MISR AUTOMATIC GEOMETRIC QUALITY ASSESSMENT AND IN-FLIGHT GEOMETRIC CALIBRATION UPDATES

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ABSTRACT:
In order to facilitate a unique georectification approach implemented for Multi-angle Imaging SpectroRadiometer (MISR) data, a specific calibration datasets need to be derived during flight. In the case of the spaceborne MISR instrument with its unique configuration of nine fixed pushbroom cameras, continuous and autonomous coregistration and geolocation of image data are required prior to application of scientific retrieval algorithm. In-flight generated calibration datasets are required to: a) assure accuracy, b) reduce processing load, and c) support autonomous aspect of the processing algorithm. The Camera Geometric Model (CGM) is the first in-flight generated calibration dataset. It is designed to deal with the static pointing errors. However, calibrated CGM is not sufficient to constantly reach required accuracy and provide means for an on-line georectification quality assessment Therefore an off-line geometric accuracy assessment is implemented and will be operated until all of the required calibration datasets are generated and utilized. An overview of the in-flight geometric calibrations and quality assessment along with the current status and discussion of the operational results is presented.

1. INTRODUCTION

The requirements for coregistration and geolocation (i.e., orthorectification), as well as stereo retrieval of a surface height from multi-temporal, multi-angle image data have been recognized since the early days of remote sensing. In order to achieve this, geometric distortions must be eliminated. In most applications, the geometric data correction is not a part of standard processing. Usually, standard digital data products have only been radiometrically and spectrally corrected before being distributed to investigators, who may then need to set up an off-line geometric processing system (Allison, 1994). In the case of the spaceborne Multi-angle Imaging SpectroRadiometer (MISR) with its unique configuration of nine fixed pushbroom cameras, continuous and autonomous coregistration and geolocation of image data are required prior to application of scientific retrieval algorithm.

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The MISR is one of the five science instruments launched in December 1999, on board of NASA's Terra spacecraft as a parts of its Earth Observing System (EOS) (Diner, 1998). The instrument and the algorithms developed to process its data represent a revolutionary approach to global remote sensing of geophysical and biophysical parameters. In order to support this approach, geometric processing is designed based on the specific accuracy requirements along with the need for unique capability of autonomous and continuous georectification. Effectively, an orthorectified global digital map will be produced every nine days during the life of the mission, estimated to about seven to eight years.

The processing strategy distributes the effort between the MISR Science Computing Facility, Jet Propulsion Laboratory, California Institute for Technology, Pasadena, and the EOS Distributed Active Archive Center (DAAC), NASA Langley Research Center, Hampton, VA, thus minimizing the amount of off-line processing required at the latter location (Jovanovic, . In-flight geometric calibration activities at the Science Computing Facility (SCF) have been designed to produce specialized datasets, which are then used as inputs to standard production at the DAAC. These datasets not only reduce the overall processing load but also assure the required georectification accuracy. In particular, the camera geometric model, reference orbit imagery and projection parameters provide facilities to take into account errors in the camera pointing geometry, including errors in the EOS project supplied navigation and attitude. The preparation of the calibration datasets represents a significant challenge given the amount of data to be exploited and produced. For example, as result of the global aspects of our objectives, the number of files required for certain datasets is always multiple of 233 (unique orbit trajectories) and 9 (number of cameras) totoaling to about 1.3 TB in size. As the calibration operations have been conducted in stages, the geometric quality assessments were implemented simultaneously in order to provide necessary feedback after major updates or for testing purposes.

In this paper, an overview of the in-flight geometric calibrations and quality assessment along with current status and discussion of the operational results is given. In order to allow better understanding of the challenges involved and the value of the obtained results, we start with a description of the MISR imaging event from the geometric point of view.

2. MISR IMAGING EVENT

Figure 1: This graphics illustrates imaging approach of MISR instrument. Nine pushbroom cameras acquire imagery continuously during the day light portion of each orbit. The data in four spectral bands are obtained for each of nine discrete camera angles.

The Terra spacecraft is in a sun-synchronous orbit, with a baseline inclination of 98.186°. The orbit period of 98.88 minutes and orbit precession rate of 0.986°/day imply a ground repeat cycle of the spacecraft nadir point of 16 days with an equatorial local crossing time of 10:30 a.m.. The orbit altitude varies from about 704 km to a maximum of 730 km. Figure 1 shows MISR nominal ground coverage during a one-day period.

The instrument consists of nine push-broom cameras, with one camera pointing toward the nadir (designated An), one bank of four cameras pointing in the forward direction (designated Af, Bf, Cf, and Df in order of increasing off-nadir angle), and one bank of four cameras pointing in the aftward direction (using the same convention but designated Aa, Ba, Ca, and Da). Images are acquired with nominal view angles, relative to the surface reference ellipsoid, of 0°, 26.1°, 45.6, 60.0°, and 70.5° for An, Af/Aa, Bf/Ba, Cf/Ca, and Df/Da, respectively. The instantaneous displacement in the along-track direction between the Df and Da views is about 2800 km (see Figure 1), and it takes about 7 minutes for a ground target to be observed by all nine cameras.

The cross-track instantaneous field of view and sample spacing of each pixel is 275 m for all of the off-nadir cameras, and 250 m for the nadir camera. In order to simplify manufacturing, same optical design is used for nadir and Af/Aa off-nadir cameras, resulting in slightly different cross- track instantaneous fields of view. Along-track instantaneous fields of view depend on the view angle, ranging from 250 m in the nadir to 707 m at the most oblique angle. Sample spacing in the along- track direction is 275 m in all cameras.

Each camera uses four charge-coupled device line arrays parallel in a single focal plane. The line array contains 1504 photoactive pixels, each 21 μm x 18 μm. Each line array is filtered to provide one of four MISR spectral bands. The spectral band shapes are approximately Gaussian, and centered at 446, 558, 672, and 866 nm. Due to the physical displacement of the four line arrays within the focal plane of each camera, there is an along track displacement in the Earth views at the four spectral bands (Zong, 1996). This as well as other geometric distortions have been removed during georectification within standard ground data processing (Jovanovic, 1998).

3. GEOMETRIC QUALITY ASSESSMENTS AND UPDATES

3.1 Overview

The science data system behind MISR data production is designed for autonomous and continuous georectification of globally acquired imagery. The ultimate use of this system is the production of orthorectified imagery within the required accuracy and simultaneous assessment of the accuracy achieved in a fully autonomous fashion. In order to achieve such us capabilities several milestones have to be reached in the following order: 1) a true static pointing knowledge of the cameras' internal geometry and orientation of the individual cameras, relative to the spacecraft attitude frame of reference has to be established, 2) ancillary datasets designed to support georectification regarding dynamic pointing errors have to be produced and tested, and 3) statistical parameters and associated threshold which are used to describe quality of the georectification, internally during production, have to be established. To successfully reach these milestones a very large amount of data has to be acquired at the Science Computing Facilities for subsequent operations. In particular, the data received are used for a simultaneous up-to-date geometric quality assessments and in-flight geometric calibration resulting in the updates of the ancillary dataset used for standard production. Both of these operations are highly automatic, in order to deal with the optimum amount of data required until final calibration datasets and quality thresholds are established. As an illustration, MISR science data system team recently reached above listed milestones 1 and 2 by processing and analysing closed to 2TB of data.

3.2 In-flight geometric calibration

The errors affecting MISR georectification and co-registration accuracy can be categorized into three groups: 1) static pointing errors, 2) dynamic pointing errors, and 3) errors associated with the topography of the projection surface. The topography errors are included with a global Digital Elevation Model (DEM) (Logan, 1999) currently in use during georectification.
The MISR in-flight geometric calibration is designed to take into account static and dynamic pointing errors. The calibration approach consists of two components producing two segments of the calibration dataset: 1) Camera Geometric Model (CGM), and 2) Projection Parameters (PP) and Reference Orbit Imagery (ROI).

The CGM dataset is designed to deal with static pointing errors. It consists of a set of parameters used in a mathematical expression that gives the pointing direction of an arbitrary pixel to the spacecraft attitude frame of reference. These parameters represent the geometry of the camera system and account for distortions from an ideal optical system (Korechoff, 1996). Some of the parameters of the camera geometric model have been calibrated during the first eight months of the mission and later on updatwed based in the quality assements.

The calibrated CGM is not sufficient to reach the required accuracy and provide a mean for on-line georectification quality assessment. This is especially true while dealing with the most oblique angles where a pointing error of 10 arcseconds will introduce a geolocation error of about 300 m. In order to routinely deal with dynamic pointing errors and facilitate automatic quality assessment, 233 pairs of PP and ROI files are being produced. A ROI file consists of cloud free MISR imagery, selected from a number of orbit passes same orbit path and mosaicked into a single image. The PP file is produced using rigorous photogrammetric methods, in order to provide accurate geolocation data for the corresponding ROI file pair. The process of creating ROI and PP pairs is similar to the regular orthorectification of time dependent imagery. A major difference is that the acquired imagery (i.e. ROI) is geolocated through PP but not resampled. A simultaneous bundle adjustment utilizing multiangle imagery and ground control information (consisting of a global Digital Elevation Model and ground control image chips) is used to model dynamic errors in the supplied spacecraft navigation data. All of the planned ROI/PP production has been completed and, at the time this manuscript is being prepared for publication, a global testing of the ROI/PP is being conducted. The final dataset will be included into standard processing, providing a global high accuracy ground truth dataset with regards to the overall georectification process.

3.3 Geometric quality assessment

Since the beginning of the missionr a continuous acquisition of certain MISR products is required for two purposes. First, these data are used to provide an overall geometric quality assessment for the general public. And second, to provide feedback and testing source once the updates to the geometric calibration datasets are made. There are several geometric quality assement types based on the objectives as related to the status of the geometric calibration updates.

First one called "absolute assessment" focuses on the total pointing error of MISR instrument prior to the georectification. It utilizes a collection of globally distributed digital Ground Control Points created from the Landsat terrain corrected data (Bailey, 1997). These GCP's are identified within as acquired MISR radiometric product giving an estimate of the geolocation accuracy prior to orthorectification.

Second type of geometric quality assessment called "relative assessment" focuses on the coregistration of nine MISR cameras once all of the calibration datasets are utilized within georectification segment of standard processing. It is based on extraction of tie-points across orthorectified data from all nine cameras and evaluation of coregistration discrepancies relative to the nadir product.

And third type of geometric quality assessment called "global assessment" is designed to check for eventual blunders in the calibration datasets. Certain MISR processing algorithms include surface stereo height retrievals with the goal of detecting cloud heights and wind vectors (Zong, 2002). These products, over clear land areas, generated with two different input configurations, are used for global testing prior to official promotion of the updated calibration dataset. A global digital elevation model (Logan, 1999) is also used in support of these assessments.

In summary, three types of MISR automatic geometric quality assessment relay on the following data products. First, MISR generated products: 1) Radiometric Product, 2) Terrain corrected georectified product, 3) Stereoscopically derived surface (i.e. cloud heights) and 4) Radiometrically derived cloud mask. Second, ground truth data used for these quality assessments are the digital Ground Control Points (GCP) datasets and the Global Digital Elevation Model. And third, Terra spacecraft provided ephemeris and attitude as the output based on the TDRSS Onboard Navigation System (TONS).

4. GEOMETRIC PERFORMANCES AND CALIBRATION UPDATES

The MISR instrument was launched in December 1999. On February 24, 2000, the science data processing team received the first image. Soon after an initial interactive analysis and a software fix, we started first series of geometric quality assessments and analysis.

4.1 Camera Geometric Model

A first comprehensive set of the quality assessment input data is the collection of radiometric products corresponding to 365 orbits acquired during the period of April 16 through May 11, 2000. The image chips from the GCP database were matched with the MISR imagery in order to identify differences between the true location and the one predicted by the initial Camera Geometric Model. As expected, the results indicated that there is no need for in-flight geometric calibration of the Camera Geometric Model parameters defining relative orientation of the four spectral bands within each camera. The pre-flight geometric calibration of the band-to-band orientation was accurate and it did not change after the launch. The band-to-band co-registration, within a camera in the Georectified Radiance Product, is better than 30 m (1σ) across all nine cameras.

At the same time, assessments regarding absolute geolocation and co-registration between nine cameras indicated definite need for in-flight geometric calibration. Important aspect of these assessments, in addition to quantifing errors, was to help decide which parameters of the Camera Geometric Model most probably needed adjustment. Even though the calibration software is capable of adjustment for all parameters at the same time, a selection of a subset is recommended in order to avoid cross-correlation effects and increase redundancy and the overall robustness of least-squares estimation.

The geometric quality is visualized as the estimated geolocation errors in the along-track and across-track directions plotted in a number of different ways. For example, the plots in Figures 2a, and 2b show the geolocation errors for the Da camera. It can be seen that the overall line error (along-track) goes up to ± 4000 m for the most oblique Da cameras. In the same time line error for camera with the less oblique angle, A's cameras, goes up to ±1000 m.

The sample error (across-track) in this example is around -1000 m but it does vary in size and direction when data for all nine cameras are examined. These kinds of error plots are used to help decide which CGM parameters need to be recalibrated in-flight. The plot shown in Figure 2a, which is the line error across the field of a pushbroom camera view, indicates large attitude bias in the conventional yaw direction.

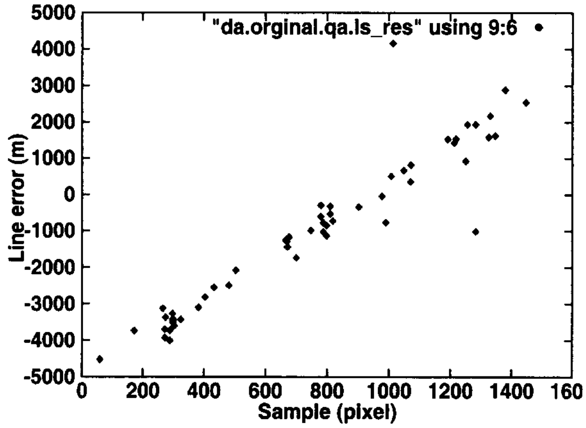

Figure 2a: Line error (along-track) as a function of pixel number across the field of view for the Da camera before CGM calibration

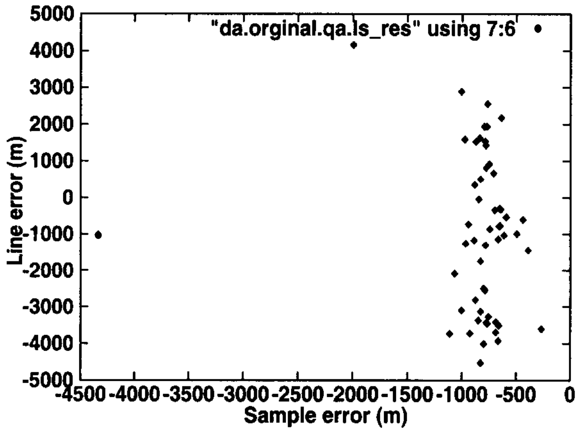

Figure 2b: Line error (along-track) plotted against sample error (across-track) for the Da camera before CGM calibration

At the same time, plot shown in Figure 2b indicate large attitude bias in the across-track direction corresponding to the conventional roll angle. It should be pointed out that this kind of error behaviour was evident in all cameras, with a different sign.

Based on these and other graphical analyses, calibration software was configured to adjust angles defining orientation (including pitch angle) between the camera and spacecraft attitude frame of reference. There was no indication that other CGM parameters needed adjustment.

After few iterations the final update of the CGM (i.e. version 6) was included as a part of standard data processing on August 25, 2000. The results of the calibration are given in Table 1. It should be noted that number of blunders automatically identified and removed from the solution is relatively small compared to the total number of measurements. In addition, a visual inspection of the residuals plots is conducted in order to assure no remaining impact of the blunders.

For illustration, Figure 3 represent quality assessment using same data as in Figure 2b with only difference being that new camera model is included into standard processing.

At this point we reached our goal number 1 of defining " a true static pointing knowledge of the cameras' internal geometry and orientation of the individual cameras, relative to the spacecraft attitude frame of reference". However, in order to verify static nature of the overall instrument pointings an automatic geometric quality assessment was implemented over a longer time period.

Camera	Number of Measurements	Number of Blunders	Corrections to pointing (arcsec)		
			Roll	Pitch	Yaw
Df	43	5	327	5	-326
Cf	63	3	323	8	86
Bf	61	0	520	3	343
Af	61	2	526	-13	661
An	56	4	274	-2	774
Aa	73	3	-67	-9	767
Ba	65	2	-214	-13	557
Ca	57	1	-920	-95	972
Da	54	1	-1030	-106	757

Table 1: Results of The In-flight Camera Geometric Model Calibration

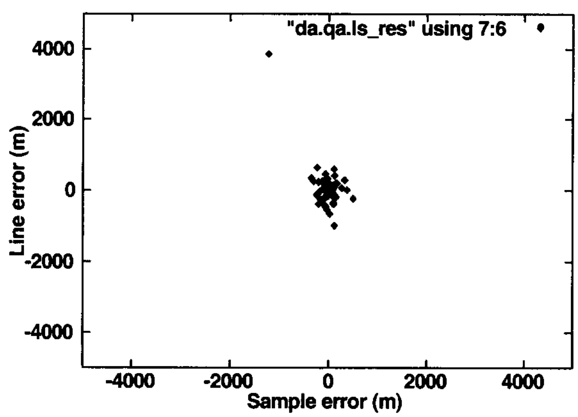

Figure 3: Line error (along-track) plotted against sample error (across-track) for the Da camera after CGM calibration.

All of the acquired MISR data from September 2000 to July 2001 was used for this purpose. Special attention was also paid to the data surrounding in-orbit maneuvers (e.g. satellite drag makeup manoeuvre), as these events could affect the CGM stability. With the exception of the Da camera, the overall geolocation performance was as expected. Figures 4a and 4b provide summary of the geometric quality assessment for this 11 months time period. The detected errors in the along-track and across track directions were used to estimate the mean error and standard deviation for the time segments corresponding to periods of 500 consecutive orbits. It should be noted that on average, there were about 100 measurements per camera, per time segment.

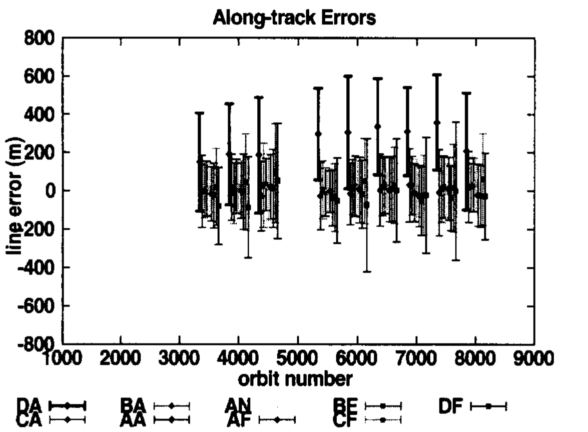

Figure 4a: CGM 6 - Along-track georectification errors as a function of time (i.e., orbit number) estimated for approximately one month (i.e. 500 orbits) time periods

However, in some cases there were too few measurements due to the lack of cloud free data. Consequently, error estimates in those cases may be less reliable. For example, error estimates in the sample direction for the Df camera for the time period centered at orbit 4500 were made from only 15 measurements, and therefore is not considered as good as estimates for other time periods. Due to the insufficient number of error estimate measurements the time segment centered at orbit 5000 is excluded from the overall summary. Nevertheless, the results displayed in Figures 4a and 4b show that stability of the CGM and the magnitude of the geolocation errors are as expected for eight out of nine cameras. For these eight cameras, the mean errors in both directions are close to and oscillate around zero with a standard deviation within the range of 100 m up to 300 m depending on the camera view angle.

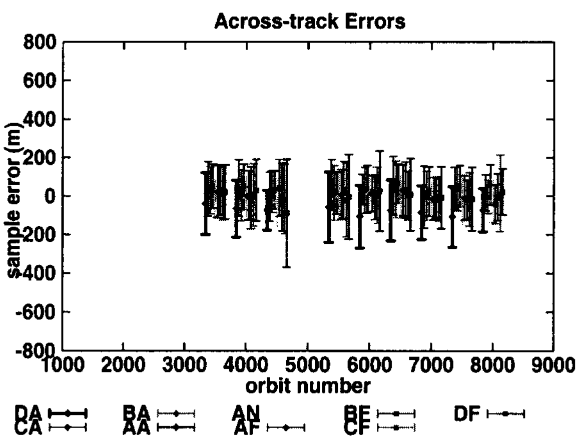

Figure 4b: CGM 6 - Across-track georectification errors as a function of time (i.e., orbit number) estimated for approximately one month (i.e. 500 orbits) time periods

These standard deviations are in agreement with the expected accuracy of image matching, used to identify ground control points, and the specified dynamic attitude errors, which are not a part of the CGM. However, the geolocation performance associated with the Da camera was not expected. Significant bias of about 300 m in the along-track and 100 m in the across-track direction has been observed since the beginning of this quality assessment. A number of attempts to recalibrate the CGM for the Da camera, using different set of parameters, or different sets of input data did not provide much better results. For example, Figure 5 illustrate geolocation performance of Da camera for the same time period by using an estimate of the CGM (version 7) based on the input data from a large number of orbits. It is clear that our assumption of the static nature of the camera model is not valid for Da camera. In this particular example, we observe a period of about three weeks for which pointing of Da camera is significantly different than any other time. Furthe investigations focusing on the Da camera pointing reveal more cases of similar unpredictable behaviour of Da camera. Nevertheless, another calibration datasets are prepared to deal with the dynamic pointing errors including non-expected issues with the Da camera.

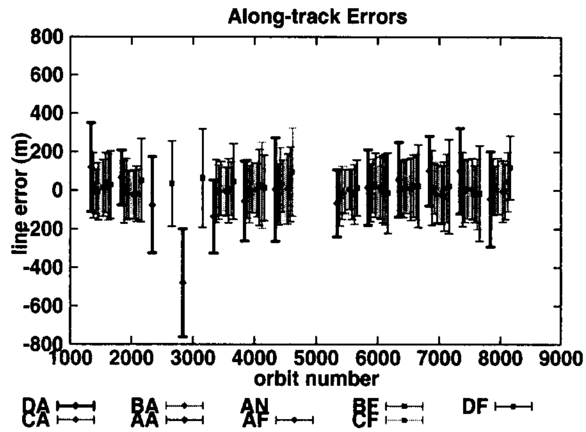

Figure 5: CGM 7 - Along-track georectification errors as a function of time (i.e., orbit number) estimated for approximately one month (i.e. 500 orbits) time periods

4.2 Projection Parameters (PP) and Reference Orbit Imagery (ROI)

In addition to the unexpected un-stability of Da camera, the PP and ROI datasets are prepared to deal with any type of error with certain dynamic nature. The most prominent of those errors are contained in the attitude data. In addition to the nominal accuracy specifications of the Terra obtained attitude, significant accuracy degradation is expected during certain contact interruptions between spacecraft and TDRSS on-board navigation system. As a result, georectification process cannot depend only on the CGM to define accurate pointing. Creation of the PP and associated ROI imagery as well as its utilization within standard processing is described in (Jovanovic, 1998).

In order to assess geometric quality with the focus on these periodic attitude errors we used procedure described in Section 3.3 for relative coregistration estimate. For example, looking on the assessment results for orbit number 9456, unusually high coregistration discrepancies are detected. The Table 2 lists mean errors for the coregistration between nadir and other eight cameras.

Cam.	Df	Cf	Bf	Af	Aa	Ba	Ca	Da
Mean (m)	1889	808	354	74	72	290	770	1778

Table 2: Mean coregistration error between nadir and other eight cameras for orbit 9456.

Just to mention here, a part of the creation process for the PP and ROI ancillary calibration datasets is the simultaneous bundle adjustment for nine cameras designed to specifically deal with the errors as experienced in the orbit 9456. A typical output from this bundle adjustment are corrections to the spacecraft attitude and ephemeris modelled as the time dependent spline functions. Spline knot separations are defined based on the number available constraint equation and estimated parameter variability. For example, Figure 6 gives cubic spline correction to a pitch angle to one of 932 orbits (4 for each of 233 orbit paths) used for generation of PP and ROI datasets.

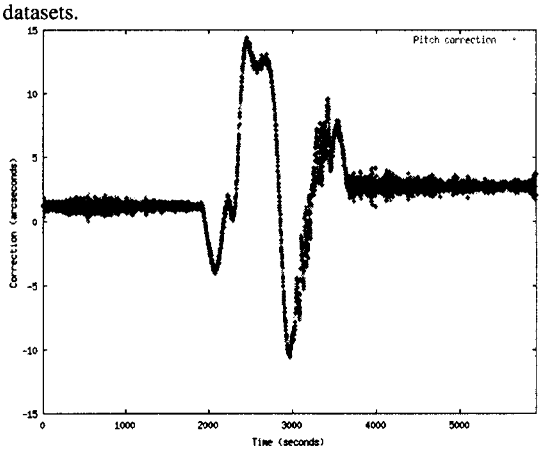

Figure 6: Cubic spline representing pitch corrections for one of the orbits used for the creation of PP and ROI datasets

Once PP and ROI datasets, created for the referenced sub spacecraft trajectory corresponding to orbit 9456, are used as part of standard processing the mean coregistration between nine cameras is significantly improved, as shown in Table 3.

Cam.	Df	Cf	Bf	Af	Aa	Ba	Ca	Da
Mean (m)	376	187	88	23	76	52	232	382

Table 3: Mean coregistration error between nadir and other eight cameras for orbit 9456 after utilization of corresponding PP and ROI datasets.

The "relative coregistration assessments" are used to collect statistics on an orbit per orbit basis with a goal of identifying special conditions and ultimately quantifying improvement by summarizing it for large number of orbits processed in both configurations with and without ancillary PP and ROI dataset. At the same time, we are conducting "global assessment" (described in the section 3.3) with the goal of detecting blunders in the creation of PP and ROI. Approach consists of evaluation of the obtained stereo height differences with the reference to the global digital elevation model. The assumption is that data produced with the PP and ROI should be closer to the reference, in a global sense, than the data produced without this ancillary information. It should be pointed out that in this test we are not focusing on very high accuracy evaluation. Instead, one of the driving requirements for this analysis is a complete first level quality evaluation of the 18873 files totalling 1.3 TB in size. In most cases, there were not significant (as defined by the thresholds of this test) differences between data produced in two configuration modes. Overall, as expected, there is a tendency of data produced with PP and ROI being closer to the reference global digital elevation model. We did not detect any discrepancies indicating problems with the data tested. An example of results for the orbit cases where significant improvement is expected is given in figure 7. It can be seen that

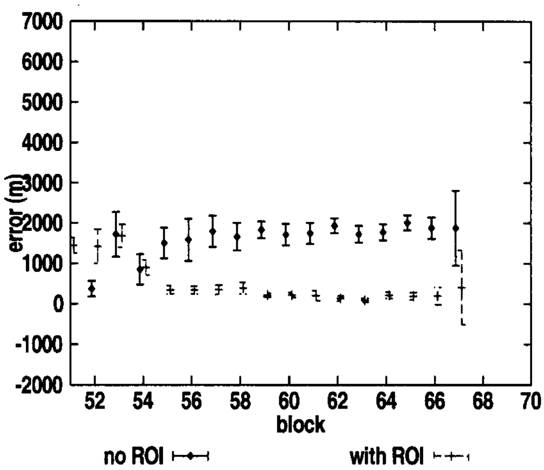

Figure 7: Mean stereo height differences between data produced with and without PP and ROI and a reference global digital elevation model.

stereo heights obtained for the data produced with the PP and ROI are significantly closer to the reference for the larger part of the orbit. Discrepancies for the other part of the orbit are equally large in both cases. Interactive analysis verified that part of the orbits with no improvement is an ocean segment at the beginning of the orbit, making it not suitable for utilization of PP and ROI. As soon as there was the first piece of clear land, corrections were made and propagated further in the orbit.

5. CONCLUSIONS AND FURTHER WORK

The ancillary datasets required for autonomous and continuous georectification of MISR imagery have been produced as the result of in-flight geometric calibrations. The Camera Geometric Model (CGM) parameters defined on the ground were updated and included into standard processing to improve knowledge of the cameras pointing relative to the spacecraft frame of reference. It was assumed that this pointing would be static over a longer period of time, if not during the entire mission. To validate this assumption, the quality of the calibrated camera model was analysed and investigated over a longer time period. The overall results show that camera geometric calibration significantly reduced georectification biases from up to 4000 m down to a 50 m range for all nine cameras. However, the stability of the CGM was verified for eight about of nine cameras. An Investigation regarding pointing behaviour of the Da camera during questionable three weeks period is underway as well as continuous monitoring of the georectification quality as the changes in the cameras pointing may be expected.

In the meantime, other datasets are prepared in order to take into account remaining pointing variability including dynamic errors in the reported spacecraft attitude and unexpected Da instability These datasets, named Projection Parameters and Reference Orbit Imagery, are being tested prior to their official promotion into the standard processing chain. The plan is to complete testing of PP and ROI testing and make it operational by the fall of 2002 in order to be ready for reprocessing of MISR data by the end of year. The remaining work regarding the georectification of MISR data will concentrate on two areas: 1) verifying algorithm and tuning up parameters designed to automatically estimate geometric quality indicators which are to be associated with the Georectified radiance product, and 2) investigate specific needs, define approach and improve the underlining Digital Elevation Model.

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