

MSTI-3 CALIBRATION AND CHARACTERIZATION

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Abstract

The objective of the Miniature Sensor Technology Integration - 3 (MSTI-3) calibration is to generate calibration equations for each of the payload sensors and fully characterize all spacecraft components. The calibration equations relate scene radiate flux to sensor output values. The parameters integrated into the calibration equations for the system include gain and integration normalization, linearity correction, dark offset, and non-uniformity correction. The absolute responsivity, spectral out-of-band sensor response, and non-ideal performance of the mid-wave infrared (MWIR), short-wave infrared (SWIR), and visible imaging spectrometer (VIS) sensors will be measured. The calibration will include estimates of measurement uncertainties generated with descriptions of their applicability to any particular on-orbit measurement objective. The procedures cover each of the sensors, payload components, bus electronics, and integrated spacecraft testing at multiple sites including Science Applications International Corporation, the Space Dynamics Laboratory Utah State University, Phillips Laboratory, and on-orbit. All requirement, procedural and test result documentation related to the system calibrations are being collected in a single document¹.

I. Calibration Approach

The objective of the calibration of the MSTI-3 spacecraft instrumentation is to obtain a functional relationship between incident flux on each sensor focal plane array (FPA) and each instrument output. The MSTI-3 short-wave and mid-wave

infrared imagers will be calibrated by Space Dynamics Laboratory Utah State University (SDL/USU); the visible wedge spectrometer by Science Applications International Corporation (SAIC) and end-to-end testing for the integrated spacecraft will be conducted by Phillips Laboratory Edwards AFB. The parameters measured independently of each other will be 1) spectral, 2) spatial, 3) temporal responsivity, and 4) absolute responsivity over the sensor's full dynamic range and covering the anticipated signal levels. Together, these individually characterized radiometric parameters comprise a complete calibration of the radiometric sensors².

II. MSTI-3 Description

The MSTI-3 spacecraft consists of two subassemblies and an interconnecting cable harness. The payload incorporates three sensors: a SWIR imager, a MWIR imager, and Visible Imaging Spectrometer (VIS) to perform its mission. To collect the required data in the infrared, MSTI-3 contains 7 spectral filters in the SW and 7 spectral filters in the MW. In addition, a star tracker is mounted directly to the payload. The payload includes a calibration plate for in-flight reference and a two-axis scanning mirror assembly that provides a 100°x180° field-of-regard.

PAYLOAD MODULE ASSEMBLY (PMA)

Short-Wave Infrared Camera
Mid-Wave Infrared Camera
Visible Imaging Spectrometer
Scanning Mirror Assembly (SMA)
Calibration Plate
Star Tracker
Electronics Control Module (ECM)

Control, communications, power, data recording, and data transfer occur through the BUS structure. To fully understand the data provided by MSTI-3, the entire system must be characterized and calibrated end-to-end as both individual components and as an integrated unit.

SPACECRAFT BUS ASSEMBLY (BUS)

- Sun Sensor
- Memory Storage Unit (EDMM)
- Reaction Wheels
- Tracking Telemetry & Control
- Solar Array
- Spacecraft Computer
- Cable Harness

III. MSTI-3 Objectives and Calibration Requirements

The MSTI-3 primary requirements are to characterize the mid-wave infrared (MWIR) below-the-horizon (BTH) clutter to sufficient fidelity for warm-body tracking, to characterize the mid-wave infrared (SWIR) BTH clutter to sufficient fidelity to impact future surveillance system designs, and to develop a near real-time state vector using a Kalman filter. A secondary requirement is to explore dual-use applications using the VIS, SWIR, and MWIR sensors. To attain these objectives the calibrations must be performed to the following fidelity:

- Relative Band-to-Band Accuracy: 1-2%
- Absolute Radiometric Accuracy: $\pm 20\%$
- Nonuniformity Correction: 0.1%
- Repeatability: 1% (Short-term Drift)
- Line-of-Sight Jitter: $\pm 25 \mu\text{rad/sec}$ (2σ)
- PSF: Characterized to 1% Peak
 Sampled at 1/5 Pixel
- Highest Temporal Frequency: 176 Hz
- Gimbal Knowledge: $\pm 50 \mu\text{rad}$

The spatial resolution and sensitivity of the optical sensors will be measured to show specifications of:

- Resolution: 50 x 50 m in SWIR and MWIR
- Resolution: <30 m in VIS
- Sensitivity: $0.03 \times 10^{-6} \text{ W/cm}^2 \text{ sr } \mu\text{m}$ in SWIR and MWIR

- Sensitivity: $10^{-7} \text{ W/cm}^2\text{-sr-}\mu\text{m}$ in VIS
- Filter Out-of Band Rejection must meet the following requirements:

Mode	Red Side	Blue Side
MWIR	1×10^{-5}	5×10^{-6}
SWIR	5×10^{-5}	5×10^{-6}

Filter #	$\lambda \geq 0$ %	$\lambda < 5$ %	$\lambda < 50$ %	$\lambda > 50$ %	$\lambda > 5$ %	$\lambda \leq 0$ %
1	4.21	4.23	4.24	4.44	4.45	4.47
2	4.21	4.23	4.24	4.42	4.43	4.45
3	4.21	4.23	4.24	4.40	4.41	4.43
4	3.43	3.53	3.58	3.98	4.04	4.16
5	4.21	4.23	4.24	4.38	4.39	4.41
6	4.21	4.23	4.24	4.34	4.35	4.37
7	4.21	4.23	4.24	4.30	4.31	4.33

MWIR Filter Wheel Definition (μm)

Filter #	$\lambda \geq 0$ %	$\lambda < 5$ %	$\lambda < 50$ %	$\lambda > 50$ %	$\lambda > 5$ %	$\lambda \leq 0$ %
1	2.66	2.69	2.705	2.945	2.96	2.98
2	2.67	2.69	2.705	2.895	2.91	2.93
3	2.67	2.69	2.705	2.855	2.87	2.89
4	2.67	2.69	2.705	2.825	2.84	2.86
5	2.67	2.69	2.705	2.795	2.81	2.83
6		2.69	Rugate		3.03	
7		2.69	Rugate w/Notch		3.03	

SWIR Filter Wheel Definition (μm)

IV. Calibration Testing and Analysis

The tests that provide the characteristics of the MSTI-3 sensors are repeated and refined as the payload and integrated spacecraft proceed through the calibration. The following is a list of tests to be conducted at the various facilities utilized for MSTI-3 characterization and calibration:

- Dark Noise/Pixel Electrical Crosstalk SWIR/MWIR/VIS
- Radiometric Sensitivity and Linear Response SWIR/MWIR/VIS
- NUC Operation and Gain for SWIR and MWIR

- Non-Uniformity of VIS
- SWIR and MWIR Cooler (Time to Function, Power, Hold Time, Noise)
- SWIR and MWIR Filter Wheel (Speed)
- SWIR and MWIR Filter
 - Out-of-Band Rejection
 - Transmittance
- Spectral Response and Integration Effects for SWIR/MWIR/VIS
- MTF SWIR/MWIR/VIS
- SMA Gimbal Angular Rate, Range, and Accuracy
- Long and Short Term Repeatability of SWIR/MWIR/VIS
- Cal-Plate Response to SWIR and MWIR / Calibration
- Payload Thermocouples: Accuracy, Sensitivity, Resolution, Repeatability
- Software Testing
 - Acquisition (Thresholding)
 - Intensity Centroiding
 - Satellite-Fixed Stare
 - Earth-Fixed Stare
 - Step Stare
 - Closed Loop Track
 - Loss of Track Coast
 - Track Stability
 - Pointing Accuracy
 - Tracking/Pointing Jitter and Accuracy
 - Open-Loop Track
- Geometric Alignment SWIR/MWIR/VIS
- Polarization SWIR/MWIR/VIS
- Solar Exclusion Angle SWIR/MWIR/VIS
- Star Tracker - Resolution, Sensitivity, Field of View, Boresight
- Telemetry Downlink Integrity and Data Compression
- Data Storage Integrity
- Bus Noise and Spacecraft Thermal Sensitivity

The calibration will include estimates of measurement uncertainties with descriptions of their relevance to any particular on-orbit measurement objective. There are several general classes of uncertainties that must be addressed³. Among these are random, calibration residual, nonideal sensor performance, and standard source uncertainties. Random uncertainties include short-term repeatability (noise) and long-term repeatability. Calibration residual uncertainties are associated with

parameters in the calibration equation. An example of a calibration residual uncertainty is the gain or integration-mode normalization parameter. Nonideal sensor performance uncertainties are a result of nonideal sensor response and are addressed in a radiometric model. The radiometric model of the sensors will characterize the relative spectral responsivity of each array. A variation across the passband gives rise to an uncertainty of absolute flux, unless the spectral distribution of the target is known. Standard source uncertainties include uncertainty in the temperature and emittance of blackbody simulators.⁴ The following paragraphs provide descriptions of the test plans to accomplish the MSTI calibration requirements.

Dark noise, dark offset, and pixel electrical crosstalk for the SWIR, MWIR and VIS sensors are of primary importance for characterization and facility-to-facility cross check. Dark noise is the short-term repeatability in the limiting case of zero radiometric input. Dark offset is the mean response to zero input flux, and dark-offset correction is the first step in applying the calibration equation to each sensor. Calibration personnel will characterize dark noise, dark offset and evaluate crosstalk between the IR and VIS sensors with and without illumination from a source at the aperture. Data will be recorded with the SWIR and MWIR camera dewar windows mechanically covered at cold temperature (photon flux below the electrical noise of the system) and the VIS covered obscuring any possible light leaks. The data will be analyzed to characterize pixel-to-pixel dark noise and crosstalk for both integration time and gain, characterize the short-term repeatability, and characterize crosstalk from the gimbal and readout electronics.

A radiometer's relative spectral responsivity is its peak-normalized responsivity to radiation at different wavelengths both within and outside its spectral passband. Calibration personnel at SDL/USU will measure the spectral

passband and the out-of-band blocking for the SWIR and MWIR array. The resulting data are used to calculate the effective flux for absolute responsivity calibrations and to interpret flight data. To characterize the filter spectral passbands, calibration personnel will process data from a harmonic distortion calibration using an external Michelson interferometer to give each array's nominal response as a function of wavelength. These spectra will be normalized with the external interferometer's output spectrum to give the relative spectral responsivity for each camera array. Calibration personnel anticipate that this method will characterize the spectral responsivity (both inside and outside the passband) of each array to approximately one percent of the peak spectral response. To characterize the radiometer's out-of-band blocking below one percent of the in-band spectral responsivity, a collimator will be used to increase the throughput from an external Michelson interferometer. Using this method, the out-of-band blocking of the radiometer filters will be characterized over the wavelength of the calibrator filter passbands. Calibration personnel will Fourier transform the resulting interferograms and normalize the resulting spectra. In previous programs, SDL/USU calibration personnel have successfully identified out-of-band leaks down to approximately 10^{-4} to 10^{-6} of the sensor's peak spectral responsivity.

A pixel-pixel non-uniformity correction matrix for the SWIR and MWIR will be derived for the focal plane arrays. This test sorts the pixels in two groups, nominal and outlying, based on the magnitude and repeatability of their NUC coefficients. The determination of nominal pixels verifies that the integration mode normalization, linearity correction, and absolute responsivity (and therefore the relative spectral responsivity) are within specified limits for the nominal pixels within the array. In addition, the determination of nominal pixels identifies outlying pixels or bad pixels (hot, dead, time-dependent). To determine the array's NUC matrix and to identify nominal

pixels, calibration personnel will record samples of the camera's response to an extended source at a minimum of three levels of illumination per decade over the full dynamic range of the camera. The uncertainty of each pixel's non-uniformity correction can be estimated from a standard deviation of NUC matrices determined from each temperature and integration mode. Calibration personnel will then sort each pixel into nominal and outlying based on the mean NUC coefficient for nominal pixels falling within the limits bounded by the standard deviation. Outlying pixels differ from nominal pixels according to the limits stated above and will be defined in a "bad pixel map" for both detectors.

Calibration personnel will ratio the offset-corrected extended source data from the nominal detector test to provide a gain factor that normalizes the responses from each integration time for each array to the longest integration time. This calibration determines the integration-time normalization factors in the sensor's calibration equations and estimates the uncertainty of each integration-time normalization. The integration-time normalization uncertainty will be determined from the internal consistency of these data.

Sensitivity and steady-state linearity calibrations for the SWIR, MWIR, and VIS provide a transfer function for converting actual sensor response to an ideal linearized response throughout the camera dynamic range. The sensitivity of the camera will be found by utilizing an extended-area source to produce outputs from zero to saturation. Blackbody temperatures or extended visible source data will be selected to provide overlapping responses. The camera output will be recorded at both gain settings, the three longest integration times (times spanning relevant background observations), and in each of the filter positions. This calibration will provide initial measured sensitivity for the camera with the dependence on filter optical transmittance accounted. The steady-state

linearity data set will be corrected for focal plane non-uniformity across the FPA and the array's nominal response computed. The temperature sets will then be merged to give camera response versus relative input flux. Calibration personnel will fit this data set to derive a steady-state linearity correction function and determine the RMS noise and standard deviation associated with each flux level.

Small-signal linearity calibrations will augment the steady-state linearity calibration by measuring changes in the radiometer's instantaneous responsivity throughout its dynamic range. This small-signal responsivity is the slope of the radiometer's linearity correction function. The small-signal linearity data will be processed to give the modulated component of response versus steady-state response. Calibration personnel will fit these data and integrate the resulting functions to provide the linearity correction functions in the radiometer calibration equations. Linearity correction uncertainties will be estimated from the residuals of the small-signal curve fit and by comparing the linearity correction functions determined in this test to the linearity correction functions determined by the steady-state linearity test.

To determine the on-axis point response (spread) function, calibration personnel will record the radiometer's response to a stationary 13-mrad collimated source at five positions in each radiometer's field of view, at the approximate center of the arrays, and near each of the four corners of the arrays. The collimated source will not intentionally be placed exactly on a pixel; rather, the response for a centered (in-scan and cross-scan) spot will be determined by interpolation. Appropriate blackbody temperatures, neutral density filters, and radiometer integration times will be chosen at the time of data collection based on the real-time sensor display to provide a good signal-to-noise ratio. Calibration personnel will offset correct and linearity correct the radiometer responses at each position. These corrected responses will

then be decommutated to give a two-dimensional response matrix for each detector. Calibration personnel will peak normalize the resulting matrices to give the on-axis point response function for each detector. This calibration will also identify spatial scatter sources in each radiometer array.

The point response function calibration will be used for several more characterizations of the MSTI-3 sensors including the effective field-of-view solid angle, MTF, and FPA-FPA crosstalk. To determine each detector's field-of-view solid angle, the relative detector positions will be determined as the centroid of the on-axis point response functions. A sensor's modulation transfer function (MTF) describes its relative responsivity versus spatial frequency. Diffraction, image quality, scatter, and finite detector dimensions all affect a radiometric sensor's MTF. Especially important will be the evaluation of spatial aliasing frequencies. Calibration personnel will compute the modulation transfer functions from the peak-normalized, two-dimensional Fourier transforms of the on-axis point response functions. Possible crosstalk between arrays will be identified in the point response functions as localized scatter sources. The MSTI-3 crosstalk calibration will characterize crosstalk between radiometer arrays by stimulating a single radiometer array and measuring the crosstalk response in the other array. This test will identify and measure possible scatter sources over as much of the MSTI field-of-regard as is possible. This test is an extension of the point response function test and will characterize additional scatter sources beyond the limits previously mapped. MTFs will be used both to predict and to correct the MSTI-3 sensor responses to a variety of on-orbit scenes.

SWIR and MWIR cryocooler operating parameters will be obtained for input to data acquisition timing sequences. Also, the FPA temperature stability as a function of cryocooler performance will be determined. A plot of the FPA temperature versus elapsed time will

determine the time at which a FPA was at operating temperature, and the time at which each cryocooler starts and stops cooling will determine hold time at ambient temperature.

A SWIR and MWIR filter wheel speed test will determine sequence times for the filter wheel. The filter wheel is rotated through all seven filters, stopping to take consecutive frames of image data at each filter setting. Analysis of the data determines the time required between each filter position and the time for the FPA to settle at each filter position with effects of rolling readout included.

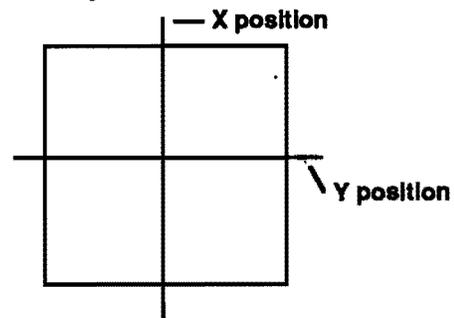
The gimbal will be fully exercised to determine settle time, angular rate, and angular range. The time to access the calibration plate, including settle time, will also be determined. Encoder accuracy and jitter estimates for the payload pointing assembly will be determined through a five-step procedure. An azimuth and elevation scan stop-to-stop provides the angular rate. A 360° rotation at the limit of mirror motion utilizing a source placed at the expected limit of the FOR and detected by the VIS focal plane will provide a measured angle from the centerline normal to the payload comparable to the XY encoder readouts. Returning to the same point repeatedly during this measurement and taking the standard deviation will provide the accuracy of the encoders. A step scan across the FOR matching the FOV dimensions provides data points for settle of the gimbal (VIS sensor operating at 30 Hz) as it views the point source centered in the FOR. A 180° rotation and settle point to the calibration plate determines the time required for gimbal rotation to view the cal-plate.

Utilizing a NIST-traceable temperature sensor the calibration plate will be set at its initial temperature and monitored to determine the time required to stabilize. Continuous SWIR and MWIR data will develop a temperature profile and image reference file over the stability period. The temperature raised to a second

setting provides a two-point response for both infrared FPAs and the settle time at the second temperature. Decreasing the temperature setting to the lower setting and measuring the time required for the temperature to again settle will develop a standard deviation of time and temperature and determine hysteresis as the temperature is raised and lowered.

An extended source will be used to measure the spectral radiance responsivity and pixel-to-pixel non-uniformity of the VIS at three levels of illumination. A well-characterized source will provide multiple lines within the wedge filters spectral response of 600 to 858 nm. The resulting spectrum divided by the source radiance gives the spectral radiance responsivity. The calibration also derives the pixel-to-pixel non-uniformity matrix for the focal plane array and identifies outlying (hot, dead, time-dependent) pixels. The test sorts the pixels in two groups, nominal and outlying, based on the magnitude and repeatability of their non-uniformity coefficients. The determination of nominal pixels described below verifies that the integration mode normalization, linearity correction, and absolute responsivity (and therefore the relative spectral responsivity) are in within specified limits for the nominal pixels within the array. In addition, the determination of nominal pixels identifies outlying pixels.

Geometric alignment of the SWIR, MWIR, and VIS is accomplished utilizing a hot wire source oriented vertically and horizontally as shown below determining



the X and Y relational pixel positions on the SWIR, MWIR, and VIS FPAs. This information will provide geometric

alignment of the FPAs relative to each other. [Another method would be to generate a point-source matrix by positioning a point source in a 20 by 20 mrad raster scan across the entire sensor field stop of each FPA and recording the camera responses at each of these points.] Translation of the source from the top to the bottom of the image FOVs and peak normalizing a matrix of responses produces a check of the effective field-of-view solid angles, sensor vignetting and scatter.

Generally sensors that use refractive lenses and anti-reflectance coatings, mirrors and high-reflectance coatings, or thin-film narrow bandpass filters are not polarization sensitive. This is because the optical components are usually circularly symmetric and the radiation falls at or near normal incidence upon these optical elements. However, polarization effects will be measured by utilizing a simple rotating-element polarimeter through the optical train. The flux will be measured with the polarizer-analyzer adjusted to maximum transmittance, Φ_{\max} , and minimum transmittance, Φ_{\min} . Maximum and minimum transmittance must include gimbil movement. The following equation (1) will indicate total optical train degree of polarization:

$$P = [(\Phi_{\max} - \Phi_{\min}) / (\Phi_{\max} + \Phi_{\min})] \times 100[\%] \quad (1)$$

Solar exclusion angles of the SWIR, MWIR and VIS sensors are determined by calculating the maximum energy the FPAs can absorb without damage through the use of the maximum power density data supplied by the focal plane manufacturers and the optical throughput. Utilizing sources and the gimbil measure the maximum angle at which the sensor can see an off-angle source without payload movement will be measured. This defines the exclusion angle for the sensors without spacecraft interaction.

VIS short-term repeatability is characterized at different levels of

illumination throughout the dynamic range of the wedge filter. Data from the spectral radiance responsivity test provides at least two levels of illumination per decade of the dynamic range. Calibration personnel will average the spectral data to obtain a standard deviation across the spectral lines sampled to give the short-term repeatability at each level of illumination.

Long-term repeatability is another contributor to measurement uncertainty. To characterize the long-term repeatability of the sensors, calibration personnel will record the following sequences each day during the calibration periods:

1. Source intensity sequence at four flux intensities (and at three wavelengths).
2. Source spectral sequence at six to eight wavelengths (at the same flux level).

The source intensity data will be processed to show flux variations over time. The wavelength sequence will provide the measured spectral radiance benchmark for the FPA. The standard deviation of these measured spectral radiances gives the long-term repeatability for each sensor.

A data stream test will determine spacecraft data downlink capabilities. Command sequences will also be tested. Format and integrity of known test data input and output from the EDMM is required prior to payload/bus integration. Communications testing exercises the command and low-rate telemetry capabilities, as well as demonstrating the ability to uplink software changes and command modifications. High-Rate Data Channel (HRDC) testing verifies the selection and reproduction of camera images, compression and expansion of PMA and spacecraft engineering data over the HRDC interface.

Power tests exercise PMA commands and verify power consumption of the PMA in all operating modes. The testing verifies the spacecraft's ability to control image acquisition parameters in response to commands. Gimbil testing also verifies correct response to input

command and validates time response to movement. Track verification demonstrates the ability to acquire and track a target with all three cameras. This is accomplished with both a fixed and moving target at several threshold levels for the tracker. Temperature sensor testing provides calibration and reference data on the temperatures provided by all spacecraft thermocouples. Finally, the physical characteristic measurements verify the dimensional, mass, center of gravity of the PMA relative to the BUS and verify compatibility.

The goal of the calibration is to describe how each camera's raw output in counts relates to the true scene in radiometric units. The above test plans consider the conversion of raw counts to true scene flux to be a two-step process. The first step converts a camera's output to a measured flux with calibration equations. The second step relates the measured flux to the true scene flux with a radiometric model. A calibration equation is generated for the MSTI-3 sensors to convert the output in counts to measured radiance.

V. Engineering and Component Level Characterization of the Payload

SAIC will accomplish initial component validation and checkout prior to integration into the payload module. Validation will include a minimum set of characterization tests including: focus and alignment on the optical train, NUC, gain, noise, responsivity, crosstalk and drift on all three sensors (SWIR/MWIR/VIS), and solar exclusion angle determination. Prior to shipment of the payload to SDL/USU the system will undergo initial software checkout. SAIC will begin visible sensor calibration in San Diego and complete testing at PL 1-90.

The SAIC tests are divided into two categories: 'Required' and 'Desired'. The 'Required' characterizations must be accomplished prior to shipment to SDL/USU, the data reviewed, and configuration changes to the spacecraft

made, if necessary, and re-verified by the SWG. The 'Desired' characterizations may be delayed to PL Area 1-90 but must still be accomplished, and the data reviewed by the SWG prior to integration with the Pegasus. The required tests are: sensitivity and linearity calibrations for the SWIR and MWIR, initial non-uniformity correction matrix for the SWIR and MWIR, cryocooler operating parameters determination, filter wheel tests, gimbal settle time, angular rate, and angular range, calibration plate hysteresis, VIS spectral radiance responsivity and pixel-pixel non-uniformity, and tracking capability using three software tests. The desired tests are: geometric alignment of the SWIR, MWIR, and VIS; polarization sensitivity; solar exclusion angles of the SWIR, MWIR, and VIS sensors; VIS linearity; sensitivity of the VIS camera; VIS short and long-term repeatability; and, VIS MTF

SAIC is also responsible for providing documentation and data from vendors on performance of base components such as DSI and Rockwell filters, the Amber focal planes, and spectral traces for all optics and optical coatings. This information will include initial out-of-band rejection data and maximum power density. Any other information available from parts vendors to increase reliability or provide initial points of reference for the calibrations is also being collected.

SAIC will perform initial software checkout as payload integration is accomplished and hardware becomes available. The checkout of the software will be an iterative process as the sensors are calibrated at the various facilities. The data stream will be collected after the SDL/USU interface utilizing the spacecraft simulator to extract data at 24 Mbits/sec from the payload. The data in raw counts will be provided to Hanscom AFB for initial data compatibility tests with the data-reduction software. (Hanscom AFB is the focal point for data management and compatibility for MSTI-3.)

VI. Engineering and Component Level Characterization of the Bus

Spectrum Astro is responsible for performing initial bus component validation and checkout prior to shipment and integration into the spacecraft at Phillips Laboratory (PL). All the tests at Spectrum Astro are being accomplished as acceptance tests; then the bus components are provided to Phillips Laboratory Edwards AFB for integration into the payload/bus system and further checkout. Format and integrity of digitally generated data input and output from the EDMM is being required prior to payload/bus integration with data input and initially tested at Spectrum Astro or PL/Edwards in parallel with the SDL/USU calibration.

The EDMM is designed and built by Spectrum Astro with a total memory capacity of 8.7 gigabytes. Acceptance testing will show data quality uniformity for the full capacity of the storage unit. The MSTI program is utilizing read only storage (ROM) on the EDMM for ten sequential frames of digital data, i.e., ten distinct images. When the cameras are available, ten sequential, but individually distinguishable frames of data will be stored in ROM. This data will then be used during end-to-end testing for noise analysis of the telemetry system and total system noise signature tracing if S/N does not meet specifications. These frames will also be available on-orbit to provide baseline comparisons in noise signature over the lifetime of the satellite.

Acceptance testing has been accomplished by Ball Aerospace Systems Group on the star tracker⁵. The tracker was examined to determine its probability of acquisition. The test used a simulated star field to acquire and track a star of magnitude 4.6. Successful acquisition is defined as providing star position data within five seconds. A probability of acquisition-vs-threshold command magnitude graph was constructed from the data. Tests at PL Area 1-90 will confirm the data obtained with the acceptance testing.

The Phillips Laboratory at Edwards AFB with oversight from the MSTI Science Working Group⁶ (SWG) will accomplish the calibration and characterization of the bus systems at the PL Area 1-90 facility. Characterization of the bus will include a minimum set of tests including star tracker resolution, sensitivity, and FOV, bus noise signature, telemetry throughput and data quality, EDMM storage capability, sun sensor resolution, and thermocouple accuracy.

The MSTI-2 spacecraft will be used for risk mitigation experiments. This is possible due to the nearly identical nature of the MSTI-2 and 3 bus. The data storage, IMU, reaction wheels, sun sensor and other moving components are duplicates between the two bus systems. Jitter induced by the bus structure can therefore be measured on the MSTI-2 bus and translated to the MSTI-3 bus. The telemetry downlink and data retrieval methodology is also the same, including data access points around the world. Any components that can be tested with the MSTI-2 spacecraft will be exercised to help understand the performance that will be inherent in the MSTI-3 spacecraft.

The primary bus feedback component that affects data collection is jitter induced by moving parts. Jitter will be present during thrust operations to adjust orbit or move the spacecraft to a new orientation. Little data will be taken during these periods and can be discounted. The MSTI-2 data will be examined for jitter from use of the reaction wheels to maintain spacecraft stability and spinning of the EDMM data storage disk. Utilizing the MSTI-2 spacecraft the reaction wheels and the EDMM will be exercised to provide a zero-G measurement of bus jitter. The wheel speed will be monitored for stability after the spacecraft is maneuvered in point mode to view the Moon. Motions from the payload will be neutralized by disabling the gimbal control in a fixed position on the Moon, the MWIR sensor will be turned off, including its cryo-cooler, and data will be taken in the SWIR

at 30 Hz for ten seconds. Fifteen seconds into the data acquisition the SWIR cooler will be turned off. The data will be analyzed for image stability by time averaging the images to determine image blur.

The data acquired with MSTI-2 will be analyzed for data quality from the receiving stations. The agency data tapes will be compared and documented from each of the real-time stations for noise patterns and drop outs.

VII. High-Fidelity Payload Calibration⁷

SDL/USU will accomplish the calibration and characterization of the infrared sensors and fundamental optical testing of the payload gimbal. The calibration will define the engineering unit characterization of both the short-wave and mid-wave infrared primary sensors. In order of priority, the measurements being accomplished are filter out-of-band, spectral response, MTF, responsivity (which includes dark current, NUC, gain, integration, sensor cross-talk), and responsivity drift. During the IR sensor measurements the on-board calibration plate will be tested for temperature stability and response time to programmed temperature variations. Data will be obtained on sensor response to the cal-plate.

SDL/USU will perform the calibration of the MSTI-3 infrared sensors by characterizing overall responsivity in terms of individual radiometric parameters. These sensor parameters will describe (1) each infrared camera's responsivity over its dynamic range, (2) its spectral responsivity, (3) its spatial responsivity, and (4) its temporal responsivity. Although individual calibration products relate to individual responsivity domains, the calibration will characterize the sensor as a complete electro-optical system, rather than as its individual components of telescope, spectral filters, detectors, and read-out electronics. When the sensor is

illuminated with an on-orbit scene, it responds in units of raw counts. The goal of the calibration is to describe how the sensor's raw output in counts relates to the true scene in radiometric units. This test plan considers the conversion of raw counts to true scene flux to be a two-step process. The first step is to convert the output of the camera to a measured flux and is accomplished with calibration equations. The second step is to relate the measured flux to the true scene flux and is accomplished with a radiometric model.

The SDL/USU testing will utilize the MIC3 infrared calibration cell and the SPAS vacuum chamber for payload operation. The MIC3 incorporates four optical functions into a single, cryogenically cooled dewar: (1) a collimated source, (2) a Jones source, (3) an extended source, and (4) a scatter source. The calibration source design is based on several previous calibration efforts, including the cryogenic infrared radiance instrumentation for shuttle (CIRIS 1A) and the infrared background signature survey (IBSS)⁸. The calibration source interfaces to the SPAS instrument chamber with vacuum, radiation-shield, and cold-shield continuity.

The calibration will also provide the estimates of random (noise), calibration residuals, nonideal sensor performance, and standard calibration source uncertainties. Some calibration products will be unique to individual detectors and/or individual integration times. For example, calibration personnel will measure and report the non-uniformity correction (flat field coefficient) for each pixel. Other calibration products are expected to be global for a given array and/or integration time. The SDL/USU calibration data archive will include responses from all detectors so global or individual response uncertainties may be calculated during post-processing as needed.

The sensor radiance calibration equation (2) below relates the camera's response to the measured radiance.

Application of the radiance equation consists of two steps. The first step is to convert the sensor response to corrected response, and the second step is to convert the corrected response to measured radiance. The following equation determines a measured radiance for each pixel and the unique measured radiance reported by each detector corresponds to the energy radiating from unique spatial locations in the measured scene.

$$L_m = \frac{1}{\mathfrak{R}_L} r_c = \frac{1}{\mathfrak{R}_L} \left[\frac{G_{it}}{NUC_{ext}} F_{Lin}(r - DO) \right] \quad (2)$$

where:

- L_m = measured radiance in W/cm²sr
- \mathfrak{R}_L = peak radiance responsivity in counts/W/cm²sr
- r_c = sensor corrected response in counts
- G_{it} = integration time normalization (unitless)
- NUC_{ext} = extended source non-uniformity correction (unitless)
- $F_{Lin}(\)$ = linearity correction function
- r = sensor response in counts
- DO = sensor dark offset in counts

The radiometric model relates the MSTI-3 radiometer's measured radiance from the calibration equations to the true scene radiance presented to the sensor. The radiometric model allows experimenters to:

1. Make a better estimate of the true scene flux
 2. Estimate measurement uncertainties.
- The radiometric model characterizes the radiometer's spatial, spectral, and temporal responsivity domains and random uncertainties. The radiometer's spatial domain will be characterized by detector positions, and the modulation transfer function (MTF). The spectral domain will be characterized by the in-band relative spectral responsivity, the out-of-band blocking, and the spectral purity for each of the radiometer filters. The spectral purity analysis will investigate the uncertainties of the radiance responsivity and radiance responsivity for varying source spectral distributions. Random

uncertainty analyses will include the radiometer's short-term repeatability over its dynamic range (including dark noise) and the radiometer's long-term repeatability.

VIII. Integrated System End-to-End Calibration

The Phillips Laboratory at Edwards AFB in conjunction with SAIC and the MSTI SWG will accomplish the calibration and characterization of the integrated payload/spacecraft at the Area 1-90 facility and Area 1-42/SPEF facility.

The end-to-end system tests at Area 1-90 will determine total system noise levels, data synchronization, data quality and system incompatibilities at ambient conditions. The test matrix accomplished at SDL/USU to determine engineering unit level testing will not be repeated at Area 1-90; however, a complete set of multiple/sequential frame data taken at Area 1-90 will provide an end-to-end system evaluation verifying the PMA/BUS interface. The characteristics to be examined from the data set collected are: noise level, signal response (multiple signal and spectral levels), jitter, repeatability, field-of-view, crosstalk, data throughput, and system control. The tests are designed to find small imperfections of spacecraft components that may drive performance (i.e., pinholes in the filter wheel will dominate out-of-band contribution, slightly imperfect solder connections may couple more strongly to EMI from the bus, etc.). Tracker signal-to-noise (S/N) and gimbal response will be examined to determine pointing function versus actual response. Tests performed at Area 1-90 will provide inputs to the data reduction software and the final calibration equations. A data-stream test will determine spacecraft data downlink capabilities and drop-out anomalies, if present.

End-to-end system calibration at the PL Area 1-42/SPEF facility will provide the pre-launch test opportunity for

radiant flux measurements at simulated on-orbit thermal load and vacuum conditions. The end-to-end system tests will determine total system noise levels for the infrared cameras, thermal drift, data synchronization, data quality and command script checkout. The test matrix will require collecting the last multiple/sequential frame data set prior to integration in the Pegasus. The characteristics to be examined from the data set collected are: noise level, signal response (multiple signal and spectral levels), repeatability, data throughput, and system control. Tests performed at SPEF will provide input to the data reduction software and the finalized calibration equations. A data-stream test will determine spacecraft data downlink capabilities and drop-out anomalies, if present, as at PL Area 1-90. To accomplish these objectives, four test sequences will be accomplished: 1&2) two backgrounds simulation sequences, a step-stare closed-loop track and a spot-stare open-loop track, utilizing both SWIR and MWIR; 3) a simulated track utilizing all three sensors; and 4) a pre/post calibration plate sequence.

IX. Performance Monitoring

Once on-orbit, a series of characterization tests are planned. Initially the spacecraft will be fully exercised to determine the sensor suite and software performance with benchmarks to the ground calibrations. Prior to and after every data collection observation a calibration procedure will be followed which includes deep space for a zero flux measurement, a two-temperature measurement of the calibration plate for the infrared cameras (representative of mean earth temperatures in the 4.3 μm absorption band and with the primary filters of the observation), and stellar observations for the visible. A periodic test will be conducted on a timeline determined from the long-term repeatability measurements that assesses sensor degradation of the optical train,

changes that may occur in off-axis scatter, and the modulation transfer function.

The fundamental tests that will be initially performed will mirror a pre- and post-shipment test (PPST) accomplished as the payload and spacecraft are moved from one calibration site to another. The PPST shows base operational conditions of power, gimbal movement, SWIR, MWIR and VIS response, and operation of the filter wheel. The data will be analyzed each time with respect to the values obtained on the previous test and will be traceable back to the payload tests performed before leaving SAIC.

The tests performed for on-orbit characterization of the sensors will provide an update to the radiance calibration equation. The two-temperature measurement provides the needed information for calculation of non-uniformity to accompany each data observation. The periodic test uses additional observations of stellar sources and the calibration plate. The measured radiances will provide changes in the ground-calibrated measures of absolute responsivity over each sensor's full dynamic range, spectral, spatial, and temporal responsivity.

X. Summary

The MSTI-3 primary objective is to provide characterization of the SWIR and MWIR BTH and limb clutter to a fidelity that will resolve issues that have been debated and remained open for twenty years. To accomplish this data collection goal, however, requires that the data collection capabilities of the MSTI-3 sensor system be thoroughly understood. Characterization and calibration is therefore an inviolate process to define the radiometric characteristics of the sensors and support system being flown on the spacecraft.

To ensure that the above process is meaningful, the MSTI-3 program is utilizing all the available resources to fully

calibrate and characterize the spacecraft system. The Science Working Group team is developing the processes to fully characterize the system and producing a single document containing all system calibration information to aid in data collection and reduction efforts.

8. Wyatt, C.L., Jacobsen, L., Steed, A., 1988, "Portable Compact Multifunction IR Calibrator," Proceedings of SPIE, Vol.940, pp. 63-72.

XI. Acknowledgments

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References

1. Gobel, R., Ratkowski, A., and Jeffrey, W., 1994, "Miniature Sensor Technology Integration-III Calibration Test Plan," ANSER, 31 July.
2. Wyatt, C.L., 1978, Radiometric Calibration: Theory and Methods, Academic Press, Inc., Orlando, FL, p.4
3. Wyatt, C.L., 1991, "Sources of Error in Radiometric and Spectrometric Measurements," SDL/USU-SDL/90-060-II.
4. Sargent, S., 1993, "Spirit III Infrared Sensor Ground Calibration Test Plan," SDL/USU-SDL/91-118A.
5. "Acceptance Test Procedure, MSTI CT-621 Star Tracker - End Item Acceptance Data," 1994, Ball Aerospace Drawing 529373, March.
6. Jeffrey, W., Fraser, J., Schneider, G., 1994, "Miniature Sensor Technology Integration-III Science Objectives," to be published, Proceedings of the 1994 Small Satellite Conference, August.
7. Jensen, G., 1994, "Radiometer Calibration," SDL/USU, draft from 16 May MSTI-3 Calibration SWG.