perform the monthly geometric calibrations.

2 GEOMETRIC CALIBRATION RANGE

The Geometric Calibration Range is a metric standard that the OrbView 3 and 4 satellites will be compared to during geometric calibration. In order to provide the best geopositioning capability from the satellite systems, it is necessary that the calibration range have good absolute and relative accuracy.

Cost is also an issue. The calibration range should be cost effective to create, use and maintain. Two types of ranges can be considered: permanent dedicated targets and controlled aerial photography. The first type of range requires a substantial commitment of land for the targets and cost for the creation and maintenance of the calibration range. However, the use of controlled aerial photography offers many advantages. For example, the calibration range *is* the set of aerial photographs. This means that no land must be acquired for a calibration range. Furthermore, as many ground control points as are needed can be generated from the set of aerial photographs. Powerful image correlation methods can be used to help reduce the cost and time needed to measure the control points in the aerial and satellite imagery. In terms of maintenance, if some of the photographs become unusable due to changes on the ground texture, such as new construction, additional aerial photography can be flown and triangulated into the block.

The following sections provide a description of the Geometric Calibration Range and how it will be constructed.

2.1 Description of the Geometric Calibration Range

The Geometric Calibration Range covers an area of 50km in the north-south direction and 50km in the east-west direction. The aerial photographs were acquired with a standard frame mapping camera at a scale of 1:25,000. The photography was acquired with 60% endlap and 60% sidelap. This geometry forms a block of 529 photographs consisting of 23 strips with 23 photographs each. The use of 60% sidelap is also known as double block geometry. The double block geometry means that all the points in the interior of the calibration range will appear on a minimum of 4 photographs and some points may fall on as many as 9 photographs. The redundancy in double block geometry leads to reliability suitable for a calibration range.

Ground control of the aerial photographs is provided through a set of 49 targeted GPS survey points. The ground control point pattern is in the form of a 7 by 7 pattern over the calibration range. The exposure stations of the aerial photographs were acquired with differential GPS in order to: increase redundancy; stiffen the block; and to allow a better self-calibration of the aerial mapping camera.

The aerial photographs were scanned with a pixel size of 14 microns. At this photo scale, the nominal ground sample distance of a pixel is 35cm. The complete set of image scans has a storage requirement of 150GB. An additional set of image files will be produced digitally by a one half reduction. This second set of images will have a nominal ground sample distance of 70cm and will require an additional 38GB of storage.

2.2 Construction of the Geometric Calibration Range

The construction of the calibration range began with a bundle block triangulation of the aerial photography. The tie points were measured with autocorrelation software and the ground control points were manually measured. The triangulation included the GPS exposure stations and control points. Added parameters for focal length, principal point and distortion were included in the self-calibration triangulation. These steps have been completed at the time of writing this paper. The following are steps to be completed.

The next step is to rerun the autocorrelation tie generator and obtain a very dense network of tie points. A minimum of 10,000 points and a maximum of 50,000 points will be obtained through this operation. Additionally, several thousand manually selected tie points may be included. Then, all of the tie point measurements are used to perform another self-calibration triangulation. The adjusted tie point coordinates and image measurements are used as control points for the satellite imagery.

3 SOFTWARE

The main components of software that will be used to perform the geometric calibration of the OrbView 3 and 4 satellites are: alignment Kalman filter, image correlator, and multi-sensor triangulation. Each of these are described in sections below. The image correlator and the triangulation software will be used to also used build the Geometric Calibration Range.

3.1 Alignment Kalman Filter

The exterior attitude orientation of the satellite is determined by using star trackers and gyroscopes. The star trackers provide an absolute attitude reference, but their update rate is not fast enough. However, the gyros provide relative attitude changes at a fast update rate. The data from the star trackers and gyros are blended in a Kalman filter to estimate the platform attitude in an absolute attitude reference frame at a high update rate with good relative attitude changes.

In order to obtain accurate platform attitude estimates the geometric calibration process needs to determine the interlock angles between the star trackers and the gyros coordinate axes. This is accomplished by carrying these interlock angles as parameters to be estimated in an algorithm called the Alignment Kalman Filter. Additional parameters estimated by the alignment Kalman filter include: gyro bias and scale factors. We can think of this filter as a self-calibration process. In order that the interlock angles be observable (estimable), the spacecraft will have to maneuver through a sufficient volume of 3D attitude space and at different angular rates. The interlock angles between the platform and camera axes are determined in the triangulation model.

3.2 Image Correlator

A flexible and efficient image correlator is key to the cost effective use of controlled aerial photography for control point generation. Since the image correlator needs to locate common image points in both the aerial and satellite imagery, it must work well with nonhomogenous image sets. The differences between the aerial and satellite imagery can be caused by temporal effects, such as fields with different crops, or by image scale and rotation. The ORBIMAGE image correlator reduces scale and rotation differences by rectifying both image sources to the same scale and orientation. The rectification is performed on the fly. Furthermore, a digital elevation model can also be used to improve the rectification. The image correlation is performed on the rectified imagery and the image coordinates of the match points are transformed back into the coordinate systems of the original images.

The image correlator also has another powerful feature. Suppose that a set of points in the controlled aerial photographs have already been obtained and that these are to used as control points for the satellite imagery. A triangulation of the aerial photography is performed to determine the object space coordinates of these points. The image correlator can use this data to perform the image matching. The image coordinates of a control point is used to locate an image patch from a photograph in the controlled aerial imagery set. The object space coordinates of the control point are used to determine the starting point of the search in the satellite imagery.

The image correlator uses many techniques such as: interest operators, resolution pyramids and check back redundancy to ensure effective and efficient searching.

3.3 Multi-Sensor Triangulation

The estimation process for the camera calibration parameters is centered on the triangulation software. This software needs to be rigorous, flexible and robust. ORBIMAGE has spent the last year in completely rewriting its triangulation software.

3.3.1 Object Orientated Design, Framework, Utilities and DTK

The software is based on an object orientation design and includes the concept of sensor classes. The user of the software can insert new sensors into the sensor factory using the Developer s Took Kit (DTK). The developer of a new sensor model only needs to write source code for things that are particular to the new sensor such as, data ingest and geometric modeling. The items that are common to all triangulations such as: the least squares adjustment engine; gross error detection; and error propagation are available to the sensor model developer through a supporting framework. Additionally, the triangulation software contains a set of utilities that are available to the sensor model developer, such as: numerical partial derivatives; orbit integration; atmospheric refraction model; Lagrange interpolation; and a numerical ground to image projection based on a user defined image to ground projection

3.3.2 Sparse Matrix Class

The least squares engine is supported by an efficient sparse matrix class. The matrix class allows the software to store and process only the non-zero blocks. The sparse matrix block structure is maintained by a set of internal pointers that the developer of the sensor models never needs to address. The standard matrix operations, such as, addition, multiplication, and transpose multiply have been included in the sparse matrix class and they automatically maintain the sparse matrix structure. For example, folding the normal equations to eliminate the object points and form the first order reduced normals is accomplished in a half a page of source code and all of the sparse block structure and manipulation is done internally by the sparse matrix class. The sparse matrix class currently contains two linear equation solvers: Conjugate Gradient (CG) method and direct inversion. A strong advantage of the CG method for multi-sensor triangulation is that the application of the method is invariant under the actual structure of the normal equations. Whereas, recursive partitioning (nested dissection) requires an intimate knowledge of the matrix structure and can limit the types of condition equations that are allowed in forming the normals. We have generally used the CG method for solution of the normal equations and the direct inversion for error propagation. Current research and development is looking at: modifying the preconditioner for the CG method to improve convergence rates ; and block iterative methods to form partial inversion.

3.3.3 BMSI Parameter Modeling

Parameterization of the geometric model is accomplished through a four level tier: Block, Mission, Strip and Image. In this structure, the block is made up of missions, a mission is made up of strips, and a strip is made up of images. For example consider the geometric calibration scenario forming a multi-sensor block adjustment containing two missions: frame photographs and OrbView satellite imagery. The frame mission consists of 23 strips with each strip containing 23 images. The OrbView imagery may be from multiple orbits (i.e. strips in this context) with several images per orbit. The strength of BMSI parameter modeling is that the appropriate parameters can be defined at each level. Consider a parameterization model for the frame camera in the example. At the mission level, interior orientation parameters can be modeled. At the strip level, drift parameters for the GPS measurement of the exposure stations can be modeled. At the image level, exterior orientation parameters can be modeled.

3.3.4 NORA Method

The parameter modeling is augmented by the NORA (Non Redundant Algorithm) method. This method allows for removing a model parameter from the normal equations. When the NORA switch is inactive, the parameter it points to is used as a constant in the condition equations. For example, a NORA switch can be used to solve for the focal length or hold it constant. The NORA method allows creating a sensor model with a large number of parameters and only solving for the ones that apply to the current job without the need to reprogram the sensor model. In effect the NORA method creates a set of switches in with the parameters to be carried in the adjustment are set at runtime. This allows the developer of the sensor model to include duplicate parameters at the MSI levels. For example, the frame sensor model can have focal length at the mission, strip and image levels and at runtime the user determines whether a global focal length for the entire mission is the best model, or whether it is best to solve for focal length for each strip, or for each image. The user can decide to not solve for focal length at all. All of these options are available to the user at runtime without changing the programming of the sensor model. One has to careful not to over parameterize the solution by accidentally including the same parameter in too many places. This can be accomplished by using internal checking coded through the DTK. The least squares engine allows a priori parameter weighting through the Unified Method. The Unified Method can also be used to hold a priori parameter values by using very large weight. However, this may cause some numerical stability issues and requires solving for more parameters than is necessary.

3.3.5 Numerical Partial Derivatives and Numerical Ground to Image Projection

The least squares engine will accept analytical partial derivatives when they are provided through the DTK. If analytical partial derivatives are not available, the least squares engine framework will compute numerical partial derivatives based on the condition equations. To determine numerical partial derivatives for time dependent condition equations, such as those for satellite imagery, the numerical partial derivative algorithm will automatically cause the necessary iterations on the condition equations to be performed. Another utility that is useful for time dependent (dynamic) systems is the framework algorithm that can be used to compute a numerical ground to image projection from a supplied image to ground projection. The advantage to modeling the condition equation as a ground to image projection is that it allows the use of an Adjustment of Indirect Observations. In this case, the coefficient matrix for the image observations is the identity matrix, which leads to faster formation of the normal equations. However, time dependent systems maybe difficult to directly model in an ground to image projection due to the difficulty of determining the time that a specific object space position was imaged. It may be relatively easier to model the image to ground projection. The image to ground projection can be accomplished by determining the direction of the photogrammetric ray (view vector) and the position of the perspective center at the moment under consideration. Since the photogrammetric relationship represents 3D information in a 2D storage, it is necessary that one coordinate in the object space be specified for a image to ground projection to be well defined. This coordinate is usually the elevation. So putting this altogether, one starts out with the measured line (time) and sample of the image point and the object space position of the point that is to be projected up into the imagery. The line (time) and sample of the image point are varied under the guide of numerical partials until the line (time) and sample of the image point corresponding to the desired ground point has been determined. The difference between the measured image point and the ground to image projection of the object point is the residual in the condition equation. The availability of both numerical partial derivatives and numerical ground to image projection can greatly shorten the development time required to model a time dependent sensor. The disadvantage is the computation burden to perform the numerical methods. With modern computational power, the computation burden can usually be accommodated. However, if the developer of a sensor model wishes to include analytical partial derivatives and/or analytical ground to image projection, the triangulation framework will accept them. The numerical methods can be used as a computational check for the analytical expressions.

3.3.6 Robust Estimation

The Danish Method of weight reduction for gross error detection will be first implemented into the framework level of the triangulation software. This method has the advantage of a relatively direct implementation. We are in the process of designing an implementation of the Data Snooping Method for gross error detection with external and internal reliability estimation.

3.3.7 Sensor Factory

Currently, the sensor factory contains several sensor classes: SPOT, LANDSAT, IRS-1C, various frame models, and a production version of the OrbView sensor. The geometric calibration sensor model for the OrbView satellites is under development. Future research is to include embedding the Alignment Kalman Filter into the triangulation software to allow for a simultaneous determinate of the all the attitude interlock angles.

4 COMPUTER HARDWARE

Off the shelf computer hardware suited to analytical triangulation is becoming widely available at reasonable prices. The computer hardware component of the Geometric Calibration System is one such example. The computer hardware requirements for the Geometric Calibration System are in the upper range of a high end workstation class machine. In particular, the system contains: dual Pentium III processors at 550MHZ; 1 GB of memory; 230 GB of storage in a RAID 5 disk tower; 24 inch (60cm) monitor; CD-RW; and a 100 BaseT network connection. The system currently inputs imagery through the CD-RW or the network connection. Prior to launch, the system will include either an 8mm or DLT tape drive for image transport and system backup. No stereo-viewing technology is required to measure points.

The operating system for the computer system is Windows NT. X windows support is provided through a software package called Interix. UPS and backup generators maintain the electrical power for the computer system at a facilities level.

Experience gained in developing the calibration range has shown that the hardware is sufficient for geometric calibration of the OrbView satellites.

5 ADDITIONAL REMARK

The components of the Geometric Calibration System are suitable for geometric calibration of many types of photogrammetric and remote sensing cameras. Higher resolution sensors can be accommodated by augmenting the calibration range with a high resolution insert.