

Mars Exploration Rover (MER) Project

Mini-TES Calibration Plan

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1 INTRODUCTION

The Athena Miniature Thermal Emission Spectrometer (Mini-TES) instrument is a Michelson interferometer derived from the Mars Observer and Mars Global Surveyor Thermal Emission Spectrometer (TES) instruments. The Mini-TES covers the wavelength range from 5 to 29.5 μm (1997 to 339.5 cm^{-1}) at a spectral sampling of 9.965 cm^{-1} . A solenoid-activated field stop can be removed from the optical path to provide an instantaneous field of view (IFOV) of 20 mrad, or inserted to provide an IFOV of 8 mrad. An integral part of the Mini-TES instrument is the Pancam Mast Assembly (PMA), which contains the Mini-TES pointing mirror for azimuth and elevation scanning and an internal calibration target. A second calibration target is mounted externally on the rover. Azimuth and elevation actuators control the pointing mirror and provide contiguous spatial coverage in both the 8 and 20 mrad IFOV modes. The pointing mirror assembly allows Mini-TES to produce spectral image cubes over a 360° range in azimuth and from -50° below to +30° above the rover deck in elevation. The pointing mirror assembly also provides a view of the internal and external full-aperture calibration targets.

1.1 Purpose

The purpose of this plan is to define a consistent method to calibrate the Mini-TES, by 1) establishing a framework for the generation of Controlled Documents used to assemble the Mini-TES, and 2) defining or referencing the methods and types of tests used to validate the radiometric, geometric, thermal, optical, and mechanical performance against the functional requirements outlined in the Mini-TES Functional Requirements Document (FRD) (MER 420-2-413, JPL D-19706) and other MER project requirements. This plan also establishes a prioritized test sequence, so that verification of requirements takes place in a systematic and timely fashion, and describes performance of preflight calibration, the result of which will be delivery of a fully tested instrument that meets or exceeds the functional requirements. The tests described in this plan will provide the data needed to clearly understand the accuracy, precision, and limitations of Mini-TES calibration.

The Mini-TES calibration plan is divided into two major parts: instrument-level tests and calibration, and integrated Mini-TES/PMA-level test and calibration. Also included is software testing, as it relates to functional tests and calibration, although more extensive software testing will be addressed in a separate procedure. Inflight calibration plans also are discussed.

1.2 Requirements

The primary goal of calibration and testing of Mini-TES is to verify that the instrument will meet or exceed all of the MER Project requirements relevant to infrared hyperspectral observations on Mars. The relevant requirements are compiled in the MER Project System Level 2 Requirements Document (JPL D-19650), MER Flight System Level 3 Requirements Document, MER Science Requirements Document (JPL D-19638; MER 420-2-128), and the MER Mini-

TES Functional Requirements Document (MER 420-2-413, JPL D-19706). The relevant requirements extracted from these documents are summarized in Table 1.2.1.

Table 1.2.1: MER Mission Requirements relevant to Mini-TES Calibration and Testing

32	The Mini-TES shall obtain high quality mid-infrared spectra at sufficient spectral and spatial resolution to estimate the mineralogy of individual rocks and soil patches remotely.
33	The Mini-TES shall image the scene from -50 degrees to $+30$ degrees in elevation and over 360 degrees of azimuth to produce a full hyperspectral panorama of the region surrounding the rover.
53	The instrument shall be able to withstand pointing as close as 5° from the sun.
55	The instrument shall operate over a spectral range of at least 5 to $29 \mu\text{m}$, with a goal of 5 to $40 \mu\text{m}$.
57	The instrument shall provide a spectral resolution of at least 10 cm^{-1} .
59	The instrument shall have two concentric IFOVs (one IFOV of $8.0 \pm 0.4 \text{ mrad}$, and one IFOV of $20.0 \pm 1.0 \text{ mrad}$).
62	The PMA-mounted scan mirrors shall allow image construction from -50° to $+30^\circ$ in elevation and 360° in azimuth.
63	The PMA shall also provide internal calibration and stow positions.
66	The elevation and azimuth scan mirror servos shall move and settle to each commanded position $\pm 1 \text{ mrad}$ within the 200 msec retrace of the Mini-TES interferometer for each pixel in the raster image except during elevation and azimuth retraces and slews to
72	The Mini-TES optical design shall provide for more than 85% of the encircled energy to be contained in an area equal to a single IFOV, 98% within an area equal to 2×2 IFOV, and 99.8% within an area equal to 3×3 IFOV.
73	Focus shall be maintained from 2 meters to infinity, with an acceptable blur of 15% of an IFOV at infinity focus.
75	The NESR of the Mini-TES for a single spectral accumulation interval at $10 \mu\text{m}$ observing a scene at 270 K and 20 mrad shall be $<1.25 \times 10^{-8} \text{ W cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$, corresponding to a signal-to-noise ratio (SNR) of at least 450 , assuming the co-addition of two observations.

76	The radiometric calibration of the Mini-TES over the required spectral range shall be performed with an absolute accuracy of 5% or better and a relative precision (pixel-to-pixel) of 2% or better, viewing a 270 K blackbody.
77	Internal and external full-field in-flight calibration targets shall be provided for the Mini-TES.
82	The internal and external targets shall be coated with a high emissivity paint as specified in the Cal Target ICDs.
83	The effective emissivity of the internal and external target surfaces shall be 0.98 or greater over the required spectral range to provide a calibration check of the instrument.
85	Mini-TES shall undergo a full pre-flight calibration process that will characterize instrument performance over a full range of expected temperatures.
88	The Mini-TES shall provide the power conditioning, timing, control, mode sequencing, data compression and data formatting electronics and algorithms necessary to process the detector signals and housekeeping data and transfer the output data to the rover.
96	The PMA, including the mast, baffles, and scan mirrors, shall be sized and aligned to the Mini-TES optical axis such that the energy from the 20.0 ± 1.0 mrad IFOV is not clipped by any element of the PMA.
99	The inside of the mast shall be painted with an emissivity of ≥ 0.65 to minimize the stray background energy from the mast.
133	Commands shall control the following (8) selectable functions: selection of 8 or 20 mrad field of view, selection of the post-amplifier gain, selection of the primary or redundant Michelson mirror start-of-scan optical encoders, Michelson motor on/off, primary laser diode on/off, redundant laser diode on/off, and laser diode heaters on/off.
153	The internal temperature sensors shall have a post-calibration absolute accuracy of $\pm 0.2^\circ$ C or better with a precision of $\pm 0.1^\circ$ C or better over the Mini-TES flight allowable temperature range.
154	Redundant external temperature sensors shall be attached to the Mini-TES at locations specified by SBRS in order to monitor the instrument's temperature when it is powered off.
155	The external temperature sensors shall have a post-calibration absolute accuracy of $\pm 0.2^\circ$ C or better with a precision of $\pm 0.1^\circ$ C or better over the Mini-TES flight allowable temperature range.

177	The flight software shall control the transfer of the data from the Mini-TES data buffer to the rover CPU memory.
178	Once the Mini-TES data are available in the rover memory, the flight software shall process the data by removing the header and telemetry and performing the FFT on the interferogram in order to generate the spectrum.
179	The flight software shall then perform data aggregation, data compression, final data formatting, data packetization, and transfer of the data packets to rover data storage for downlink.
180	The flight software shall also control and synchronize the azimuth and elevation mirror movements during the Mini-TES data acquisitions.
182	The Mini-TES data transfers during an image acquisition shall be controlled and synchronized by the Mini-TES flight software running on the rover CPU.
183	Data transmissions from the Mini-TES data buffer through the rover interface electronics into the rover CPU memory shall occur during each 200 msec retrace period.

1.3 Scope

This plan covers all Mini-TES “Deliverables” as described in the MER Project Implementation Plan (MER 420-1-101, JPL D-19620).

1.4 Applicable Documents

- MER Quality Assurance Project Plan (MER 420-1-137, JPL D-18676)
- MER Configuration Management Plan (MER 420-1-102, JPL D-19641)
- Mini-TES Functional Requirements Document (MER 420-2-413, JPL D-19706)
- MER Flight System Technical Resource and Margin Policy (MER 420-4-482, JPL D-19844)
- Mini-TES IICD (MER 420-3-480.e, JPL D-20253)
- Project Safety Plan (MER 420-1-106, JPL D-19496)
- Environmental Requirements Document (MER 420-2-415, JPL D-19272)
- MER Planetary Protection Plan (MER 420-1-109, JPL D-19534)

1.5 Calibration Overview

The Mini-TES instrument will be calibrated and tested prior to shipment to the Jet Propulsion Laboratory (JPL) at Raytheon Santa Barbara Remote Sensing (SBRs). The primary objectives of these tests will be to determine: (1) the in-field radiance response; (2) the out-of-field radiance response; (3) the spectral line shape; (4) the spectral sample position; (5) the absolute radiometric accuracy using two laboratory reference blackbody sources; (6) the radiometric precision using laboratory reference blackbody sources; (7) the instrument performance characteristics over temperature; and (8) the piece-part emissivity and temperature calibration of the two flight calibration targets that will eventually be mounted in the PMA and on the rover. In addition to these calibrations, an extensive set of tests will be performed under ambient and vacuum conditions to verify the instrument functional performance, including tests of the field of view actuator and the command and data links.

The Mini-TES uses two flight calibration targets for absolute radiometric calibration. These targets will be calibrated by using the Mini-TES to transfer the calibration of two precision reference blackbody sources to the two Mini-TES flight calibration targets under realistic pressure and temperature conditions. This approach has been successfully used on the MO and MGS TES instruments and the 2001 Mars Odyssey Thermal Emission Imaging System (THEMIS) instruments. An initial calibration of the flight calibration targets will be performed at SBRs prior to delivery to JPL.

Once the Mini-TES instrument is delivered to the Jet Propulsion Laboratory (JPL), it will be integrated with the PMA for system-level calibration. The objectives of these tests will be to: (1) determine the field-of-view definition of the Mini-TES/PMA integrated assembly; (2) to determine the spatial position, accuracy, repeatability, and settling time of the Mini-TES pointing mirror; (3) to perform the absolute radiometric accuracy calibration of the two flight calibration targets at the system level; (4) to verify the relative precision of the integrated Mini-TES/PMA system; and (5) to verify the performance of the integrated Mini-TES/PMA system over temperature. Each of the calibration tests are described in the subsequent sections.

2 MINI-TES INSTRUMENT-LEVEL TESTING AND CALIBRATION

2.1 Test Conditions and Overview

2.1.1 Bench-Level Tests

Bench-level testing of the Mini-TES instrument will be performed at Santa Barbara Remote Sensing in Goleta, California in two phases. The first phase will consist of piece-part and system-level testing of the spectral performance of each sub-section. These tests will be performed under ambient conditions. The second phase will consist of field of view and out-of-

field tests conducted before and after vibration and thermal-vacuum testing to determine and confirm the instrument field-of-view and alignment.

2.1.2 Thermal Vacuum Tests

The Mini-TES instrument will be tested and calibrated in vacuum at SBRS at instrument temperatures of -30 , -15 , 0 , 15 , and 30 °C. The calibrations will be performed viewing the reference blackbody sources set to temperatures of 150 K, 175 K, 200 K, 240 K, 270 K, 300 K, and 325 K.

2.1.3 Instrument and Test Fixture Properties and Calibration

2.1.3.1 Calibration Reference Blackbody Properties and Instrumentation

Two precision calibration reference blackbodies (Bench Checkout Units; (BCU-1 and BCU-2)) will be used within the thermal vacuum chamber. These blackbodies are identical, 7.25" diameter, 15° half-angle cones machined at Arizona State University (ASU) and assembled at SBRS.

The two reference and one flight calibration target (Cal1 or Cal2) will be mounted inside the SBRS thermal vacuum (TV) chamber. The Mini-TES will view the reference blackbody sources and the flight target using a mirror mounted on a rotary stage inside the TV chamber. The reflectivity of this mirror will be measured prior to use. However, because the Mini-TES views both the reference blackbody sources and the flight calibration target through this mirror, its reflectivity is removed in the calibration process. The emissivity of the reference blackbodies was determined on the MGS TES Program to be >0.998 over the Mini-TES wavenumber range. Because the Mini-TES aperture is significantly smaller than the TES aperture (2.5 inches versus 6 inches), the Mini-TES will view a much deeper portion of the blackbody cone than was viewed by TES. Therefore, it is expected that the effective emissivity of the reference blackbodies will be higher than determined for the TES viewing conditions. It will therefore be assumed that the emissivity of the two reference blackbodies is unity at all Mini-TES wavenumbers.

Each reference blackbody is instrumented with two pairs of platinum thermistors placed at the front and back of the cone surface. Only one of each pair will be used during calibration; the second is for redundancy. These thermistors were calibrated prior to shipment from the manufacturer to an absolute accuracy of 0.1 °C ($\pm 0.5\%$ resistance). The calibration of the reference blackbody thermistors will be verified at SBRS prior to use in the Mini-TES Calibration Program.

The digitization of the BCU telemetry points varies from ~ 0.01 °C at -190 °C to 0.02 at 35 °C. The means and standard deviations of the front and back thermistors in the cold calibration blackbody (BCU-1) and the hot calibration blackbody (BCU-2) were determined for the MGS TES experiment. The temperature stability is within the digitization level over >1 minute time periods. The front and back temperatures agree to within 0.7 °C for the space blackbody. The planet blackbody thermistors agree to within

~0.25 °C for cold temperatures, increasing to 1.5 °C for hot temperatures. In all cases the rear thermistor is colder than the front thermistor. The accuracy and precision of these reference sources will be verified prior to use in the Mini-TES Calibration Program.

2.1.3.2 Flight Calibration Target Properties and Instrumentation

The calibration of the Mini-TES at Mars requires knowledge of the emissivity and absolute temperature of the two flight calibration targets. These targets will be calibrated relative to the reference blackbody sources using the Mini-TES as the transfer mechanism.

The emissivity of the two flight targets will be measured for reference only at Arizona State University (ASU) using the ASU Spectrometer Laboratory.

Each flight calibration target is instrumented with two platinum thermistors placed at two locations on each of these targets. These thermistors will be calibrated to an absolute accuracy of 0.1 °C and a precision of 0.05 °C prior to acceptance from the vendor. These thermistors will be calibrated at SBRS after installation in the flight calibration targets prior to use in the SBRS thermal vacuum tests.

2.2 Tests and Procedures

Table 2.2.1 provides an overview of the Mini-TES instrument-level calibration and testing requirements. Each of these tests is described in more detail in subsequent sections.

Test	Environmental Conditions	Brief Description
Field of view mapping	Ambient	Define the field of view shape, position, and FWHM in azimuth and elevation
Near-field out-of-field response	Ambient	Search for regions of significant out-of-field contribution
Far-field out-of-field response	Ambient	Search for regions of significant out-of-field contribution
Spectral Characterization: Sample Position and Spectral Line Shape	Model	Determine sample position and spectral line shape for each spectral sample
Flight target emissivity determination	Ambient	Determine the emissivity of the flight calibration targets at the piece-part level
Instrument response versus time - bench tests pre-instrument-delivery	Ambient	Track the instrument response function over time during assembly and test
Instrument response versus instrument temperature	Thermal vacuum; Instrument temperatures of -30°C, -15°C, 0°C, 15°C, and 30°C	Determine instrument response over the full range of in-spec instrument operational temperatures at the Mini-TES at the system level.
Absolute radiometric accuracy calibration	Thermal vacuum; Instrument temperatures of -30°C, -15°C, 0°C, 15°C, and 30°C	Determine the absolute accuracy of the radiometric calibration at the Mini-TES at the system level.
Radiometric precision	Thermal vacuum; Instrument temperatures of -30°C, -15°C, 0°C, 15°C, and 30°C	Determine the precision of the radiometric calibration at the Mini-TES at the system level.
Gain	Thermal vacuum; Instrument temperatures of -30°C, -15°C, 0°C, 15°C, and 30°C	Determine the gain of the Mini-TES at the system level.

2.3 Schedule

The Mini-TES instrument-level tests requiring thermal/vacuum conditions will be performed in chambers at SBRS. The calibration data has been collected for Mini-TES I. The schedule for calibration testing for Mini-TES II is given in Table 2.3.1.

Table 2.3.1: Mini-TES II Calibration and Test Schedule

Activity	Days
Functional testing	14
Field of View mapping	5
Near-field out-of-field response	2
Far-field out-of-field response	2
Non-operating Thermal	3
Operating Thermal	3
Radiometric Calibration	15

2.4 Mini-TES Instrument-Level Test Descriptions

2.4.1 Spatial Calibration

2.4.1.1 Field of View Mapping Test

Priority: High

Purpose and Description

Field of view characterization data will be acquired using a precision collimator at SBRS. A thermal source will be projected through a 1-mrad wide, 40-mrad long slit into the Mini-TES aperture. The Mini-TES will be manually rotated to move the slit at a 1-mrad spacing across the focal plane; 31 points will be measured from -15 to +15 mrad in azimuth; 31 points will be measured from -15 to +15 mrad in elevation. The detailed discussion of the field of view measurements is given in the Mini-TES Field of View Procedure, SBRS drawing #154759.

The data recorded on the working data sheets, computer files, and plots will be referenced to an arbitrary zero point on the collimator. For the final field of view positions, taken immediately prior to shipment from SBRS, the field of view will be referenced to the Mini-TES alignment cube

Three observations will be collected and averaged at each spatial location. Using these data the final field of view positions will be determined using the following processing:

- 1) Observations will be collected at 0 mrad at the beginning and end of each test. These data were used to remove instrument drifts that might occur during the test.
- 2) The data will be normalized to 0.0 (minimum) and 1.0 (maximum).
- 3) The location of half-power and centroid locations and the full-width, half-maximum field of view size will be determined using these processed values.

Parameters and Range

31 points will be measured from -15 to +15 mrad in azimuth.

31 points will be measured from -15 to +15 mrad in elevation.

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$

IR blackbody source stable to $\pm 2^\circ \text{C}$ over 20 minutes

Slit position to ± 0.1 mrad

Environment

Ambient

Supporting Equipment

Precision collimator

Precision rotary stage

IR blackbody source with variable slits and IR shutter

Calibration Report Data Products

Data product will be the relative response versus position. The relative response will be determined using averaged values of interferogram peak-to-peak signal viewing IR source value minus peak-to-peak signal with shutter-closed, normalized to peak signal. Instrument and/or target drift during test will be removed by linear interpolation between first and last observation. The locations of the field of view center and half-power points will be computed and archived.

Digital files and plots will be archived for: (1) 20-mrad elevation data, (2) 20-mrad azimuth data, (3) 8-mrad elevation data, and (4) 8-mrad azimuth data.

2.4.1.2 Near-Field Out-Of-Field Response Test

Priority: High

Purpose and Description

The radiance from an extended area covering ± 14.7 mrad in azimuth and ± 19.6 mrad in elevation will be measured using a 2.4×2.4 mrad source that will be stepped in 2.45 mrad

steps in both azimuth and elevation. At each grid point, five observations will be collected with the aperture open and five observations with the aperture blocked to correct for the background radiance. This study will be performed to look for obvious problems and search for regions of significant out-of-field contribution.

Parameters and Range

13 points will be measured from -14.7 to $+14.7$ mrad in azimuth.
17 points will be measured from -19.6 to $+19.6$ mrad in elevation.

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$
IR blackbody source stable to $\pm 2^\circ$ C over 20 minutes
Slit position to ± 0.5 mrad

Environment

Ambient

Supporting Equipment

Precision collimator
Precision rotary stage
IR blackbody source with variable slits and IR shutter

Calibration Report Data Products

Data product will be the relative response versus position. The relative response will be determined using averaged values of interferogram peak-to-peak signal viewing IR source value minus peak-to-peak signal with shutter-closed, normalized to peak signal. Instrument and/or target drift during test will be removed by linear interpolation between first and last observation.

Digital files and plots will be archived for: (1) 20-mrad; and (2) 8-mrad position data.

2.4.1.3 Far-Field Out-Of-Field Response Test**Priority: Medium****Purpose and Description**

The radiance from an extended area covering ± 196 mrad in azimuth and ± 200 mrad in elevation will be measured using a 40×32 mrad source that will be stepped in 32 mrad steps in azimuth and 40 mrad steps in both elevation. At each grid point, five observations will be collected with the aperture open and five observations with the aperture blocked to correct for the background. This study will be performed to look for obvious problems and search for regions of significant out-of-field contribution.

Parameters and Range

13 points will be measured from -196 to $+196$ mrad in azimuth.
11 points will be measured from -200 to $+200$ mrad in elevation.

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$.
 IR blackbody source stable to $\pm 2^\circ \text{C}$ over 20 minutes
 Slit position to $\pm 0.5 \text{ mrad}$.

Environment

Ambient

Supporting Equipment

Precision collimator
 Precision rotary stage
 IR blackbody source with variable slits and IR shutter

Calibration Report Data Products

Data product will be the relative response versus position. The relative response will be determined using averaged values of interferogram peak-to-peak signal viewing IR source value minus peak-to-peak signal with shutter-closed, normalized to peak signal. Instrument and/or target drift during test will be removed by linear interpolation between first and last observation.

Digital files and plots will be archived for: (1) 20-mrad; and (2) 8-mrad position data.

2.4.2 Spectral Characterization: Sample Position and Spectral Line Shape**Priority: High****Purpose and Description**

In an ideal interferometer with an on-axis point detector, the spectral samples are uniformly distributed in wavenumber and the full-width, half maximum (FWHM) of each sample is simply determined by the optical displacement of the Michelson mirror. The Mini-TES uses a laser diode with a line at $0.980 \mu\text{m}$ in the visible interferometer to sample the IR interferometer. The ideal sample spacing of the interferometer is given by:

$$\text{Sample spacing} = \frac{1}{(0.980 \times 10^{-4} \text{ cm}) * N_{\text{pts}}}$$

where N_{pts} is the number of points in the FFT. The Mini-TES flight software processes the interferogram data using a prime factors FFT with 1024 points. The resulting ideal sampling for the Mini-TES is 9.965 cm^{-1} .

For a large detector, the two beams of the interferometer are not in phase over the entire areal extent of the detector, producing “self-apodization”, or widening of the instrument line shape. As a result, the mirror must move farther to produce interference of the off-axis rays, producing a shift of the center frequency of each spectral sample to a higher apparent wavelength (lower wavenumber) than its true spectral position.

A numerical model has been developed to model the self-apodization effects and to determine the true spectral position, FWHM, and spectral line shape of each sample. This model will be used to generate the true sample position for the Mini-TES detector size and prime factors FFT.

Parameters and Range

Done by modeling.

Calibration Report Data Products

Digital files of model-derived values of true sample position, FWHM, and line shape for each spectral sample.

2.4.3 Radiometric Calibration

2.4.3.1 Derivations

The Mini-TES instrument will be radiometrically calibrated using thermal vacuum data acquired at SBRS. These tests will determine: (1) the emissivity and effective temperature of the flight calibration targets at the piece-part level; (2) the emissivity of the instrument; (3) the instrument response function and its variation with instrument temperature; (4) the absolute radiometric accuracy; (5) the relative precision (noise) characteristics; and (6) the instrument gain values.

The measured output voltage (V_{measured} , in units of TES Numbers (TN)) from the Mini-TES spectrometer as a function of wavenumber is given by:

$$V_{\text{measured}} = \{(R_{\text{emitted}} + R_{\text{reflected}}) - R_{\text{instrument}}\} \times \text{irf} \quad (2-1)$$

where R_{emitted} is the radiance emitted by the target, $R_{\text{reflected}}$ is the radiance emitted by the environment and reflected off of the target, $R_{\text{instrument}}$ is the radiance emitted by the instrument, and irf is the instrument response function. High emissivity targets (>0.99) will be used for all of the calibration tests. Therefore, the $R_{\text{reflected}}$ term will be insignificant and can be ignored in all subsequent discussions.

During the stable thermal-vacuum tests, observations will be acquired of the two reference blackbody sources, one cold and one hot, and a flight calibration target (“target”) over a period of 360 seconds. The relationships between the measured instrument signal (V) and the instrument and target radiance (R) for the cold, hot, and target observations are given by:

$$V_c = (R_c - R_i) \times \text{irf} \quad (2-2a)$$

$$V_h = (R_h - R_i) \times \text{irf} \quad (2-2b)$$

$$V_t = (R_t - R_i) \times \text{irf} \quad (2-2c)$$

where R is the radiance of the cold (c), hot (h), and target (t) targets and the instrument (i). The radiance of each target is given by ϵB , where ϵ is the emissivity of each target and B is the Planck function radiance at the target temperature, giving:

$$V_c = (\epsilon_c B_c - R_i) \times \text{irf} \quad (2-3a)$$

$$V_h = (\epsilon_h B_h - R_i) \times \text{irf} \quad (2-3b)$$

$$V_t = (\epsilon_t B_t - R_i) \times \text{irf} \quad (2-3c)$$

All of the values are determined at each spectral wavenumber (subscript omitted). The instrument response function (irf) is assumed to be independent of signal magnitude based on TES I and II results. This assumption will be verified later in the absolute radiance calibration. However, irf is a function of instrument temperature.

The spectra from each target will be acquired over a relatively short period of time under stable conditions, so it is assumed that the instrument temperature will be the same for all three observation sets. Thus R_i and irf are assumed to be constant in all three equations. The temperature stability of the external targets and target surface will be determined using the thermistors located in or on each target surface, and the average temperature of each target over the time interval of data collection will be used in the calibration.

Equations 2-3a-c give three equations and five unknowns (ϵ_c , ϵ_h , ϵ_t , R_i , and irf). It is also reasonable to assume that $\epsilon_c = \epsilon_h$ and set these to “ ϵ_{cone} ”. This assumption is valid because the two external targets had identical geometry and surface paint, which was applied in an identical manner on a single day. This assumption gives 3 equations and 4 unknowns. As a result, it is only possible to determine ratios of the remaining emissivity terms. The ratios that will be determined are:

$$\frac{\epsilon_{\text{cone}}}{\epsilon_{\text{target}}} \quad \frac{\epsilon_i}{\epsilon_{\text{cone}}} \quad \frac{\epsilon_t}{\epsilon_r}$$

Using Eq. 2-2a and 2-2b to determine irf and R_i gives:

$$\text{irf} = \frac{V_c - V_h}{R_c - R_h} \quad (2-4a)$$

and

$$R_i = \frac{R_h V_c - R_c V_h}{V_c - V_h} \quad (2-4b)$$

Solving for R_t using Eq. 2-2c gives:

$$R_t = \frac{R_c(V_t - V_h) + R_h(V_c - V_t)}{V_c - V_h} \quad (2-4c)$$

Replacing R_t , R_c , and R_h by their equivalent ϵB term gives:

$$\varepsilon_t B_t = \frac{\varepsilon_c B_c (V_t - V_h) + \varepsilon_h B_h (V_c - V_t)}{V_c - V_h}$$

Finally, replacing ε_c and ε_h by $\varepsilon_{\text{cone}}$ and rearranging gives:

$$\frac{\varepsilon_{\text{cone}}}{\varepsilon_t} = \frac{B_t (V_c - V_h)}{B_c (V_t - V_h) + B_h (V_c - V_t)} \quad (2-5)$$

Returning to Eq. 2-4b and replacing R by εB gives:

$$R_i = \frac{\varepsilon_h B_h V_c - \varepsilon_c B_c V_h}{V_c - V_h} \quad (2-6a)$$

or

$$\varepsilon_i B_i = \frac{\varepsilon_h B_h V_c - \varepsilon_c B_c V_h}{V_c - V_h} \quad (2-6b)$$

Again assuming $\varepsilon_c = \varepsilon_h = \varepsilon_{\text{cone}}$ gives:

$$\frac{\varepsilon_i}{\varepsilon_{\text{cone}}} = \frac{B_h V_c - B_c V_h}{B_i (V_c - V_h)} \quad (2-7)$$

The ratio of $\varepsilon_i/\varepsilon_t$ can be determined using cold and reference observations to give:

$$R_i = \frac{\varepsilon_t B_t V_c - \varepsilon_c B_c V_t}{V_c - V_t}$$

and

$$\frac{\varepsilon_i}{\varepsilon_t} = \frac{B_t V_c - \frac{\varepsilon_c}{\varepsilon_t} B_c V_t}{B_i (V_c - V_t)} \quad (2-8)$$

Note that in this case, because it cannot be assumed that $\varepsilon_t = \varepsilon_c$, there is an additional $\varepsilon_c/\varepsilon_t$ term. However, because: (1) $\varepsilon_c = \varepsilon_t$ to within 0.002 (see below); and (2) $B_c V_t$ is small relative to $B_t V_c$, Eq. 2-8 can be approximated by:

$$\frac{\varepsilon_i}{\varepsilon_t} = \frac{B_t V_c - B_c V_t}{B_i (V_c - V_t)} \quad (2-9)$$

with acceptable accuracy.

2.4.3.2 Calibration Error Analysis

The flight calibration errors consist of absolute accuracy errors in the determination of the instrument response function (irf) and instrument radiance (Ri) (Eq. 2-3c), and precision errors in the determination of the instrument response function and the measured scene signal (Eq. 2-3c). The absolute accuracy errors in the determination of the instrument response are due to errors in the emissivity and temperature of the two flight calibration targets. The resulting error in the instrument response function can be determined for any known or assumed values for the errors in these emissivity and temperature terms. Table 2.4.3.2 gives examples of the percent error in instrument response for errors in the known temperature of the two targets of $\pm 1^\circ\text{C}$ and errors in the target emissivity of ± 0.005 for a particular set of conditions; actual target temperatures and errors will be determined from pre-launch calibration and at-Mars conditions.

Table 2.4.3.2-a. Instrument Response Error (%) – 339 cm^{-1}

Cold Target = 180K	Warm Target = 290 K						
	$\Delta T = -1^\circ\text{C}$			$\Delta T = +1^\circ\text{C}$			
		$\Delta\varepsilon = -0.005$	$\Delta\varepsilon = 0$	$\Delta\varepsilon = +0.005$	$\Delta\varepsilon = -0.005$	$\Delta\varepsilon = 0$	$\Delta\varepsilon = +0.005$
$\Delta T = -1^\circ\text{C}$	$\Delta\varepsilon = -0.005$	-0.81					2.65
	$\Delta\varepsilon = 0$					1.73	
	$\Delta\varepsilon = +0.005$				0.80		
$\Delta T = +1^\circ\text{C}$	$\Delta\varepsilon = -0.005$			-0.82			
	$\Delta\varepsilon = 0$		-1.80				
	$\Delta\varepsilon = +0.005$	-2.80					0.80

Table 2.4.3.2-b. Instrument Response Error (%) – 1997 cm^{-1}

Cold Target = 180K	Warm Target = 290 K						
	$\Delta T = -1^\circ\text{C}$			$\Delta T = +1^\circ\text{C}$			
		$\Delta\varepsilon = -0.005$	$\Delta\varepsilon = 0$	$\Delta\varepsilon = +0.005$	$\Delta\varepsilon = -0.005$	$\Delta\varepsilon = 0$	$\Delta\varepsilon = +0.005$
$\Delta T = -1^\circ\text{C}$	$\Delta\varepsilon = -0.005$	-4.00					3.86
	$\Delta\varepsilon = 0$					3.37	
	$\Delta\varepsilon = +0.005$				2.89		
$\Delta T = +1^\circ\text{C}$	$\Delta\varepsilon = -0.005$			-3.00			
	$\Delta\varepsilon = 0$		-3.52				
	$\Delta\varepsilon = +0.005$	-4.04					3.82

2.4.3.3 Flight Calibration Target Emissivity Determination

Priority: High**Purpose and Description**

The emissivity of the flight calibration targets and the instrument will be determined to the piece-part level at SBRS using Equations 2-5 and 2-7 respectively. Based on TES I and II results, it will be assumed that $\epsilon_{\text{cone}} = 1.0$ at all wavenumbers.

Parameters and Range

Emissivity of flight targets from 5 to 40 μm .

Accuracy

Emissivity to ± 0.01 .

Environment

Ambient

Supporting Equipment

Precision calibrated reference blackbodies.

Calibration Report Data Products

Digital files and plots will be archived for the emissivity versus wavenumber of both internal and external flight calibration targets

2.4.3.4 Instrument Response Function

2.4.3.4.1 Instrument Response Function Versus Time – Bench Tests Pre-Instrument Delivery

Priority: Medium**Purpose and Description**

The instrument response will be determined throughout the Mini-TES test and calibration phase using Eq. 2-3 in two methods. The response function for bench tests will be determined using Eq. 2-3b with a hot external target and assuming a known instrument radiance (R_i) calculated using the spectrometer detector thermistor telemetry. This approach is necessitated because often it will only be possible to view a single target at a single temperature. In all vacuum and in-flight tests, the instrument response will be determined using observations of both the cold and hot reference sources (Eq. 2-3a and 2-3b).

Parameters and Range

All ambient tests.

Accuracy

Instrument response function $\pm 20\%$.

Environment

Ambient

Supporting Equipment

External target (“hot plate”) instrumented to set the plate temperature to $\pm 2^\circ\text{C}$ and control the plate temperature to $\pm 1^\circ\text{C}$.

Calibration Report Data Products

Digital files and plots of instrument response versus wavenumber for selected bench-level tests. Trend plots will be produced for selected wavenumbers to document instrument response changes over time.

2.4.3.4.2 Instrument Response Versus Instrument Temperature**Priority: High****Purpose and Description**

It is expected that the instrument response function will vary with temperature based on MO and MGS TES experience. The primary causes for the variations in response are: (1) variations in the detector response with temperature; and (2) minor variations in the interferometer alignment over temperature. Overall, the performance is expected to be best near room temperature, where the spectrometer will be aligned and the detector performance is nearly optimal.

The actual variation with temperature will be determined in flight as part of the standard calibration process. However, the Mini-TES response function will be determined over temperature during SBRS TV testing in order to verify the compliance with the system functional requirements, and to characterize the expected Mini-TES performance under martian conditions.

Parameters and Range

Instrument temperatures of -30°C , -15°C , 0°C , 15°C , and 30°C .

Target temperatures of 150 K, 175 K, 200 K, 240 K, 270 K, 300 K, and 325 K.

Accuracy

Precision calibration reference blackbody temperatures to $\pm 1.0^\circ\text{C}$

Precision calibration reference blackbody emissivity ≥ 0.995

Instrument response to $\pm 5\%$ over all wavenumbers

Environment

Thermal vacuum

Supporting Equipment

Precision calibration reference blackbodies (Bench Checkout Units; BCU-1 and BCU-2).

Calibration Report Data Products

Digital files and plots of instrument response versus wavenumber for all thermal-vacuum calibration tests. Trend plots will be produced for selected wavenumbers to determine instrument response changes over temperature. Second-order polynomial functions will be fit to the response versus temperature data for each wavenumber. These fit coefficients will be archived and used, if necessary, to produce instrument response as a function of temperature at Mars.

2.4.3.5 Absolute Radiometric Accuracy Calibration

Priority: High

Purpose and Description

The absolute radiometric accuracy of the Mini-TES will be determined in vacuum at SBRS in the following manner:

- 1) The instrument response and instrument radiance will be determined using observations of the cold and hot reference blackbody sources. The reference blackbody radiances will be determined using the average of the front and back thermistor temperatures and assuming unity emissivity.
- 2) Measurements of the flight calibration targets will be converted to calibrated radiance using the instrument response function and instrument radiance determined from the cold and hot reference observations.
- 3) The brightness temperature of the flight blackbody will be determined to provide an estimate of the effective absolute temperature error in the calibration. The brightness temperature will be determined at all wavenumbers and averaged from wavenumber 300 to 1100 to determine the “best-fit” planet temperature. If this derived temperature is less than 190 K, then the brightness temperature will be recomputed using only wavenumbers from 300 to 500 in order to provide a more accurate weighting of the long wavelengths where the radiance was highest. This derived flight calibration target temperature will be then compared to the measured temperature of this target to determine the absolute calibration error.

Parameters and Range

Instrument temperatures of -30°C , -15°C , 0°C , 15°C , and 30°C .

Target temperatures of 150 K, 175 K, 200 K, 240 K, 270 K, 300 K, and 325 K.

Accuracy

Precision calibration reference blackbody temperatures to $\pm 1.0^{\circ}\text{C}$

Precision calibration reference blackbody emissivity ≥ 0.995

Instrument response to $\pm 5\%$ over all wavenumbers

Absolute calibrated radiance to $\pm 5\%$.

Environment

Thermal vacuum

Supporting Equipment

Precision calibration reference blackbodies (Bench Checkout Units; BCU-1 and BCU-2).

Calibration Report Data Products

Digital files and plots of calibrated radiance and radiance error versus wavenumber for all thermal-vacuum calibration tests. Trend plots will be produced for selected wavenumbers to determine radiance error over instrument and target temperature.

2.4.3.6 Radiometric Precision**Priority: High****Purpose and Description**

The 1- σ noise equivalent spectral radiance (NESR) of the Mini-TES will be determined using the standard deviation, derived in the standard way, as a measure of the noise in instrument. This approach produces an upper limit to the 1- σ noise levels (a lower limit to the 1- σ SNR) because other sources of variance may be present that are unrelated to the instrument itself. The most likely of these is due to variations in the radiance from the various targets due to cyclic variations in their temperature. NESR will be computed by converting standard deviation to radiance using the instrument response function.

Parameters and Range

Instrument temperatures of -30°C , -15°C , 0°C , 15°C , and 30°C .

Target temperatures of 150 K, 175 K, 200 K, 240 K, 270 K, 300 K, and 325 K.

Accuracy

Precision calibration reference blackbody temperatures to $\pm 1.0^{\circ}\text{C}$

Precision calibration reference blackbody emissivity ≥ 0.995

Instrument response to $\pm 5\%$ over all wavenumbers

Calibrated radiance to $\pm 5\%$.

Environment

Thermal vacuum

Supporting Equipment

Precision calibration reference blackbodies (Bench Checkout Units; BCU-1 and BCU-2).

Calibration Report Data Products

Digital files and plots of noise equivalent spectral radiance (NESR) versus wavenumber for all thermal-vacuum calibration tests. Trend plots will be produced for selected wavenumbers to determine NESR over instrument and target temperature.

Signal-to-noise ratio (SNR) versus wavenumber will be computed and archived for all thermal vacuum tests as a function of wavenumber. SNR at the Mini-TES reference

point (10 μm , 270 K target temperature, 20-mrad mode) will be computed for functional requirement verification.

2.4.3.7 Gain

Priority: High

Purpose and Description

The Mini-TES spectrometer has two internal gain settings that nominally differ by a factor of two. A concerted attempt will be made to achieve these values using 1% precision resistors.

The actual instrument gain settings will be evaluated in by viewing a stable target in both gain settings.

Data will be collected in thermal vacuum at SBRS at instrument temperatures of -30 , -10 , 10 , and 30 °C. The data will be collected viewing a reference blackbody set to a temperature to provide sufficient signal without saturating in the high-gain state.

Parameters and Range

Instrument temperatures of -30 °C, -15 °C, 0 °C, 15 °C, and 30 °C.

Target temperatures as appropriate to not saturate signal in high gain state.

Accuracy

Gain to ± 0.01

Environment

Thermal vacuum

Supporting Equipment

Precision calibration reference blackbodies (Bench Checkout Units; BCU-1 and BCU-2).

Calibration Report Data Products

Digital files and plots of gain versus wavenumber for appropriate thermal-vacuum calibration tests.

3 INTEGRATED MINI-TES/PMA SYSTEM-LEVEL CALIBRATION TESTING

3.1 Test Conditions and Overview

3.1.1 Bench-Level Tests

Bench-level testing of the integrated Mini-TES/PMA system will consist of field of view and out-of-field tests conducted after integration and before and after all vibration and

thermal-vacuum testing to determine and confirm the instrument field of view and alignment. These tests will be performed under ambient conditions.

3.1.2 Thermal Vacuum Tests

The Mini-TES instrument will be tested and calibrated in vacuum at JPL at instrument temperatures of -30 , 0 , and 30 °C. The calibrations will be performed viewing the reference blackbody sources set to temperatures of 150 K, 200 K, 270 K, 300 K, and 325 K.

3.1.3 Relevant Instrument and Test Fixture Properties and Calibration

For this test, the same two precision reference blackbody sources discussed in section 2.1.3.1 above (Bench Checkout Units; BCU-1 and BCU-2) will be used. The Mini-TES will view the reference blackbody sources as well as the flight calibration targets (section 2.1.3.2) using the scan mirror assembly in the PMA. Because the Mini-TES views both the reference blackbody sources and the flight calibration targets through this mirror, its reflectivity is removed in the calibration process.

3.2 Tests and Procedures

Table 3.2.1 provides a prioritized overview of the Mini-TES/PMA system-level calibration and testing requirements. Each of these tests is described in more detail in subsequent sections.

Table 3.2.1: Mini-TES/PMA System-Level Calibration and Testing		
Test	Environmental Conditions	Brief Description
Field of view mapping	Ambient	Define the field of view shape, position, and FWHM in azimuth and elevation
Near-field out-of-field response	Ambient	Search for regions of significant out-of-field contribution
Far-field out-of-field response	Ambient	Search for regions of significant out-of-field contribution
PMA mast vignetting	Ambient	Verify lack of vignetting of Mini-TES beam by the PMA
PMA stray radiance	Ambient	Verify stray radiance rejection by PMA
PMA pointing mirror accuracy, precision, repeatability, and settling	Ambient	Verify mechanical performance of the PMA pointing mirror
PMA pointing mirror alignment	Ambient	Verify PMA pointing mirror alignment
Flight target emissivity determination	Thermal vacuum; Instrument temperatures of -30°C , -0°C , and 30°C	Determine the emissivity of the flight calibration targets at the system level
Instrument response versus time	Ambient	Track the instrument response function over time during assembly and test
Instrument response versus instrument temperature	Thermal vacuum; Instrument temperatures of -30°C , -0°C , and 30°C	Determine instrument response over the full range of in-spec instrument operational temperatures at the Mini-TES at the system level.
Absolute radiometric accuracy calibration	Thermal vacuum; Instrument temperatures of -30°C , -0°C , and 30°C	Determine the absolute accuracy of the radiometric calibration at the Mini-TES at the system level.
Radiometric precision	Thermal vacuum; Instrument temperatures of -30°C , -0°C , and 30°C	Determine the precision of the radiometric calibration at the Mini-TES at the system level.
Gain	Thermal vacuum; Instrument temperatures of -30°C , -0°C , and 30°C	Determine the gain of the Mini-TES at the system level.

3.3 Schedule

The Mini-TES/PMA system-level tests requiring thermal/vacuum conditions will be performed in chambers at JPL. The schedule for calibration testing for Mini-TES (assuming that we have hardware access during two shifts per day) is given in Table 3.3.1.

Table 3.3.1: Mini-TES/PMA System-Level Calibration and Test Schedule	
Activity	Days
Functional Testing	2
Field of View Mapping	4
Near-field out-of-field response	1
Far-field out-of-field response	1
PMA mast vignetting	1
PMA stray radiance	1
PMA pointing mirror accuracy, precision, repeatability, and settling	2
Bench-level Mini-TES to Pancam coalignment	2
Non-operating Thermal Vacuum	2
Thermal vacuum radiometric calibration	3
Rover-level Mini-TES to Pancam coalignment	1

3.4 Mini-TES/PMA System-Level Test Descriptions

3.4.1 Spatial Calibration

3.4.1.1 Field of View Mapping Test

Priority: High

Purpose and Description

Field of view characterization data of the integrated Mini-TES/Pancam will be acquired under ambient conditions using a precision collimator at JPL. A thermal source will be projected through a 1-mrad wide, 40-mrad long slit into the PMA aperture. The PMA will be rotated to move the slit at a 1-mrad spacing across the focal plane; 61 points will be measured from -30 to +30 mrad in elevation; 61 points will be measured from -30 to +30 mrad in azimuth; 91 points will be collected in a diagonal direction. This set of tests (azimuth, elevation, diagonal) will be performed at four azimuth/elevation points with a vertical orientation of the PMA mast and four azimuth quadrants at the maximum tilted data-collection position of the PMA mast. The detailed discussion of the field of view measurements is given in the Mini-TES/PMA Field of View Procedure, SBRS drawing #154759.

Three observations will be collected and averaged at each spatial location. Using these data the final field of view positions will be determined using the following processing:

- 1) Observations will be collected at 0 mrad at the beginning and end of each test. These data were used to remove instrument drifts that might occur during the test.
- 2) The data will be normalized to 0.0 (minimum) and 1.0 (maximum).
- 3) The location of half-power and centroid locations and the full-width, half-maximum field of view size will be determined using these processed values.

Parameters and Range

61 points will be measured from -30 to +30 mrad in azimuth.

61 points will be measured from -30 to +30 mrad in elevation.

91 points will be measured in a diagonal direction.

This set of tests will be repeated for four azimuth/elevation positions with the PMA mast vertical and four azimuth quadrants with the PMA mast tilted to its maximum data-collection angle.

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$

IR blackbody source stable to $\pm 2^\circ \text{C}$ over 20 minutes

Slit position to ± 0.1 mrad

Environment

Ambient

Supporting Equipment

Precision collimator
Precision rotary stage
IR blackbody source with variable slits and IR shutter

Calibration Report Data Products

Data product will be averaged values of interferogram peak-to-peak signal viewing IR source value minus peak-to-peak signal with shutter-closed, normalized to peak signal. Instrument and/or target drift during test will be removed by linear interpolation between first and last observation.

Digital files and plots will be archived for all tests.

3.4.1.2 Near-Field Out-Of-Field Response

Priority: High

Purpose and Description

The radiance from an extended area covering ± 14.7 mrad in azimuth and ± 19.6 mrad in elevation will be measured using a 2.4×2.4 mrad source that will be stepped in 2.45 mrad steps in both azimuth and elevation. At each grid point, five observations will be collected with the aperture open and five observations with the aperture blocked to correct for the background radiance. This study will be performed to look for obvious problems and search for regions of significant out-of-field contribution.

Parameters and Range

13 points will be measured from -14.7 to $+14.7$ mrad in azimuth.
17 points will be measured from -19.6 to $+19.6$ mrad in elevation.

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$
IR blackbody source stable to $\pm 2^\circ$ C over 20 minutes
Slit position to ± 0.1 mrad

Environment

Ambient

Supporting Equipment

Precision collimator
Precision rotary stage
IR blackbody source with variable slits and IR shutter

Calibration Report Data Products

Data product will be averaged values of interferogram peak-to-peak signal viewing IR source value minus peak-to-peak signal with shutter-closed, normalized to peak signal. Instrument and/or target drift during test will be removed by linear interpolation between first and last observation.

Digital files and plots will be archived for: (1) 20-mrad; and (2) 8-mrad data.

3.4.1.3 Far-Field Out-Of-Field Response

Priority: High

Purpose and Description

The radiance from an extended area covering ± 196 mrad in azimuth and ± 200 mrad in elevation will be measured using a 40×32 mrad source that will be stepped in 32 mrad steps in azimuth and 40 mrad steps in both elevation. At each grid point, five observations will be collected with the aperture open and five observations with the aperture blocked to correct for the background radiance. This study will be performed to look for obvious problems and search for regions of significant out-of-field contribution.

Parameters and Range

13 points will be measured from -196 to +196 mrad in azimuth.
11 points will be measured from -200 to +200 mrad in elevation.

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$.
IR blackbody source stable to $\pm 2^\circ$ C over 20 minutes
Slit position to ± 0.1 mrad.

Environment

Ambient

Supporting Equipment

Precision collimator
Precision rotary stage
IR blackbody source with variable slits and IR shutter

Calibration Report Data Products

Data product will be averaged values of interferogram peak-to-peak signal viewing IR source value minus peak-to-peak signal with shutter-closed, normalized to peak signal. Instrument and/or target drift during test will be removed by linear interpolation between first and last observation.

Digital files and plots will be archived for: (1) 20-mrad; and (2) 8-mrad data.

3.4.1.4 PMA Mast Vignetting

Priority: High

Purpose and Description

The purpose of this test is to verify the Mini-TES/PMA system alignment and verify that vignetting of the Mini-TES by the PMA does not occur. This test will cover the full range of azimuth and elevation pointing.

Parameters and Range

61 points will be measured from -30 to $+30$ mrad in azimuth.

61 points will be measured from -30 to $+30$ mrad in elevation.

91 points will be measured in a diagonal direction.

This set of tests will be repeated for four azimuth/elevation positions with the PMA mast vertical and four azimuth quadrants with the PMA mast tilted to its maximum data-collection angle.

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$.

IR blackbody source stable to $\pm 2^\circ$ C over 20 minutes

Slit position to ± 0.1 mrad

Environment

Ambient

Supporting Equipment

Precision collimator

Precision rotary stage

IR blackbody source with variable slits and IR shutter

Calibration Report Data Products

Data product will be averaged values of interferogram peak-to-peak signal viewing IR source value minus peak-to-peak signal with shutter-closed, normalized to peak signal. Instrument and/or target drift during test will be removed by linear interpolation between first and last observation.

Digital files and plots will be archived for: (1) 20-mrad; and (2) 8-mrad data.

3.4.1.5 PMA Stray Radiance**Priority: High****Purpose and Description**

Variations in the temperature of the PMA mast with time can potentially affect the absolute Mini-TES calibration if a significant fraction of this energy enters the Mini-TES field of view. The PMA mast is designed with baffles to minimize stray reflected radiance, but time-varying emission from the mast (including the baffles) is a potential source of calibration error. The magnitude of this possible effect will be determined by heating the mast along its length in each of four quadrants. The mast will be heated above the ambient mast temperature. Mini-TES spectra will be collected while viewing a

stable source to measure the effect of mast temperature variations on the observed radiance.

Parameters and Range

The mast will be heated to 30 °C above ambient

The heating will be applied to four quadrants at three different heights along the mast

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$.

Mast temperatures to $\pm 2^\circ\text{C}$

IR blackbody source stable to $\pm 2^\circ\text{C}$ over 20 minutes

Environment

Ambient

Supporting Equipment

IR blackbody source with variable slits and IR shutter

Calibration Report Data Products

Data product will be delta radiance between ambient and heated mast conditions

3.4.1.6 PMA Pointing Mirror Accuracy, Precision, Repeatability, and Settling Time**Priority: High****Purpose and Description**

The Mini-TES scan mirror assembly in the PMA head provides the pointing capability for the Mini-TES instrument. The accuracy, precision, repeatability, and settling time of this mirror assembly will be determined under ambient conditions. These measurements will be collected using a combination of observations of thermal geometric targets and optical measurements.

Parameters and Range

The Mini-TES will acquire data of the L-targets placed at four elevation locations in each of ten azimuth positions.

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$.

IR blackbody source stable to $\pm 2^\circ\text{C}$ over 20 minutes

Environment

Ambient

Supporting Equipment

Mini-TES L-targets

Calibration Report Data Products

Data product will be plots of L-target position as determined from Mini-TES data versus known position.

3.4.1.7 Mini-TES to Pancam Coalignment**Priority: High****Purpose and Description**

The alignment of the Mini-TES to the Pancam using the PMA scan mirror assembly will be determined by coordinated observations by Pancam and Mini-TES of the L-targets.

Parameters and Range

The Pancam and Mini-TES will acquire data of the L-targets placed at four elevation locations in each of ten azimuth positions.

Accuracy

Interferogram peak-to-peak signal to $\pm 3\%$.
IR blackbody source stable to $\pm 2^\circ$ C over 20 minutes

Environment

Ambient

Supporting Equipment

Mini-TES L-targets

Calibration Report Data Products

Data product will be plots of L-target position as determined from Mini-TES and Pancam data versus encoder elevation and azimuth positions.

3.4.2 Radiometric Calibration**3.4.2.1 Flight Calibration Target Emissivity Determination****Priority: High****Purpose and Description**

The emissivity of the flight calibration targets and the instrument will be determined at the system level at JPL using Equations 2-5 and 2-7 respectively. Based on TES I and II results, it will be assumed that $\epsilon_{\text{cone}} = 1.0$ at all wavenumbers.

Parameters and Range

Emissivity of flight targets from 5 to 40 μm .

Accuracy

Emissivity to ± 0.01 .

Environment

Thermal vacuum

Supporting Equipment

Precision calibrated reference blackbodies (Bench Checkout Units; BCU-1 and BCU-2).

Calibration Report Data Products

Digital files and plots will be archived for the emissivity versus wavenumber of both internal and external flight calibration targets.

3.4.2.2 Instrument Response Function**3.4.2.2.1 Instrument Response Versus Time****Priority: Medium****Purpose and Description**

The instrument response will be determined throughout the Mini-TES/PMA test and calibration phase using Eq. 2-3 in two methods. The response function for bench tests will be determined using Eq. 2-3b with a hot external target and assuming a known instrument radiance (R_i) calculated using the spectrometer detector thermistor telemetry. This approach is necessitated because often it will only be possible to view a single target at a single temperature. In all vacuum and in-flight tests, the instrument response will be determined using observations of both the cold and hot reference sources (Eq. 2-3a and 2-3b).

Parameters and Range

All ambient tests.

Accuracy

Instrument response function $\pm 20\%$.

Environment

Ambient

Supporting Equipment

External target (“hot plate”) instrumented to set plate temperature to ± 2 °C and control plate temperature to ± 1 °C.

Calibration Report Data Products

Digital files and plots of instrument response versus wavenumber for selected tests. Trend plots will be produced for selected wavenumbers to document instrument response changes over time.

3.4.2.2.2 Instrument Response Versus Instrument Temperature

Priority: Medium

Purpose and Description

It is expected that the instrument response function will vary with temperature based on MO and MGS TES experience. The primary causes for the variations in response are: (1) variations in the detector response with temperature; and (2) minor variations in the interferometer alignment over temperature. Overall, the performance is expected to be best near room temperature, where the spectrometer will be aligned and the detector performance is nearly optimal.

The actual variation with temperature will be determined in flight as part of the standard calibration process. However, the Mini-TES/PMA response function will be determined over temperature during TV testing in order to verify the compliance with the system functional requirements, and to characterize the expected performance under martian conditions.

Parameters and Range

Instrument temperatures of -30°C , 0°C , and 30°C

Target temperatures of 150 K, 200 K, 270 K, 300 K, and 325 K

Accuracy

Instrument response to $\pm 5\%$

Environment

Thermal vacuum

Supporting Equipment

Precision calibration reference blackbodies (Bench Checkout Units; BCU-1 and BCU-2)
Mini-TES Internal and External Flight Calibration Targets.

Calibration Report Data Products

Digital files and plots of instrument response versus wavenumber for all thermal-vacuum calibration tests. Trend plots will be produced for selected wavenumbers to determine instrument response changes over temperature. Second-order polynomial functions will be fit to the response versus temperature data for each wavenumber. These fit coefficients will be archived and used, if necessary, to produce instrument response as a function of temperature at Mars.

3.4.2.3 Absolute Radiometric Accuracy Calibration

Priority: High

Purpose and Description

The radiometric accuracy of the integrated Mini-TES/PMA will be determined in vacuum at JPL in the following manner:

- 1) The instrument response and instrument radiance will be determined using observations of the cold and hot reference blackbody sources. The reference blackbody radiances will be determined using the average of the front and back thermistor temperatures and assuming unity emissivity.
- 2) Measurements of the flight calibration targets will be converted to calibrated radiance using the instrument response function and instrument radiance determined from the cold and hot reference observations.
- 3) The brightness temperature of the flight blackbodies will be determined to provide an estimate of the effective absolute temperature error in the calibration. The brightness temperature will be determined at all wavenumbers and averaged from wavenumber 300 to 1100 to determine the “best-fit” planet temperature. If this derived temperature is less than 190 K, then the brightness temperature will be recomputed using only wavenumbers from 300 to 500 in order to provide a more accurate weighting of the long wavelengths where the radiance was highest. The derived flight calibration target temperatures will be then compared to the measured temperatures of these targets to determine the absolute calibration error.

Parameters and Range

Instrument temperatures of -30°C , 0°C , and 30°C

Target temperatures of 150 K, 200 K, 270 K, 300 K, and 325 K

Accuracy

Calibrated radiance to $\pm 3\%$

Environment

Thermal vacuum

Supporting Equipment

Precision calibration reference blackbodies (Bench Checkout Units; BCU-1 and BCU-2)

Mini-TES internal flight target instrumented in full flight configuration.

Mini-TES external flight target instrumented in full flight configuration.

Calibration Report Data Products

Digital files and plots of calibrated radiance and radiance error versus wavenumber for all thermal-vacuum calibration tests. Trend plots will be produced for selected wavenumbers to determine radiance error over instrument and target temperature.

3.4.2.4 Radiometric Precision

Priority: Medium

Purpose and Description

The $1\text{-}\sigma$ noise equivalent spectral radiance (NESR) of the integrated Mini-TES/PMA will be determined using the standard deviation, derived in the standard way, as a measure of the noise in the instrument. This approach produces an upper limit to the $1\text{-}\sigma$ noise levels (a lower limit to the $1\text{-}\sigma$ SNR) because other sources of variance may be present that are unrelated to the instrument itself. The most likely of these is due to variations in the radiance from the various targets observed due to cyclic variations in their temperature. NESR will be computed by converting standard deviation to radiance by dividing by the instrument response function.

Parameters and Range

Instrument temperatures of -30°C , 0°C , and 30°C

Target temperatures of 150 K, 200 K, 270 K, 300 K, and 325 K

Accuracy

Calibrated radiance to $\pm 3\%$

Environment

Thermal vacuum

Supporting Equipment

Precision calibration reference blackbodies (Bench Checkout Units; BCU-1 and BCU-2).

Calibration Report Data Products

Digital files and plots of noise equivalent spectral radiance (NESR) versus wavenumber for all thermal-vacuum calibration tests. Trend plots will be produced for selected wavenumbers to determine NESR over instrument and target temperature.

Signal-to-noise ratio (SNR) versus wavenumber will be computed and archived for all thermal vacuum tests as a function of wavenumber. SNR at the Mini-TES reference point ($10\ \mu\text{m}$, 270 K target temperature, 20-mrad mode) will be computed for functional requirement verification.

4 MINI-TES FLIGHT SOFTWARE TESTING

The Mini-TES flight software is incorporated in the Rover Flight Software. The development, test, and verification of this software is done by the Flight Software Development Team.

5 MINI-TES SPECIAL TESTS

5.1 Mini-TES Instrument-Level Spectral Target Tests

Priority: Medium

Purpose and Description

A set of rock and mineral targets will be observed by the Mini-TES instrument at SBRS. These tests are designed to quantify the Mini-TES ability to determine quantitative mineral abundance in geologic samples of unknown composition. These targets will also be viewed by the Pancam, APXS, and Mössbauer instruments and used to cross-calibrate the observations from the entire Athena payload suite.

Parameters and Range

Spectral measurements of selected rock samples.

Each rock sample placed at focal plane of collimator and heated to ~20° C above ambient. Approximately 100 Mini-TES calibrated radiance spectra will be collected of each sample.

Accuracy

Calibrated radiance to $\pm 3\%$

Environment

Ambient

Supporting Equipment

Precision calibration reference blackbodies (Bench Checkout Units; BCU-1 and BCU-2).

Precision collimator

Rock slab samples from R. Morris

Calibration Report Data Products

Digital files and plots of calibrated radiance and emissivity versus wavenumber for selected rock samples.

5.2 Mini-TES/PMA System-Level Spectral Target Tests

Priority: Medium**Purpose and Description**

A rock and mineral target prepared by R. Morris will be observed by the Mini-TES/PMA system during rover-level system testing at JPL. This test is designed to quantify the Mini-TES ability to determine quantitative mineral abundance in geologic samples of unknown composition. These targets will also be viewed by the Pancam, APXS, and Mössbauer instruments and used to cross-calibrate the observations from the entire Athena payload suite.

Parameters and Range

Spectral measurements of selected rock samples.

Approximately 100 Mini-TES calibrated radiance spectra will be collected of each sample.

Accuracy

Calibrated radiance to $\pm 3\%$

Environment

Thermal vacuum

Supporting Equipment

Mini-TES internal flight target instrumented in full flight configuration.

Mini-TES external flight target instrumented in full flight configuration.

Rock target from R. Morris

Calibration Report Data Products

Digital files and plots of calibrated radiance and emissivity versus wavenumber for each rock sample.

6 MINI-TES END-TO-END SYSTEM TESTING

To confirm, end-to-end, the ability of the Mini-TES instrument and ground data software to produce science data products, selected Mini-TES data products will be generated using ground data processing software and available calibration data during the course of the Mini-TES calibration process. These products include calibrated spectral radiances, spectral radiances image cubes, and spectral emissivity image cubes. At least one data product for each set will be produced and verified.

7 IN-FLIGHT CALIBRATED SPECTRAL RADIANCE ALGORITHM**7.1 Definition of an In-Flight Calibrated Radiance**

The measured signal (V_{planet}) viewing Mars, as a function of frequency (ν), is given by:

$$V_{\text{planet}}(\nu) = \left[\sum_{p=1}^n \{ \epsilon_p(\nu) B(T_p, \nu) \} - \epsilon_i B_i(T_i, \nu) \right] * \text{irf}(\nu) \quad (6-1)$$

where: n = number of surface components, p

ϵ_p = planet emissivity of surface component p

T_p = temperature of surface component p

B = Planck function radiance

T_i = Instrument temperature

$\epsilon_i B_i = \text{Instrument radiance} = R_i$

irf = instrument response function

Solving for the calibrated radiance ($\sum_{p=1}^n \epsilon_p(\nu)B(T_p, \nu)$) gives:

$$\text{Calibrated Radiance} = \sum_{p=1}^n \epsilon_p(\nu)B(T_p, \nu) = \epsilon_i B_i(T_i, \nu) - \frac{V_{\text{planet}}(\nu)}{\text{irf}(\nu)} \quad (6-2)$$

To compute calibrated radiance, both irf and $\epsilon_i B_i(T_i, \nu)$ must be determined. The objectives in flight are: (1) to minimize the noise on these functions by taking advantage of their repetitive and predictable forms; and (2) to develop an effective means for interpolating the instrument radiance $\epsilon_i B_i(T_i)$ between calibration observations.

7.2 Instrument Response Function

The instrument response function (irf) should be slowly varying except for the small variations due to changes in instrument temperature. As long as observations of the two flight calibration targets are obtained close together in time (within 10-20 sec) then these two observations can be used directly to calculate irf given (subscripts ν omitted) by:

$$\text{irf} = \frac{V_{\text{cal1}} - V_{\text{cal2}}}{\epsilon_{\text{cal1}} B(T_{\text{cal1}}) - \epsilon_{\text{cal2}} B(T_{\text{cal2}})} \quad (6-3)$$

where ϵ_{cal1} and ϵ_{cal2} will be derived from SBRS and JPL thermal vacuum testing, and T_{cal1} and T_{cal2} are from the average of the calibration target thermistor temperatures.

The noise in the instrument response function (irf) from a single pair of cal1, cal2 observations can be reduced by combining multiple determinations over a period of time. However, the statistical variations in irf must be separated from the expected variations in irf due to variations in instrument temperature. This separation will be done by fitting a function to the complete set of instrument response data from the time period of interest.

7.3 Instrument Radiance

The instrument radiance, $\epsilon_i B_i(T_i)$, is obtained by viewing the PMA calibration target, which provides an excellent target of known temperature and emissivity. For each internal calibration view:

$$V_{\text{cal1}} = [\epsilon_{\text{cal1}} B(T_{\text{cal1}}) - \epsilon_i B_i(T_i)] * \text{irf} \quad (6-4)$$

$$\epsilon_i B(T_i) = R_i = B(T_{\text{call}}) - \frac{V_{\text{call}}}{\text{irf}} \quad (6-5)$$

In practice it is not typically necessary to separate the instrument radiance into separate ϵ_i and B_i terms and only the product, R_i , is required, which is given by Equation 6-5. The noise in an individual R_i determination can be reduced in one of three ways:

Method 1:

Simply smooth (filter) the $R_i(T_i)$ data over frequency. These data should have very little inherent spectral structure because the instrument radiance comes from a cavity that is essentially blackbody in nature. Thus, the spectral “variations” are primarily due to noise and can be removed by smoothing with no loss in accuracy.

Method 2:

Compute $R_i(T_i)$ for each wavenumber and determine a best fit T_i to get an “effective” instrument temperature. In the simplest case this best fit is done by inverting the Planck function to calculate $T_i(\nu)$ over an appropriate range of frequencies where the signal-noise was high enough to get a reasonable determination. A uniform weighting (average) of the derived instrument temperatures over a specified wavenumber range is used to determine the instrument temperature. This “effective” instrument temperature is used in the Planck function to compute a noise-free R_i term. This method is essentially a smoothing operation as well, except in this case the “smoothing” function is the Planck function. The advantage is that it provides a physically plausible function for smoothing; the disadvantages occur if the instrument was not isothermal and the associated computational complexities and potential radiance errors introduced by representing the instrument radiance by a series of Planck functions.

Method 3:

This method is identical to Method 2, except that the R_i term used in the calibration of the planet observations is further refined by dividing by the instrument emissivity (ϵ_i) to better remove the measured, non-unit emissivity of the instrument.

Once the background radiance is determined at each internal calibration target observation, this radiance is interpolated for all of the intervening planet observations and used with irf to determining the calibrated radiance for each planet observation. In all methods the instrument radiance for each planet view will be determined using a functional fit to the instrument energies determined for the nearest, bounding calibration views. Initially, a simple linear interpolation between bounding calibration values will be used; with time at Mars, a more complex function will be determined to account for repetitive, periodic variations in instrument temperature. For Method 1, the interpolation would be between the smoothed, derived instrument radiance. For Methods 2 and 3, the interpolation would be between the derived instrument temperature(s). These later

methods have the advantage of more accurately representing the parameter (instrument temperature) that is actually varying.