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*Title:* DESIGN CONSIDERATIONS, MODELING AND ANALYSIS FOR THE MULTISPECTRAL THERMAL IMAGER

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# Design considerations, modeling and analysis for the Multispectral Thermal Imager.

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**ABSTRACT**

The design of remote sensing systems is driven by the need to provide cost-effective, substantive answers to questions posed by our customers. This is especially important for space-based systems, which tend to be expensive, and which generally cannot be changed after they are launched. We report here on the approach we employed in developing the desired attributes of a satellite mission, namely the Multispectral Thermal Imager. After an initial scoping study, we applied a procedure which we call: "End-to-end modeling and analysis (EEM)." We began with target attributes, translated to observable signatures and then propagated the signatures through the atmosphere to the sensor location. We modeled the sensor attributes to yield a simulated data stream, which was then analyzed to retrieve information about the original target. The retrieved signature was then compared to the original to obtain a figure of merit: hence the term "end-to-end modeling and analysis." We base the EEM in physics to ensure high fidelity and to permit scaling. As the actual design of the payload evolves, and as real hardware is tested, we can update the EEM to facilitate trade studies, and to judge, for example, whether components that deviate from specifications are acceptable.

**Keywords**: Modeling, Analysis, System Design, Multispectral Imaging, Thermal Imaging, Calibration.

## 1. INTRODUCTION

The Multispectral Thermal Imager (MTI) program is designed to demonstrate the utility of multispectral remote sensing from a satellite platform for a variety of applications of interest to the U. S. Department of Energy. These applications include characterization of industrial facilities, environmental impacts of effluents, global change (Ref: Piltz), hazardous waste sites, resource exploitation, crop health, and others. Additionally, the project supports other agencies through the MTI Users Group, MUG. A key component of the program is the design, development, calibration, testing, deployment and operation of a sophisticated satellite instrument, which is scheduled for launch at the end of 1999. We will obtain data from the satellite for at least a year, and compare the retrieved signatures to ground truth obtained from in-situ measurements and through interactions with collaborative facilities in the United States.

Our ultimate goal is to answer questions of interest to our customers. We devolved these questions into categories, and examined possible technologies. Fortunately we were able to build on the experience of others (Ref: Vane, Chen, Kramer), combining key insights from several arenas to achieve a self-consistent set of attributes for the MTI project. We quickly determined that we need an imaging system with moderate spatial resolution and spatial coverage, multispectral signatures of scenes at or near the

ground in the visible and infrared spectral domains, simultaneous atmospheric characterization, excellent accuracy and precision, and sophisticated modeling and analysis techniques. The MTI mission has a unique niche in the ensemble of existing and planned satellite-based remote sensing systems (Ref: Glackin, Slattery, Wilson). The subject of this paper is the quantitative transition from these general insights to defining an appropriate set of system attributes.

## 2. END-TO-END MODELING (EEM)

We used "end-to-end modeling" (EEM) to develop our measurement strategies (Ref: Weber, IEEE99). The philosophy is to develop a complete, closed-loop, physics-based model of the measurement system. We include targets, target signatures, atmospheric propagation, sensor attributes, data processing, and analysis codes to compare directly the "answers" from our simulated experiment to the truth, defined as the target properties with which we started. We define "physics-based" as using information from physical understanding (as represented by equations) in contrast to using fits to test results or scaling approximations. By basing the models in physics, we generate confidence in the ability, for example, to extend validated results from previous measurements into new applications or into new regimes. We also note that full confidence can only be obtained even from a physics-based system if we incorporate all of the important attributes of the entire measurement strategy. We define an attribute as being "important" if it affects the bottom line answer at a level that is significant to our customer(s).

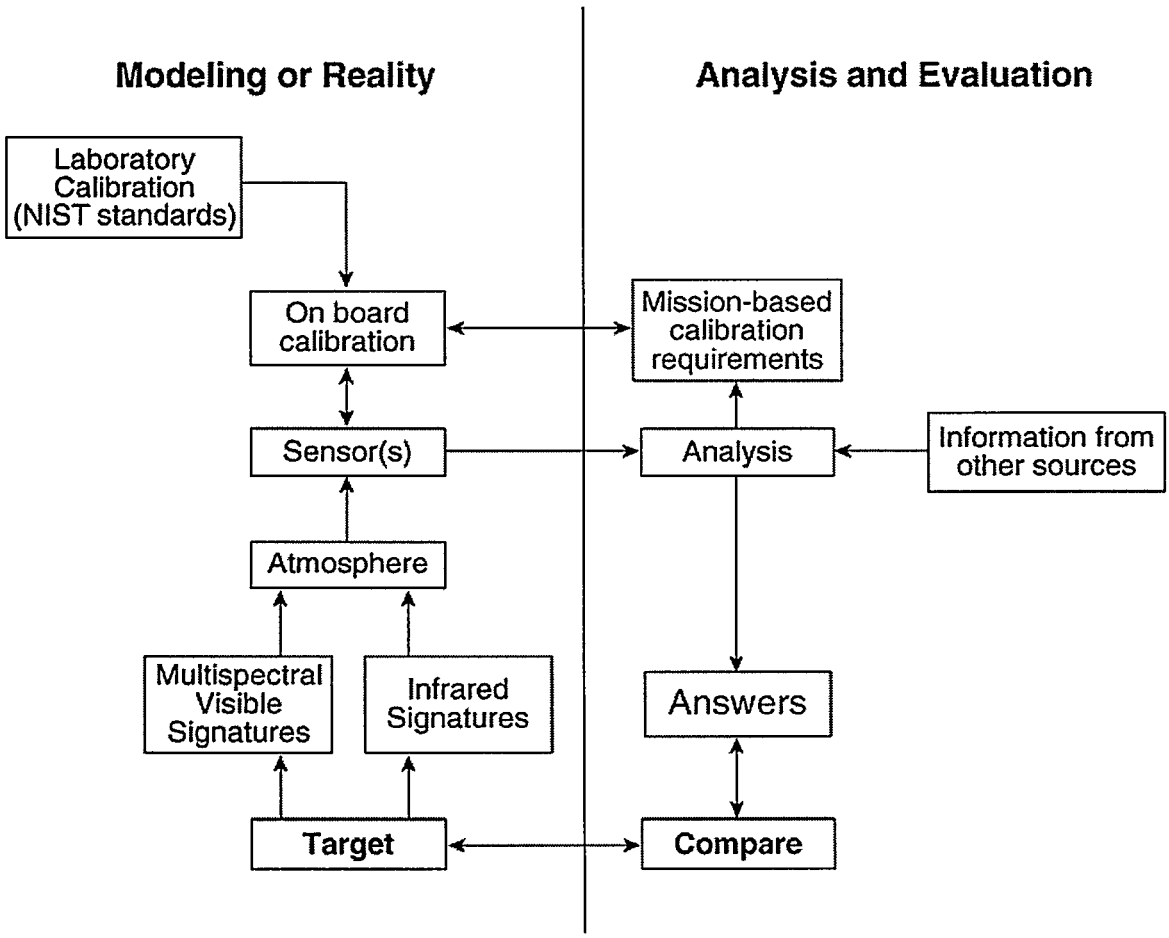



Figure 1: Simple depiction of an end-to-end model.

A very simple and rather generic flow diagram for an end-to-end model is shown in Figure 1. The goal is to supply answers (bottom right) to questions posed by our customers. The starting point for our model is the multispectral and thermal information that characterizes ground-based targets. The atmosphere both distorts the signature through absorption and scattering, and adds photons due to atmospheric emission (path radiance). The sensor converts selected photons to electrical signals, which are then analyzed either at the sensor, or, after data transmission, on the ground. The Analysis module uses data from our own sensor and potentially data from other sources, and yields the "answers". This lower segment of Figure 1. has obvious uncertainties in fidelity of representing targets, the atmosphere, and the sensor, and we need to ensure that we have a sensible balance in which no single uncertainty dominates. For example, it is well-known that models of the atmosphere are made tractable by making simplifying assumptions such as limiting the number of spatial directions included in radiative transfer computations (Ref: Goody and Yung). Further, even the best atmospheric models have systematic errors in areas such as the continuum spectrum attributable to atmospheric water vapor (Ref: ARM proceedings). In the early phases of modeling, sensor attributes are represented by typical values from manufacturers' data sheets: the actual hardware used may deviate from these specifications, or we may need to extend the state-of-the-art to achieve our goals. The upper segment of Figure 1 shows calibration needs, as derived from the mission requirements, as implemented by laboratory calibration systems, and as limited by calibration hardware that we can afford to include with the sensor package. A key insight is that the upper and lower segments should also be balanced with respect to the effects on the "answers": there is no overall gain in calibrating a sensor to a better precision or accuracy than that which the analysis tools can use, and vice-versa.

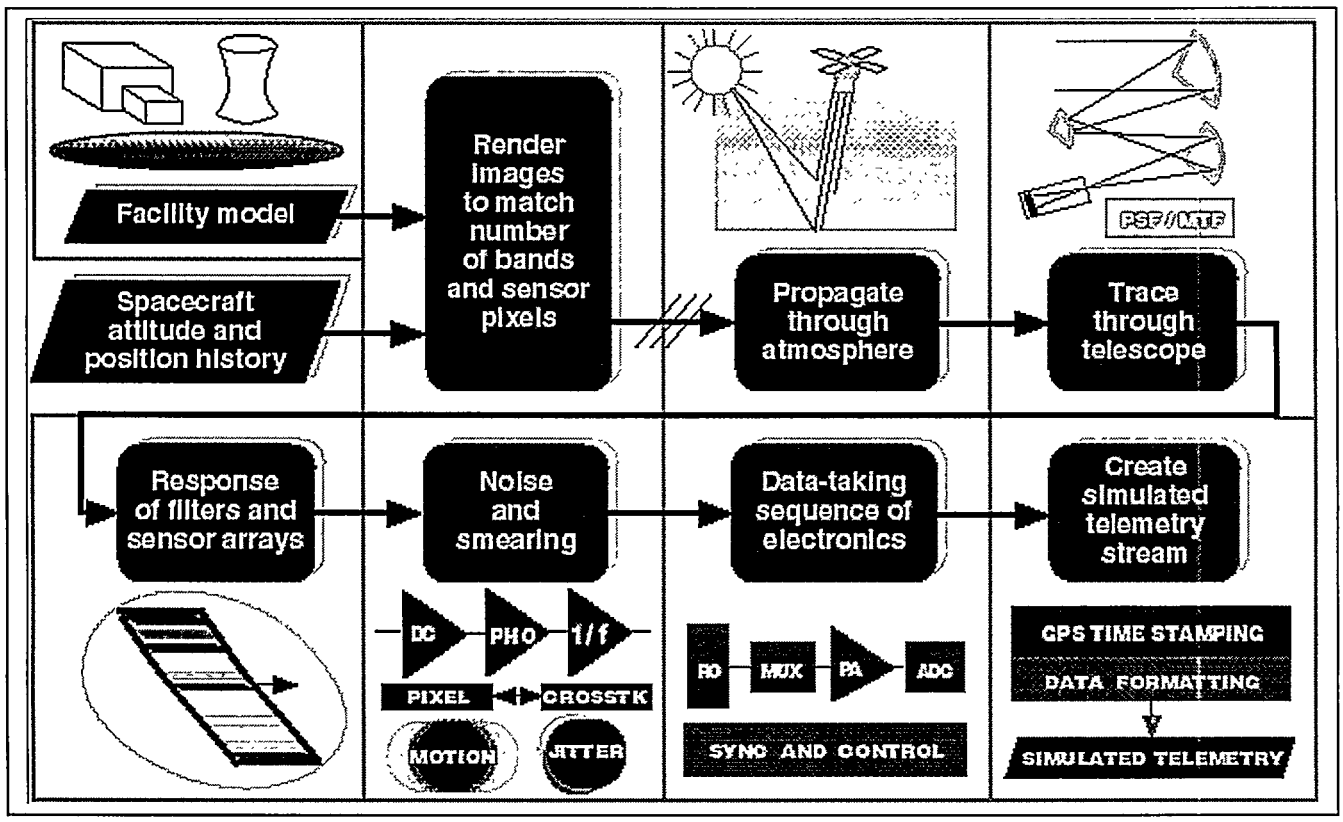



Figure 2(a) : Block diagram of the specific implementation of the front end of the end-to-end modeling system for the MTI.

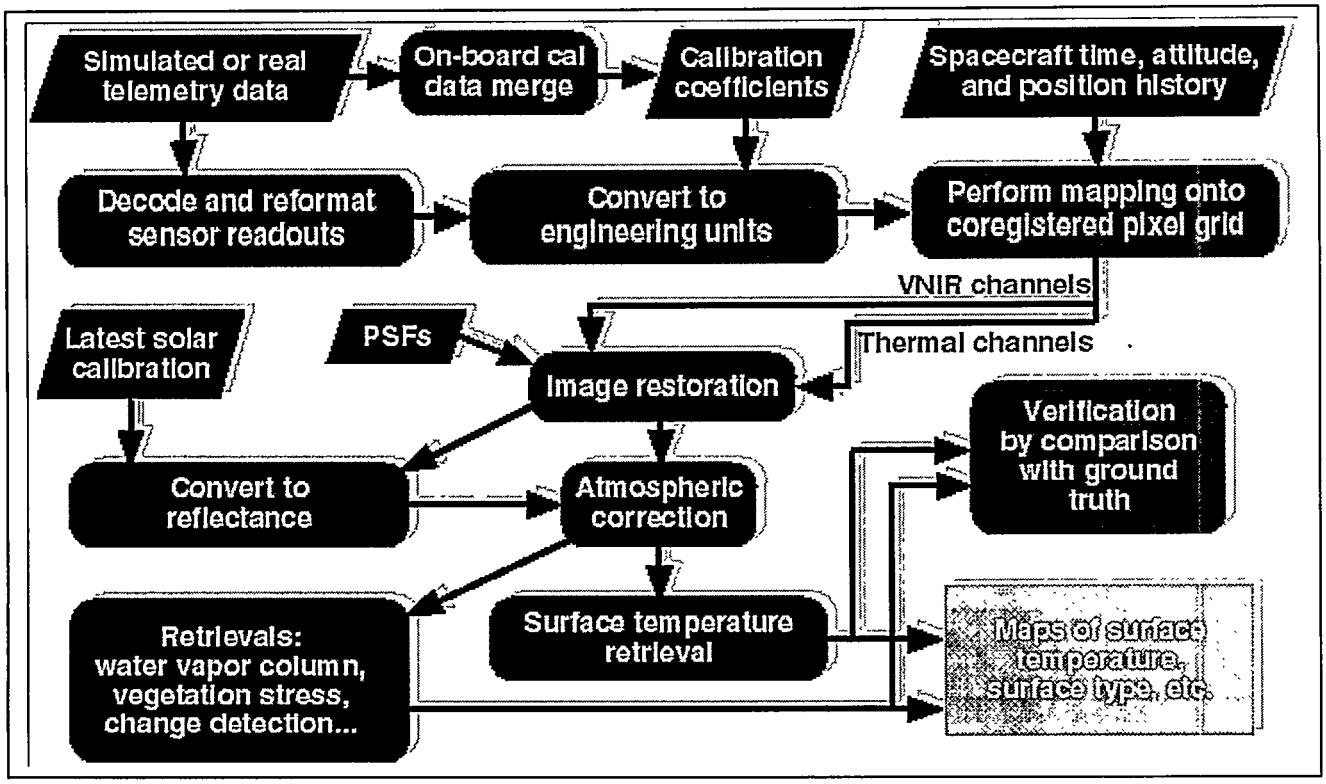



Figure 2(b) : Block diagram of the specific implementation of the back end of the end-to-end modeling system for the MTI.

The specific implementation of the EEM for MTI is shown in Figure 2, including the "front-end" or forward modeling segment and the "back-end" or analysis segment. We begin with a facility description, which may be based on ground truth, airborne data, or satellite data. We also use self-consistent targets using 3-D models generated in CAD systems, or thermal models generated from codes such as DIRSIG (Ref: Schott) or 3-D thermal models (Ref: Garrett and Auchampaugh). The advantage of modeled targets is that one knows the starting point exactly, the disadvantage is that one never captures all the realism of an actual scene. For water targets we include effects of wind, shadowing, and surface roughness, as well as polarization (ref: Cox and Munck, Henderson). The models generate the spectral signatures at the targets in the wavelength regime 0.4 to 15 microns, limited at each end by atmospheric absorption and by sensor limitations. To test specific retrievals, one may chose to limit the spectral bandwidth and / or the spectral resolution. The signature is then propagated through representative atmospheres, as simulated using codes such as MODTRAN and FASCODE (Ref: AFGL) to the sensor location: for a satellite that location, as a function of time, is determined from orbit calculations (Ref: Decker). The optical system is modeled at high fidelity by Code V (Ref: Code V), though we usually do not require that fidelity and use the Point Spread Function or Modulation Transfer Function. (We do use Code V data to validate our pixel location mapping during the calibration of the distortion in the optical and focal plane systems.) At the focal plane, we model the ability to produce the desired spectral band-pass filters (Ref: LaDelfe), and substitute manufacturer specifications later in the cycle. We model the actual detectors using physics-based models for the Silicon, InSb, HgCdTe detector arrays and associated electronics (Ref: Cooke). Noise sources include photon statistics, DC offsets, so-called 1/f drifts, and limitations on the count rate and total accumulated charges, as well as cross talk between the pixels in an array. At this point we also add in the

satellite motion and estimated jitter; the vibrational spectrum of the satellite and payload are simulated by mechanical analysis, and by the limits imposed by specifications on the spacecraft manufacturer. The charges from the focal plane read-out then move through models of multiplexers, amplifiers, and digitizers into a mass memory. The contents of the memory are then formatted and compressed, and augmented by simulated state-of-health data to form a simulated telemetry stream. All of these items are replaced with the attributes of real hardware as such details become available, and, when the satellite flies, the real telemetry will be substituted for the simulated version. In the meantime, the simulated telemetry is used as the input to the "back -end" or analysis segment of the EEM.

The back-end or analysis component closes the EEM, and also provides the basis for the robust data analysis codes which are transitioned to the MTI Data Processing and Analysis Center, DPAC (Ref: Szymanski). Thus we can test the analysis algorithms very early in the program. The Back-end interchangeably uses the real or simulated telemetry stream, or data obtained at the Los Alamos Radiometric Calibration System, and decodes the data to allow immediate visualization of the raw sensor outputs. Calibration data are obtained from the ground-based calibrations (Ref: Bender, Byrd,...) or from on-board calibration hardware (Ref: Zalewski), or from vicarious calibrations on-orbit. The consistent and appropriate treatment of data from these various calibration sources and on-orbit activities is the subject of another paper (Ref: Clodius, et al.). Application of the calibration factors to each pixel allows conversion into engineering units. The next step is the mapping of each pixel into the image domain. This task is complicated by the fact that MTI is a push-broom imager with a segmented focal plane array: thus each spectral band contains data from a slightly different time, and from three areas on the Focal Plane Assembly (FPA) (Ref: Rienstra). A further complication is that we have only crude vibration data from three accelerometers on the outside of the MTI payload: thus we do not have a sufficiently detailed vibration history to help in the deconvolution. A special set of techniques, using the fact that some of the spectral data are correlated, has been developed to solve this problem (Ref: Theiler). At this stage one also corrects for the distortion in the optical system: this correction is based on data obtained in the Los Alamos calibration system. Once all the pixels are registered, we can optionally apply image restoration, using the modeled properties of the sensor system to formulate the PSF kernels. We have now convert the radiance in visible and near-infrared (VNIR) bands to reflectance, and apply atmospheric corrections to transform to the ground target attributes.

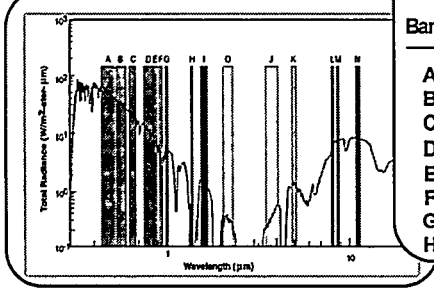
These ground-referenced measurements are then compared to the target scenes or modeled targets with which we started the front end of the EEM, allowing the question: "how well did we do in terms of answering the questions about the targets of interest to our customers?" We need to pose such questions quantitatively. For example, did we retrieve the temperature maps of a lake to a sufficient accuracy to understand how much waste heat is dissipated from an industrial facility that uses the lake for cooling? Are we able to measure the health of vegetation well enough to judge whether pollution is damaging a regional ecosystem? Can we detect thermal signatures of wastes buried decades ago at a former nuclear weapons production facility like the Hanford Reservation? In the next section, we will look at a few of the EEM studies that we did for MTI.

## 3. SOME SPECIFIC STUDIES FOR THE MULTISPECTRAL THERMAL IMAGER.

We performed a considerable number of studies to help define the MTI attributes. We will illustrate here with a few representative examples. We point out that the end-to-end modeling and analysis is an iterative process, so the examples can start from the initial scoping studies, or from previous runs of the EEM.

We begin with a quick look at spatial resolution, and concomitant sizing of the optical system. We started with high-resolution representations of thermal targets and their environs, since the diffraction limited resolution of the

optics will scale directly with wavelength. And the mass and volume of the spacecraft scale as a high power of the linear dimension of the telescope aperture (Ref: Weitz), strongly driving costs. One now degrades the spatial resolution of the images by inserting various choices for telescopes into the EEM, observing the effects on retrievals of thermal loads. The choice of telescope aperture is inextricably tied to the range of questions that we can answer. Large apertures would allow examination of small industrial facilities, whereas with a small telescope we would be limited to look at multi-Gigawatt power stations. Since MTI is a research instrument to explore scientific, engineering, and procedural concepts, we concluded that we could access a representative set of examples with spatial sampling of thirty meters in the thermal bands, translating to an unobstructed aperture size of 0.25 meters at a nominal 500-km orbit altitude. Of course a larger telescope permits measurements on smaller or more complex targets, so the actual MTI has a 0.36 m primary mirror. If this telescope were to be diffraction limited at visible wavelengths, it would set a limit of order a meter at blue colors. A similar study for visible targets shows that this is better than required for the set of targets defined by considerations on thermal signatures - five-meter GSD is quite adequate, saving greatly on number of visible light detectors, data volume, data down-links, etc.




| Band | Wavelength Range (microns) | Band | Wavelength Range (microns) |
|---|---|---|---|
| A | 0.45 - 0.52 | I | 1.55 - 1.75 |
| B | 0.52 - 0.60 | J | 3.50 - 4.10 |
| C | 0.62 - 0.68 | K | 4.87 - 5.07 |
| D | 0.76 - 0.86 | L | 8.00 - 8.40 |
| E | 0.86 - 0.90 | M | 8.40 - 8.85 |
| F | 0.91 - 0.97 | N | 10.20 - 10.70 |
| G | 0.99 - 1.04 | O | 2.08 - 2.35 |
| H | 1.36 - 1.39 | | |

Figure 3: Selection of spectral bands for the MTI.

Spectral band selection was driven by the need for accurate or precise retrievals on one hand, and limited by cost and complexity considerations on the other hand. Details of spectral band selection are found in a paper by Clodius, et al, 1998: we give just an overview here. Figure 3 shows an example of a typical spectrum to be measured by MTI: this is just one of many hundreds such spectra that we processed, incorporating a variety of targets, atmospheres and sensor concepts. A primary mission is to obtain accurate thermal signatures for temperatures from 273 to 350K. We referenced the "split-window" results for Sea Surface Temperature (SST) retrievals exploited by, for example, the weather satellites (Ref: Stephens, Bates) in which one uses bands at 3.7, 11, and 12 microns to allow a fit to the Planck function, and to provide discrimination against clouds. However, this method does not discriminate against other changes in atmospheric conditions, such as aerosols from volcanic eruptions, or atmospheric water vapor, leading to significant deviations (Reynolds, 1988). For regional weather measurements, one can obtain the water vapor concentrations using microwave sounders at spatial resolutions of kilometers. This is not an attractive option for our twenty-meter ground sampling distances or for the realistic situation in which the weather data is also likely to be obtained at a very different time to our satellite overpasses. Thus we include our own detection bands for clouds, water vapor, and aerosols.

Referencing Figure 3, we chose the following: Band N is at 10.2-10.7 microns, in a spectral region that is quite clear of contamination. The upper cut-off wavelength was reduced from our original request of 11.5 microns after a trade study between the cost and ability to produce the focal plane and the accuracy of retrievals. The cost of the focal plane would have been higher with a longer cut-off wavelength due to technological issues with the

HgCdTe detector materials. Very little is lost in retrieval accuracy using multiple bands with the lower cut-off wavelength on band N, so we allowed the vendor to reduce the stressing specification.

Bands L and M located to allow a ratio measure of water vapor: band L is in the water vapor absorption band, while band M is not. We then obtain analogous leverage to the "split-window" SST technique using the mid-wave infrared (MWIR) region. However, we chose to use a two MWIR bands: band J at 3.5 to 4.1 microns roughly copies the weather satellite band, but we obtain additional leverage from a new band, dubbed band K, at 4.87 to 5.07 microns. Band K allows us the use of an MWIR band in the daytime, since undesired contribution from sunlight is small in band K - but debilitating in band J. Band K does have contamination from some atmospheric constituents, including ozone, water vapor and carbon monoxide: careful tuning of band edges and study of variability of the contaminants led to a decision to incorporate this new band (Clodius, 1998).

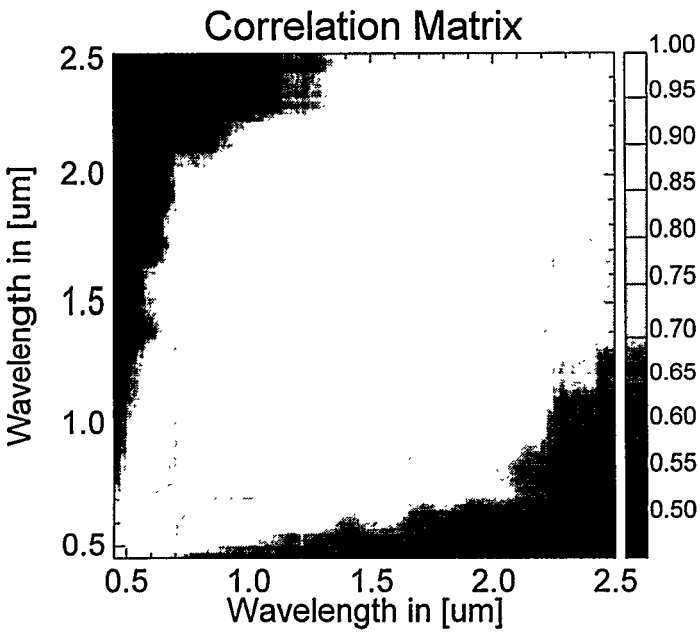



Figure 4: Correlations matrix for 209 spectra of materials in the VNIR wavelength regime.

Other spectral bands shown in Figure 3 were defined using similar methodologies. The astute reader will observe that band O is out of sequence, at 2.08 to 2.35 microns. This band was added rather late in the process following a study on materials identification (Borel, et al). Three studies were performed to determine whether to add band O. First we selected a spectral data base (NEFDS) and computed the correlation matrix between eighty channels ranging from 0.45 to 2.5 microns. This matrix is shown in Figure 4: the spectral region above 2.1 microns is quite poorly correlated with the short wavelength bands, which promises additional information from addition of a 2.1-2.35 micron band. Second we tried using a Principal Components (PC) analysis followed by a k-means clustering to separate various materials using either the VNIR bands or the VNIR bands plus a single band at 2.1-2.35 microns: the results from this study showed little support for adding band O. Third we tried analyzing some representative scenes, using an eigenvalue approach. This showed that the addition of band O clearly improves the information content for leaf reflectances, soil reflectances, and other spectra in the NEFDS data base. In the final analysis, we did not have a strong internal motivation for adding band O, but the incremental cost was relatively small, and some other research groups were starting to discuss some in-field successes using the similar

bands. Thus we decided to add the band so that we could test its efficacy against real-world spectra rather than limiting ourselves to data bases.

Studies using various combinations of spectral bands further confirmed our choices for these wavelengths (Clodius 1998) and we proceeded to procurement. During the procurement process, we had several occasions to use the EEM, including the reduction of the upper wavelength cutoff on Band N, and an iteration on some spectral filters that did not meet the original specifications. Again using the EEM we inserted the as-built performance of these filters, examined the effects on the "answers to customer questions", and found an effect which we then balanced against the cost and schedule implications of rejecting the filters.

As discussed above, we need to balance the error budget sensibly between uncertainties in the modeling and analysis, and the calibration of the sensor system. Our initial attempt at this division was to equally divide the error budget, and then to assess the feasibility and costs of achieving the concomitant calibration accuracies. This was an appropriate choice, in that the desired accuracies and precisions can be achieved, though at the very edge of the state of the art. The calibration requires several pieces: obtaining NIST-traceable standards; transferring those radiances to the payload; on-orbit calibration systems, and vicarious calibrations while in operation. Some details on the calibration systems have been presented (Ref: Byrd et al, Bender et al,...)

These considerations then determined the desired signal-to-noise ratios for the detectors. We proceeded to model all of the noise sources as shown in Figure 5.

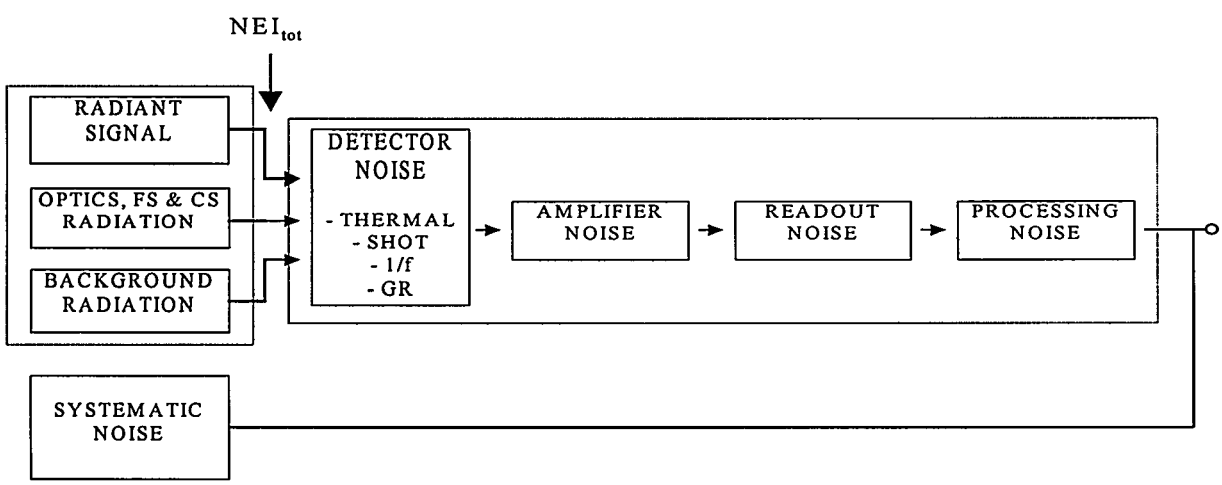



Figure 5. System noise components. Note: FS ≡ field-stop, CS ≡ cold-shield and GR ≡ generation recombination.

System noise, as illustrated in Figure 5, can be broken into three primary components – i) photon noise, ii) detector, amplifier, readout, and processing noise, and iii) systematic noise. We define the resulting detection signal-to-noise ratio[i], where Signal represents the mean value of the desired physical measurement and Noise the signal standard deviation due to system noise, as

$$SNR = \frac{Signal}{Noise} = \frac{\Phi_s}{NEI_{tot}},$$

where:

| | |
|---|---|
| $\Phi_s$ | signal irradiance, |
| $NEI_{tot} = \sqrt{NEI_{ph}^2 + NEI_{dar}^2 + NEI_{sys}^2}$ | total noise equivalent irradiance, |
| $NEI_{ph}^2 = NEI_s^2 + NEI_{op}^2 + NEI_{fs}^2 + NEI_{cs}^2 + NEI_{bg}^2$ | photon noise: signal + optics + field-stop + cold-shield + background, |
| $NEI_{dar}^2 = NEI_{\det}^2 + NEI_{amp}^2 + NEI_{ro}^2 + NEI_{dig}^2$ | electronic noise: detector + amplifier + readout + digitization, |
| $NEI_{sys}^2 = NEI_{xt}^2 + ....$ | systematic: cross-talk + .... etc. |

All of the above noise equivalent irradiances are referenced at the detector. When evaluating the detection SNR, the signal and detection noise can be referenced at any point in the system – at the aperture, between the optical train and filter, at the detector, at the amplifier etc. We reference the surface of the detector because it is an electro-optical system's natural optical ↔ electronic interface.

These considerations resulted in concerns on several of the spectral bands. Specifically, the predicted 1/f noise on the LWIR bands appeared to be a performance-limiting attribute at the anticipated operating temperatures. However, by lowering the focal plane temperature some five degrees we predict a sufficient amelioration; of course this has a significant impact on the performance of the cryogenic coolers for the focal plane array. Also, band H, designed to detect Cirrus cloud, was predicted to have a marginal signal-to-noise performance. The solution here was to use two sets of detector elements, and then perform a summing over the multiple pixels. Performance in the other spectral bands was predicted to be perfectly acceptable.

Other studies were performed starting in the conceptual design phase, and continuing through procurement of parts, and through assembly and testing sequences.

## 4. SUMMARY

We have described the use of physics-based end-to-end modeling and analysis as the context and foundation for the design of the Multispectral Thermal Imager. The EEM includes all of the relevant physics, and is allows a quantitative evaluation of design choices as measured by the bottom line: answers to questions posed by our customers. Using a physics-based system provides us with increased confidence in our results, especially where we need to extrapolate from the existing knowledge base.

As of the date of this writing, the MTI payload (Ref: Kay et al) is in calibration at Los Alamos National Laboratory for several months. The payload will be integrated with the satellite bus this Spring, with launch scheduled at the end of 1999. The ultimate test of our efforts will, obviously, come with on-orbit operations, in which we will quantitatively compare results from satellite measurements to known ground-truth. At that time the end-to-end model will contain all known as-built attributes of the MTI, and will be used as a tool to validate our understanding. The back-end of the EEM is transitioning into the analysis software that will be used at the Data Processing and Analysis Center. When the EEM is validated by actual measurements, it will be an even stronger tool, and, being based in physics, it can be applied to a number of other possible missions.

## ACKNOWLEDGMENTS

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## REFERENCES

1. Rick Piltz, Editor, *Our Changing Planet,* Global Change Research Information Office, University Center, MI, 1998.
2. H. S. Chen, Space *Remote Sensing Systems,* Academic Press, New York 1985.
3. H. J. Kramer, *Observation of the Earth and its Environment*, Springer-Verlag, New York, 1994.
4. Gregg Vane and Alexander F. H. Goetz, "Terrestrial Imaging Spectrometry: Current Status, Future Trends", *Remote Sensing of the Environment, 44, 117-12, 1993.*
5. David L. Glackin: "Overview of International Remote Sensing through 2007", in *Sensors, Systems and Next-Generation Satellites,* Hiroyuki Fujisada, Editor, Proceedings of SPIE Vol. 3221, 504-511 (1997).
6. James E. Slattery and Paul R. Cooley, "Space-Based Infrared Satellite System (SBIRS) Requirements Management" *1998 IEEE Aerospace Applications Conference Proceedings,* 223-232, 1998.
7. Tom Wilson and Robert Felt, "Hyperspectral Remote Sensing Technology (HRST) Program", *1998 IEEE Aerospace Applications Conference Proceedings,* 193-200, 1998.
8. Paul G. Weber, James Theiler, Barham W. Smith, Steven P.Love, Peter C. LaDelfe, Bradly J. Cooke, William B. Clodius, Christoph C. Borel and Steven C. Bender, "Measurement Strategies for Remote Sensing Applications", Invited paper at the 1999 IEEE Aerospace Conference, Colorado, March 6-13 1999 (1999).
9. R. M. Goody and Y. L. Yung, *Atmospheric Radiation Theoretical Basis,* Oxford University Press, New York, 1989.
10. A. M. Vogelmann, V. Ramanathan and W. C. Conant: "Comparison of Water Vapor Data at the Souther Great Plains Site and its Implications for Water Vapor Continuum Absorption in the Near Infrared During the ARM Enhanced Shortwave Experiment Period" Proceedings of the Sevenh Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 3-7, 1997, San Antonio, Texas, DOE report CONF-970365 (1998).
11. J. R. Schott, B. V. Brower, R. Bashkar, R. Raqueno and C. Salvaggio, technical Report RIT/DIRS 90/91-51-140, Digital Imaging and Remote Sensing Laboratory, Rochester Institute of Technology 1991.
12. A. J. Garrett and D. W. Hayes, "Cooling Lake Simulations Compared to Thermal Imagery and Dye Tracers." J. Hydr. Engineering., 123(10), 885-894, 1997.
13. C. Cox and W. Munk, "Measurement of the Roughness of the Sea Surface from Photographs of the Sun's Glitter", J. Opt. Soc. Am. Vol. 44, 838-850, 1954.
14. James Theiler and Bradley G. Henderson, "A Geometrical Constraint on Shadowing in Rough Surfaces", *Infrared Spaceborne Remote Sensing V,* Marija Strojnik and Bjorn Andresen, Editors, Proceedings of SPIE Vol. 3122, 271-279, 1997.
15. Bradley G. Henderson, James Theiler and Pierre V. Villeneuve, "The Polarized Emissivity of a Wind-Roughened Sea Surface: A Monte Carlo Model", *Remote Sensing of the Environment, 1997.*

16. Air Force Geophysics Laboratory, Hanscomb, MA.
17. Max L. Decker, Sandia National Laboratory, private communication (1993).
18. Optical research Associates, Pasadena, CA.
19. Peter C. LaDelfe, Los Alamos national Laboratory, private communication (1993).
20. Bradly J. Cooke, Bryan E, Laubscher, Christoph C. Borel, Terrence S. Lomheim and Christopher F. Klein, "Methodology for Rapid Infrared Multi-Spectral, Electro-Optical Imaging System Performance Analysis and Synthesis", *Aerospace / Defense Sensing and Controls,* Proceedings of SPIE, 8-12 April 1996.
21. John J. Szymanski, Christoph C. Borel, William Clodius, Anthony Davis, James B. Krone, Keri Ramsey, Barham Smith, Kathy Smith, James Theiler, Pierre Villeneuve and Paul G. Weber: "MTI Ground Data Processing and Science Retrieval Pipeline Architecture" *Proc. SPIE (1999) to be published* (1999).
22. D. A. Byrd, W. B. Maier II, S. C. Bender, et al: "Visible / Infrared Radiometric Calibration Station", Proceedings of the SPIE, Vol. 2268, 398-403, 1994.
23. S. C. Bender, W. B. Maier II, D. Byrd, et al, "The Los Alamos Calibration Laboratory for Multi-spectral and Thermal Imaging Radiometer Systems", *Proceedings Fourth SDL/USU Symposium on Infrared Radiometric Sensor Calibration, 1994.*
24. D. A. Byrd, F. D. Michaud, S. C. Bender, et al, "Design, Manufacture, and Calibration of Infrared radiometric Blackbody Sources", *Aerospace / Defense Sensing and Controls,* Proceedings of SPIE Vol 2743, 221-226 (1996).
25. D. A. Byrd, W. H. Atkins, S. C. Bender, R. W. Christensen and F. D. Michaud, "Vacuum-Compatible Standard Diffuse Source: Manufacture and Calibration" in *Illumination and Source Engineering,* Proceedings of SPIE, Vol. 3428, 9-22 (1998).
26. E. F. Zalewski, W. M. Rapoport, F. R. Sileo, et al, "On-board Calibration System for a Visible-to-Thermal Infrared Multispectral Imaging Sensor", Proceedings of the SPIE, Vol. 3439, paper 47, 1998
27. Jeffrey Rienstra and Mary Ballard, "Multispectral Focal Plane Assembly for Satellite Remote Sensing", 1998 *IEEE Aerospace Applications Conference Proceedings,* 233-241, 1998.
28. James Theiler, Bradley G. Henderson and Barham W. Smith, "Algorithms Using Inter-band Cross-correlation for Pixel Registration and Jitter Reconstruction in Multi-channel Push-broom Imagers", Proceedings of SPIE Vol. 3163 (1997).
29. James R. Wertz and Wiley J. Larson, Editors, *Space Mission Analysis and Design,* Kluwer Academic Publishers, Boston, 1991.
30. W. B. Clodius, P.G. Weber, C. C. Borel and B. W. Smith, "Multi-spectral band selection for satellite-based systems", SPIE Conference on Imaging Systems: design, Modeling and testing IX, 15-16 April 1998, Orlando, Florida, to be published in Proc. SPIE Vol. 3377, paper 3377-02 (1998).
31. Graeme L. Stephens, *Remote Sensing of the Lower Atmosphere,* Oxford University Press, New York, 1994.
32. John J. Bates, "A Decade of Multispectral Sea Surface Temperature Observations from Space", *Advances in Space Research,* 14, 5-14, 1994.
33. R. W. Reynolds, "A Real-Time Global Sea Surface Temperature Analysis", J. Climate Vol 1., 75-86 (1988).
34. R. Rex Kay, Brian C. Brock, Tammy D. Henson, Jeffrey L. Rienstra, Max L. Decker, N. Glenn Rackley, Paul G. Weber, Steven C. Bender and Donald A. Byrd, "An introduction to the Department of Energy's Multispectral Thermal Imager Project Emphasizing the Imaging and Calibration Subsystems", Proc. 12th AIAA/USU Conference on Small Satellites, Utah State University, September 1998 (1998)

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Paul Weber earned a Ph.D. in Physics from the Flinders University of South Australia. He then accepted a research position at Columbia University, where he worked on the equilibrium and stability of plasmas at high pressures. Since 1980 he has been at Los Alamos starting in the Advanced Diagnostics Group where he developed several particle beam, laser and spectroscopic systems. In 1986 he assumed responsibility for the experimental Reversed Field Pinch Physics program. In 1991 he moved to the Space Science and Technology Division, where he initiated several programs in optical and infrared remote sensing. Paul now leads the Space and Remote Sensing Sciences Group, and continues as Los Alamos Project Leader for the Multispectral Thermal Imager. He is the author, or co-author, of over 170 publications, conference papers and reports.