CALIBRATION REPORT

FOR THE
THERMAL EMISSION IMAGING SYSTEM
(THEMIS)

FOR THE 2001 MARS ODYSSEY MISSION

Philip R. Christensen
Department of Geology
Arizona State University
Tempe, AZ 85287-1404

Rev. 0.98 Sept. 12, 2002

<u>Revisons</u>
Rev. 0.97 May 22 2002
Rev. 0.96 May 16, 2002
Rev. 0.94 March 29,
2002
Rev. 0.92 March 14, 2002

1 OVERVIEW

1.1 INSTRUMENT OVERVIEW

The Thermal Emission Imaging System (THEMIS) instrument consists of separate infrared and visible focal plane assemblies that share the telescope through a beamsplitter but have independent power and data interfaces to the spacecraft to provide system redundancy. The instrument was developed by Arizona State University (ASU) with Santa Barbara Remote Sensing (SBRS). The infrared focal plane and electronics were provided by the Santa Barbara Research Center (SBRS). The visible imager focal plane and electronics were provided by Malin Space Science Systems (MSSS). The details of the instrument design are given in **Table 1-1**. The telescope is a three-mirror anastigmat telescope with a 12-cm effective aperture and a speed of f/1.6. The IR and visible imagers have independent power and data interfaces to the spacecraft . The IR focal plane is an uncooled microbolometer with 320 cross-track pixels and 240 down-track pixels with an instantaneous field of view (IFOV) of 0.25 milli-radians (100 m from 400 km altitude). The focal plane is temperature stabilized to ~0.001 K using a temperature controller driving a thermo-electric heater/cooler. Ten stripe filters are placed over the microbolometer array to produce ten ~1-μm wide spectral bands at nine separate wavelengths centered from 6.8 to 14.9 μm. Two filters (Bands 1 and 2) cover the same spectral region centered at 6.8 μm. The nine THEMIS IR wavelengths include eight surface-sensing wavelengths (Bands 1-9) and one atmospheric wavelength (Band 10). Time delay integration (TDI) of 16 consecutive rows is performed by firmware in the THEMIS IR imager. The THEMIS visible imager contains 1,024 cross-track pixels with an IFOV of 0.045 milli-radians (18 m from 400 km altitude) covering a 18.4 km swath bore-sighted with the IR imager. The visible imager has five stripe filters**, e**ach covering 192 rows on the detector. These 192-line framelets are collected every 1 second, producing 26 rows of downtrack overlap in successive framelets at an orbital velocity of 3.0 km/sec. An internal calibration flag, the only moving part in the instrument, provides thermal calibration and IR flat-fielding, and is used to protect the detectors from unintentional direct illumination from the Sun. The instrument weighs 11.2 kg, is 29 cm by 37 cm by 55 cm in size, and consumes an orbital-average power of 14 W.

Figure 1-1 shows computer-generated drawings of the instrument, including the optical ray trace (**Figure 1-1a**) and an exploded view of the instrument components (**Figure 1-1b**). **Figure 1-2** shows the completed instrument prior to installation on the 2001 Mars Odyssey spacecraft.

THEMIS images are calibrated in flight using periodic views of the internal calibration flag. The calibration shutter flag is stored against a sidewall that maintains the flag at a known temperature. **Figure 1-3** shows a computer-generated view of the internal flag mounted in the housing; **Figure 1-4** provides views of the flag during instrument assembly. The flag is closed, imaged, and reopened at selectable intervals throughout each orbit. This process produces gores in the surface observations lasting approximately 50 seconds for each calibration. Calibration data are acquired every ~3-10 minutes as necessary. The optimum spacing of these observations is chosen to meet the calibration accuracy requirements, while minimizing the loss of surface observations.

The THEMIS IR imager internal analog-to-digital converter (ADC) produces a 12-bit signal (DN values of 0-4095). The digital output signal from the ADC is digitally adjusted by gain and offset terms and the result is converted to an 8-bit output value that is returned to Earth. The gain term determines how the dynamic range of the 12-bit signal from the ADC is converted to the 8-bit output. At a gain of 1, the full 4096 DN input range is used and is converted to an 8-bit number by dividing by 16. At a gain of two the input dynamic range is 2048, etc, up to a gain of 16 that uses a dynamic range of 256. Thus, a gain of 1 uses the full input dynamic range, but with a factor of 16 loss in precision; a gain of 16 preserves the full precision from the ADC with a factor of 16 reduction in dynamic range. Gains higher than 16 are not appropriate as they result in a lower input dynamic range than is available in the 8-bit output. The position of the selected dynamic range relative to the full 4096 input values is determined by the offset term. The offset term is measured relative to the mid-point (2048) of the input signal. The input to output conversion is given by:

$$\text{output} = (\text{gain} / 16) * \text{input} - (256 * (\text{offset} + 8))$$

The analog gain of the THEMIS IR imager was adjusted during assembly to provide a 1-sigma variance of approximately 0.5 DN at the maximum useful digital gain of 16.

The data returned from the instrument in flight are converted to scene spectral radiance (W cm^{-2} str^{-1} μm^{-1}) by: (1) adjusting for the gain and offset that were applied in the instrument to optimize the dynamic range and signal resolution for each scene; (2) correcting for any signal drift or offset that occur between observations of the calibration flag; and (3) converting signal to radiance using the measured signal and temperature of the calibration flag, together with the instrument response function determined prior to launch.

Table 1-1. THEMIS INSTRUMENT DESIGN SUMMARY

Quantities to be measured:	Emitted spectral radiance in 10 ~1-μm bands (9 different wavelengths) centered between 6.8 and 14.9 μm at 100 m spatial resolution Solar reflected energy in 5 ~50 nm bands centered from 0.425 to 0.860 μm at 18 m spatial resolution
Detectors:	Multi-spectral IR imager: 320 x 240 element uncooled microbolometer array Visible imager: 1,024 x 1,024 element silicon array
Expected performance:	NEΔ□ @ 245K & 10 μm = 0.005. NEΔT @ 245K & 10 μm = 0.5 K. NEΔT @ 180K = 1 K. SNR > 100 in visible imager at 0.25 albedo, 60° solar incidence angle
Optical/Mechanical Design:	12-cm effective aperture f/1.6 telescope to view nadir shared by multi-spectral IR and visible imagers. Internal calibration flag provides calibration and Sun avoidance protection functions. IR spectrometer is 10-strip filter pushbroom design with time delay integration. Visible multi-spectral imager is 5-strip filter frame-scan design.
Fields of View:	IR imager has a 4.6° (80 mrad) cross-track by 3.5° (60 mrad) down-track FOV with a 0.25 mrad (100 m) IFOV at nadir. Visible imager has a 2.66° (46.4 mrad) cross-track by 2.64° (46.1 mrad) down-track FOV with 0.045 mrad (18 m) IFOV in 1024 x 1024 pixels at nadir. The two imagers are spatially bore-sighted.
In-Flight Calibration:	Periodic views of an internal calibration flag.
Thermal Requirements:	Operating range -30°C to +30°C. Non-operating range -30°C to +45°C. No detector cooling required.
Digital Data	8-bit delta radiance in IR imager 8-bit radiance in visible imager

Data rate:	IR imager has instantaneous internal rate of 1.17 Mbits/sec. Data rate to spacecraft after real-time compression is approximately 0.6 Mbits/sec. Visible imager has instantaneous internal rate of up to 6.2 Mbits/sec. Data rate to spacecraft is <1.0 Mbits/sec. 4 Mbyte RAM internal data buffer for data processing and buffering for delayed output to spacecraft.
On-board Data Processing:	IR imager: Gain and offset; time delay integration, and data compression in electronics; data formatting using spacecraft computer. Visible imager: Lossless and predictive compression in firmware; selective readout and pixel summing on spacecraft.
Solar Protection:	Provided by calibration flag in stowed position.
Mass:	11.2 kg
Size:	29.2 x 38.4 x 54.7 cm
Power:	13 W orbital average

1.2 PRE-LAUNCH CALIBRATION OVERVIEW

The calibration, test, and characterization of the THEMIS was performed at SBRS prior to instrument installation on the Mars 2001 Odyssey spacecraft at Lockheed Martin in Denver. The THEMIS calibration was performed by personnel from SBRS and ASU. The purpose of this report is to describe the requirements, procedures, and results of those pre-launch tests.

The primary objectives of these tests were to determine:

1) the geometric performance of the infrared and visible imagers, including the point-spread function, out-of-field response, camera model, and the focus performance over temperature;

2) the relative spectral response of the infrared and visible imagers; and

3) the radiometric performance of the infrared and visible imagers, including the instrument response function, the absolute radiometric calibration, the radiometric precision (noise equivalent spectral radiance), the performance metrics, and the analysis of systematic errors.

In addition to these calibrations, an extensive set of tests were performed under ambient and vacuum conditions to verify the instrument functional performance, including the command and signal processors, the command and data links, and the calibration flag actuator. Each of the calibration tests is described in the subsequent sections.

2 MEASUREMENT REQUIREMENTS

2.1 GEOMETRIC REQUIREMENTS

The geometric requirements for the THEMIS are to provide a 100-m projected spot size for the IR imager from an altitude of 400 km, and an 18-m spot size for the visible imager. These instantaneous field of view requirements must be met at a modulation transfer function (MTF) at a specified value at the Nyquist frequency consistent with the desired projected spot size averaged cross- and along-track. The specified values are 30% for the IR and 10% for the visible imager.

2.2 SPECTRAL REQUIREMENTS

2.2.1 Infrared Imager

The signal-to-noise performance of the THEMIS instrument is the primary design challenge. While narrower filters would improve the surface component detectability, this improvement would be offset by the corresponding reduction in the SNR performance. Therefore, the THEMIS filters shall be at least 1 μm wide in all bands.

The microbolometer detector array has 240 rows in the downtrack direction. The time delay integration (TDI) will be performed using16 rows to achieve the minimum SNR performance. A gap of 8 rows is required between filters to allow their fabrication, and a spacing of 2 rows is required along the detector edge to ensure that the filter assembly is properly mounted to the detector array.

The THEMIS design is a 10-filter system with:

Edge spacing	2 rows
Filter assemblies; 9 * (16 + 8)	216 rows
Filter assembly; 1 * (16)	16 rows
Edge spacing	2 rows
Total	236 rows

The shortest wavelength filters (Bands 1 and 2) are designed to cover the carbonate absorption band from 6.3 to 7.3 μm, with the maximum absorption at 6.6 μm. Bands 1 and 2 shall be identical and shall therefore extend from 6.3 to 7.3 μm. In order to maximize the discriminability of carbonate, Band 3 shall not overlap Bands 1 and 2 at the half power point. Band 3 shall therefore extend from 7.3 to 8.3 μm.

The maximum wavelength that can be observed by THEMIS is 17 μm due to the use of yttrium oxide as the long wavelength blocking filter. Use of this material therefore excludes the possibility of THEMIS bands at wavelengths longer than the 15 μm CO_2 gas absorption band.

The maximum overlap that shall occur between bands shall be 0.2 μm.

Band 10 shall be centered in the CO_2 gas band to provide an estimate of the atmospheric temperature. This allows eight ~1-μm wide filters with ~0.2 μm overlap to be devoted to the atmospheric window between 6.3 and 13.1 μm.

The CO_2 band (Band 10) shall have the minimum out-of-band response possible to reject the large surface energy signal at both shorter and longer wavelengths that would significantly degrade the scientific utility of this band. Conversely, this band shall have a minimum full-width half-maximum (FWHM) of 0.9 μm to provide adequate signal-to-noise.

The spectral requirements for the THEMIS IR filters are summarized in **Table 2-1**.

Table 2-1. THEMIS IR Filter Spectral Requirements

	50%		10%		1%	
Band	Min.	Max.	Min.	Max.	Min.	Max.
	(μm)	(μm)	(μm)	(μm)	(μm)	(μm)
1 and 2	6.3 ± 0.1	7.3 ± 0.05	6.15	7.45	5.8	7.8
3	7.3 ± 0.05	8.3 ± 0.1	7.15	8.45	6.8	8.8
4	8.1 ± 0.1	9.1 ± 0.1	7.95	9.25	7.6	9.6
5	8.9 ± 0.1	9.9 ± 0.1	8.75	10.05	8.4	10.4
6	9.7 ± 0.1	10.7 ± 0.1	9.55	10.85	9.2	11.2
7	10.5 ± 0.1	11.5 ± 0.1	10.35	11.65	10.0	12.0
8	11.3 ± 0.1	12.3 ± 0.1	11.15	12.45	10.8	12.8
9	12.1 ± 0.1	13.1 ± 0.1	11.95	13.25	11.6	13.6
10	14.55 ± 0.05	15.45 ± 0.05	14.35	15.65	14.2	15.8

2.2.2 Visible Imager

The visible imager shall have five filters centered at approximately 0.45, 0.55. 0.65, 0.75, and 0.85 μm. The color capability of the visible imager is a goal, rather than a requirement, for the THEMIS investigation. In addition, the visible imager was a best-effort "build-to-print" replication of the Mars Climate Orbiter Mars Color Imager (MARCI) focal plane. Therefore, no additional requirements were placed on the location or spectral quality of the visible filters.

2.3 Radiometric Requirements

2.3.1 IR Imager

The radiometric requirements are based on the band depth of minerals likely to be found on the martian surface weighted by their abundance. The absorption band depths of particulates of the key quartz and carbonate minerals are ~0.5 in the 6-14 μm range; sulfates, phosphates, and clays are ~0.6; typical volcanic minerals pyroxene, plagioclase, and olivine range from 0.7-0.8 (**Figure 2-1**). A surface containing carbonate grains at 10% abundance with an emissivity of 0.5 at 6.6 μm, mixed with 90% silicate with an emissivity of 1.0 would produce an absorption feature with an emissivity of 0.95. In order to observe this absorption feature, a noise equivalent delta emissivity (NE$\Delta\epsilon$) of ~0.02 would be required. (Note that the signal-to-noise ratio (SNR) is the reciprocal of NE$\Delta\epsilon$). The imaging nature of THEMIS will permit spatial aggregation of pixels and a spatial context to be developed, again increasing the acceptable noise level in each pixel (the detection of interesting sites will not depend on the occurrence of 10% carbonate in a single pixel). Near 10 μm where a number of minerals have absorption features, it is desired to have a higher NE$\Delta\epsilon$ to allow mineral discrimination. Thus, the minimum NE$\Delta\epsilon$ requirement for THEMIS is 0.02 in the 6.8 μm band (SNR =50) and 0.007 (SNR = 143) in the 8-12.5 μm bands for each pixel.

The local time (4-5 PM) of the Mars Odyssey orbit presents a challenge to all optical remote sensing instruments. However, the surface is still relatively warm at 4:30 PM, with typical temperatures of 245 K for all thermal inertias [Kieffer, 1977 #519]. The surface temperature follows the sub-solar point, but remains ≥245 K over a wide latitude range. For example, in southern hemisphere summer, the temperatures are between 245 and 270 from -45° to 30° N and in northern hemisphere summer the temperatures range from 235 to 250 K between 0° and 45° N. These latitude ranges encompass expected future rover/lander allowable ranges, and include 70% of the total surface area of Mars. A conservative requirement of a surface temperature of 245 K has been selected to set the instrument performance requirements.

The NE$\Delta\epsilon$ requirement translates to a NEΔT requirement of 0.9 K at 7 μm and 0.5 K at 10 μm for a surface temperature of 245K. The identification of nighttime temperature anomalies can be achieved with a broadband NEΔT of 1 K at a typical nighttime surface temperature of 180 K.

2.3.2 Visible Imager

The visible imager is intended to provide morphologic information on the surface of Mars. To meet this requirement, a signal-to-noise ratio for the visible imager for low albedo (0.1), solar incidence angle of 75°, and illumination conditions at aphelion of 100 is required. No additional requirements were placed on the radiometric performance of the visible imager.

3 CALIBRATION METHOD

3.1 Infrared Imager

The THEMIS infrared imager is calibrated in flight using periodic observations of an internal calibration flag mounted in the THEMIS optical path immediately in front of the IR/visible beamsplitter (**Figure 1-3**). Observations of this flag are used to automatically flat field the IR detectors prior to data acquisition, and to radiometrically calibrate the THEMIS data at the end of each data acquisition.

Figure 3-1 shows the processing flow for the IR imager. The basic process steps are outlined below; the relevant sections in which the details of the measurements and/or processes are discussed are indicated.

1) Acquire raw Mars image and flag-closing image.

2) Adjust Mars and flag-closing images for applied gain and offset – convert to signal level (Gain=1; offset=0).

Integer values of gain and offset (DN at a gain of 1) are available. In flight only gains of 1, 2, 4, 8, or 16 will be used. The DN offset will be adjusted to prevent saturation at either the high or low end depending on scene temperature.

3) Remove image offset due to focal plane thermal equilibration using the measured calibration flag signal at end of image sequence.

The instrument firmware automatically sets the signal level when viewing the internal calibration flag to 128 DN for a gain of 1, offset of 0. During observations of external targets the THEMIS focal plane and internal temperatures drift slightly as these components attempt to equilibrate with the radiance of the observed scene. In flight this image offset component will be removed by observing the calibration flag at the end of each observing sequence and finding the maximum or minimum calibration flag signal value as appropriate.

4) Compute the delta signal (scene minus calibration flag)

5) Correct for residual image signal drift.

The major signal drift occurs within the first two minutes after the calibration flag is opened, and the effect of signal drift is minimized by not acquiring images during this period.. Any minor signal drift that occurs during the image sequence can removed if necessary.

6) Compute the delta spectral radiance using the instrument response function.

7) Compute the calibration flag spectral radiance using the measured calibration flag temperature, the calibration flag emissivity, and the spectral-radiance-versus-temperature function determined pre-launch.

8) Compute the initial spectral radiance using the calibration flag spectral radiance and the delta spectral radiance.

9) Remove systematic noise.

a) Remove column- and row-correlated systematic noise.

Column-correlated noise occurs due to minor changes in detector response relative to the pre-launch response function. Row-correlated noise occurs due to minor fluctuations in the detector read-out bias voltage.

b) Remove time-domain signal variations.

Minor (~0.001 °C) focal-plane temperatures in time produce signal variations in time. These signal variations are constant across a row in each band and are correlated in time between bands. Because each band is viewing a different point on Mars at a given time, these correlations in time are offset in space.

10) Remove optical stray light.

11) Return calibrated spectral radiance.

Figure 3-2 shows the processes performed at SBRS using a precision blackbody calibration target to obtain the data necessary to determine the signal offset and residual drift, the relative spectral response, the flag radiance, the spectral-radiance-versus-temperature function, and the instrument response function. The basic processing steps are outlined below; the relevant sections in which the details of the measurements and/or processes are discussed are indicated.

1) Collect blackbody calibration target and flag-closing images.

2) Adjust each image for applied gain and offset – convert to signal level (Gain=1; offset = 0).

3) Determine the image offset as a function of instrument and scene temperature (Section 7.3.1).

4) Determine residual image drift over time as a function of instrument and scene temperature (Section 7.3.1).

5) Compute delta signal (scene minus calibration flag).

6) Determine the relative spectral response of each IR band (Section 7.2.1).

7) Calculate the spectral radiance versus temperature function (Section 7.3.3).

8) Determine the flag radiance using measurements of the flag temperature and emissivity (Section 7.3.2) and the spectral-radiance-versus-temperature function.

9) Compute the delta spectral radiance (blackbody calibration target minus calibration flag)

10) Determine the instrument response function (delta signal versus delta spectral radiance) as a function of instrument and scene temperature (Section 7.3.4).

11) Characterize any systematic noise.

Figure 3-3 shows the planned Mars data calibration flow.

3.2 VISIBLE IMAGER

Figure 3-4. THEMIS visible imager Mars data processing flow.

Figure 3-5. THEMIS visible imager pre-launch calibration data collection process.

Figure 3-6. THEMIS visible imager planned Mars data calibration flow.

4 CALIBRATION TEST HISTORY

4.1 GEOMETRIC TESTS

4.1.1 Infrared Imager

Figure 4-1. IAC

4.1.2 Visible Imager

4.2 SPECTRAL TESTS

4.2.1 Infrared Imager

The relative spectral response of the infrared imager was determined using measurements acquired at SBRS at the piece-part level prior to THEMIS instrument integration. The relative spectral response was calculated from measurements of the transmission of the filters, the focal plane assembly window, and the beamsplitter, along with measurements of the mirror reflectivity and estimates of the detector relative response.

4.2.2 Visible Imager

The relative spectral response of the visible imager was determined using measurements of the filter and focal plane assembly window acquired at MSSS prior to THEMIS instrument integration. These measurements were used with the measurements of the beamsplitter transmission and mirror reflectivity to calculate the relative spectral response.

4.3 RADIOMETRIC TESTS

4.3.1 Infrared Imager

Radiometric testing, instrument characterization, and calibration of the infrared imager were performed in thermal vacuum at SBRS between February, 2000 and January, 2001. **Figure 4-2** shows the THEMIS instrument in the SBRS thermal vacuum chamber. Between February, 2000 and January, 2001 six separate thermal vacuum cycles were completed to fully test and evaluate the THEMIS performance in vacuum conditions over the full range of operating temperatures, to identify and resolve all instrument performance anomalies, and to complete the absolute radiometric calibration of the instrument. Observations were made of a a full-aperture, precision reference blackbody source that was placed inside the vacuum chamber (**Figure 4-3**; Section 6.3.1), a precision visible integrating sphere outside the chamber (**Figure 4-4**; Section 6.3.1), and the IAC (**Figure 4-1**; Section 4.1). The accomplishments, anomalies, and instrument modifications in each TV cycle are described in the following paragraphs.

Thermal Test Cycle 1 (2/29/00 - 3/9/00). This cycle performed the first system-level thermal vacuum testing of the integrated THEMIS instrument. During this test hundreds of commands were issued to the instrument to test the command link and to collect sets of calibration images in different instrument states. During these tests it was found that the rapid transmission of multiple commands could cause the IR command decoding electronics to lock-up and cease command interpretation. The instrument was removed from the vacuum chamber and an error in the command and control FPGA was identified. The field programmable gate array (FPGA) was reprogrammed, replaced, and successfully tested.

Thermal Test Cycle 2 (4/1/00 - 5/13/00). TV Cycle 2 performed the first extensive testing of the THEMIS over its full operational temperature range. During this test it was found that sending commands to the instrument produced temperature shifts in the temperature stabilized focal plane of up to 10 milli-K, which in turn caused a shift of up to 50 (out of 255) data numbers (DN) of the output image signal. This change in signal is equivalent to scene temperature change of ~10 °C. The cause of this anomaly was traced to conducted electrical noise in the focal plane temperature controller feedback and radiated noise through the temperature controller integrator stage. The temperature controller circuit board was redesigned and a new EMI-tight cover/housing was fabricated.

Thermal Test Cycle 3 (5/13/00 - 6/23/00). The THEMIS instrument was again operated over its full temperature range during TV Cycle 3. These tests showed that the modified focal plane temperature control circuit was unstable between 4.6 °C and 13.2 °C In addition, 10 - 20 DN offsets occurred randomly during image acquisition. At this point the use of original temperature controller inherited from the military IR imager on which THEMIS was based was abandoned, and a complete redesign of the temperature controller was performed. A new circuit was designed, breadboarded, and tested. A new flight circuit board was fabricated, tested and installed in the THEMIS instrument. Radiometric calibration of the visible imager was completed during TV Cycle 3.

Thermal Test Cycle 4 (6/23/00 - 7/13/00). Testing during TV Cycle 4 showed that the new temperature controller design had large thermal drifts, and large, random DN offsets. In addition, the flight model circuit board showed DN offsets that were twice the levels observed on the breadboard circuit. These offsets were traced to switching noise on the power lines. The THEMIS was removed from the vacuum chamber and minor changes were made to individual chip resistors. The repaired circuit showed extremely low temperature drifts over time and maximum offsets of less than 8 DN, well within specification.

Thermal test cycle 5 (7/14/00 - 7/29/00). Complete calibration of the infrared imager was during TV Cycle 5. No problems observed during this cycle. However, immediately following the completion of these tests, an ambient test was performed on 8/3/00 to 8/4/00 to image the mountains immediately north of SBRS. During this test it was found that the output DN of hot objects in the scene went to zero intermittently for short (several second) intervals. This problem was dubbed the "data dropout problem".

EMI Testing (8/8/00 – 8/15/00). EMI testing was performed at JPL.

LMA System-level Thermal Vacuum Testing (9/3/00 – 10/20/00). On September 3, 2000 the THEMIS was delivered to the Odyssey spacecraft in Denver for initial spacecraft system-level integration and system-level thermal vacuum testing.

Data Drop Out investigation and Rework (10/23/00 – 1/13/01). The intermittent data drop out problem was investigated and corrected between 10/23/00 and 1/13/01. The problem was traced to broken circuit board traces in the Digital Signal Processor (DSP) circuit board. These traces had been broken during the numerous vibration tests that were performed throughout the THEMIS system testing. The DSP board enclosure was redesigned to have greater stiffness and support in order to reduce the flexure during vibration to acceptable levels. A new DSP board was built and installed in the THEMIS for final thermal vacuum calibration.

Thermal test cycle 6 (1/14/01 – 1/24/01). The final infrared imager calibration data were collected during TV Cycle 6. This thermal vacuum cycle was performed with the THEMIS directly observing the blackbody calibration target within the vacuum chamber so no correction for the transmission/emission of the pointing mirror was required. The THEMIS instrument was delivered directly to Cape Canaveral on January 28, 2001 for final installation on the Odyssey spacecraft prior to launch on April 7, 2001.

4.3.2 Visible Imager

Radiometric testing of the visible imager was performed under vacuum conditions at instrument temperatures of –30, -15, 0, 15, and 30 °C during TV Cycle 3 (5/13/00 – 6/23/00). These tests viewed an integrating sphere (**Figure 4-4**; Section 6.3.1) through a window in the vacuum chamber. The transmission effects of this window were removed using ambient observations of the integrating sphere acquired on _.

5 INSTRUMENT PARAMETERS

5.1 Internal Instrument Telemetry

The internal temperature of the THEMIS instrument is measured at 10 telemetry points given in **Table 5-1** using AD590MF thermistors. The absolute accuracy of these thermistors was specified from the vendor to be ±1.7 °C over a temperature of –55 to +150 °C.

Table 5-1. THEMIS Internal Temperature Telemetry

Location	Telemetry Field	PDS Field
Secondary Mirror	temps[1]	rdt_mirror_temp
Primary Mirror	temps[2]	pri_mirror_temp
Calibration Flag Side Wall	temps[3]	f;ag_temp
IRS Electronics	temps[4]	irs_temp
IR Detective Assembly	temps[5]	ir_temp
Beamsplitter	temps[6]	beamsplitter_temp
Tertiary Mirror	temps[7]	tert_mirror_temp
IRS Housing 1	temps[8]	iris_1_temp
IRIS Housing 2	temps[9]	iris_2_temp
Main Baffle	temps[10]	baffle_temp

The internal currents and voltages of the THEMIS instrument are measured at 20 telemetry points given in **Table 5-2**.

Table 5-2. THEMIS Internal Current and Voltage Telemetry

Location	Telemetry Field	PDS Field
±12 V Voltage DC/DC Converter (Vdc)	voltage[1]	converter_p12v
±5 V Voltage DC/DC Converter (Vdc)	voltage[2]	converter_p5v
+5 V Current IRS Board(mAdc)	voltage[3]	irs_p5v
-12 V Voltage DC/DC Converter (Vdc)	voltage[4]	converter_n12v
+5V Current IRIS LMS12 (mAdc)	voltage[5]	lms12_p5v
+5V Current IRIS EEPROM (mAdc)	voltage[6]	eeprom_p5v
TE cooler temperature (Vdc)	voltage[7]	tec_temp
+5 V Current IRIS Non-Latchup (mAdc)	voltage[8]	iris_p5v
+5 V Total current all boards (mAdc)	voltage[9]	total_p5v
+5 V Current TE Cooler (mAdc)	voltage[10]	tec_p5v
-12 V Current IRIS (mAdc)	voltage[11]	iris_n12v
+12 V Current IRIS (mAdc)	voltage[12]	iris_p12v
-12 V Current IRS (mAdc)	voltage[13]	irs_n12v
+12 V Current IRS (mAdc)	voltage[14]	irs_p12v
V1 Current Latchup , Comparator Voltage (DN)	voltage[15]	latchup_v1
VNSTRIP Voltage (Vdc)	voltage[16]	vnstrip
5 V IRIS Current Latchup, comp. Voltage (DN)	voltage[17]	latchup_5v
V2 Current Latchup, comp. Voltage (Vdc)	voltage[18]	latchup_v2
Spare	voltage[19]	spare
TE Temp. Shutdown, Comp. Voltage (DN)	voltage[20]	tec_shutdown_temp

5.2 INSTRUMENT COMMANDABLE INSTRUMENT STATE PARAMETERS

The THEMIS IR imager has _ commandable instrument state parameters that are listed in **Table 5-3**. _explanation of each parameter_. The VNSTRIP parameter is the variable negative bias voltage that is applied to the focal plane. The analog gain was set such that the 1-sigma DN noise level is approximately 0.5 DN for default parameters of _.

Table 5-3. THEMIS IR Commandable Instrument State Parameters

During pre-launch testing of the THEMIS, only the VNSTRIP parameter was varied to optimize the image quality over temperature; the other parameters were left at their default levels. The default levels used in flight are _.

The values of VNSTRIP used for TV Cycle 5 as a function of internal THEMIS temperature (calibration flag side wall temperature) are given in **Table 5-4**. **Figure 5-1** gives the best-fit function for these data using the equation;

VNSTRIP = 207.45 + 0.222 * calibration_flag_temperature (°C)

This best-fit linear equation is used to predict the appropriate VNSTRIP setting for the in-flight observations.

Table 5-4. VNSTRIP Values Versus Instrument Temperature

Calibration Flag Side Wall Temperature	VNSTRIP (Decimal Value)
-32.400	201.00
-30.800	201.00
-31.400	201.00
-30.800	201.00
-31.400	201.00
-30.800	201.00
-28.800	201.00
-27.000	201.00
-19.500	203.00
-15.500	204.00
-16.100	204.00
-16.400	204.00
-15.800	204.00
-15.800	204.00
-15.100	204.00
-14.500	204.00
-14.500	204.00
-13.500	204.00
-10.000	205.00
-5.5000	206.00
-1.0000	207.00
-1.1100	207.00
-0.79000	207.00
0.16100	207.00
0.16100	207.00
0.80000	207.00
0.80000	207.00
0.80000	207.00
1.5000	207.00
3.5000	208.00
8.2500	209.00
12.000	210.00

14.000	211.00
14.500	211.00
13.600	211.00
14.200	211.00
14.200	211.00
14.200	211.00
14.500	211.00
15.200	211.00
15.500	211.00
18.500	212.00
22.250	213.00
27.000	214.00
29.200	213.00
28.300	214.00
28.600	214.00
28.600	214.00
28.900	214.00
29.900	214.00
30.800	214.00

6 TEST PROCEDURES AND EQUIPMENT

6.1 Geometric Tests

6.1.1 Infrared Imager

6.1.2 Visible Imager

6.2 Spectral Tests

6.2.1 Infrared Imager

6.2.2 Visible Imager

6.3 Radiometric Tests

6.3.1 External Calibration Sources

The THEMIS infrared imager was calibrated over temperature under vacuum using a full-aperture, precision reference blackbody source that was placed inside the vacuum chamber and viewed directly by the THEMIS instrument (**Figure 4-3**).□This reference blackbody was developed for the SBRS Moderate resolution Imaging Spectrometer (MODIS) instrument, and is a calibrated source traceable to NIST standards with an uncertainty of ± 0.032 K (one sigma). Included in this assessment is a temperature uniformity of 0.020 K, a stability of 0.010 K and an emittance 0.99995 ±0.00005 [Young, 1999 #2333; Young, 1999 #2334].

The THEMIS visible sensor was calibrated over temperature under vacuum by viewing an external calibrated integrating sphere (**Figure 4-4**). This sphere was developed for the SBRS Landsat program and is calibrated to a NIST standard with a 1-sigma accuracy of 3.5%. Short term stability is maintained at less than 1% over 14 days [Young, 1999 #2335]. Overall uniformity of illumination is better than 0.25% [Young, 1999 #2335].

6.3.2 Infrared Imager

Calibration data for the IR sensor were collected at five instrument temperatures (-30, -15, 0, 15, and 30° C) and seven target temperatures (-103, -83, -63, -26, -11, 19, and 34 °C) during thermal vacuum Cycle 6. The test names and conditions for these tests are given in **Table 6-1**. These temperatures were chosen to cover the range of operating and scene temperatures expected at Mars.

Table 6-1. Thermal Vacuum Infrared Imager Radiometric Tests

	Instrument Temperature				
Target Temperature	**-30° C**	**-15° C**	**° C**	**15° C**	**30° C**
-103 °C					
-83 °C					
-63 °C					
-26 °C					
-11 °C					
19 °C					
34 °C					

For each calibration data set the instrument and reference blackbody were temperature stabilized to ≤0.1 °C. Observations were acquired of the THEMIS internal calibration flag immediately before the collection of a set of calibration images. A 9-sec image was acquired for selected points in a matrix of five different gains (1, 2, 4, 8, and 16) and five offsets (-8, -4, 0, 4, and 8 DN) with time-delay integration (TDI) on and data compression off (15 images total; **Table 6-2**) that cover the range of values to be used at Mars. In addition, three images with TDI off and two images with image compression on were acquired (**Table 6-2**). At the completion of this series of images, the calibration flag was reimaged to determine any temperature drift or offset that occurred (image number 50; **Table 6-2**). The image number, gain, and offset used at each test condition for the determination of the instrument response function are given in **Table 6-3**.

Table 6-2a. Calibration Initialization Test Conditions

Image Number	Activity	Duration	Gain	Offset (DN)	Time-Delay Integration	Data Compression
--	Shutter opening	5 sec	--	--	--	--
--	Equilibrate	3 min	--	--	--	--
--	Close shutter, calibrate	20 sec	--	--	--	--
--	Shutter opening	5 sec	--	--	--	--
00a	Drift image	2 min	8	Variable	on	on
00b	Shutter closing image	10 sec	16	0	on	off
--	Shutter opening (end Part a)	5 sec	--	--	--	--
--	Equilibrate	3 min	--	--	--	--
--	Close shutter, calibrate	20 sec	--	--	--	--
--	Shutter opening	5 sec	--	--	--	--
--	Equilibrate	2 min	--	--	--	--
See Table _b	Calibration image collection	~200 sec	See Table 6-2b	See Table 6-2b	See Table 6-2b	See Table 6-2b

Table 6-2b. Calibration Image Test Conditions

Image Number	Activity	Duration	Gain	Offset (DN)	Time-Delay Integration	Data Compression
1	Image	9.1 sec	16	0	on	off
2	Image	9.1 sec	8	0	on	off
3	Image	9.1 sec	4	0	on	off
4	Image	9.1 sec	2	0	on	off
5	Image	9.1 sec	1	0	on	off
6	Image	9.1 sec	16	4	on	off
7	Image	9.1 sec	8	4	on	off
11	Image	9.1 sec	16	8	on	off
12	Image	9.1 sec	8	8	on	off
13	Image	9.1 sec	4	8	on	off
16	Image	9.1 sec	16	-4	on	off
17	Image	9.1 sec	8	-4	on	off
21	Image	9.1 sec	16	-8	on	off
22	Image	9.1 sec	8	-8	on	off
23	Image	9.1 sec	4	-8	on	off
26	Image	9.1 sec	16	0	off	off
27	Image	9.1 sec	4	0	off	off
28	Image	9.1 sec	1	0	off	off
35	Image	9.1 sec	16	0	on	on
36	Image	9.1 sec	4	0	on	on
50	Shutter closing image	9.1 sec	16	0	on	off

Table 6-3. Calibration Image Number and Instrument Gain and Offset

	Instrument Temperature				
Target Temperature	**-30° C**	**-15° C**	**0 ° C**	**15° C**	**30° C**
-103 °C **(170 K)**	irradq59 Image 1 Gain 16 Offset 0	irrads17 Image 6 Gain 16 Offset 4	irrads23 Image 6 Gain 16 Offset 4	irrads25 Image 11 Gain 16 Offset 8	irrads30 Image 12 Gain 8 Offset 8
-83 °C **(190 K)**	irradq60 Image 1 Gain 16 Offset 0	irrads18 Image 6 Gain 16 Offset 4	irradq68 Image 6 Gain 16 Offset 4	irrads26 Image 11 Gain 16 Offset 8	irrads31 Image 12 Gain 8 Offset 8
-63 °C **(210 K)**	irradq61 Image 1 Gain 16 Offset 0	irrads21 Image 1 Gain 16 Offset 0	irrads24 Image 6 Gain 16 Offset 4	irrads27 Image 11 Gain 16 Offset 8	irrads32 Image 12 Gain 8 Offset 8
-26 °C **(247 K)**	irradq62 Image 1 Gain 16 Offset 0	irrads22 Image 1 Gain 16 Offset 0	irradq69 Image 1 Gain 16 Offset 0	irrads28 Image 6 Gain 16 Offset 4	irrads33 Image 11 Gain 16 Offset 8
-11 °C **(262 K)**	irradq63 Image 1 Gain 16 Offset 0	irradq64 Image 1 Gain 16 Offset 0	irradq71 Image 1 Gain 16 Offset 0	irrads29 Image 6 Gain 16 Offset 4	irradq77 Image 6 Gain 16 Offset 4
19 °C **(292 K)**	irradr5 Image 16 Gain 16 Offset -4	irradq65 Image 16 Gain 16 Offset -4	irradq73 Image 1 Gain 16 Offset 0	irradq75 Image 1 Gain 16 Offset 0	irradq78 Image 1 Gain 16 Offset 0
34 °C **(307 K)**	irradr6 Image 21 Gain 16 Offset -8	irradq66 Image 21 Gain 16 Offset -8	irradq74 Image 16 Gain 16 Offset -4	irradq76 Image 1 Gain 16 Offset 0	irradq79 Image 1 Gain 16 Offset 0

6.3.3 Visible Imager

The visible response function was calculated using a linear fit to the measured signal, with dark current removed, versus calibrated lamp radiance. The measured visible filter functions were integrated over the measured lamp output spectra to produce band-integrated signal versus radiance functions. The visible response function was calculated using a quadratic fit to the measured signal, with dark current removed, versus calibrated lamp radiance. The measured visible filter functions were integrated over the measured lamp output spectra to produce band-integrated signal versus radiance functions.

7 INFRARED IMAGER CALIBRATION RESULTS

7.1 GEOMETRIC TEST RESULTS

7.1.1 Modulation Transfer Function (MTF)

Table 7-1 , 7-2?

Figure 7-1, 7-2

7.1.2 Out-of Field Response

7.1.3 Camera Model

7.2 SPECTRAL TEST RESULTS

7.2.1 Relative Spectral Response

The transmission of each of the ten THEMIS infrared filters, the focal plane assembly window, and the dichroic beamsplitter were measured at SBRS prior to assembly into the THEMIS instrument. The filter and window data are shown in **Figure 7-3;** the beamsplitter transmission is given in **Figure 7-4**. The relative spectral response of the microbolometer detector array of a typical assembly was and found to be uniform within each band to within the measurement capability. Based on this finding, the spectral response of the detector is assumed to be uniform across each THEMIS spectral band. The reflectivity of the three yttrium-oxide-coated aluminum telescope mirrors is given in **Figure 7-5**. Based on these measurements, the mirror reflectivity is assumed to be uniform across each spectral band.

The analog beamsplitter transmission data were digitized manually at 0.25 μm intervals from 4 to 17 μm. These data were then resampled to the same wavelength points collected for the filter and window transmission data.

The transmission values of the IR filters, window, and beamsplitter used to compute the relative spectral response are archived in Unix computer system files:

/themis/data/archive/themis_ir_filter_window_beamsplitter_transmission.vm
(ascii version with vm header)

/themis/data/archive/themis_ir_filter_window_beamsplitter_transmission.ascii (ascii version without header)

/themis/data/archive/themis_ir_filter_window_beamsplitter_transmission.000 (tdb version)

The values of all three components are archived in excel file:

IRDA_rel_spectral_resp_v2.xls on sheet “Combined Transmission Data”, columns A through M.

Using all of these measured or assumed values, the normalized relative spectral response of each of the ten bands was computed and is given in **Figure 7-6**. This computed value of relative spectral response is used in the generation of the THEMIS Calibrated Radiance Standard Data Products.

The digital values of normalized relative spectral response versus wavenumber for each of the ten infrared bands are archived in Unix computer system files:

/themis/calib/themis_IR_filter_response_norm_v2.vm. (ascii version with vm header)

/themis/calib/themis_IR_filter_response_norm_v2.ascii. (ascii version without header)

/themis/calib/themis_IR_filter_response_norm_v2.000. (tdb version)

and Excel spreadsheet:

IRDA_rel_spectral_resp_v2.xls on sheet “Relative Spectral Response”, columns A through K.

These files are controlled by version number during the mission and the version number will be updated any time a change is made to the contents of these calibration coefficients.

Table 7-3 gives the wavelength position of the mid-point (half maximum) of the normalized relative spectral response for each IR spectral band. This table also gives the computed full-width, half-maximum (FWHM) and computed mid-point of each IR spectral band. For comparison, the band integrals defined as:

band integral (μm) = Σ(relative spectral response(λ) * Δwave)

(see Section 7.3.3) are also given.

Table 7-3. THEMIS IR Imager Filter Characteristics

Band	Left Half-max point (μm)	Right Half-max point (μm)	Band Width (FWHM) (μm)	Band Center (μm)	Band Integral (μm)
1	6.27	7.28	1.01	6.78	0.868
2	6.27	7.28	1.01	6.78	0.868
3	7.38	8.47	1.09	7.93	1.06
4	7.98	9.14	1.16	8.56	1.11
5	8.75	9.95	1.20	9.35	1.18
6	9.66	10.76	1.10	10.21	1.09
7	10.45	11.64	1.19	11.04	1.17
8	11.26	12.33	1.07	11.79	1.09
9	12.17	12.98	0.81	12.57	0.826
10	14.45	15.32	0.87	14.88	0.829

7.2.2 IR Filter Locations

Sixteen rows of the microbolometer focal plane are used for TDI in each of the ten infrared bands. The location of the rows used for each band are given in **Table 7-4**.

Table 7-4. Detector Row Number for Each IR Filter

Band	Start Row	End Row	Assumed Center (used for geometry)
1	1	16	9
2	17	32	25
3	43	58	51
4	69	84	77
5	95	110	103
6	121	136	129
7	147	162	155
8	173	188	181
9	198	213	206
10	224	239	232

Table 7-5 gives the detector rows that are used in each filter when TDI is off. These rows were selected to have the fewest non-active detectors for each filter. Note that the offsets between rows is not uniform.

Table 7-5. TDI-Off Detector Row

Band	TDI Off Detector Row
1	9
2	24
3	52
4	77
5	102
6	129
7	155
8	181
9	206
10	232

7.3 Radiometric Test Results

7.3.1 Signal Offset and Drift

7.3.1.1 Signal Drift

The THEMIS IR detectors are DC devices that measure changes in the total radiance incident on the detector surface. The THEMIS IR imager firmware sets this DC signal level to 128 DN for a gain of 1, offset of 0 when viewing the internal calibration flag. Scene signals are measured relative this value, with the appropriate gain and offset terms applied to maximize the dynamic range while avoiding signal saturation. As a result, targets colder than the flag have signal DNs (gain and offset removed) <128, whereas warmer scenes have a DN>128.

The signal level produced varies with changes in either the external radiance reaching the detector (normal operation), or in changes in the detector temperature. The detector temperature is controlled by a thermoelectric (TE) temperature controller to approximately ±0.001 °C, which corresponds to a signal level of ~1 DN (~0.5 °C) at a gain of 16 for a 245 K scene. In an ideal case, the changes in the external radiance are due solely to changes in the scene (Mars) temperature. In reality the temperature of the THEMIS housing, telescope, beamsplitter, IR filter assemblies can also change slightly over time and affect the total radiance reaching the detector.

The temperature of the THEMIS housing, telescope, beamsplitter, IR filter assemblies, and focal plane will typically be different than the temperature of the external scene. Therefore, the THEMIS components can drift slightly in temperature as they attempt to radiatively equilibrate with the radiance of the scene. As a result, the radiance reaching the detector can vary slightly with time, and the output signal DN level can drift slightly, even when viewing a highly stable thermal target.

Figure 7-7 provides a schematic example of the signal changes with time when viewing a scene that is colder than the calibration flag temperature. (When the scene is warmer than the calibration flag, the behavior is simply the mirror image about 128 DN.) As the flag opens the signal decreases to the level consistent with the scene temperature. Over the next several minutes the instrument reequilibrates and cools, the delta radiance comes less negative, and the signal drifts back toward a value of 128 DN. Over time this drift stabilizes, resulting in a ΔDN at the end of the image sequence that is very slowly changing. At the end of the image sequence the flag is commanded closed and simultaneously imaged. In the case where the scene temperature is colder than the flag, ΔDN will be positive. As the flag closes the instrument warms and the signal drifts back toward 128 DN, with ΔDN drifting downward toward (**Figure 7-7**).

Measurements of the extremely stable calibration blackbody at SBRS provided a detailed determination of the signal drift characteristics. **Figure 7-8** shows an example of the signal drift observed for a warm instrument, cold scene case (test irrads32, images 00a (target) and 00b (flag-closing)) similar to that shown schematically in **Figure 7-7**. (The complete set of drift and flag-closing images are given in Appendix B.) As seen in

Figure 7-8 the signal begins to rise immediately following the opening of the calibration flag, and increases in an approximately $1/e^{-t/\tau}$ fashion to a near-steady-state value. This behavior is consistent with the closing of the calibration flag producing a warming of the instrument components, and opening the flag causes the components to cool. The time constant of the signal equilibration to a new scene radiance is approximately 30-35 seconds.

Figures 7-9a-e show a summary of all of the SBRS calibration tests done at the five instrument temperatures (-30, –15, 0, 15, and 30 °C) and seven target temperatures for all 10 IR bands. The signal value of the target was determined immediately after the flag opened, and all subsequent target values were referenced to this initial value to determine the amount of signal drift. Five instrument properties are immediately apparent from these data.

1) The signal-level drift occurs with a characteristic thermal time constant (τ) and is therefore most pronounced immediately following a flag-closing sequence.

2) The magnitude of the signal drift and the time required for the signal level to stabilize varies with the difference in the scene and flag radiance. For typical Mars observing conditions (0 °C instrument, 245 K (-26 °C) scene), the drift is approximately 0.1-0.3 DN/minute (gain = 8) two minutes after the flag is opened (**Figure 7-9c**).

3) All 10 bands have essentially the same magnitude, rate, and timing of drift. This observation is highly significant because it demonstrates that the spectral character of the IR images will be essentially unchanged by these signal drifts.

4) The total magnitude of the change in signal from the coldest to the hottest targets for a given instrument temperature is essentially the same for all instrument temperatures. This property is expected because the drifts in signal are a function of the delta radiance between the detectors and the scene. Thus, the total range in delta radiance between the detectors at any given temperature and the fixed temperatures of the hottest and coldest scene is approximately the same for each instrument temperature. Ignoring anomalous data (see below) the total range of signal drift between the hottest and coldest target temperatures at the end of these two-minute tests is approximately 13-15 DN at a gain of 8 (**Figure 7-9**). For example in **Figure 7-9a** the coldest scene has an ending drift of approximately –10 DN, while the warmest good scene has an ending drift of ~5 DN.

5) The signal level begins to reequilibrate immediately upon flag closing, so the maximum (or minimum) signal level must be determined immediately after the flag is fully closed. This new signal level is used to account for the signal drift and is set to the measured flag temperature to provide the THEMIS radiometric calibration.

In addition to these simple drifts, a set of more complex, repeatable behaviors were observed in the IR imager during TV testing. Detailed analysis of the drift and flag-closing data showed five typical behaviors in response to the thermal perturbations produced by viewing external scenes and the closing of the calibration flag.

The observed signal behaviors are:

Type 1) A rapid offset within the first few seconds (**Figure 7-9a; Figure 7-10**), that varies from 1 DN to ~10 DN. Following this initial offset the thermal equilibration drift is similar to that seen at other target temperatures. Several sub-sets of this behavior were observed, including a single large offset (1a; **Figure 7-10**; test irradq59; instrument temperature –30 °C, target temperature –103 °C); an offset followed by a signal increase and decrease (1b; **Figure 7-11**; test irrads24); and several DN offsets in the first 300-600 frames (1c). All of these cases appear related to the instrument re-equilibrating when it is cold.

Type 2) An offset of 3-5 DN (gain = 8) in the flag DN that occurs ~100 frames (3.5 seconds) after the flag is closed. An example is given in **Figure 7-12** for test irradq76.

Type 3) Unusual 1-3 DN variation in signal occurs in the 30 °C instrument, 29 and 34 °C target cases (e.g. (**Figure 7-13**; test irradq79; **Figure 7-8e**). The full data set for this case (test irradq79; **Figure 7-13**) suggests that an unusual instability occurred in the instrument in this warm instrument, warm scene case. This anomaly remains unexplained.

Type 4) Stable drift (**Figure 7-8**; test irrads32).

Type 5) Essentially no drift – instrument equal to target temperature (**Figure 7-14**; test irradq75).

A separate anomaly occurred in two bands (4 and 5) in the 30 °C instrument , -103 °C target case (**Figure 7-8e**). This anomaly is due to signal saturation at a value of 0 DN.

Table 7-6 summaries the occurrences of these four behaviors for the 35 SBRS calibration test cases.

Table 7-6. Summary of IR Drift Behavior (Types 1-5)

	Instrument Temperature				
Target Temperature	**-30° C**	**-15° C**	**0 ° C**	**15° C**	**30° C**
-103 °C	1a	1a	4	4	4
-83 °C	1a	1a	1a/1b	1a	4
-63 °C	1a/1b	4	1a	1a	4
-26 °C	5	1a	1a	1a	4
-11 °C	2	5	1a	1a	4
19 °C	2	2	4	5	3
34 °C	2	2	2	2	3

As seen in **Table 7-6** the rapid signal offsets at the beginning of the imaging sequence (Type 1) occur when the target is significantly colder than the instrument. The anomalous flag-closing offset (Type 2) occurs when the target is warmer than the instrument. The unusual variations in signal (Type 3) only occur when the instrument and target are both warm.

The total signal drift observed 120 seconds after the flag opening is summarized in **Tables 7-7 and 7-8. Table 7-7** gives the signal drift for one Band (Band 4) for all instrument/target temperature combinations; **Table 7-8** give the signal drift at one instrument temperature (0 °C) for all band and target temperature combinations.

Table 7-7. DN Drift (Gain = 8). Total drift 120 seconds after flag opening. One band (Band 4), all temperature tests. Average of all detectors. Data from TV Cycle 6, "00a and 00b" files.

	Instrument Temperature (External Housing Temperature)				
Target Temperature	-30° C	-15° C	0° C	15° C	30° C
-103 °C	---	7.75	7.28	10.93	---
-83 °C	6.29	7.42	9.77	10.88	8.84
-63 °C	5.46	6.51	7.92	8.84	9.64
-26 °C	-0.52	2.94	4.75	7.27	8.27
-11 °C	-2.33	-0.61	20.78	6.07	6.66
19 °C	-6.20	-4.17	-1.81	-0.11	3.97
34 °C	-9.39	-6.62	-3.86	-1.92	---

Table 7-8. DN Drift (Gain = 8). Total drift 120 seconds after opening. One instrument temperature (0 ° C), all bands and target temperatures. Average of all detectors. Data from TV Cycle 6, "00a and 00b" files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	6.83	9.95	8.41	5.12	---	-1.72	-3.93
2	7.26	9.84	8.53	5.18	---	-1.84	-4.06
3	7.27	9.64	8.15	4.92	---	-1.87	-3.83
4	7.28	9.77	7.92	4.75	---	-1.81	-3.86
5	7.35	9.69	7.99	4.90	---	-1.85	-3.94
6	7.63	7.67	6.78	3.96	---	-1.84	-3.84
7	7.28	7.42	6.95	3.88	7.24	-1.82	-3.94
8	7.06	7.06	6.89	3.66	4.86	-1.76	-3.82
9	7.16	7.26	6.82	3.42	4.02	-1.91	-3.89
10	7.04	6.86	6.89	3.52	4.37	-1.82	-3.86

Given the rapid DN offsets observed immediately after the flag is opened, it is more useful to consider the total drift fro 30 to 120 seconds as indicative of the thermal reequilibration of the instrument. **Table 7-9** gives these values for instrument temperatures of –30, 0, and 30 °C for all bands, all target temperatures.

Table 7-9a. DN Drift (Gain = 8). Total drift from 30 to 120 seconds after opening. Instrument temperature = -30 ° C. Average of all detectors. Data from TV Cycle 6, "00a and 00b" files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	4.42	2.81	1.06	-0.06	-0.74	-2.77	-4.20
2	3.39	2.69	1.03	0.22	-0.58	-2.92	-4.32
3	2.97	2.41	0.88	0.03	-0.67	-2.88	-4.05
4	2.46	2.52	0.84	0.05	-0.85	-2.57	-4.18
5	2.37	2.75	0.69	-0.09	-1.13	-2.39	-3.82
6	2.76	2.52	0.85	0.09	-1.09	-2.57	-3.94
7	3.49	2.59	0.85	-0.03	-1.29	-2.58	-3.78
8	2.64	2.35	0.79	0.09	-1.19	-2.41	-3.77
9	2.70	2.22	0.75	0.13	-1.08	-2.55	-3.89
10	2.75	2.25	0.66	-0.03	-0.92	-2.23	-3.70

Table 7-9b. DN Drift (Gain = 8). Total drift from 30 to 120 seconds after opening. Instrument temperature = 0 ° C. Average of all detectors. Data from TV Cycle 6, "00a and 00b" files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	4.03	2.38	3.48	1.08	1.27	-0.91	-2.03
2	4.07	2.38	3.61	1.06	0.98	-0.94	-2.07
3	3.63	2.35	3.32	0.95	1.85	-0.83	-1.77
4	3.60	2.27	3.14	0.95	1.69	-0.83	-1.79
5	3.43	2.28	3.07	0.99	1.99	-0.88	-1.80
6	3.72	2.34	3.02	0.93	1.50	-0.79	-1.64
7	3.42	2.32	3.07	1.02	1.61	-0.73	-1.65
8	3.16	2.30	2.95	0.94	1.49	-0.62	-1.68
9	3.03	2.26	2.92	0.95	1.90	-0.76	-1.73
10	3.14	2.17	2.88	0.88	1.80	-0.76	-1.71

Table 7-9c. DN Drift (Gain = 8). Total drift from 30 to 120 seconds after opening. Instrument temperature = 30 ° C. Average of all detectors. Data from TV Cycle 6, "00a and 00b" files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	3.38	5.89	5.52	4.11	3.83	2.67	0.38
2	3.46	5.76	5.35	4.00	3.87	2.59	0.64
3	3.36	5.71	5.66	4.21	3.67	2.70	1.05
4	---	5.22	5.42	4.24	3.72	2.88	1.43
5	---	5.41	5.49	4.14	3.64	3.04	1.97
6	3.14	5.42	5.11	4.02	3.63	2.94	2.15
7	3.22	5.30	5.29	4.14	3.79	3.03	2.16
8	2.91	5.04	5.21	4.18	3.53	2.71	2.10
9	2.91	5.11	4.82	3.96	3.39	2.62	1.90
10	3.01	5.14	4.66	3.73	3.31	2.39	1.85

The data in **Table 7-9** show that:

1) The DN drift is highly consistent for all bands. The 1-sigma variance of the total DN drift between all bands for any given test condition varies from 0.08 to 0.35 DN, with typical values of ~0.15 DN for a gain of 8.

2) The drift is positive when the target is colder than the instrument, and negative when the target is warmer than the instrument.

3) The largest DN drifts occur at the extremes. The coldest instrument, warmest target cans has a drift of ~-4 DN (Gain = 8); the warmest instrument, coldest target case has a drift of ~5.5 DN.

4) For these extreme cases, assuming no correction for the drift using the flag-closing image, the scene DN would be uncertain to approximately –4 to +5.5 DN after several minutes. At a gain of 8, these values correspond to temperature uncertainties of approximately –4 to +5.5 °C at 245 K (see Section 7.3.5). These values provide an estimate of the worst-case absolute temperature uncertainties due to signal level drift.

Finally, it is useful to consider the DN drift during the last 30 seconds of these test images when the drift has nearly stabilized. These values are given in **Table 7-10** for instrument temperatures of –30, 0, and 30 °C for all bands, all target temperatures. These drift values range from ~1.5 DN/30-sec to –0.9 DN/30-sec (Gain = 8) for the extreme cases. Typical values for the nominal instrument operating temperature (0 °C) for expected Mars temperatures of 180 K (-83 °C) to 262 K (-11 °C) range from 0.08 to 0.6 DN/30-sec. These values indicate that the signal drift approximately 2 minutes after flag opening will be ≤ ~1.2 DN/minute at a gain of 8, or ≤ ~2.5 DN/minute at a gain of 16.

Table 7-10a. DN drift (Gain = 8) from 90 to 120 sec after flag opening; Instrument Temperature = -30 ° C. Average of all detectors. Data from TV Cycle 6, "00a and 00b" files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	1.562	0.353	0.215	-0.114	-0.275	-0.400	-0.612
2	1.371	0.023	0.239	-0.151	-0.232	-0.528	-0.913
3	1.137	-0.015	0.132	0.063	-0.231	-0.670	-0.836
4	0.558	0.058	0.125	-0.088	-0.089	-0.336	-0.746
5	0.744	0.128	0.165	-0.073	-0.021	-0.347	-0.569
6	0.737	0.215	0.186	0.023	-0.100	-0.350	-0.759
7	0.919	0.099	0.257	-0.018	-0.001	-0.413	-0.705
8	0.961	0.053	0.229	0.037	-0.122	-0.414	-0.876
9	1.031	0.237	0.190	-0.097	-0.088	-0.537	-0.895
10	1.060	0.166	0.161	0.095	-0.047	-0.322	-0.776

Table 7-10b. DN drift (Gain = 8) from 90 to 120 sec after flag opening. Instrument Temperature = 0 ° C. Average of all detectors. Data from TV Cycle 6, "00a and 00b" files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	0.829	0.556	0.337	0.154	0.022	-0.047	-0.268
2	0.804	0.426	0.369	0.128	0.024	-0.113	-0.241
3	0.575	0.551	0.310	0.070	0.112	-0.193	-0.163
4	0.574	0.484	0.243	0.084	0.368	-0.128	-0.280
5	0.536	0.606	0.212	0.078	1.017	-0.203	-0.287
6	0.782	0.636	0.271	0.017	0.706	-0.142	-0.186
7	0.375	0.526	0.355	0.160	0.499	-0.181	-0.213
8	0.197	0.689	0.391	0.117	0.407	-0.070	-0.235
9	0.343	0.647	0.429	0.073	0.297	-0.074	-0.155
10	0.386	0.621	0.337	0.224	0.882	-0.170	-0.226

Table 7-10c. DN drift (Gain = 8) from 90 to 120 sec after flag opening. Instrument Temperature = 30 ° C. Average of all detectors. Data from TV Cycle 6, "00a and 00b" files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	0.234	1.572	1.193	0.690	0.390	0.305	---
2	0.279	1.382	1.116	0.481	0.405	0.330	---
3	0.300	1.478	1.356	0.503	0.257	0.310	---
4	0.113	1.500	1.178	0.715	0.191	0.334	---
5	0.051	1.473	1.060	0.699	0.274	0.510	---
6	0.140	1.440	0.756	0.526	0.181	0.451	---
7	0.205	1.301	0.785	0.534	0.170	0.484	---
8	0.174	1.448	0.710	0.671	0.170	0.255	---
9	0.140	1.412	0.616	0.648	0.109	0.365	---
10	0.226	1.513	0.562	0.619	0.119	0.382	---

Another measure of the predictability of the signal drift can be obtained by comparing the predicted to the measured DN of the flag in the flag-closing image (see **Figure 7-7**). **Table 7-11** summarizes these results for instrument temperature of –30, 0, and 30 °C for all bands and target temperatures. Cases with known anomalies have been excluded from this table.

Table 7-11a. Measured flag-closing DN minus predicted DN. Instrument temperature = -30 ° C. Average of all detectors. Data from TV Cycle 6, “00a” and “00b” files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	---	-10.9	-9.5	2.6	2.3	1.0	0.9
2	---	-10.9	-9.5	2.7	1.8	1.3	2.1
3	---	-9.8	-8.9	2.7	2.0	1.0	1.0
4	---	-8.9	-8.8	2.9	2.3	-0.2	-0.5
5	---	-9.3	-9.2	2.6	2.2	-0.5	-0.8
6	---	-6.9	-6.2	2.5	2.3	0.5	0.4
7	---	-6.9	-5.6	2.5	2.2	0.7	-0.1
8	---	-6.8	-4.9	3.0	2.2	0.5	-0.1
9	---	-6.5	-4.7	2.4	1.7	0.3	0.0
10	---	-6.2	-4.2	3.2	1.2	-0.2	-0.5

Table 7-11b. Measured flag-closing DN minus predicted DN. Instrument Temperature = 0 ° C. Average of all detectors. Data from TV Cycle 6, "00a" and "00b" files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	4.6	---	-9.3	-6.9	---	-3.6	-1.8
2	4.2	---	-9.6	-7.0	---	-3.6	-1.8
3	4.8	---	-9.0	-6.7	---	-3.6	-2.3
4	5.1	---	-7.9	-6.0	---	-4.1	-2.6
5	4.6	---	-7.8	-6.0	---	-3.6	-2.5
6	3.8	-6.9	-5.9	-4.5	---	-3.7	-2.4
7	4.5	-6.4	-6.2	-4.3	---	-3.7	-2.2
8	4.9	-5.7	-6.1	-3.9	---	-3.8	-2.4
9	4.7	-6.1	-6.0	-3.4	---	-3.5	-2.3
10	5.0	-5.3	-6.1	-3.6	---	-3.7	-2.3

Table 7-11c. Measured flag-closing DN minus predicted DN. Instrument Temperature = 30 ° C. Average of all detectors. Data from TV Cycle 6, "00a" and "00b" files.

	Target Temperature						
Band	-103 °C	-83 °C	-63 °C	-26 °C	-11 °C	19 °C	34 °C
1	-5.1	-9.2	-10.3	-8.0	-8.8	-3.9	3.6
2	-5.5	-9.2	-10.1	-8.2	-8.9	-4.0	2.8
3	-5.0	-9.1	-9.8	-8.5	-8.2	-3.7	1.6
4	-5.9	-3.8	-7.7	-7.9	-7.4	-3.7	1.5
5	-5.4	-4.7	-8.2	-8.1	-7.5	-4.2	1.1
6	-5.3	-8.2	-8.7	-8.8	-8.1	-4.5	0.7
7	-5.2	-8.6	-9.6	-8.6	-8.6	-4.7	0.8
8	-5.5	-8.1	-8.9	-8.9	-7.9	-4.3	0.5
9	-5.1	-8.1	-8.7	-8.4	-8.0	-4.1	0.9
10	-5.0	-7.9	-8.0	-8.1	-8.0	-3.7	1.1

7.3.1.2 Flag-closing DN Value

The DN value of the calibration flag is determined at SBRS and in flight using a flag-closing image. This DN level is used to account for the signal drift and is set to the measured flag temperature to provide the THEMIS radiometric calibration. DN values taken in Band 1 at two early points in the image are used to determine whether the scene is colder than the flag, in which case the maximum of the flag-closing image should be used to determine the flag DN (e.g. **Figure 7-7**), or the scene is warmer than the flag, in which case the minimum DN is used. All 320 detectors are averaged and the resulting values filtered in the time dimension with a 3-point unity-weight filter to reduce the noise in these measurements. The true maximum (or minimum) DN can only be determined for Bands 1-5 because of the time delay built into the data processing firmware to account for the offset in time for which each band observes the same point on the martian surface. As a result, the maximum (or minimum) DN in Bands 6-10 occurs before the processing firmware begins collecting data from these bands, and the true maximum (or minimum) is not recorded. This value can, however, be estimated for Bands 6-10 by measuring the DN offset for Bands 6-10 relative to Band 5 at the same moment in time. This offset is 26 lines for Band 6, 52 lines for Band 7, 78 lines for Band 8, 104 lines for Band 9, and 130 lines for Band 10. This DN offset is added to the measured maximum (or minimum) flag DN for Band 5 to determine signal drift for Bands 6-10.

7.3.1.3 Summary

The effect of signal drift on the absolute radiometric accuracy can be summarized as follows:

1) The magnitude and rate of signal drift is nearly constant for all bands. Two minutes after the flag is opened the DN delta between bands is typically less than 0.15 DN at a gain of 8. Thus, the relative signal errors between bands are less that the random noise level (~0.25 DN at a gain of 8; see Section 7.3.5).

2) After two minutes the signal drift has stabilized to ≤1.2 DN/minute (gain = 8) in worst cases, and is typically 0.1-0.3 DN/minute. In flight a minimum of one minute will be allotted between the flag opening and the beginning of an image. IR images of up to 5-10 minutes duration (900-1800 km in length) are expected to have less than approximately 0.5 to 3 DN of signal drift at a gain of 8. This signal error corresponds to an absolute temperature uncertainty of 0.5 to 3 °C at 245 K.

3) When processing Mars images the total signal drift will be determined using the flag-closing image, and this offset will be applied uniformly to the entire image sequence. In this case, the temperature uncertainties will be smallest at the end of the imaging sequence, immediately before the flag-closing image is acquired, and greatest at the beginning of the sequence. With experience in Mars orbit it may be possible to refine the drift estimates to provide a better estimate of the signal offset versus time during the image sequence. However, signal drifts produced by the varying Mars surface and atmosphere temperature may be comparable in magnitude and impossible to remove.

4) As seen in the data presented in this section, there are systematic offsets that consistently occur as the flag is opened and closed. These effects are present in the data used to create the instrument response function (see Section 7.3.4). To the extent that these same effects occur for similar instrument and target temperatures at Mars, they will be properly accounted for by applying the pre-launch instrument response function.

5) Given the complex signal drift in the THEMS IR imager, the formal accuracy errors are difficult to quantity. However, it is roughly estimated that the absolute temperature due to signal drifts will be on the order of 1-3 °C for a 245 K surface temperature. This accuracy estimate will be studied at Mars by comparison with Mars Global Surveyor TES data and observations of surfaces whose temperatures can be accurately estimated.

6) Signal drift will be minimized in flight by leaving the calibration flag in the open (Mars-viewing) position whenever the instrument is in a data collection mode.

7.3.2 Calibration Flag Characteristics

7.3.2.1 Emissivity

The surface of the THEMIS calibration flag that is viewed by the detectors was painted with _ at SBRS. The opposite side of the calibration flag was painted with _ at the Jet Propulsion Laboratory. This white paint was used to maximize solar reflectivity in order to minimize the solar energy absorbed by the flag in the event of direct Sun viewing, while also maximizing the thermal emissivity. The emissivity of the black calibration and white (wall-facing) surfaces of a spare calibration flag was measured in the ASU Thermal Emission Spectral Laboratory. The emissivity was determined by assuming that the measured emissivity, filtered with a unity square-wave filter of size 15 samples, was unity at some point within the measured spectral range [_]. This approach was necessary because it was not possible to instrument the spare flight hardware to directly measure the kinetic temperature of the flag. Laboratory work on typical high emissivity materials has shown that this approach is generally accurate to within several percent.

The emissivity of the spare flag is given in **Figure 7-15.** As seen in **Figure 7-15a** the black paint has an emissivity ≥0.975 at all wavelengths within the THEMIS spectral range (~1660 to 650 cm^{-1}). The small measured deviations from unit emissivity will not be mapped onto Mars for the following reasons. When the flag is closed for viewing, a cavity is produced in which energy from the flag, the side walls, and the detector/filter assembly is commingled. The nominal operating temperature of the instrument and flag is 0 °C. The detector/filter assembly is controlled at 15 °C. Assuming a simple model where the detector energy at 15 °C is reflected off of the flag at 0 °C would give an apparent temperature error of +0.4 °C for a flag emissivity ≥ 0.975 (reflectivity ≤0.025). A flag emissivity of 0.985 (**Figure 7-15a**) would give a temperature error of +0.25 °C. As a result, a less-than-unit flag emissivity results in a higher measured flag radiance when the flag is colder than the detector array, and a lower measured flag radiance when the flag is warmer than the detector array. Thus, the delta radiance between the scene and the flag is slightly different than the delta radiance if the flag was a perfect blackbody. Making the simplifying assumption that the flag has unit emissivity results in a slightly higher calculated slope in the instrument response function than would be computed if the exact emissivity were used and the precise radiance emitted and reflected from the flag were known. However, because this effect is present in both the pre-launch calibration and Mars data, the effect is indistinguishable from a higher instrument response, and no systematic errors are introduced into the Mars data by assuming a unity emissivity for the calibration flag. Furthermore, because of the difficulties and potential errors in using the measured flag emissivity and accounting for the complex emitted and reflected radiance when viewing the flag, any attempt to model this effect would most likely increase, rather than decrease, any potential systematic errors.

The digital values of emissivity versus wavenumber are archived for reference in Unix computer system files:

/themis/calib/_

7.3.2.2 Temperature

The temperature of the calibration flag is used to set the flag radiance that corresponds to the observed flag signal in the flag-closing image acquired at the end of each THEMIS observation. The flag temperature cannot be determined directly due to the complexity and risk of mounting thermistors on this critical moving mechanism. Instead, the flag temperature is determined indirectly using a thermistor mounted in the side wall of the THEMIS housing against which the calibration flag is stowed when THEMIS is collecting data.

The temperature of the calibration flag is assumed to be equal to the side wall thermistor temperature based on the isothermal nature of the inner THEMIS enclosure and the radiometric coupling between the flag and the side wall and inner enclosure. Thermistors mounted at three points (calibration flag side wall (temps[3]), IR detective assembly (temps[5]), and tertiary mirror (temps[7])) within the THEMIS housing were observed during thermal vacuum testing to be consistent within 4 °C over the full range of instrument and target temperatures, with the majority of cases within 2.5 °C. Much of the temperature variation within the housing is likely to be due to true temperature variability, but serves as an indication of the upper limit in the uncertainly of the calibration flag temperature. The time required for the flag to close and acquire this image is less than 5 seconds, during which time its temperature will not change significantly (<0._°C).

The absolute radiometric accuracy of the THEMIS IR imager is not strongly dependent on the accuracy to which the calibration flag temperature is known since this surface was used as a transfer standard from the highly accurate precision reference blackbody source. It is assumed that the temperature field within the THEMIS enclosure is the same in flight as it was in the SBRS vacuum chamber for a given instrument temperature. Thus, any systematic errors between the actual temperature of the flag and temperature derived from the side wall thermistor will be the same in flight as they were in the vacuum chamber. As a result, the delta radiance between the scene and the calibration flag will be similar at Mars to those in the vacuum chamber, and any systematic errors will be reduced.

7.3.3 Spectral Radiance Versus Temperature

The spectral radiance as a function of temperature was computed by summing the relative spectral response in each band times the Planck blackbody function over wavelength, and dividing by the sum of the sum of the relative spectral response:

$$\text{Spectral Radiance} = \frac{\sum_{i=1}^{n} \left(B_{(T,\lambda_i)} * R_{\lambda_i} * \Delta\lambda_i \right)}{\sum_{i=1}^{n} \left(R_{\lambda_i} * \Delta\lambda_i \right)}$$

where:

B is the Planck function (W cm^{-2} str^{-1} $micron^{-1}$)

T is the temperature in kelvin

λ is wavelength in microns

$R(\lambda)$ is the relative spectral response normalized to unity over each spectral bandpass (unitless)

$\Delta\lambda$ is the delta wavelength interval in microns

Σ is the sum over each THEMIS band

The units of spectral radiance are W cm^{-2} str^{-1} μm^{-1}.

The band integral, defined as:

band integral (μm) = $\Sigma(R(\lambda) * \Delta\lambda)$

was computed for each THEMIS IR band.

The band integral data are archived in Unix computer system file:

/themis/calib/ir_band_width_v2

This file is controlled by version number during the mission and the version number will be updated any time a change is made to the contents of these calibration coefficients.

Table 7-3 gives the band integral and the full-width half-maximum (FWHM) of each THEMIS IR band.

Spectral radiance was computed and stored in a look-up table for temperatures from 100 to 380 K at 0.5 K intervals. This look-up table is used to convert between spectral radiance and temperature in the THEMIS radiometric calibration using a linear interpolation between table entries. A test was performed in which the radiance-versus-temperature function was computed at 0.1 K intervals; the interpolated values for any band at any temperature agreed with the 0.5 K interval case to within 0.005 K.

The spectral-radiance-to-temperature look-up table is archived in Unix computer system files:

/themis/calib/temp_rad_v4

This file is controlled by version number during the mission and the version number will be updated any time a change is made to the contents of these calibration coefficients.

7.3.4 Instrument Response Function

For each of the 35 thermal vacuum test conditions (seven target temperatures at each of five instrument temperatures (**Table 6-1**), a set of images were acquired with gains that varied from 1 to 16 and offsets of –4, 0, or +4 DN (for a gain of 1). The external instrument housing temperature, target temperature, and test name of each of these tests is given in **Table 6-1**. The image used for the determination of the instrument response function was selected to give the highest gain possible without saturating the signal. In three cases (irrads30, irrads31, and irrads32) it was necessary to use a gain of 8 to avoid saturation; in all other cases a gain of 16 was used (**Table 6-3**).

For each test case the delta radiance between the flag and the precision reference blackbody source was calculated. The radiance of the flag was calculated using the side wall thermistor at the time the flag-closing image was acquired. The measured delta signal between the signal from the source and the signal from the calibration flag was also calculated. The signal from the flag was measured from the flag-closing image. The resulting delta signal (scene-flag) versus delta radiance (scene-flag) was fit with a linear function to determine the instrument response function for each of the 320 detectors in each band.

Two of the 35 calibration sets were excluded from the determination of the instrument response function. The data from instrument temperature 0 °C, target temperature 170 K were excluded because of anomalous flag-closing image DN values. The data from instrument temperature 30 °C, target temperature 307 K were excluded because of anomalous oscillations in the target observation data.

Figures 7-16a through **7-16j** show the delta signal versus delta radiance for the average of all 320 detectors (TDI on) for each band. These data confirm that the delta signal (output) is linear with delta radiance (input) for these microbolometer array detectors. Also shown in **Figures 7-16a** through **7-16j** are the best-fit linear function:

$$y = a + b * x$$

for the average of all detectors for each band. A linear function was fit for each detector in each band and the slope and offset coefficients of this best-fit linear function is the instrument response function that is used to convert DN to spectral radiance for the Mars data.

The slope (b) and offset (a) coefficients of the best fit to the instrument response data from thermal vacuum Cycle 6 are archived in Unix computer system file:

/themis/calib/irf_fit_all_tv6_v3.0_1_2_v3.0

This file is controlled by version number during the mission and the version number will be updated any time a change is made to the contents of these calibration coefficients.

7.3.4.1 Linearity

The measured response values are closely linear and show no instrument temperature effects. The best-fit response function does not pass through the origin because of the fact that the view of the calibration flag does not include the slightly absorbing fore-optics. Thus, the delta-signal appears slightly negative (less apparent energy) when viewing a scene at the same temperature as the flag. Because the functions shown in **Figure 7-16** will be used in flight, this effect is exactly reversible and will not result in any systematic errors in the Mars observations.

7.3.4.2 Variation Among Detectors

The variation in the offset of the best-fit linear function to the instrument response function is shown in **Figure 7-17a** for all bands; the variation in the slope of the best-fit linear function to the instrument response function is shown in **Figure 7-17b**. A histogram of the offset for each of the ten THEMIS infrared bands is given in **Figure 7-18-1**. A histogram of the slope for each of the ten THEMIS infrared bands is given in **Figure 7-18-1**. The 1-sigma variation in the slope of the instrument response is typically 1.5-2.5%, with a maximum of 5.3% in Band 2 (**Figure 7-18-2**), confirming the measurement requirement of <10% variability in the response over the microbolometer detector.

7.3.5 Radiometric Performance

7.3.5.1 Image Noise (DN)

The 1-sigma standard deviation of the infrared imager output signal at a gain of 16 for 64 consecutive images was computed for each detector in each band for each of the 35 thermal vacuum test conditions listed in **Table 6-1**. The results for each band for the TDI-on case for instrument temperatures of –30, 0, and 30 °C, target temperature of 247 K are shown in **Figure 7-19**. The 1-sigma standard deviations for each band for the TDI-off case for an instrument temperature of 0 °C are shown in **Figure 7-20**. **Table 7-12** gives the average of the 1-sigma variance in DN (Gain =16; TDI on) for all detectors in each band for an instrument temperature of 0 °C, target temperature of 247 K.

The digital values of 1-sigma standard deviation in DN for each pixel in each band are archived in Unix computer system file:

/themis/calib/ _.

7.3.5.2 Noise Equivalent Spectral Radiance (NESR)

The 1-sigma noise equivalent spectral radiance (NESR; W cm^{-2} str^{-} μm-^{1}) was computed from the 1-sigma standard deviation in the output signal by dividing by the instrument response function. The NESR values for each band for the TDI-on case for instrument temperatures of –30, 0, and 30 °C, target temperature of 247 K are shown in **Figure 7-23**. **Table 7-12** gives the average of the 1-sigma variance in NESR (Gain =16; TDI on) for all detectors in each band for an instrument temperature of 0 °C, target temperature of 247 K.

The digital values of NESR for each pixel in each band are archived in Unix computer system file:

/themis/calib/ _.

7.3.5.3 Signal-to-Noise Ratio (SNR)

The signal-to-noise ratio (SNR) was computed at a reference temperature of 245 K by dividing the spectral radiance at 245 K (signal) by the noise equivalent spectral radiance (noise). The SNR values for each band for the TDI-on case for instrument temperatures of –30, 0, and 30 °C, target temperature of 247 K are shown in **Figure 7-24**. **Table 7-12** gives the average of the SNR for all detectors in each band for an instrument temperature of 0 °C, target temperature of 247 K.

The digital values of SNR for each pixel in each band are archived in Unix computer system file:

/themis/calib/_.

7.3.5.4 Noise Equivalent Delta Emissivity (NE□□)

The 1-sigma noise equivalent delta emissivity (NE□□) was computed at a reference temperature of 245 K by dividing the noise equivalent spectral radiance (NESR) by the spectral radiance at 245 K. **Table 7-12** gives the average of the NE□□ for all detectors in each band for an instrument temperature of 0 °C, target temperature of 247 K.

7.3.5.5 Noise Equivalent Delta Temperature (NE□T)

The 1-sigma noise equivalent delta temperature (NE□T) was computed at reference temperatures of 180 and 245 K by converting the 1-sigma noise equivalent spectral radiance (NER) to temperature at each reference temperature using temp_rad_v4. **Table 7-12** gives the average of the NE□□ for all detectors in each band for an instrument temperature of 0 °C, target temperature of 247 K.

Table 7-12. THEMIS IR Imager Pre-launch Performance Results

Band	Band Center (μm)	Sigma (DN) Gain=16	NER (W cm^{-2} str^{-1})	NESR (W cm^{-2} str^{-1} μm^{-1})	SNR @245 K	NE□□ @245 K	NE□T (K) @245 K	NE□T (K) @180 K
1	6.78	0.524	3.90e-6	4.49e-6	32.7	0.0306	0.86	8.31
2	6.78	0.518	3.71e-6	4.28e-6	34.3	0.0291	0.82	8.00
3	7.93	0.526	2.35e-6	2.21e-6	104	0.00957	0.32	2.34
4	8.56	0.532	1.85e-6	1.67e-6	163	0.00616	0.22	1.37
5	9.35	0.524	1.98e-6	1.67e-6	186	0.00538	0.21	1.07
6	10.21	0.525	2.09e-6	1.91e-6	179	0.00560	0.24	1.01
7	11.04	0.520	2.18e-6	1.85e-6	193	0.00519	0.24	0.88
8	11.79	0.518	2.30e-6	2.11e-6	171	0.00585	0.29	0.93
9	12.57	0.520	2.24e-6	2.72e-6	132	0.00759	0.39	1.15
10	14.88	0.517	2.09e-6	2.52e-6	128	0.00781	0.47	1.09

7.3.6 Systematic Noise

7.3.6.1 Random Signal Offsets

During the early THEMIS testing at SBRS (TV Cycles 1-5), random offsets in the signal level of up to10-15 DN (Gain= 8) occurred over approximately 200 frames (6.7 sec) while the infrared imager was staring at a stable target. These offsets were minimized during instrument development by the redesign of the infrared focal plane controller. During the final thermal vacuum testing offsets of approximately 3 DN (Gain = 8) were detected on only two occasions during approximately 900 minutes of image collection.

No offsets were observed during spacecraft-level testing at Denver or at Cape Canaveral. If these offsets occur in flight they will be identified and removed on a best-effort basis.

7.3.6.2 Correlated Noise

Two types of correlated noise are observed in calibrated THEMIS IR images – "column noise" and "row noise". Column noise appears as correlated stripes in the downtrack image direction and occurs because of detector-to-detector differences that are not removed when the image is converted to radiance using the instrument response function of each individual detector. Row noise occurs as small, correlated random increases or decreases in the signal level of an entire row of pixels.

As discussed in Section 7.3.4, the total variation in the instrument response within any band is typically 1.5-2.5%, with a maximum of 5.3% in Band 2. This detector-to-detector variation is removed using the instrument response function. The microbolometer arrays used in THEMIS can experience a small number of pixels whose response is erratic, varying of both short (seconds) and longer time scales. These pixels cannot be calibrated using standard procedures and must be corrected using scene-base "destriping" algorithm. THEMIS has approximately 2-8 pixels (out of 5,120) in each band that exhibit this behavior. This random detector-to-detector noise, when averaged by TDI, is approximately 1-2 DN at a gain of 16.

Correlated row noise occurs at levels below the random noise levels (~0.5 DN at a gain of 16. The correlated row noise is typically less than _ DN and is most likely produced by temporal variations in the detector bias voltage that affects the readout of all detectors along a single line. Because the entire array of 240 rows is readout at 30 Hz, the time between the readout of any single line (or set of lines that are integrated together during TDI, is approximately 1/30 sec. Thus, any changes in detector bias on timescales less than this will appear as small row-to-row changes in the signal level in each band. This noise will not be removed during standard processing unless it exceeds the random noise levels.

7.3.6.3 Destripe Algorithm

7.3.7 Error Analysis

8 VISIBLE IMAGER CALIBRATION RESULTS

8.1 Geometric Test Results

8.1.1 Modulation Transfer Function (MTF)

8.1.2 Focus Versus Instrument Temperature

8.1.3 Out-of Field Response

8.1.4 Camera model

8.2 Spectral Test Results

8.2.1 Relative Spectral Response

The transmission of each of the five THEMIS visible filters with window were measured by MSSS prior to delivery to SBRS. The reflectance of the dichroic beamsplitter and the reflectivity of the mirror coatings were measured prior to assembly into the THEMIS instrument. The filter/window data are shown in **Figure _;** the beamsplitter reflectance is given in **Figure _**; the reflectivity of the three yttrium-oxide-coated aluminum telescope mirrors is given in **Figure _**. The relative spectral response of the visible detector array is assumed to be uniform within each band.

The analog beamsplitter transmission data and mirror reflectivity data were digitized manually at 0.01 μm intervals from 0.39 to 0.90 μm.

The transmission/reflectivity values of the visible filter/window sets, the beamsplitter reflectance, and the mirror reflectance used to compute the relative spectral response are archived in Unix computer system files:

/themis/data/archive/themis_vis_filter_beamsplitter_mirror.vm (ascii version with vm header)

/themis/data/archive/themis_vis_filter_beamsplitter_mirror.ascii (ascii version without header)

/themis/data/archive/themis_vis_filter_beamsplitter_mirror.000 (tdb version)

The values of all three components are archived in excel file:

themis_vis.xls

Using all of these measured or assumed values, the normalized relative spectral response of each of the ten bands was computed and is given in **Figure 7-6**. This computed value of relative spectral response is used in the generation of the THEMIS Calibrated Radiance Standard Data Products.

The digital values of normalized relative spectral response versus wavenumber for each of the ten infrared bands are archived in Unix computer system files:

/themis/calib/themis_vis_filter_response_norm_v1.vm. (ascii version with vm header)

/themis/calib/themis_vis_filter_response_norm_v1.ascii. (ascii version without header)

/themis/calib/themis_vis_filter_response_norm_v1.000. (tdb version)

and Excel spreadsheet:

themis_vis.xls

These files are controlled by version number during the mission and the version number will be updated any time a change is made to the contents of these calibration coefficients.

Table 7-3 gives the wavelength position of the mid-point (half maximum) of the normalized relative spectral response for each IR spectral band. This table also gives the computed full-width, half-maximum (FWHM) and computed mid-point of each IR spectral band. For comparison, the band integrals defined as:

band integral (μm) = □(relative spectral response(□) * □wave)

(see Section 7.3.3) are also given.

THEMIS Visible Band Characteristics

Band Number	**Filter Number**	**Band Name**	**Center Wavelength (μm)**	**Half Power Point – Short Wavelength (μm)**	**Half Power Point – Long Wavelength (μm)**	**Bandwidth (Full Width Half Power) (μm)**
1	2	Blue	0.425	0.400	0.449	0.049
2	5	Green	0.540	0.515	0.566	0.051
3	3	Red	0.654	0.628	0.686	0.053
4	4	IR1	0.749	0.723	0.776	0.053
5	1	IR2	0.860	0.837	0.882	0.045

8.3 Radiometric Test Results

8.3.1 Instrument Response Function

8.3.1.1 Variation with Signal

8.3.1.2 Variation with Temperature

8.3.1.3 Variation Among Detectors

8.3.2 Radiometric Performance

8.3.2.1 Image Noise (DN)

8.3.2.2 Noise Equivalent Spectral Radiance (NESR)

8.3.2.3 SNR

8.3.2.4 Noise Equivalent Delta Reflectivity (NEΔr)

8.3.3 Systematic Noise

8.3.4 Error Analysis

9 FIGURE CAPTIONS

Figure 1-1. Computer generated THEMIS instrument drawings. (a) Optical ray trace. (b) Explode view of instrument components.

Figure 1-2. THEMIS flight instrument prior to installation on the 2001 Mars Odyssey spacecraft.

Figure 1-3. Computer-generated view of the internal flag mounted in the housing;

Figure 1-4. THEMIS internal calibration flag.

Figure 2-1. Infrared spectra of representative minerals. (a) Laboratory spectral resolution. (b) Simulated THEMIS spectral resolution.

Figure 3-1. THEMIS IR imager Mars data processing flow.

Figure 3-2. THEMIS IR imager pre-launch calibration data collection process.

Figure 3-3. THEMIS IR imager planned Mars data calibration flow.

Figure 3-4. THEMIS visible imager Mars data processing flow.

Figure 3-5. THEMIS visible imager pre-launch calibration data collection process.

Figure 3-6. THEMIS visible imager planned Mars data calibration flow.

Figure 4-1. THEMIS IR and visible geometric calibration collimating target at SBRS (IAC; _). This external collimator calibration target was used to determine focus quality and imager co-registration over temperature.

Figure 4-2. Installation of the THEMIS instrument in the SBRS thermal vacuum chamber. (a) Installation. (b) Final setup and blanketing .

Figure 4-3. THEMIS vacuum chamber layout showing the relative location of the instrument and the full-aperture, precision reference IR blackbody source during TV Cycle 6.

Figure 4-4. THEMIS visible external calibration integrating sphere source.

Figure 5-1. VNSTRIP commandable instrument parameter versus temperature.

Figure 7-1. MTF – IR imager.

Figure 7-2. ??

Figure 7-3. Measured transmission of the THEMIS flight infrared filters and infrared window versus wavenumber.

Figure 7-4. Measured transmission of the THEMIS flight dichroic beamsplitter versus wavenumber.

Figure 7-5. Measured reflectivity of the THEMIS flight yttrium-coated aluminum mirrors versus wavelength. (a) IR reflectivity. (b) Visible reflectivity

Figure 7-6. Computed THEMIS IR imager normalized relative spectral response – all 10 filters. (Note: filters 1 and 2 are identical).

Figure 7-7. Schematic example of the IR imager signal drift over time. The effects of opening and closing the calibration flag and viewing a scene colder that the instrument are illustrated.

Figure 7-8. Actual example of IR imager signal drift versus time. Test irrads32; instrument temperature 30 ° C; target temperature -63 °C. Frame rate was 30 frames/sec.

Figure 7-9. Signal drift versus time for all 35 calibration tests, Band 5. (a) Instrument temperature of –30 °C. (b) Instrument temperature of –15 °C. (c) Instrument temperature of 0 °C. (d) Instrument temperature of 15 °C. (e) Instrument temperature of 30 °C.

Figure 7-10. Signal drift behavior. Type 1a. Test irradq59; instrument temperature –30 °C, target temperature –103 °C.

Figure 7-11. Signal drift behavior. Type 1b. Test irrads24; instrument temperature 0 °C, target temperature –63 °C

Figure 7-12. Signal drift behavior. Type 2. Test irradq76; instrument temperature 15 °C, target temperature 34 °C

Figure 7-13. Signal drift behavior. Type 3. Test irradq79; instrument temperature 30 °C, target temperature 34 °C

Figure 7-14. Signal drift behavior. Type 5. Test irradq75; instrument temperature 15 °C, target temperature 19 °C

Figure 7-15. Emissivity of the THEMIS spare calibration flag assembly. The emissivity was measured in the ASU Thermal Emission Spectral Laboratory.

Figure 7-16. Delta signal versus delta radiance with the best-fit linear function for the average of all 320 detectors in each IR band. (a) Band 1. (b) Band 2. (c) Band 3. (d) Band 4. (e) Band 5. (f) Band 6. (g) Band 7. (h) Band 8. (i) Band 9. (j) Band 10.

Figure 7-17. Variation in the coefficients of the best-fit linear function to the instrument response function for each of the ten THEMIS infrared bands. (a) offset term. (b) slope term.

Figure 7-18-1. Histogram of the offset of the best-fit linear function to the instrument response function for each of the ten THEMIS infrared bands. (a) Band 1. (b) Band 2. (c) Band 3. (d) Band 4. (e) Band 5. (f) Band 6. (g) Band 7. (h) Band 8. (i) Band 9. (j) Band 10.

Figure 7-18-2. Histogram of the slope of the best-fit instrument response function for each of the ten THEMIS infrared bands. (a) Band 1. (b) Band 2. (c) Band 3. (d) Band 4. (e) Band 5. (f) Band 6. (g) Band 7. (h) Band 8. (i) Band 9. (j) Band 10.

Figure 7-19. Standard deviation in output signal level, Bands 1-10, TDI-on case. a) Instrument temperature of –30 °C; test irradq62. b) Instrument temperature of 0 °C; test irradq69. c) Instrument temperature of 30 °C; test irrads33.

Figure 7-20. Standard deviation in output signal level, Bands 1-10, TDI-off case, instrument temperature of 0 °C; test irradq69.

Figure 7-21. Deleted.

Figure 7-22. Deleted.

Figure 7-23. The 1-sigma noise equivalent spectral radiance (NESR; W cm^{-2} str^{-1} μm^{-1}). TDI-on case for instrument temperatures of –30, 0, and 30 °C, target temperature of 247 K.

Figure 7-24. The IR imager signal-to-noise ratio (SNR) at a reference temperature of 245 K. TDI-on case for instrument temperatures of –30, 0, and 30 °C, target temperature of 247 K.

Figure _. MTF – Visible imager.

Figure _. Focus images.

Figure _. Geometric registration.

Figure _. Camera model.

APPENDIX A – THEMIS PRE-LAUNCH TEST LOG

APPENDIX B – DRIFT PLOTS