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Title:

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ABSTRACT

The mission of the Multispectral Thermal Imager (MTI) satellite is to demonstrate the efficacy of highly accurate multispectral imaging for passive characterization of urban and industrial areas, as well as sites of environmental interest. The satellite makes top-of-atmosphere radiance measurements that are subsequently processed into estimates of surface properties such as vegetation health, temperatures, material composition and others. The MTI satellite also provides simultaneous data for atmospheric characterization at high spatial resolution. To utilize these data the MTI science program has several coordinated components, including modeling, comprehensive ground-truth measurements, image acquisition planning, data processing and data interpretation and analysis. Algorithms have been developed to retrieve a multitude of physical quantities and these algorithms are integrated in a processing pipeline architecture that emphasizes automation, flexibility and programmability. In addition, the MTI science team has produced detailed site, system and atmospheric models to aid in system design and data analysis. This paper provides an overview of the MTI research objectives, data products and ground data processing.

Key words: Multispectral analysis, remote sensing algorithms, thermal infrared, data processing centers

1. INTRODUCTION AND GOALS

The Multispectral Thermal Imager (MTI) satellite project has a purely research and development mission – to explore advanced multispectral and thermal imaging from space. As described elsewhere in this volume[1] the MTI provides unique attributes in the existing remote sensing satellite constellation. These unique attributes center on the superb absolute and relative calibrations, the number of spectral bands combined with good spatial resolution and the atmospheric characterization bands (again at good resolution). As an R&D experiment the MTI was built with limited redundancy and imaging capacity and is executed by a relatively small team. Yet, the band structure is rich, the system continues to operate despite hardware failures, and the small but dedicated team continues to produce results and distribute data products. The main sponsor of the MTI, the US Department of Energy, is to be commended for this managed-risk approach. Another attribute of the project is close-coupling between the science, calibration and data processing teams, resulting in design choices and algorithm development that take into account disparate considerations.

The purpose of this paper is to provide details of the MTI science goals and data processing operations as well as an overview of the results to date. More details of techniques and science results will follow in the remaining MTI papers in this volume. The MTI ground truth measurements are discussed in Garrett et al.[2] The data processing operations are covered exclusively in this paper.

2. MTI SCIENCE GOALS

A hallmark of the MTI program is that it includes all the elements necessary to evaluate the technology and to obtain remote sensing and results for science applications. This is not to say the program is completely self-sufficient, as it relies on

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ground-truth data and other inputs from related remote sensing efforts. Nevertheless, the program is balanced among all the major elements of an experimental program, including (1) in-depth site, system and atmospheric modeling, (2) a broad set of science retrieval algorithms, (3) detailed calibration and registration, (4) the data processing center infrastructure and (5) ground-truth measurements.

2.1 Thermal imaging

Why operate a multispectral imager with thermal capability? There are numerous multispectral imaging satellites with various motivations. Of course, the MTI reflective bands have many uses as well, but we shall concentrate here on good resolution thermal imaging. Applications of MTI data are discussed later.

One of the fundamental reasons for operating a thermal imaging satellite is the large interest in sea-surface temperatures (SSTs). For example, the NASA Earth Observing System (EOS) Terra spacecraft has several instruments that measure temperatures, including the MODerate resolution Imaging Spectroradiometer (MODIS) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Global climate monitoring, forest-fire characterization and similar applications typically motivate the temperature measurements taken with these instruments. These instruments have spatial resolutions many times larger than the MTI with corresponding larger area coverage. The MTI contributes not in large-area monitoring but rather in precise and accurate measurements of local phenomena, leading to better understanding of regional and/or continental effects.

An example of the study of local phenomenology leading to a better understanding of regional effects is the thermal bar that forms in large inland bodies of water during the spring thaw.[3] The thermal bar forms in the springtime as the lakes warm by in-flow from the shore. The bar itself is formed as cold water (< 4 °C) in the center of the lake mixes with warm near-shore water. The cold water is in its winter stratification state, with colder, less dense water on top. The warm (> 4 °C) near-shore water is in summer stratification, with warmer, less dense water on top. At the point where the water is 4 °C and of maximum density, a down-flowing current exists, which effectively eliminates mixing between the portions of the lake in opposite stratification. Lack of mixing results in concentration of shore-produced pollutants and potentially drastic effects on local biosystems. In the critical early stages of thermal bar formation, the high-resolution thermal bands of MTI would provide a detailed map of the bar while it is located close-in to shore, and has the largest potential influence. Specific work in this area with the MTI will begin during the spring 2001 thaw on Lakes Ontario and Baikal.

Many biosystems are very sensitive to temperature changes. For example, numerous coral bleaching events have been observed that were associated with rises in SST. Changes of as little as 1 °C over average maximum seasonal SST are associated with severe bleaching (and high coral mortality).[4] Such problems are typically worse in the tropics, because organisms are often already living near their upper temperature range. Once again, MTI data can be used in this situation to study local thermal effects that lead directly to ecosystem changes and/or the connection of the local effects to more widespread issues. Another example are boreal forests, where temperature increases release carbon dioxide into the atmosphere.

Another area where thermal imaging is of great utility is in fire monitoring. The MTI has a mission-averaged site revisit time of approximately once per week, meaning the system can't be used for quick response. Nevertheless, a long-burning fire can be imaged and the MTI spatial resolution can be used to look at small-scale dynamics to make comparisons with fire models. In the case of the Cerro Grande fire that occurred in and around Los Alamos National Laboratory (LANL) and the Los Alamos townsite, MTI data are being used for terrain categorization and subsequent fire rehabilitation as well as fuel-loading studies.

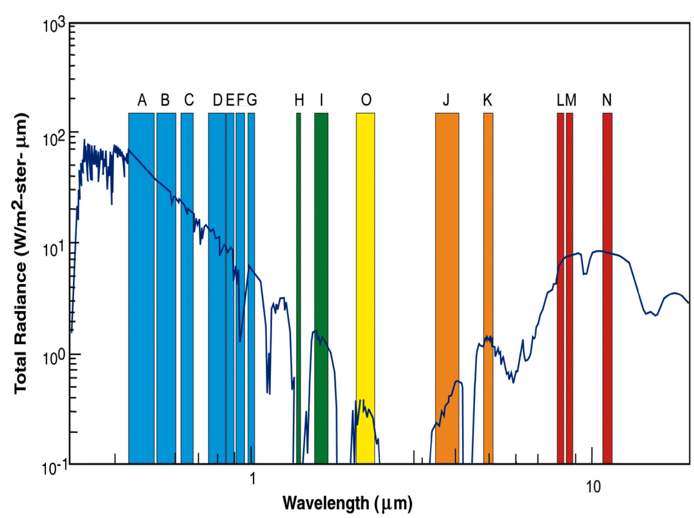

Figure 1. The MTI spectral bands are shown above. Superimposed on the bands are a solar spectrum and a thermal emission spectrum, both modulated by atmospheric absorption features.

There are a number of uses for multispectral imaging in general and thermal imaging in particular. The following section (section 2.2) outlines the specific geophysical quantities being retrieved with algorithms produced by the LANL MTI science team and section 2.3 gives application examples for MTI data.

2.2 Retrieval Algorithms

The MTI science team at LANL has been developing algorithms to retrieve a number of geophysical quantities of interest. Details are reported elsewhere in this volume as well as in previous publications.[5] These retrievals form the basis of the MTI science applications done by this team. Other MTI users are pursuing other applications but their work is not covered in detail here. Some of these capabilities are degraded due to the hardware failures, most notably the SST retrievals.

We discuss features and limitations of the MTI imaging system to better understand the retrievals. The MTI spectral bands are shown in Fig. 1. Images are typically taken in pairs, with the first a near-nadir image and a second look taken at approximately 60° zenith angle. The second look is not always acquired and longer swaths may be taken with a single look. The MTI orbit is sun-synchronous with equatorial crossing times of 1 a.m. and 1 p.m. and an altitude of approximately 575 km. The field of regard is ± 200 km, which gives a site revisit time of approximately 1 week, averaged throughout the mission. The focal plane is highly programmable, including integration times, which bands are active, selecting among redundant detector elements and readout rates. The focal plane is divided into three sensor-chip assemblies (SCAs), which means that raw images are in three segments and need to be co-registered.

1) Sea-surface temperatures. In practice MTI imagery is used to retrieve surface temperatures for quite small water bodies, not just true sea-surface temperatures, but the nomenclature "SST" will still be used. The team has two methods for retrieving SSTs: [6,7]
   a) A "robust" method that uses a linear combination of many different atmospheric states.
   b) A "physics-based" method that searches a space of effective atmospheric parameters and locates the best set by finding the best surface temperature agreement between the bands.

2) Water vapor. Two algorithms are used to retrieve column water vapor column density: [8,9]
   a) The Continuum-Interpolated Band Ratio (CIBR). CIBR determines the water vapor abundance in each pixel by taking a ratio of the radiance inside and outside of a water vapor absorption feature and comparing the ratio to an atmospheric model (Modtran4).
   b) The Atmospherically-Precorrected Differential Absorption (APDA) algorithm. APDA determines the water vapor abundance in each pixel by trying to fit the path radiance effects in a water absorption feature with the use of an atmospheric model (Modtran4).

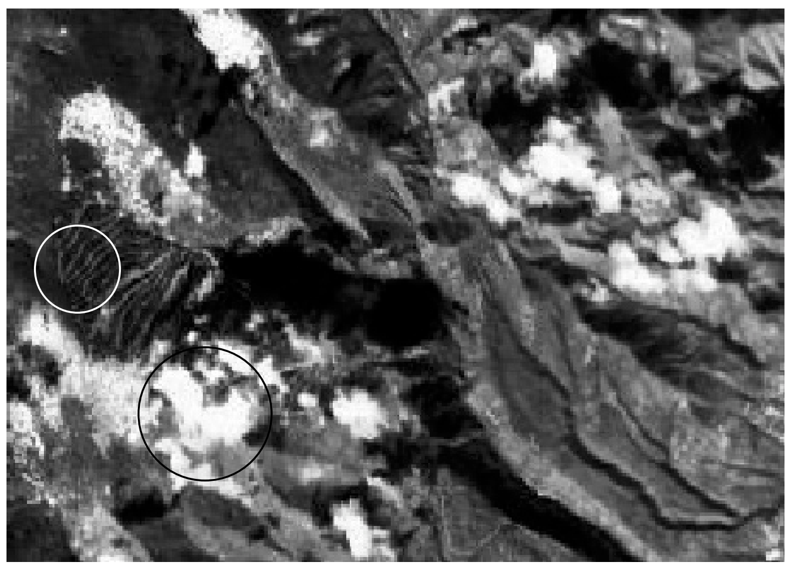

Figure 2. Snow on the upper portions of the ski slopes (white circle) is readily differentiated from clouds (black circle) in this composite of near-IR and short-wave IR bands F, I and O.

3) Water mask and water-quality studies. The water mask identifies water pixels in a given scene using the 5 m visible and near-IR bands. MTI has limited short-wavelength bands for water-quality measurements, but at least relative water-quality measurements will be done.

4) Aerosol correction for surface reflectance measurements. The aerosol optical depth for a scene is estimated from the

change in the known spectra of dense dark vegetation and deep clear water and comparing it to an atmospheric model of the scene (using the 6S atmospheric modeling code). Once the aerosol optical depth is calculated, the aerosol effects are removed from the whole scene in order to get the corrected surface reflectance.

5) Cloud mask. Because cloud properties can vary considerably from scene to scene, the algorithms used for producing both the dense-cloud mask and its thin-cirrus counterpart are interactive.[10] In parallel, we are assessing the performance of dense-cloud mask algorithms that are evolved from the genetic programming tool GENIE (GENetic Imagery Exploitation).[11] Several papers describe the GENIE software in more detail.[12,13]

6) MTI two-look imagery provides useful perspective views of isolated clouds that may be used to measure upwelling and downwelling radiation from clouds. Recent theoretical work relates the upwelling and downwelling radiation to the optical depth of the cloud, which, in turn, is related to the effect of clouds on the earth's radiation budget.

7) Snow-cloud discrimination. The MTI short-wave infrared bands allow separation of snow from clouds. Studies are yet to be done to quantify this effect for MTI imagery. Figure 2 shows a portion of an MTI image of the Los Alamos area. The upper portions of the ski slopes (in the white circle) were snow-covered in this late-October view. They are clearly differentiated from clouds (in the black circle).

8) Gas-plume detection. Multispectral imagers are typically not optimized for gas detection. Nevertheless the MTI is sensitive to SO_2, and volcanic plumes have been observed.

Several more-advanced analyses are planned for MTI imagery. These include:

1) Materials identification. An important aspect of material identification is distinguishing man-made objects from natural objects. Many groups of materials are uniquely identifiable with the spectral signatures measured in the MTI channels. Some simple spectral classifications have been done with MTI images, but detailed identification will be done using clustering about centers determined from spectral libraries. The six MTI bands A, B, C, D, I and O will likely be used (perhaps also using bands E and G, which are on the wings of the 0.94 µm water-absorption feature), as the other bands are either too near atmospheric absorption features or are thermal emission bands.

2) Subpixel temperature retrieval. The present method is designed to measure water temperatures for pixels that are mixed land-water. The method uses MTI bands A-D to obtain a water mask at 5 m ground-sample distance. Then the known water emissivities, the water fraction determined by the water mask, and average soil emissivities are used to retrieve the water temperature.[14]

3) Vegetation health. The first goal is to measure vegetation stress of any kind, with the ultimate goal of separating naturally-stressed vegetation from anthropogenically-stressed vegetation. From a remote sensing point of view, the only aspect of plant stress that can be measured is the manner in which the plant reacts to the stress. These plant coping mechanisms (both chemical and architectural) will often depend on the type and degree of stress encountered. Studies will continue in this area as imagery is acquired of relevant sites.

2.3 Applications

There is neither enough space in this paper nor expert-level knowledge on the MTI team to explore the full application set of MTI data. Nevertheless, it is useful to briefly describe some of the areas where the imagery is being applied. This list will certainly expand as time goes on.

<u>Hydrology</u>

We mentioned above one example of hydrological studies with the MTI: the thermal bar and water quality measurements on Lakes Ontario and Baikal. Another example is snow-cloud discrimination with the obvious implication for mountain snowpack and watershed studies. MTI data are to be applied to glacier characterization as a supplement to the Global Land-Ice Measurements from Space (GLIMS) program.[15] GLIMS is a pilot program to measure the location, sizes, material classification and dynamical properties of all the earth's glaciers (outside interior Greenland and Antarctica). The good spatial resolution of the MTI will be used for algorithm validation and detailed studies of some specific glaciers. MTI data are also being applied to estuarine studies, looking for thermal effects on tidal vegetation.

Volcanology
The MTI is turning out to be an excellent tool for studies of volcanoes. Many volcanoes have been imaged with the MTI, including Mauna Loa, Mt. Stromboli, Mt. Etna, Popocatepetl (near Mexico City), Taal (a volcanic crater lake in the Phillipines) and others. Balick et al., give some details of measurements taken at Mauna Loa.[16] There are several MTI images of Popocatepetl acquired during a recent period of activity in December 2000 – January 2001. MTI images are used to detect SO_2 plumes and observe thermal structure details of volcanic domes. One possible analysis using MTI data is to classify materials within craters and combine that information with the thermal bands to make a model of volcanic domes with unprecedented detail. Another analysis would be to measure the distribution of hot ejecta to better understand the potential for catastrophic glacial melting from eruptions. Fig. 3 shows a December 2000 thermal image taken in MTI band N of Popocatepetl. Thermal features are present in both the dome (located in the main crater) and in the surrounding ash field. It remains to be determined if the ash field contains volcanic "bombs" that retain heat from the volcano itself or if the field is warm due to solar heating.

Forestry
MTI data are being used for landcover categorization of the Los Alamos area following the Cerro Grande fire. The MTI may also be used for similar purposes in a number of other communities at high fire risk. The landcover categorization is being done with the GENIE software. Of course, independent of fire management/suppression, landcover categorizations have myriad purposes for forest management and characterization. MTI data are also useful for determining burn severity. Again using the Cerro Grande fire as an example, the loss of vegetative cover and soil damage produced an extreme flood danger for Los Alamos and surrounding communities. An intensive soil-damage-remediation and reseeding campaign immediately followed the fire. The flood remediation efforts concentrated on the severely burned areas, which are most readily identified over large areas with remote sensing techniques (although MTI data were not used in the recovery efforts immediately after the Cerro Grande fire, they are being used for landcover studies).

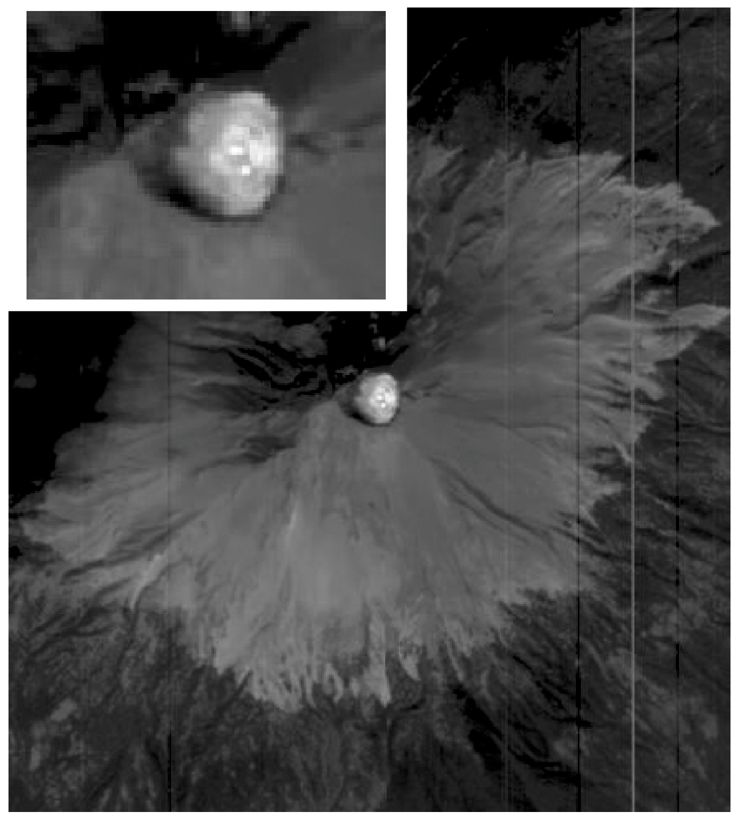

Figure 3. December 2000 thermal image taken in MTI band N of Popocatepetl. Thermal features are present in both the dome (shown in the inset) and in the surrounding ash field. It remains to be determined if the ash field contains volcanic "bombs" that retain heat from the volcano itself or if the field is warm due to solar heating.

Vegetation Canopy Studies
The MTI will be used in directional temperature measurements with and without leaf canopies. Leafless forests have larger temperature variations with direction than leafed canopies due to the thermal inertia of tree trunks, branches, etc. and differing view geometry of the ground surface. In contrast leafed forests change temperature with angle less quickly and are to some approximation at the temperature of the surrounding air.

Cloud Radiation Transport Studies
MTI two-look imagery provides useful perspective views of isolated clouds that may be used to measure upwelling and downwelling radiation from clouds which, in turn, is related to the effect of clouds on the Earth's radiation budget. For example, if isolated clouds are viewed at relatively shallow angles then the upwelling radiation observable at satellite level can be decomposed into reflected and transmitted parts. This is a configuration more easily achieved with MTI's second look than with nadir-looking spaceborne instruments with comparable spatial resolution. These side observations are

geometrically impossible in the standard plane-parallel cloud model and the associated 1-dimensional radiative transfer used routinely in cloud remote sensing. However, recent theoretical work in 3D radiative transfer by members of the MTI science team relates these reflected and transmitted quantities to the optical depth of the cloud. This is a key parameter in all cloud radiation studies, including the prediction of global downwelling fluxes.

Lunar Geology

During the lunar eclipse of January 9, 2001, MTI imaged the moon while it was in partial and full eclipse. The aim was to study the thermal structure on the moon while it passed from full to no sunlight. See Fig. 4. Note the lunar details that are significantly hotter (typically 10s of K) than their surroundings. Other MTI images show lunar thermal structure at half-moon – a portion of the moon had spent days out of sunlight and a portion had been in sunlight for days. The complete set of images will be analyzed to better understand lunar geology via thermal characterization.

3. DATA PROCESSING AND ANALYSIS CENTER

The central repository for algorithms, data, metadata, and general analysis tools is the MTI Data Processing and Analysis Center (DPAC) located at Los Alamos National Laboratory. After data are downlinked from the satellite to the ground station located at Sandia National Laboratories, they are sent to the DPAC, where processing begins automatically. For more on MTI operations, see Decker et al. in this volume.[17] The DPAC was described in a previous paper,[18] with an overview included here.

The DPAC processes all raw MTI data to produce several levels of data products, with each succeeding level applying more sophisticated and often more interactive analyses. The MTI data product levels follow the convention presented in the *Earth Observing System* (EOS) *Reference Handbook*.[19] Roughly, Level 0 data products include state-of-health data and uncalibrated, unregistered images. Because the MTI focal plane is segmented into three sensor-chip assemblies, images are in three sections at this level. The spectral bands are not co-aligned at Level 0. Level 1 starts with the calibration, which is one of the emphases for the MTI project. The 3 sub-images and 15 bands are then coregistered, which is the end of the automated processing. Other Level 1 products include ephemeris and georeferenced products. The geophysical quantities of interest (most of the items discussed in section 2.2) are produced at Level 2 and Level 3 products are time-series of Level 2 products. Level 4 products are more advance analyses, several of which are listed in section 2.2.

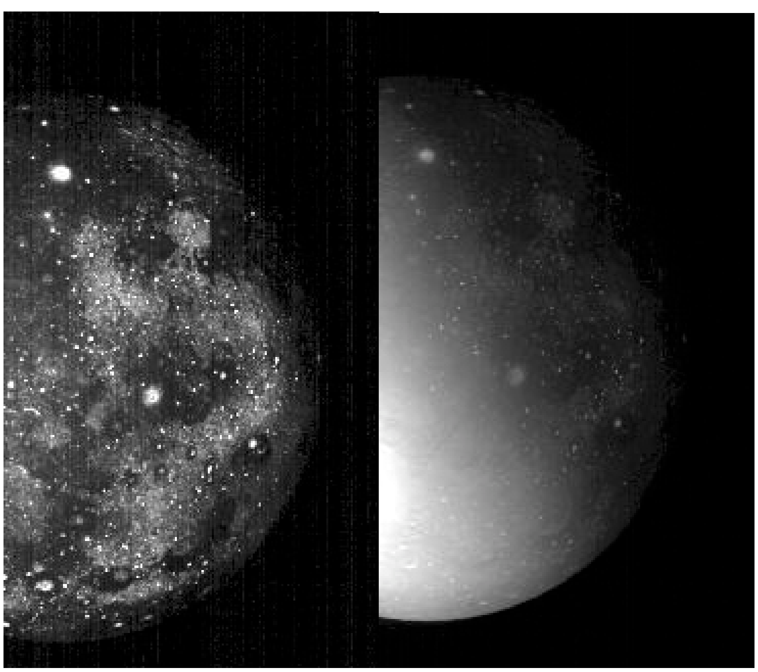

Figure 4. Views of the moon during the full eclipse of January 9, 2001. Both images were taken in the midwave infrared band K. The right image was taken while the upper-right portion was in partial eclipse, and the left image was taken during full eclipse. The radiance scale is 60 times lower in the left image.

Several of the Level 1 products bear more description. The first Level 1 product consists of separate images for each band for which the radiometric calibration has been applied. The calibration techniques and preliminary results for the MTI are published elsewhere.[20,21,22] The calibration is based on a sophisticated ground calibration along with a set of on-board sources. The on-board calibration was lost due to hardware failure, but MTI data products based on the reflective bands should be nearly as good as pre-hardware failure. This is because the reflective calibration was largely using ground calibration data. However, the thermal calibration is not likely to be as good now as when the on-board sources were available, particularly for the longwave infrared bands. The longwave bands (L, M, N) use HgCdTl detectors, which are notoriously unstable.

The team is using several calibration techniques to make up for the loss of the on-board calibration sources, in addition to regular ground-truth campaigns to provide a vicarious calibration of the system. For example, the satellite is acquiring regular images of the moon to monitor optical degradation and perhaps to be used as a calibration source for the reflective bands. Studies are underway to determine if the moon can be used as a thermal calibration source. Images are being acquired with the detector arrays aligned parallel with the satellite sweep direction. These are being done over open water targets that have temperature-measurement buoys, to monitor the thermal calibration. Ground targets will be imaged in the same way to monitor the reflective band calibration.

The co-registration of the spectral bands and the three sections of the focal plane is performed next at Level 1. The co-registration is presently done in two ways: all images are passed through the automated registration and selected images are co-registered interactively. The automated registration relies on downlinked satellite position and orientation information. The position of each pixel on the focal plane is mapped through the optics, based on a distortion map measured during ground calibration, and projected to the surface of the earth. All pixels in all bands and all SCAs are resampled to a common grid defined in ground coordinates.

The interactive registration allows the user to produce subpixel alignment of bands in the along-track and cross-track directions. The image is not warped or rotated. The three segments of the focal plane are joined in a similar way. Smith et al. describe another co-registration tool.[23]

After the bands and three image sections are co-registered, selected images are georeferenced. The purpose of the georeferencing process is to align the rows and columns of an MTI image with the cardinal directions of a map projection. This is achieved by associating features in a co-registered MTI image with their corresponding locations on a reference map. These coordinate pairings are used to solve for the coefficients of an affine transformation. The affine transformation is then used to guide a resampling of the MTI data onto a georegistered output grid. Georeferenced MTI imagery can be input to a Geographic Information System (GIS) so that it may be combined with other geospatial datasets, such as hydrological vectors, rasterized maps, and ground truth data. Conversely, the locations of features of interest in an MTI image can be easily extracted once a georeferenced product has been created.

Features of the DPAC include:
1) The pipeline is completely automated through most of Level 1.
2) Performance: a complete MTI image is processed through the automated part of Level 1 in about an hour.
3) A complete copy of the MTI data set online.
4) Tight coupling with two relational databases. The operations database is used to guide the processing, and information is output to the database to monitor progress and post results. The other database is for state-of-health data.
5) The ability to process imagery multiple times, as the processing algorithms are updated.
6) An archive of all ground-truth data and meteorological data taken in conjunction with MTI collects.
7) A number of applications for internal and external users to access MTI data and metadata.
8) The repository for MTI data analysis techniques and documentation.

As of the middle of February, the DPAC has processed ~1700 ground images of ~300 sites, produced 250 CDs for users, and stores 800 GB of imagery and data products.

It's hard to quantify effort for this type of project, but the DPAC hardware and software infrastructure is the result of 5-10 person-years of effort. We believe this is quite a modest effort for the level of performance the DPAC maintains. How was this achieved? Most of the code is written in IDL (the Interactive Data Language), a rapid prototyping, science-analysis package. Portions of the software are also C, Perl, shell scripts and Java, as appropriate. It is risky to use such a high-level language, but careful attention to its limitations and to software engineering principles has resulted in a robust, maintainable system. In addition, in most cases the scientist responsible for a given algorithm implemented that algorithm for the pipeline. Being a research-and-development system, formal requirements and reporting for MTI software outside the team were minimal, resulting in a streamlined development process. Internal requirements were maintained to ensure the pipeline software was robust and validated.

A few words on user interaction with the DPAC follow. Access to MTI data is gained through a web interface, after authorization is granted to the user. The web interface allows users to find images of interest by providing access to the DPAC operations database, which contains extensive metadata for MTI imagery. Once images of interest are found, users can request imagery over the web interface (although all request must be accompanied by signed paperwork). The data products are subsequently sent to the user via CD or Digital Linear Tape (web downloads are not possible at this time). MTI data products are stored in the Hierarchical Data Format (HDF), with ancillary data available in the same file as the image data.[24] A header file (in both text and HDF formats) also accompanies data products.

4. GROUND-TRUTH CAMPAIGNS

The MTI ground-truth (or Validation and Verification, or V&V) program is lead by the Savannah River Technology Center (SRTC) and is covered in detail elsewhere in this volume.[2] Major campaigns to date include ground reflectance and atmospheric characterization at Ivanpah Playa and Mauna Loa. The SRTC team has also done advanced studies of the skin-temperature depression on water bodies and its effect on water-temperature measurements.[25]

Additional data used to compare with MTI results are obtained from a number of sources, including:

1) The Southern Great Planes, Tropical Western Pacific[26] and North Slope Alaska DOE Atmospheric Radiation Measurements (ARM) sites.[27]
2) The NASA Stennis satellite validation and verification site.[28]
3) NOAA "weather"[29] and "climate"[30] buoys.
4) AERONET (AErosol RObotic NETwork) sites.[31]
5) Some of the MODIS and ASTER ground-truth sites.

5. SUMMARY

MTI has a strong research program that combines the expertise of instrument scientists, remote sensing researchers, climate researchers, as well as software and hardware developers. The MTI researchers are studying techniques to retrieve geophysical quantities such as water temperature and surface reflectance. These quantities are in turn used to answer questions in a variety of application areas. This research program would not be possible without the strong support of the US Department of Energy, not only financially, but also in developing teams and facilities at Los Alamos National Laboratory, Savannah River Technology Center, and Sandia National Laboratories and in encouraging the strong collaboration between these institutions.

ACKNOWLEDGEMENTS

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