LANL Experience with Coregistration of MTI Imagery

P. Pope, J. Theiler, and A. Galbraith*
Space and Remote Sensing Sciences Group
Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT

The fifteen-channel Multispectral Thermal Imager (MTI) provides accurately calibrated satellite imagery for a variety of scientific and programmatic purposes. To be useful, the calibrated pixels from the individual detectors on the focal plane of this pushbroom sensor must be resampled to a regular grid corresponding to the observed scene on the ground. In the `LEVEL1B_R_COREG` product, it is required that the pixels from different spectral bands and from different sensor chip assemblies all be coregistered to the same grid. For the `LEVEL1B_R_GEO` product, it is further required that this grid be georeferenced to the Universal Transverse Mercator coordinate system. It is important that an accurate registration is achieved, because most of the higher level products (e.g. ground reflectance) are derived from these `LEVEL1B_R` products. Initially, a single direct georeferencing approach was pursued for performing the coregistration task. Although this continues to be the primary algorithm for our automated pipeline registration, we found it advantageous to pursue alternative approaches as well. This paper surveys these approaches, and offers lessons learned during the three years we have been addressing the coregistration requirements for MTI imagery at the Los Alamos National Laboratory (LANL).
Keywords: MTI, image processing, registration, direct georeferencing, operational experience, lessons learned

1. BACKGROUND

The fifteen-channel Multispectral Thermal Imager (MTI) provides accurately calibrated satellite imagery for a variety of scientific and programmatic purposes. Imagery is collected in a pushbroom fashion by sixteen linear CCD arrays (one for each band, with bands H1 and H2 being redundant) arranged on three sensor chip assemblies (SCAs) (Fig. 1). Individual arrays are turned on in a timing sequence that is designed to maximize the overlap of the ground coverage for all of the bands. Although viewing geometries encountered under operational conditions vary substantially from one image to another (especially for the off-nadir images), the same timing sequence is used for each image acquisition. This leads to varying band-to-band alignments within an SCA, and between the different SCAs, of the imagery contained in the `LEVEL1B_U` product. Therefore, the coregistration task is to collate the output of these different bands and SCAs into a single, spatially consistent, multispectral image cube.

To be useful for spectral analysis and physical retrievals, such as water surface temperature and land cover classification, the calibrated pixels from the individual detectors on the focal plane of this pushbroom sensor must be resampled to a regular grid corresponding to the observed scene on the ground[1,2]. In the `LEVEL1B_R_COREG` product, it is required that the pixels from different spectral bands and from different SCAs all be registered to the same grid. For the `LEVEL1B_R_GEO` product, it is further required that this grid be georeferenced to the Universal Transverse Mercator (UTM) coordinate system. Therefore, the registration of MTI imagery requires approaches to address the band-to-band and SCA-to-SCA misregistrations which are evident in the spectrally calibrated imagery contained in the `LEVEL1B_U` product. Addressing these effects permits a single image stack of all sixteen bands from all three SCAs to be created. This is the final image product output by the registration methods we have developed at the Los Alamos National Laboratory (LANL).

*papope@lanl.gov, jt@lanl.gov, amyg@lanl.gov

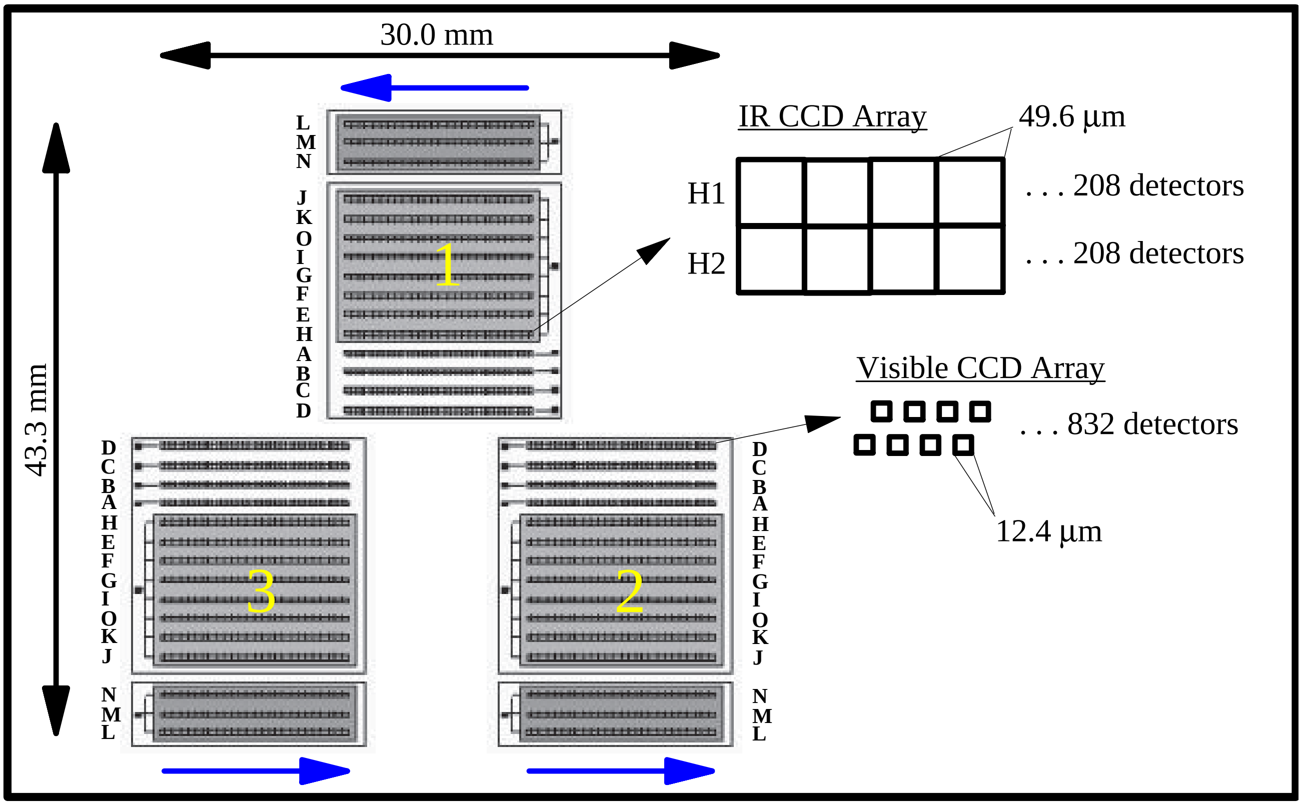


Figure 1. Illustration of the MTI focal plane layout. The SCA numbers are in yellow, and the blue arrows indicate the readout directions.

Initially, a single direct georeferencing approach was pursued for performing the coregistration task. Although this was the primary algorithm for LANL's automated pipeline registration, we found it advantageous to pursue alternative approaches as well. A survey of the various registration methods which were developed at LANL in support of the MTI project is provided next. Then various "hindsights", or "lessons learned", from our research, development, and operational experience with the registration of MTI imagery are discussed.

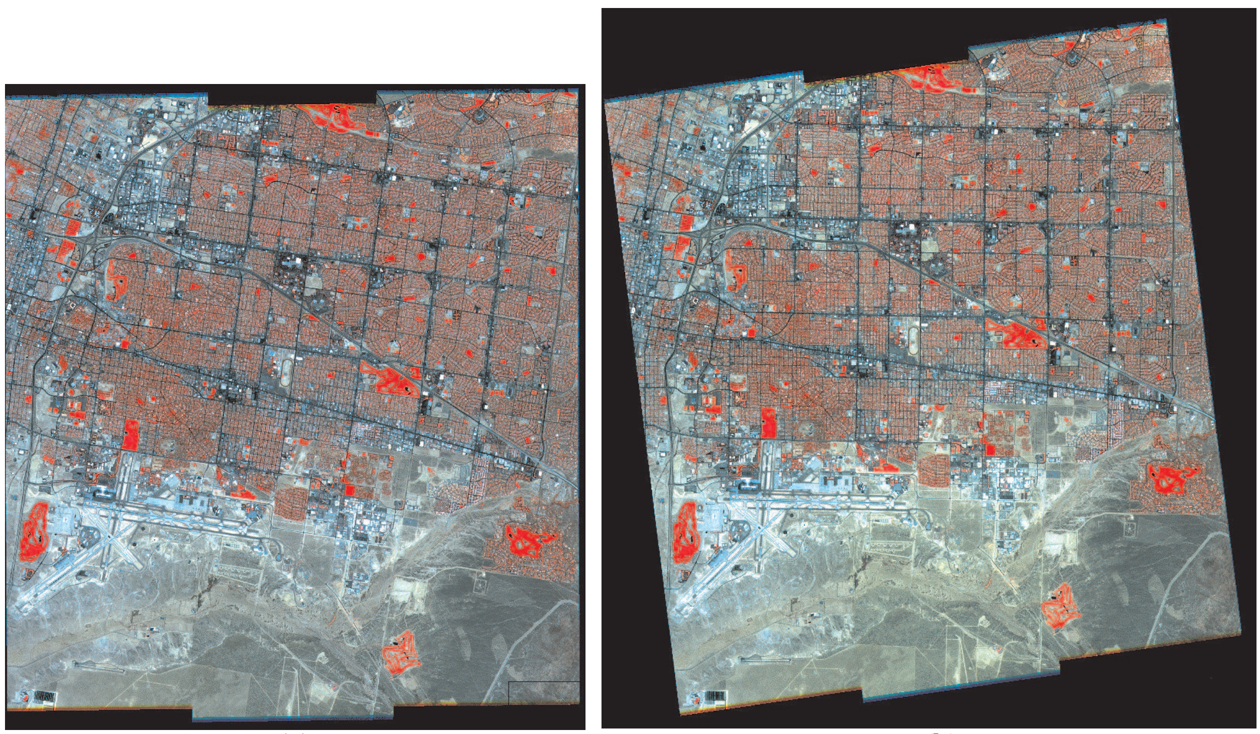
2. REGISTRATION METHOD REVIEW

The four registration methods developed at LANL in support of the MTI project are known as direct georeferencing, simple image registration (SIR), automated image registration (AIR), and photogrammetric image registration (PIR). A brief discussion of each of these methods is provided in the subsections which follow. Only the relevant details of how each method addressed the general problem of MTI image registration are provided here. These details are required to provide a background for the discussion concerning our operational experience. More information about these methods can be found in previously published papers which are referenced in the sections below.

2.1 Direct Georeferencing Approach

The main image registration method we developed was a direct georeferencing approach[3]. The direct georeferencing approach models the image acquisition event as a means to create coregistered imagery. This approach requires detailed and accurate information about the sensor optics, location of the detectors on the focal plane, and the position and orientation of the satellite platform relative to the Earth's position and orientation. The position and orientation of the satellite platform (exterior orientation) are measured by a Global Positioning System (GPS) receiver and an Inertial Measurement Unit (IMU) on-board the satellite. This information is telemetered from the satellite to the ground station. The major advantage of this approach is its autonomous nature and its ability to remove the bulk of the spatial distortions which result in misregistrations within the raw data.

The direct georeferencing approach is used to create both the standard "coreg" product (LEVEL1B_R_COREG) and the "geo" product (LEVEL1B_R_GEO) (Fig. 2). Coreg products can be created by using an "orbit-aligned" or a "geo-aligned" output grid. Geo products are created on an "as needed" basis since they require the manual definition of ground control points. Ground control points are visually established by setting conjugate points, which are features that can be identified within both the LEVEL1B_U imagery and a digital map.



(a) (b)

Figure 2. A coreg product (a) and a geo product (b) created from LEVEL1B_U imagery of Albuquerque, NM. MTI bands D,C, and B are displayed as red, green, and blue, respectively. The alignment of the geo product with the cardinal directions is evident from the grid-like network of city streets. The geo product is larger than the coreg product because of the increased padding required for the geo-aligned image.

As the direct georeferencing approach evolved, several modifications were made. Two capabilities to "tweak" the registered images produced by the direct georeferencing method were added. The first was an ability to make slight modifications to the measured velocity of the satellite (a delta velocity, or "delvel" capability) through manual inspection of the band-to-band or SCA-to-SCA misregistration. The second was an ability to modify the band-to-band registration through the use of image-to-image cross correlation. Also, two new spectral resampling methods were implemented to complement the standard weighted-area resampling method. These spectral resampling methods are discussed briefly in the next subsection.

2.1.1 Spectral Resampling Methods

The standard MTI coregistration product originally used a weighted-area approach to achieve the spectral resampling required to place the calibrated data values of the LEVEL1B_U product onto the regular spacing of cells in the output grid. This method was aided by use of the pixel quality information ("quality images") contained in the standard coreg product. The weighted-area spectral resampling approach tended to over-smooth the imagery and reduce the detection of small, high contrast features. This was especially apparent in the geo product whose output grid was not aligned with the rows and columns of the LEVEL1B_U imagery. Therefore, other spectral resampling methods (a tunable distance-weighted resampling method and a nearest-neighbor resampling method) were implemented to improve the final coregistered image[4].

2.2 Simple Interactive Registration (SIR)

The Simple Interactive Registration (SIR) method achieves band-to-band and SCA-to-SCA registration of MTI imagery through whole or fractional pixel translations of the imagery relative to a particular band and SCA. The method is similar to a semi-autonomous method developed by Sandia National Laboratory[5]. However, the SIR method is a completely manual process.

The SIR method utilizes a Graphical User Interface (GUI) to display two images at a time, overlaid on one another. This overlay is achieved by assigning one image to red, and the other image to green. Therefore, bright features in the first image appear as bright red, and bright features in the second image appear as bright green on the display. The operator then applies whole and fractional pixel shifts to the second image, using the first image as a reference, until matching features overlap as much as possible (e.g. the same bright object on both images would then appear as a single, bright yellow feature). This procedure is used to manually determine the band-to-band and SCA-to-SCA shifts required to create a single visible or IR-sized stack of imagery.

2.3 Automated Image Registration (AIR)

The Automated Image Registration (AIR) method was developed as an autonomous means of implementing the previously described translation-only approach to image registration[6]. That is, the AIR method is an automated means of deriving the translations required to perform band-to-band and SCA-to-SCA registration. The bulk of the systematic misregistration effects is addressed by the AIR method through the use of linear shift prediction equations which mimic the sequential timing information used to acquire the imagery. Image-to-image matching (maximum cross correlation method) is then used to ascertain and eliminate the residual misregistrations between the various bands of multispectral imagery. A weighted least squares approach to optimizing this information was also developed as part of this effort.

2.4 Photogrammetric Image Registration (PIR)

The photogrammetric image registration (PIR) approach uses a photogrammetric bundle adjustment to derive the exterior orientation of the sensor model as a function of time[7]. The PIR method is very similar to the direct georeferencing method. The major differences are the source of information about the exterior orientation of the sensor model as a function of time, as well as the projection surface used. The PIR method requires the manual definition of ground control points identified within the `LEVEL1B_U` imagery. These ground control points are then used as input to a photogrammetric bundle adjustment to derive the trajectory of the sensor, while the direct georeferencing method uses direct measurements of the sensor's position and attitude. The PIR method projects each pixel onto a model of the terrain surface, whereas the direct georeferencing method uses a flat plane as the projection surface. A major operational difference is that the PIR method requires manual input, while the direct georeferencing method is an autonomous technique.

2.5 Registration Method Comparisons

Several broad similarities connect various pairs of our four registration methods. First, the direct georeferencing and PIR methods are parametric in nature, while the SIR and AIR methods are non-parametric. The term parametric refers to a physics-based (reductionist) approach, whereby the viewing geometry of the image acquisition event is modeled and the model is governed by parameters which represent actual physical quantities, such as position, angle, and time. The term non-parametric refers to an image-based (empirical) approach. A second similarity is that the direct georeferencing and AIR methods are autonomous, while the SIR and PIR methods require user intervention and manual input. A third similarity is that both the direct georeferencing and AIR methods are "hybrid" methods since they combine both parametric and non-parametric approaches. In a hybrid approach, a parametric method is used first to address the bulk of the misregistration effects. Then a non-parametric method is used to apply "tweaks" which correct the remaining (residual) misregistrations. A fourth similarity is that the direct georeferencing and PIR approaches can register both nadir and off-nadir imagery, whereas the SIR and AIR methods are primarily applicable only to the registration of nadir acquisitions.

3. LESSONS LEARNED

Various "hindsights", or "lessons learned", from our research, development, and operational experience with the registration of MTI imagery are discussed next. They are presented in order starting with "major" recommendations and finishing with more "minor" points and suggestions.

Spatial registration, whether relative (i.e. band-to-band and SCA-to-SCA) or absolute (i.e. georeferencing), is of critical importance to the successful development of higher level products (e.g. reflectance imagery). Therefore, it is important that adequate resources and effort are anticipated and devoted to understanding the sensitivity of the registration accuracy that can be expected given the accuracy of the inputs required by any registration algorithm proposed. Physics-based modeling of the image acquisition event is a means of achieving this understanding.

The various sources of image misregistration can be ordered according to the size of the spatial error they induce. The ordering which follows is based on our experience and will most likely be different for other efforts. For example, we had the benefit of accurate geometric calibration of the MTI sensor optics prior to launch[8,9]. This ordering also represents a suggestion for prioritizing the research, design, and implementation of models which mimic these effects, so that they can be predicted and compensated for. For a pushbroom sensor such as MTI, the largest source of misregistration is due to inaccuracies in the information about the exterior orientation of the platform during image acquisition. Next are errors due to inaccuracy in modeling the sensor optics and focal plane, and the Earth's surface (terrain). Finally, the smallest errors are due to inaccuracies in modeling the Earth's shape (ellipticity), platform jitter, atmospheric refraction, and relativistic effects.

We found that devoting effort to address each of these levels of error through a parametric (physics-based) registration approach eventually led to a point of diminishing returns. That is, to identify and account for smaller and smaller systematic errors required increasing levels of effort. Eventually, it became more cost-effective to pursue the development of non-parametric methods. Non-parametric methods are useful because they can address residual errors on an image-by-image basis, and are not constrained by an *a priori* need for accurate and detailed knowledge about the physical phenomena which induce these errors. Therefore, we found it advantageous to invest time and effort into two registration approaches; one which is parametric to address the bulk of the systematic misregistration effects, and one which is non-parametric to address the misregistration residuals remaining after application of the parametric technique. Although this was anticipated at the beginning of this project[10], the utility of developing both parametric and non-parametric registration methods, as well as the combination of these methods into a more holistic or "hybrid" approach, was only fully appreciated in hindsight.

To successfully implement an automated, parametric approach within a production environment, accurate and well-defined information about the dynamic viewing geometry must be available. This consists of the following basic components which are common to any parametric image registration approach. First, the forward and inverse transformations between the coordinate systems associated with the focal plane, optics, platform, Earth Centered Inertial (ECI) coordinates, and Earth-Centered Earth-Fixed (ECEF) coordinates must be rigorously and explicitly defined. Second, the timing information, such as start and stop times, integration length, and scan rate, must be accurately communicated. Finally, accurate geometric calibration of the detector elements on the focal plane must be obtained, through pre-flight laboratory measurements, or possibly through in-flight geometric calibration.

Conversely, the parametric approach to image registration is limited by the accuracy of the aforementioned information. For example, the fact that the MTI satellite had more accurate position information on-board than was telemetered to the ground meant that the MTI satellite could image a target with more accuracy than the acquired imagery could be georeferenced via the direct georeferencing approach. Having more accurate position information may have enabled the creation of geo products to be fully automated.

We conducted the research, development, and implementation of our parametric and non-parametric registration efforts in a parallel manner. This facilitated cross-checking between the results produced by the various methods, provided redundancy in capability, and led to a hybrid approach which could fully address the basic requirement of achieving the most accurate registration possible in support of the spectral analyses which motivated the creation of the MTI project.

Redundancy in capability was especially important from our experience. When the direct georeferencing method was undergoing major revisions, the SIR method enabled the Data Processing and Analysis Center (DPAC) to continue producing registered image products until the improved direct georeferencing method was ready to be implemented into the pipeline. Redundancy in capability was also important when the position and attitude information were unavailable (Fig. 3).

Figure 3. An AIR product (bands N,O,E (RGB)) created from an MTI acquisition of Barrax, Spain for which exterior orientation information was unavailable. Note the accurate band-to-band registration, as evidenced by the high contrast between the edges of the agricultural fields, and the accurate SCA-to-SCA registration, as evidenced by the continuity of field edges between SCAs and the continuity of the diagonal road cutting through the center of the image. The lack of a substantial number of scan lines for SCA 1 (center) led to a large amount of padding (black). The blurring between SCAs 1 and 2 (center right) is due to detector damage incurred from accidental exposure of the focal plane to direct sunlight.

Implementing a capability to create both orbit-aligned and geo-aligned variants of the coreg product was a fruitful endeavor. The orbit-aligned product was a logical choice since the output grid was nominally aligned with the rows and columns of the `LEVEL1B_U` imagery. The orbit-aligned grid also exhibited greater contrast for point-like features. The geo product was useful because it facilitated the comparison and integration of MTI imagery with other geospatial data sets within a Geographic Information System (GIS).

The decision to resample by going back to the original raw data when creating the geo product was a good one, since it avoided a large loss in contrast by resampling the resampled data contained in the coreg product. However, some loss in contrast was still incurred. This was due to the fact that the geo-aligned grid was rotated relative to the orbit-aligned grid of the coreg product. Therefore, development of "tuneable" spectral resampling methods was also worthwhile, since it added a capability to create higher contrast imagery for small target detection while still retaining cartographic fidelity to permit the overlay of ancillary geospatial information. As previously mentioned, including the quality images in the standard coreg product aided the spectral resampling required to place the pixels of the `LEVEL1B_U` product onto the output grids of the coreg and geo products.

Initial programming efforts to develop the direct georeferencing method included a decision to hold all of the imagery in memory. Eventually we found that registering the `LEVEL1B_U` imagery on a band-by-band basis yielded a major breakthrough in computer memory conservation. This enabled the creation of coreg products from longer images (e.g. 4X nominal length) to be handled routinely, as well as the creation of geo products from extreme off-nadir acquisitions.

In closing, we propose that if the MTI focal plane were to be reused in any future design, some slight modifications might be advantageous. Duplication of band L near the inner portion of the focal plane would provide redundant imagery which could ease automated image-to-image matching of the multispectral imagery through use of a cross correlation algorithm. This may improve the accuracy of the registration shift information which could be deduced from such a non-parametric approach. In addition, or in lieu of the previous suggestion, including a high spatial resolution panchromatic band may aid in the use of image-to-image matching to improve band-to-band registration between multispectral images. Increasing the SCA-to-SCA overlap would aid in SCA-to-SCA registration, but with a reduction in cross-track coverage if the CCD arrays were kept at their present length.

4. CONCLUSIONS

We have successfully developed, implemented, tested, and utilized several image registration methods in a research and operational basis in support of the MTI project. This experience has not only resulted in technical contributions to the field of image registration research, as evidenced by our various contributions to the literature on this subject, but has also afforded us the ability to share our operational experience in conducting this endeavor. These operational experiences, or "lessons learned", have been communicated to the user community via this paper with the goal of increasing the breadth and depth of understanding among individuals and agencies contemplating similar work in the future.

Major suggestions, based on our experience, are as follows:

(1) Develop a parametric approach to address the bulk of the systematic misregistration effects. A parametric approach can be automated by using the exterior orientation information about the sensor, as measured by instruments on-board the platform during image acquisition. Alternatively, a parametric method can use photogrammetric methods to derive the trajectory of the sensor, but this may require manual input.

(2) Enable autonomous and/or manual "tweaking" of the parametrically corrected imagery through use of a non-parametric, image-based approach. This will enable the correction of residual misregistrations remaining after removal of the bulk distortions due to systematic effects.

(3) Develop an auxiliary, stand-alone method which is image-based to handle the case when the information required by the parametric method is corrupted or otherwise unavailable.

ACKNOWLEDGEMENTS

We wish to acknowledge the generous support of the entire MTI team, including our colleagues at the Sandia National Laboratory in Albuquerque, NM and the Savannah River Technical Center in Aiken, SC. We make special note of the efforts of Chris Borel for original development of the SIR method, and to Jim Krone, Kathy Smith, Keri Ramsey, and Kim Pollock, who integrated the SIR method within the operational environment of the DPAC. Thanks also to Jaquin Santiago "Santi" Ortega for providing assessments of the absolute and relative accuracies of the coreg and geo products, which aided our understanding of their quality and helped guide efforts to improve the direct georeferencing method. Finally, our sincere thanks and admiration goes to the entire DPAC team for their dedication and hard work. This research was supported by the U.S. Department of Energy.

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