PERMANET VALIDATION OF THE GEOMETRIC CALIBRATION AS A COMPLEMENT TO MISR DATA PRODUCTION SYSTEM

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ABSTRACT:

This paper focuses on the validation aspect of the geometric calibration approach as implemented for the Multi-angle Imaging SpectroRadiometer (MISR), a part of the payload for NASA's Terra spacecraft. The MISR instrument, launched in December 1999, continuously acquires a systematic, global, multi-angle imagery in reflected sunlight in order to support and improve studies of Earth's ecology and climate. Moderate-resolution data acquired with a unique configuration of nine fixed pushbroom cameras need to be autonomously georectified prior to use in subsequent scientific retrievals. A robust data production algorithm is based on in-flight generated calibration datasets produced at the beginning of the mission and operationally validated in the first two years. However, in order to maintain required subpixel co-registration accuracies, globally and throughout the life of the mission, data production operations are complemented with a quality monitoring system. This system has been critical in: 1) resolving impact issues that georectification quality may have on subsequent retrievals, 2) providing bases for decisions regarding updates of the calibration datasets and production algorithm, and 3) evaluating and summarizing overall pointing stability and georectification performance. With the series of quality investigations focusing on the georectification requirements, it was determined that the pointing stability of one of the cameras is not as good as the other eight cameras. As a result, the data production algorithm has been updated to assure uniform georectification and co-registration performance prior to processing a final data collection for the entire life of the mission. Presented in this paper will be: an overview of the calibration approach and related quality monitoring system, operational results prior to and after the final implementation and the global summaries on geospatial data accuracies.

1. INTRODUCTION

Many modern Earth observing sensors are designed to acquire remote sensing data on a global basis for an extended period of five to ten years. Powerful science data processing systems have been implemented to keep up with the high data acquisition rate, and to provide the user community with retrieved and validated parameters in a timely manner. These operational systems use autonomous algorithms devised to convert raw instrument data into calibrated and geo-located measurements and subsequently into globally gridded maps of science data products. MISR production algorithms, (Bothwell et al., 2002), include an integrated, digital photogrammetric approach with an emphasis on the ancillary datasets generated as part of in-flight geometric calibrations. The initial in-flight calibration datasets were produced during the first year of the mission and the corresponding operational results have been published, (Jovanovic et al., 2002). A full set of in-flight calibration datasets have subsequently been completed and are included in standard production operations.

The MISR instrument, (Diner et al., 1998), with its unique configuration of nine pushbroom cameras globally acquiring pole-to-pole daylight data required a mechanism to assure that geometric accuracy is consistently within requirements over an extended mission time of approximately eight to nine years. This is quite relevant given the sensitivities of subsequent science retrievals particularly height resolved cloud motion vectors, (Zong et al., 2002). Consequently, a geometric quality monitoring system was implemented as the complement to the production system, in order to verify its performance on a global basis over specific time periods. As it happened, this system was principally effective in regard to identifying a problem with the pointing stability of one of the most oblique cameras, and the performance verification of the other cameras.

This paper begins with an overview of the MISR global imaging event and required georectified data products. The next section outlines the baseline geo-rectification approach including the description of its complementary quality monitoring system. The remainder of the paper deals with the operational results prior to and after the final update to the production system.

2. GLOBAL IMAGING AND DATA PRODUCTS

2.1 Data acquisition

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. From the orbit altitude of about 705 km the zonal overlap swath width of MISR imaging data (that is, the swath seen by all nine cameras simultaneously along a line of constant latitude) is nominally 360 km providing multiangle coverage of the Earth in nine days at the equator and two days near the pole. The data in 36 spectral channels (nine cameras times four spectral bands per camera) are continuously acquired, pole-to-pole, on the dayside of the orbit. To illustrate, Figure 1 shows map projected data acquired by nadir camera during one-day period 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.

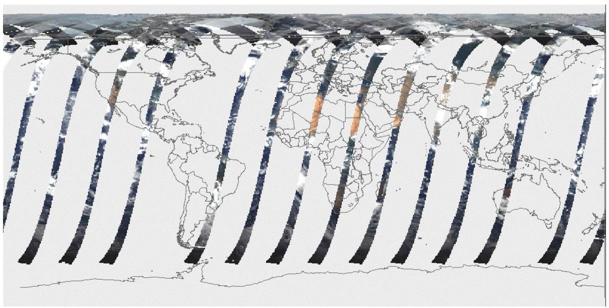


Fig 1. Data acquired by MISR nadir camera during one-day period.

2.2 Instrument geometric and radiometric characteristics

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 afward 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 2), and it takes about seven minutes for a ground target to be observed by all nine 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 [5]. This as well as other geometric distortions have been removed during georectification within standard ground data processing.

2.3 Virtual instrument concept

In order to meet coregistration and geolocation requirements, the multi-angle multispectral data are processed to a common map projection. We have selected Space Oblique Mercator, (Snyder, 1987), as the reference map projection grid, because it is designed for continuous mapping of satellite imagery. The ground resolution of the map grid is 275 m. We define this segment of ground processing as "georectification", and the derived product as the Georectified Radiance Product. There are two basic parameters in the Georectified Radiance Product depending on the definition of the reflecting surface: a) ellipsoid-projected radiance, and b) terrain-projected radiance.

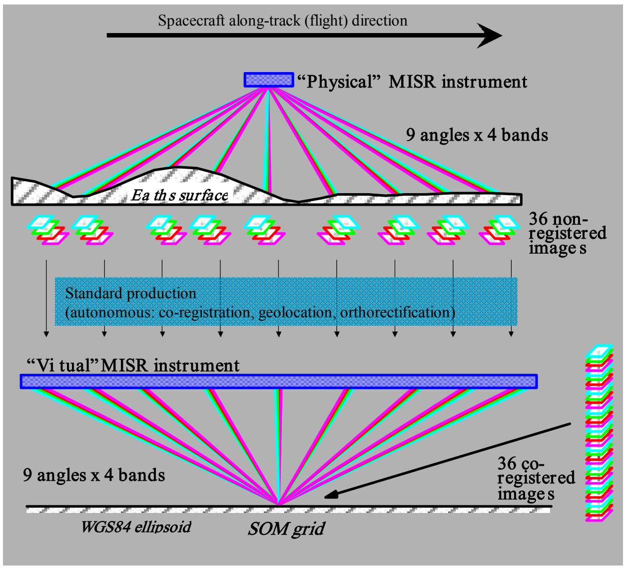


Fig. 2: Standard production converts the data so it looks like it came from the virtual instrument.

The ellipsoid-projected radiance is referenced to the surface of the WGS84 ellipsoid (no terrain elevation included) and the terrain-projected radiance is referenced to the same datum including a digital elevation model over land and inland water. An ideal instrument would collect each angular view for the terrain-projected and ellipsoid- projected radiance parameters for a ground point at the same instant, giving the radiance for each band and angle for that ground point (the so-called "virtual" MISR instrument). Naturally, the real MISR does not have these capabilities. It is up to geometric processing to produce data as if it were collected by the "virtual" MISR. The spatial horizontal accuracy goal associated with these products and required by the science algorithms is an uncertainty better then $\pm$275 m at a confidence level of 95%. Obviously this kind of accuracy requires knowledge of a digital elevation model and removal of topographic displacements. In addition, the accuracy specifications for the supplied spacecraft navigation and attitude data suggest the possibility of horizontal errors of about 2 km in the most oblique cameras.

3. GEOMETRIC CALIBRATION AND QUALITY MONITORING

A number of in-flight geometric calibration datasets have been produced and used as the ancillary input to standard production. These data were critical in two main aspects:1) removal of the distortions and errors affecting the accuracy of georectification and co-registration, and 2) optimization of standard processing computing load dominated by a very high data volume. Overall georectification approach and algorithm details have been describe previously, (Jovanovic et al., 1998). In this section an overview of calibration datasets is given as a preview to the description of the quality monitoring system.

In order to assure that we meet our specific accuracy requirements and to keep up with the high data acquisition rate, we adopted a production strategy that distributes the overall effort into three main segments,: 1) In-flight geometric calibration, 2) Standard production (geo-rectification), and 3) Geometric quality monitoring (see Figure 3).

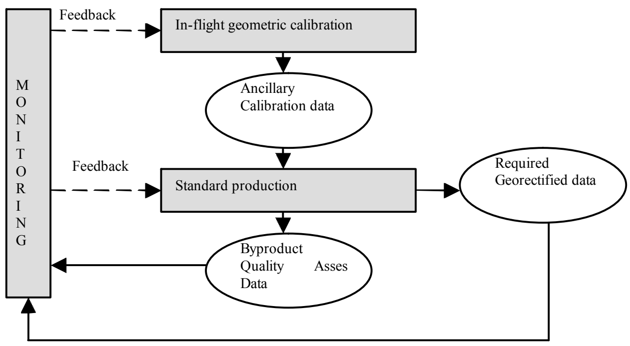


Fig 3: Overview of MISR autonomous georectification and quality monitoring

3.1.1 In-flight geometric calibration: In-flight geometric calibration activities have been designed to produce specialized datasets, which are then used as inputs to standard production. These datasets not only reduce the overall processing load but also assure the required geo-rectification accuracy. In particular, the camera geometric model (CGM), reference orbit imagery (ROI), and projection parameters (PP) provide facilities to take into account errors in the camera pointing geometry including errors in the spacecraft supplied navigation and attitude.

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 in the spacecraft attitude frame of reference. These parameters represent the geometry of the camera system and account for distortions from an ideal optical system. The calibrated CGM is not sufficiently accurate to reach the required product accuracy or to provide a means for on-line geo-rectification quality assessment. This is especially true in the case of the most oblique angles where a pointing error of 10 arc seconds will introduce a geo-location error of about 300 m.

In order to routinely deal with dynamic pointing errors and to facilitate automatic quality assessment, 233 pairs of PP and ROI files were produced, one pair for each of the 233 unique MISR orbit paths. A ROI file consists of cloud free MISR imagery, selected from a number of orbit passes over the same orbit path and mosaicked into a single image. The PP file is produced, using rigorous photogrammetric methods, to provide accurate geo-location data for the corresponding ROI file pair. The process of creating ROI and PP pairs is similar to regular ortho-rectification of time dependent imagery. A major difference is that the acquired imagery (ROI) is geo-located through PP but not re-sampled. A simultaneous bundle adjustment utilizing multi-angle imagery and ground control information (consisting of a global Digital Elevation Model (Logan, 1999) and ground control image chips) is used to model dynamic errors in the supplied spacecraft navigation data. As of October 2002, the final ROI dataset was included in standard processing, providing a global high accuracy ground truth dataset with regards to the overall geo-rectification process.

3.1.2 Standard processing: Given the geometric calibration datasets as an input, the geo-rectification process during standard processing has been significantly simplified. In particular, geo-rectification is facilitated by image-to-image registration between new MISR imagery and reference imagery. It has been demonstrated that this process is robust, since the registration is occurring between images with the same viewing geometry. An image point intersection algorithm is employed, using backward projection based on the camera model and supplied navigation, in order to obtain an initial guess for the tie points to be used during registration, (Jovanovic et al., 1998). Final location of the tie points, prior to re-sampling, is obtained through least-square area-based matching. The terrain-projected radiance product generated during geo-rectification is used as the input to Level 2 Aerosol/Surface retrievals and cloud mask generation. Another part of the geo-rectified product, ellipsoid-projected radiance, is used for Level 2 Top-of-Atmosphere/Cloud stereoscopic retrievals.

3.1.3 Geometric Quality Monitoring: Implemented as an off-line activity, geometric quality monitoring is based on utilization of quality measurement data obtained from two sources: 1) a direct posteriori assessment of the final product, and 2) information by-products of standard production. In the first case, an automatic point measurement algorithm, which uses a combination of interest point extraction and least-square image matching to localize high fidelity multi-image conjugate points, is applied to the final Geo-rectified Radiance Product. It provides a systematic and global measure of the overall co-registration with reference to nadir imagery. In the second case, inclusion of the Reference Orbit Imagery into standard processing created an opportunity to begin a systematic and permanent monitoring of the pointing stability of all nine MISR cameras. In particular, the performance of the image-to-image registration between the ROI and the newly acquired images provides a basis for evaluating so-called Geometric Data Quality Indicator (GDQI). This GDQI is stored within the final product as well as in separate QA files. Additionally, QA files contain Image Coordinate Corrections (ICC) representing two dimensional transformations between reference and new images as obtained for every X number of lines or Y seconds worth of data.

Due to their high coverage and reliability, both the co-registration and ICC data have been invaluable in detecting and resolving localized spatial accuracy issues as well as permitting long term assessment of data quality prior to deciding on updates to standard production algorithms. In fact, an improved version of the co-registration measurement algorithm has been folded into standard processing in addition to remaining a part of posteriori quality assessment. The GDQI algorithm was not fully effective as originally designed, because it incorrectly assumed that pointing stability performance would be similar for all nine cameras. However, this was not the case and a newly devised GDQI was included

Cam	AA	AF	AN	BA	BF	CA	CF	DA	DF
Mean	0.24	0.25	0.20	0.17	0.24	0.03	0.34	1.5	0.13
Rms	0.38	0.40	0.36	0.50	0.50	0.71	0.84	2.98	1.26

as part of the final update as described later.

4. INITIAL OPERATIONAL RESULTS

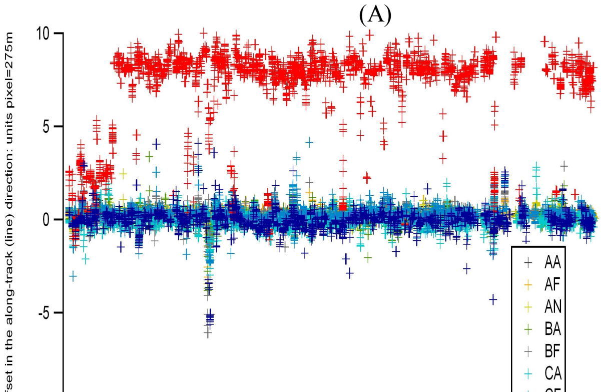
The first operational results that address geo-rectification and co-registration requirements were related to the performance of the Camera Geometric Model (CGM) with its pre-launch calibration, (Korechoff et al., 1996, Jovanovic et al., 2002). Geo-location errors measured over a globally distributed set of Ground Control Points, (Bailey et al., 1997), data were used as the input to the calibration algorithm. After several iterations, a final estimate of the CGM parameters was generated and included into operations in April, 2002. The intent of the final delivery was to include static estimates of the overall pointing with the best fit to the data available up to that time. To further deal with any dynamic pointing changes within an orbit or eventual static changes in the overall pointing, we created final ROI files which were included in standard production in October, 2002. Once this final delivery of the ancillary datasets was made, focus shifted to completion of the quality monitoring system along with analyses of the geo-rectification performance that are presented in this section.

The principal objectives of the quality assessment measurements are to evaluate: a) pointing stability of all nine cameras, b) geo-location and co-registration errors in the final product, and c) reliability of the Geometric Data Quality Indicator (GDQI) in the final product. Pointing stability and errors in the final product on a local and global basis will be presented in the remainder of this section. The initial GDQI values were not adequate and are not presented here; the results of the final, updated GDQI implementation are presented in Section 5.2.

4.1 Pointing stability

The Reference Orbit Imagery (ROI) provides a stable "ground truth" and is used as an integral part of standard production. The nine MISR camera images are compared to the ROI's in order to estimate coefficients of a two dimensional transformation describing the fit between images for a predefined length of a labelled image block (i.e., image segment). One image block is 563.2 and 140.8 km long. There are about 142 image blocks worth of data in one orbit pass.

(A)



(B)

Fig 4: Pointing stability as evaluated in the along track line direction for nine MISR cameras: A) ICC plotted against orbit number corresponding to approximately 25 days of data, July 4-29, 2001, , B) Mean and RMS of ICC obtained from 5000 orbits during period from Dec 2000 – Nov. 2001

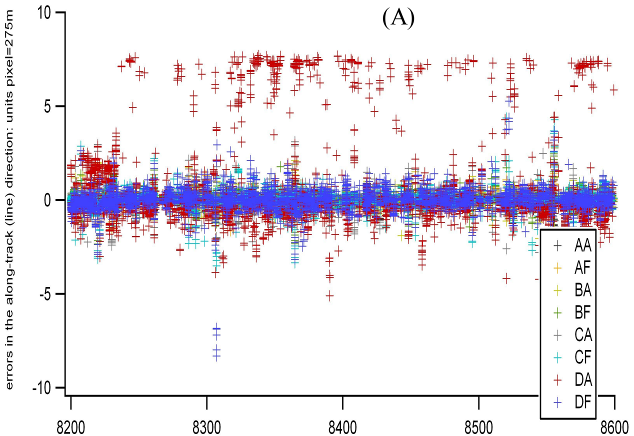
These coefficients, called Image Coordinate Corrections (ICC), were subsequently used in the processing software to optimally "warp" new images to match the reference. The ICC were also collected and summarized in order to give insight into pointing stability over desired time periods during the mission. In the Figure 4, we report the measure of pointing stability as the sum of the ICC in the along track (line) direction for every block. The ICC in the across-track direction were also collected but are less dominant due to the nine camera configuration where viewing angles change significantly along the flight direction.

The ICC are reported in pixel units, where a pixel is equal to 275 m, which is also the ground sampling distance of the MISR cameras. As an illustration of pointing stability, plot in Figure 4 shows ICC's corresponding to a time period defined by the orbit number range on the x-axis. As can be seen from the plot, most of the time eight out of nine cameras are very close to the reference with occasional deviations corresponding to spacecraft orbit maneuver activities. However, the DA camera exhibits an irregular pointing change significantly larger than the other cameras. Figure 4 also includes a table with mean and standard deviations of ICC's as obtained for 5000 orbits closely corresponding to a one year time period. Again, these are as expected for all but the DA camera, revealing the small biases of the static camera model as well remaining dynamic errors in the supplied spacecraft attitude. The analysis regarding whether these measured offsets are sufficient to assure final geo-location and co-registration accuracy for all cameras including DA is addressed next.

4.2 Geo-spatial accuracy

For the purpose of validation, the final geo-located products were scanned with a version of the image-to-image matching program (CameraMatch) that evaluated and reported co-registration errors for each camera relative to the nadir (AN) using 275 meter resolution, red band images.

(A)



(B)

Fig 5: Geolocation and co-registration as evaluated in the along track line direction for nine MISR cameras: A) errors plotted against orbit number corresponding to approximately 25 days of data July 4 – 29, 2001, B) Mean and RMS error obtained from 5000 orbits during period from Dec 2000 – Nov. 2001

The algorithm performed numerous image-matching operations and computed the mean, fractional pixel offset errors per fixed image segment size of 512 lines (called a block) for both along-track and across-track directions. For simplicity, we report only errors in the along-track direction. As can be seen in Figure 5 in which errors are displayed for exactly the same time ranges as in Figure 4, most of the static pointing biases are removed and the RMS errors are within the limits of the automatic image matching algorithm. However, it is clear that nominal implementation of the standard production algorithm was inadequate to fully take into account the pointing instability of the DA camera. Improvement certainly has been made but with limited coverage. The slightly larger then expected mean error of the BF camera should also be noted.

4.3 Global geometric performance assessment

The previously described geometric performance assessments, performed for certain time periods as data became available, were a good indicator of the potential problems with the nominal implementation of the standard production algorithm.

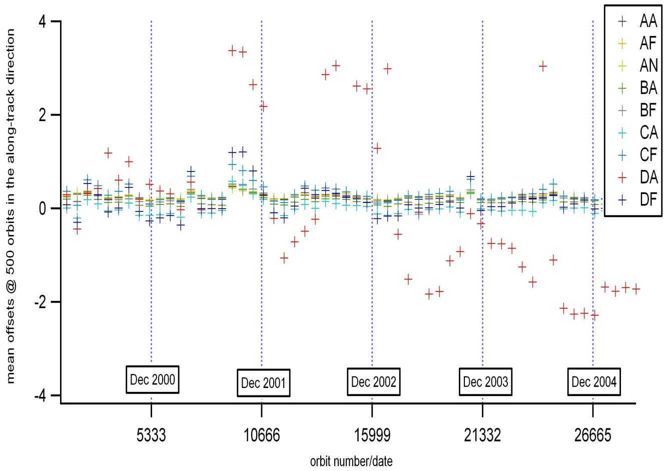
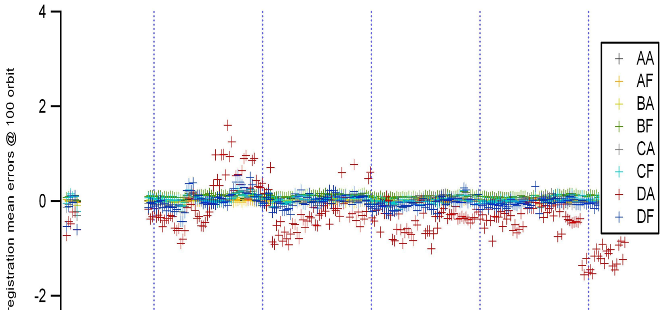


Fig 6: Global geometric performance for nine MISR cameras : Pointing - ICC means at 500 orbits plotted against orbit number.



Cam	AA	AF	AN	BA	BF	CA	CF	DA	DF
Mean	0.01	0.00	NA	0.02	0.11	0.00	0.04	0.41	0.01
Rms	0.17	0.17	NA	0.24	0.27	0.40	0.40	1.5	0.65

Figures 6 and 7 summarizes the quality assessment data to illustrate the pointing stability and co-registration performance for a four-year period. Figure 6 is the plot of mean offsets

Fig 7: Global geometric performance for nine MISR cameras : Geospatial accuracy - mean co-registration errors at 100 orbits plotted against orbit number.

They were also useful when dealing with occasional reduced accuracies in the supplied spacecraft ephemeris and attitude data as occurred during periodic orbit maneuvers. Nevertheless, any decision to update the standard production algorithm needed to be supported by a global analysis. As illustrated, Figures 6 and 7 summarize the quality assessment data to illustrate the pointing stability and co-registration performance for a four-year period. Figure 6 is the plot of mean offsets (ICC) taken for every 500 orbits. The pointing stability is fairly good for eight out of nine cameras. Some variations of approximately a one-year time period are considered acceptable and controllable by nominal standard processing. They seem to correspond to spacecraft inclination maneuver history, which is certainly more dominant at the beginning of the mission prior to the spacecraft reaching a stable orbit. This is not the case for the DA camera which exhibits an independent and very irregular pointing change. Figure 7 serves as the confirmation that sub-pixel geo-location co-registration accuracies have been attained for eight cameras during the entire mission. Mean and RMS errors are very similar to those from tables in Figures 4 and 5.

5. UPDATES AND FINAL PERFORMANCE

The analysis of overall geometric performance, along with the height/wind retrieval sensitivity studies (Horvath, et al., 2001) , made it clear that at least two cameras (Da and Bf) had systematic co-registration errors large enough to significantly affect the accuracy of Level 2 stereo height/wind retrievals. The Da camera problem was particularly severe with variable co-registration errors on the order of more then 2 pixels. The software solution that was adopted to correct this problem was to add two new components to the standard processing stream after nominal geo-located products were generated, followed by a second pass of geo-rectification as originally implemented. The first new component was an enhanced version of the CameraMatch program to identify and quantify co-registration errors. The second generated a corrected set of coefficients for "warping" the images and quantifying the uncertainties in these values. The final pass of geo-rectification then applied the co-registration corrections to selected cameras.

This final update to the geo-rectification component of MISR standard processing has been operational since May, 2005. In addition to being applied to data acquired since then, this new version of the algorithm has also been applied to data from other acquisition periods as a result of the regular reprocessing schedule and special reprocessing requests for shorter time periods. Final geo-rectification performance metrics, including co-registration errors and GDQI evaluation, have been obtained from all data processed since May, 2005, with an emphasis on the years 2000 and 2005.

5.1 Final geo-location and co-registration performance

As in Figure 7, Figure 8 shows the global quality of the geo-rectified product by summarizing co-registration errors. However, this figure uses data obtained from the final version of the product. The available data from 2000 and 2005/2006 show obvious improvement when compared with Figure 7. DA camera performance is no longer significantly different from other cameras, and virtually all of the mean errors overlap within a +- 0.1 pixel range.

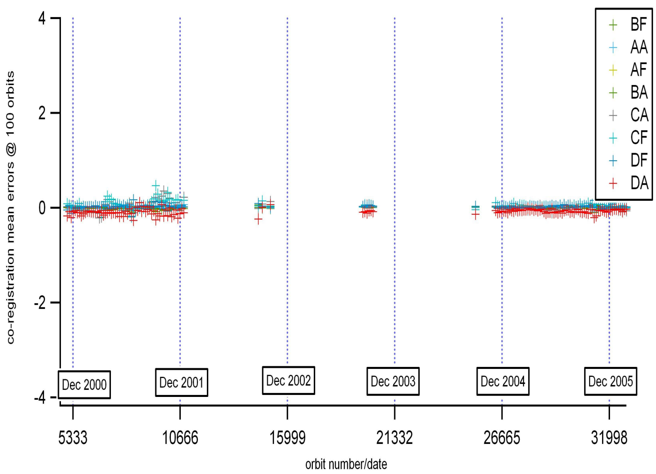


Fig. 8. Final global geometric performance for nine MISR cameras: Mean co-registration errors at 100 orbits plotted against orbit number

5.2 Final GDQI results

The Level 1 ellipsoid- and terrain-referenced products have always carried a field named GDQI (Geographic Data Quality Indicator). The intent of the field was to indicate, for each camera and block in an orbit, whether the geo-location of the image was acceptable for use. Prior to this final version, the GDQI was only marginally useful due to unexpected pointing issues with the DA camera. This latest update to standard processing provided an opportunity to quantify, with much higher confidence, the likelihood that geo-registration (relative to the nadir) camera was good

In order to assess the degree to which the co-registration correction process and the GDQI determination were successful, the CameraMatch program was run against the output of the final L1B2-corrected products. Almost 10,000 orbits between orbits 1024 and 32859 were analyzed. The data consist of along-swath and across-swath residual co-registration errors (in units of 275 meter pixels) for each block in each orbit where a CameraMatch match was found along with the corresponding block-GDQI values. About 100,000 blocks are represented.

The results are summarized in the bar-charts of Figure 9. To save space, only cameras BF and DA are shown as representative of all nine cameras. In the charts, the GDQI range of [-1,+1] is divided into 21 bins. The along-swath and across-swath residual errors are accumulated for the all the blocks whose GDQI values fall into the bin. An estimate of the overall co-registration error for each block is made by finding the "diagonal" error, i.e., the square root of the sum of the squares of the along-swath and across-swath errors. The mean "diagonal" error of all the blocks in each bin is then computed and plotted in blue at the GDQI bin location. The number of blocks that were used in computing this mean residual error for each bin is plotted in red.

The results are as expected. For each camera, the mean, residual co-registration error has a high, negative correlation with the GDQI value. The number of blocks has a high positive correlation with the GDQI value. At the left where the GDQI indicates poor registration, the mean error is large and the number of blocks that are poorly registered is small. At the right where the GDQI indicates good registration, the mean error is small, converging to about 0.2 pixels for most cameras, and the number of blocks that are well registered is large.

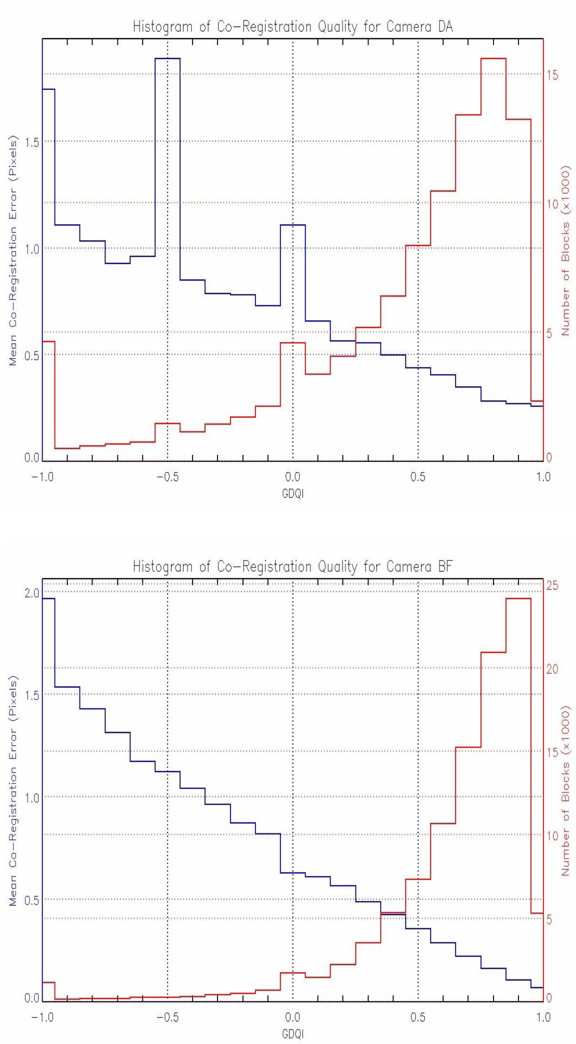


Fig. 9: Summary of GDQI performance for Da and Bf cameras.

The distribution of number of blocks in the GDQI bins indicates that the bulk of the data are well registered. This trend is modified slightly by the observation that the more oblique cameras have a larger fraction of blocks with poor GDQI. Nevertheless, the Da camera, which had mean co-registration errors of 1 to 2 pixels before the programmatic fix, now has errors less than 0.5 pixels for 70% of the blocks.

The large peak in the Da camera bar-graph at GDQI equals -0.5 is a consequence of the special attention given this camera, whereby the GDQI for all blocks is set to -0.5 when there are no CameraMatch corrections and no ROI corrections in an orbit.

6. SUMMARY

A nominal design of MISR geo-rectification processing as implemented and evaluated during the first four years of the mission fully met geo-location and co-registration accuracy requirements for eight out of nine cameras. Dynamic pointing instability of one of the most oblique cameras, namely Da, could not be corrected with the original algorithm. These conclusions have been made based on results from a global geometric quality monitoring system which continuously acquired and summarize performance assessment data as complement to production cycle.

Consequently, a revised version of the geo-rectification production algorithm has been implemented. Final results show that the co-registration performance of all nine cameras meet the expected goals. Finally, the revised algorithm includes a new method for generating the GDQI metadata product which now is fully suitable for quality control purposes.

7. ACKNOWLEDGMENTS

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