Use of Stereo-Matching to Coregister Multiangle Data From MISR

Catherine Moroney, Ákos Horváth, and Roger Davies

***Abstract*—The pattern-matching algorithms originally developed for Multi-angle Imaging SpectroRadiometer (MISR) (flying on the Earth Observing System (EOS) Terra platform) cloud retrieval have also proven useful in independently providing quality assurance of the coregistration of multiangle measurements with the nadir view. Two new techniques developed to test the coregistration are described in this paper along with results of the misregistration detection on both historical and current data. No ground-control points are strictly necessary for these calculations—just simultaneous clear-sky land imagery for three cameras and knowledge of the terrain altitude. The difficulty of registration increases with the obliquity of the view angle, so our emphasis is on coregistering to the nadir view. This paper also provides proxy validation of the stereo-matching algorithms for clear-sky land scenes.**

***Index Terms*—Coregistration, Multi-angle Imaging SpectroRadiometer (MISR), multiangle, stereo-matching, winds.**

I. Introduction

CONVENTIONAL registration of single-angle satellite imagery of the earth makes use of ground control points to develop camera geometric models (CGMs) [1] that account for the location and orientation of the camera with respect to some reference surface. Because a number of specific ground control points must be found for each orbital path, requiring clear sky conditions at each point, it may take considerable time after launch before such CGMs can be developed. Dynamic changes to the roll, pitch, or yaw of the satellite due to possible motion of on-board instrumentation or to orbital maneuvers also affect the registration, and these typically create a registration uncertainty that increases with viewing zenith angle.

The multiangle pushbroom scanning approach of MISR depends critically on accurate CGMs for precise coregistration of its multiangle measurements. The nine cameras of MISR are labeled Df, Cf, Bf, Af, An, Aa, Ba, Ca, and Da, where "f" indicates forward viewing in the along-track direction and "a" aftward viewing. The viewing angles of the D, C, B, and A cameras are 70.4°, 60.0°, 45.6°, and 26.1°, respectively, and the nadir (An) camera points straight down. Each of these cameras is registered with respect to the surface ellipsoid (located near sea level) as well as to the actual terrain elevation. This means that a feature located on the surface ellipsoid will have the same (line, sample) location in all nine views. A feature located at the terrain altitude would have coincident locations in the terrain-referenced imagery. This paper deals with the ellipsoid-registered data only. With correctly registered images, the shift (or disparity) of a feature with camera angle is equal to its height above the surface ellipsoid multiplied by the tangent of the viewing zenith angle. For proper coregistration, we demand that all the images are properly registered with respect to each other (using the An camera as the reference), but we do not depend on correct geolocation of the An image itself.

Coregistration is important for retrieving cloud properties such as cloud-top height, cloud motion winds, and cirrus detection [2], [3], [5], [6], more so than is absolute registration. Accurate coregistration of the most oblique measurements, from the D cameras, is especially important for the wind and cirrus retrievals. Fortunately, the high resolution (275 m at nadir) and good signal discrimination (14-bit) of the MISR data have allowed us to develop two new methods of confirming the quality of the coregistration, described in the following.

Our original motivation for developing these methods stemmed from a need to retrieve cloud properties during the early stages of CGM development, in part to explain erroneous wind retrievals. The CGMs have since improved to the point where there is only pixel quantization error in all but the most oblique cameras, and the new methods now serve mainly as quality assurance for regions lacking ground control points. They can also be viewed as a test of the precision of the stereo-matching algorithms which are used heavily in the subsequent retrieval of cloud properties [2].

Both of the new coregistration correction techniques require clear-sky conditions, but do not require the identification of specific ground control points. In the version described below, they assume the correct prior registration of at least two near nadir cameras. This assumption followed the historical need to check the coregistration of the more oblique views and facilitated a convenient way of identifying clear scenes. Knowledge of the surface height is also assumed. However, since the error in the height retrievals (both of terrain and clouds) is on the order of 400 m, the smaller uncertainty of the digital elevation model (DEM) (75 m) used to obtain the surface height is not considered to be an important factor [8].

This paper first describes the two methods and their respective use of stereo-matching and cloud-motion retrieval algorithms. Results from their application to the early CGMs are then described, finishing with the results using the current CGMs.

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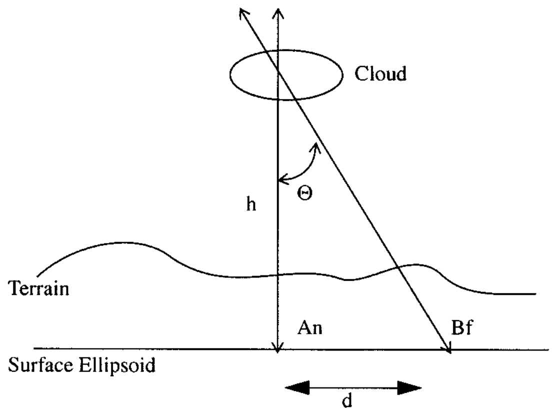


Fig. 1. MISR viewing geometry for the An and Bf cameras.

II. New Methods of Assessing Coregistration

Both of our new methods are based on the stereo-matching algorithms developed for operational processing of cloud properties from MISR. Thorough descriptions of these algorithms can be found in [2] and [4], with operational examples of the retrievals detailed in [5]. One method compares the heights retrieved from the stereo-matchers with those of the surface terrain, and the other uses stereo to retrieve the apparent wind of a 70.4-km domain. Both apply tests to ensure the scenes are clear, and are applied, for efficiency, to similar sparsely sampled triplets of three-camera measurements to yield a single estimate of misregistration for each domain.

A. Find-Ground

The same feature observed from nadir and from a viewing zenith angle of Θ will have an apparent horizontal displacement, or disparity d, between its location in the two images that increases with the height h of the feature above the reference surface according to (see Fig. 1)

$$d = h \tan \Theta. \tag{1}$$

For clear scenes, the expected disparities can be calculated directly, knowing the height of the terrain from a digital elevation model as a function of latitude and longitude. The height resolution of the stereo retrievals can therefore be calculated as the difference in height resulting from a disparity difference in a single pixel. (The stereo-matchers lack any subpixel accuracy due to time constraints [4], [5].) In the default case of matching the Bf and An cameras, where the B cameras have a 45.6° viewing angle, a single 275-m pixel of disparity translates into a height resolution of 275 m. However, the overall error in the height retrieval is estimated to be 400 m due to the added uncertainty in the wind retrievals caused by the same one-pixel error in disparity.

We implement this technique in two steps. First, the intermediate (nominally Bf or Ba) and reference (usually An) cameras are used to filter the data for clear scenes over land, assuming their coregistration is accurate. The feature heights, as calculated from the disparities returned by the stereo-matcher, are compared against the true surface heights. No attempt is made to correct for wind, and oceanic regions are excluded because clear oceans are usually featureless. If the actual and retrieved heights agree within a prescribed threshold, equal to 1.5 times the height resolution, then the feature is accepted as being clear and is retained for the next step.

The second step takes each of the clear pixels that have been found and uses the stereo-matcher to find the corresponding disparity for the intermediate/comparison (B/D) camera pair. Usually, the An, B, and D cameras are used in this algorithm, but it is applicable to any triplet of cameras, as for example when the registration of the C camera is being checked. The B cameras are preferred for the intermediate camera choice because they have a better height resolution than do the Af–An camera pair.

The true disparity for this pair based on the terrain height is subtracted to obtain a local estimate of the misregistration. The individual results of the disparity error are then combined into a single number for this 70.4-km domain by finding the modal value of the distribution and averaging all those results that fall within two pixels of the modal value. This average is then called the misregistration error of the D camera for this domain. If the distribution of the individual misregistrations does not contain enough data points or is not strongly peaked, the retrieval is considered to have failed.

B. Zero-Wind

This algorithm is based on the MISR wind retrieval technique [6] which matches solar reflectivity patterns within a 70.4-km mesoscale domain for three appropriately spaced view angles and then solves the resulting equations for the average motion and height of the clouds found within that domain. It utilizes the fact that for stationary surface features the wind retrieval should return near zero-wind and the average domain elevation should be located near the surface. A retrieved wind larger than the expected uncertainty of the calculations is indicative of camera-to-camera misregistration errors. The uncertainty of the wind retrieval depends on the choice of camera triplets, and the algorithm works best when applied to the An–Bf–Df or An–Ba–Da triplets. However, it can be applied to other camera combinations that are suitable for wind retrieval [6].

The camera-to-camera coregistration correction is then determined by shifting the measured image locations, in both the along-track and across-track directions, until the magnitude of the computed motion vector reaches a minimum. In the most general case, one camera (An) is fixed, and the other two image locations (B and D) are perturbed. However, no misregistration errors were observed with the B cameras, so only the D camera locations had to be shifted, which speeds up the calculation considerably.

Since this method can be noisy in the presence of cloud-contamination, additional filtering can be performed on the triplets used, accepting only those whose B/An disparity passes the clear-sky mask as used in the find-ground method. A final cut is made on the result by mandating that the retrieved minimum wind be less than a threshold and the height associated with this wind vector be within a certain distance of the average surface height for that region. Solving the equations of motion for an individual matched triplet of camera views also yields a height measurement. The wind retrieval process determines the motion vector and height that are the most representative of this domain by a histogramming process [2]. It is these final values of the

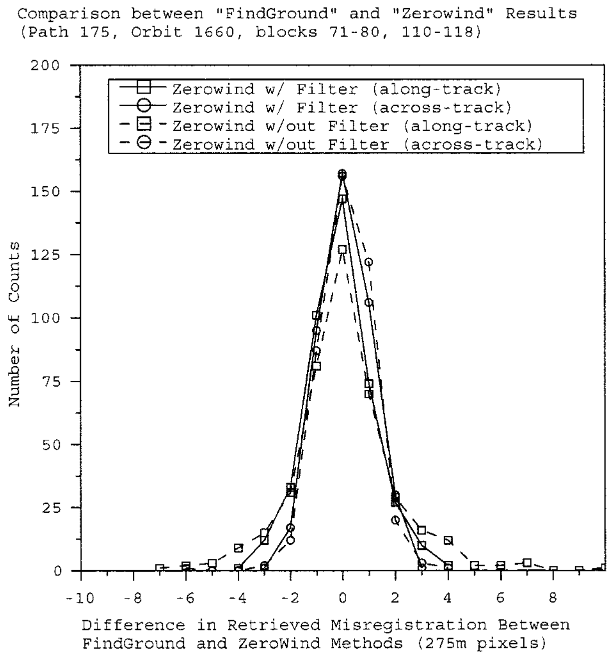


Fig. 2. Comparison of the find-ground and zero-wind methods for path 175, orbit 1660. A histogram distribution of the differences between the two methods are shown, with separate statistics being gathered for the Df and Da cameras in both the along- and across-track directions.

wind and height that are compared to zero-wind and the terrain elevation in the final-step of this zero-wind method.

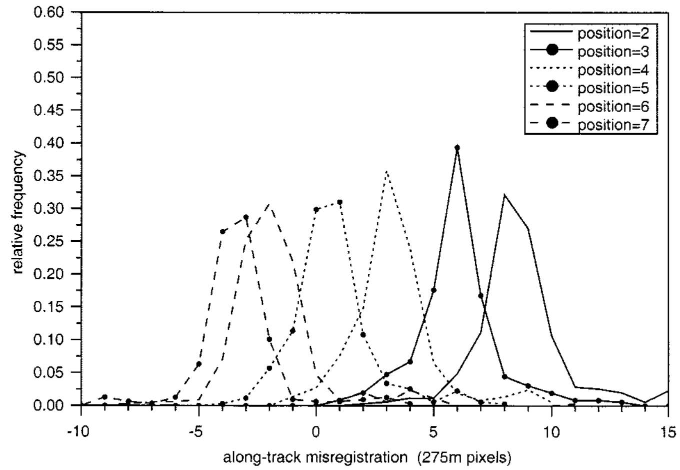
These two algorithms were compared and found to be very similar. The along- and across-track differences between (a) find-ground and zero-wind with the prefilter and (b) find-ground and zero-wind without the prefilter were calculated and plotted (see Fig. 2). There is no bias evident between the find-ground and zero-wind methods, and the difference distribution is peaked at zero for all cases with the bulk of the discrepancies less than two pixels. The addition of the prefiltering in the zero-wind method makes no apparent difference in the cross-track direction, but the along-track results of the two algorithms are in closer agreement when the prefiltering is applied.

III. Results

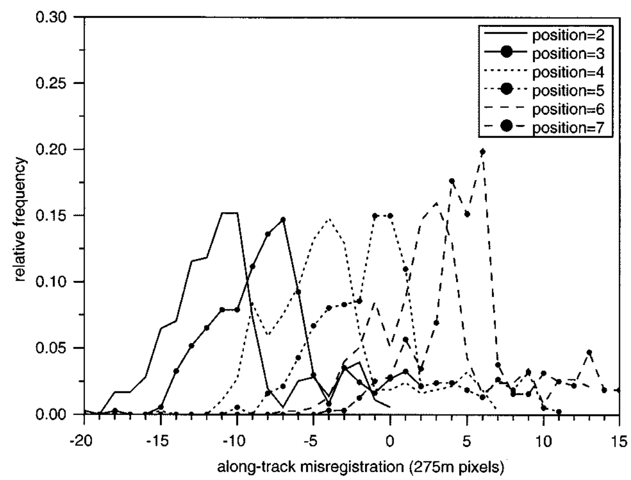
The Level 1B2 Ellipsoid-projected data from MISR are registered to the surface ellipsoid such that a pixel whose altitude coincides with the ellipsoid has exactly the same coordinates in all nine cameras. However, for data processed with version 4 of the CGM (prior to August 2000), the more oblique cameras were significantly misregistered by up to 15 pixels. Data processed from version 5 onward are vastly improved. The difference in coregistration accuracy between CGM4 and CGM5 allows us to very clearly demonstrate application of our new coregistration methods.

A. Coregistration Accuracy Using CGM4

The data that were processed with version 4 of the CGM showed a clear rotation of the swath in the Ca, Df, and Da cameras, and also exhibited some latitudinal dependences. This is illustrated in Fig. 3, which shows relative frequency distributions from several orbits of the along-track misregistration retrievals for the Df and Da cameras, for each domain position across the



(a)



(b)

Fig. 3. Retrieved misregistration of (a) the Df camera and (b) the Da camera, for version 4 of the CGM. "Position" refers to domain number from the left edge of the swath.

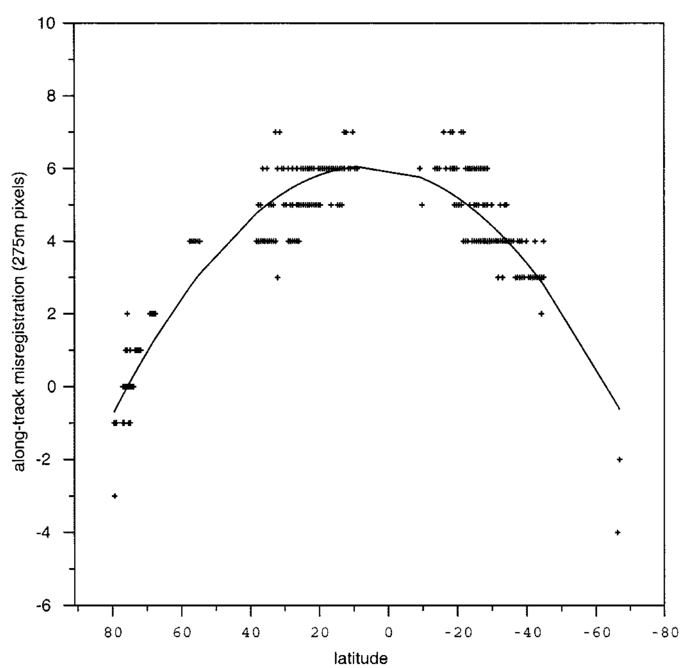


Fig. 4. Retrieved misregistration for the Da camera for version 4 of the CGM versus latitude. Results shown are for a single domain (across-track position = 7) gathered across multiple orbits. The solid line is a second-order polynomial fit to the data.

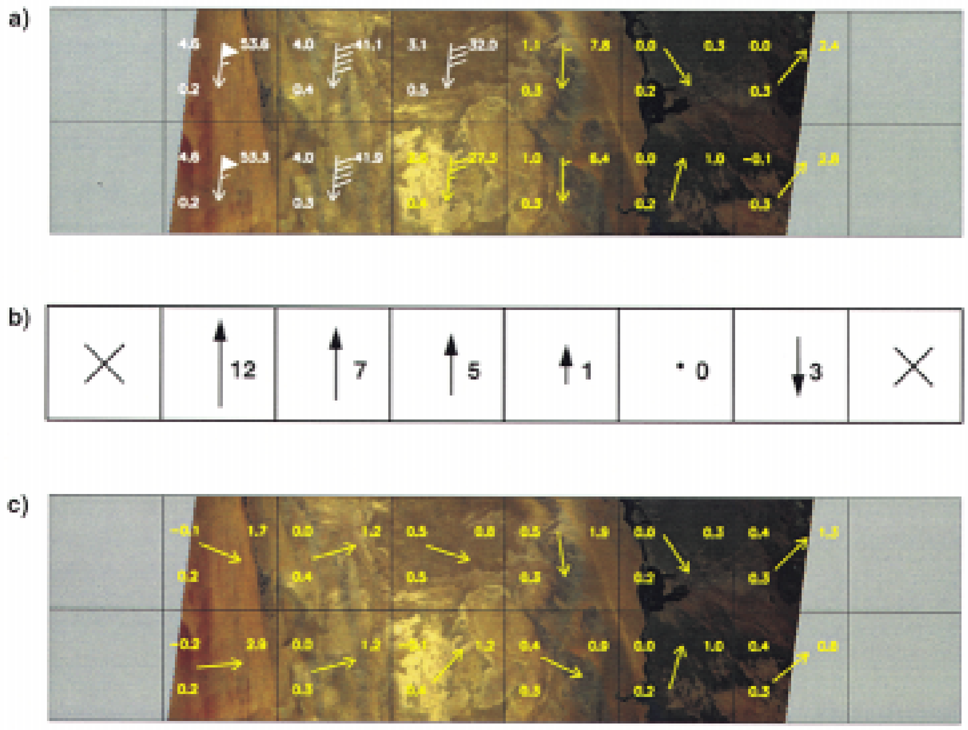


Fig. 5. Registration correction with the "zero-wind" method for path 175, orbit 1660, block 71. The area shown is just to the northeast of Nasser Lake, Egypt, with north pointing to the top of the image. (a) Wind retrievals without correction. (b) Df camera along-track correction (in 275-m pixels) as a function of cross-track position. (c) Wind retrievals with the correction given in (b).

swath using both methods. Note that the edges of the swath, corresponding to domain positions 1 and 8, have insufficient data for this retrieval and are not shown. The amount of misregistration is clearly stratified by domain number and increases as one moves out to the swath edges. Examination of a number of other orbits gave very similar results and yields a constant modal misregistration amount for each domain and camera. No significant cross-track misregistration was observed.

The misregistration of CGM4 was also found to vary as a function of latitude. Fig. 4 shows a composite plot of the Da misregistration for a given domain (cross-track position = 7), gathered from multiple orbits. Toward the poles, the cameras are shifted uptrack for the Ca, Df, and Da cameras, as well as for all domains.

Wind retrievals with CGM4 are shown in Fig. 5(a), which is a clear-sky scene over Egypt. Both the magnitude and direction of the retrieved winds change considerably across the swath. The strong northerly winds at the western edge of the swath gradually turn into light southerly winds at the eastern edge. Note the strong correlation between the retrieved heights and the along-track winds. These obviously erroneous results are due to a counterclockwise rotation in the Df image around a point located somewhere in domain 6. This can be corrected for by applying the counterclockwise rotation as a function of position shown in Fig. 5(b), which leads to the considerably improved retrievals shown in Fig. 5(c). The top right number in each domain lists the wind speed in meters per second, the retrieved height in kilometers is shown in the top-left, and the true (averaged) height is displayed in the bottom-left. The wind vectors are color-coded according to their height (white $\geq$ 3 km, yellow $<$ 3 km). For each domain, the winds are now less than 3 m/s, which falls within the expected uncertainty for the An–Bf–Df camera combination. The corrected heights are also within 500 m of the true surface elevation. No cross-track correction of the misregistration was necessary.

B. Coregistration Accuracy Using Current CGMs

The situation improved dramatically once versions 5 (and later 6) of the camera model went into production. Histograms of the observed along-track misregistrations for all domains gathered across several orbits are shown in Fig. 6(a) and (b). Note that the peak of all the histograms are at zero, which is very different from the CGM4 results. The histograms are also very similar across the domains, showing that the observed rotation of the swath in version 4 has been solved. Additionally, there is no observed latitudinal dependence. The cross-track misregistration is of the same good quality. The Da misregistration histograms show a longer tail than do the Df histograms, so there is still some difference between the cameras. There was no significant difference between the version 5 and version 6 results, although with version 6 the percentage of pixels in the Df camera that were coregistered to within one pixel increased from 80 to 90%. A similar but smaller improvement (90 to 92% for the cross-track direction and 77 to 80% for the along-track direction) was observed for the Da camera.

IV. Summary and Discussion

The preceding results serve a number of purposes. We have demonstrated the utility of two closely related approaches to

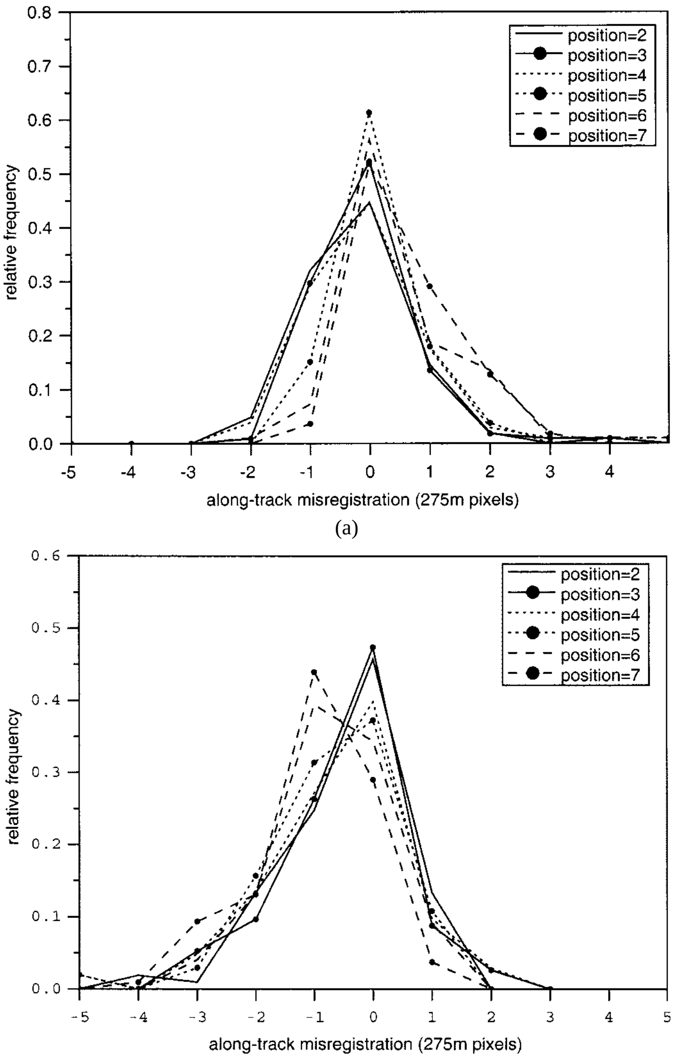


Fig. 6. Retrieved misregistration for (a) Df and (b) Da cameras for version 6 of the CGM. Combined misregistration distributions for several orbits are shown for six equally spaced domains across the swath.

checking the coregistration of multiangle measurements by MISR. We have confirmed the significant improvement in the current camera geometric models compared to the earlier models. In so doing, we have also indirectly confirmed that the stereo algorithms used for height and wind retrieval work satisfactorily when applied to images of clear land.

The two coregistration approaches described here, called "find-ground" and "zero-wind," give very consistent results. The zero-wind method is slightly more accurate, but requires considerably more computation time. Neither method requires *a priori* ground control points to be identified, simply the availability of a digital elevation map and sufficient clear-sky data. We depend on the correct registration of the An camera to retrieve the proper terrain heights, although this is not critical unless the terrain heights vary significantly over distances of the scale of a few pixels.

The misregistration results retrieved using the find-ground and zero-wind techniques are consistent across a number of different paths/orbits, and with each other. The data obtained from these algorithms illustrated the swath-rotation problem and the latitudinal dependence of the registration error of the earlier versions of the data. They now confirm the accuracy of the current coregistration to within one pixel. It is clear from these results that the MISR stereo-matching algorithms perform well enough over clear land that they can be used in the calculation of other parameters.

It should be made clear that the CGM4 results are presented here for historical purposes only—the MISR camera-to-camera geolocation is now good to within one pixel most of the time with no cross-track or latitudinal dependences. More specifically, in the subset of orbits studied, about 50% of the retrieved registration corrections were exactly zero pixels with up to 90% of the data having a misregistration of one pixel or less. The reference orbit imagery is expected to come on-line in the fall of 2002 and will further improve the registration quality by providing a database of georectified MISR clear-sky imagery and ground-control points [7].

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