The Miniature Thermal Emission Spectrometer for the Mars Exploration Rovers

by

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ABSTRACT

The Miniature Thermal Emission Spectrometer (Mini-TES) will provide remote measurements of mineralogy and thermophysical properties of the scene surrounding the Mars Exploration Rovers, and guide the Rovers to key targets for detailed in situ measurements by other Rover experiments. The specific scientific objectives of the Mini-TES investigation are to: (1) determine the mineralogy of rocks and soils; (2) determine the thermophysical properties of selected soil patches; and (3) determine the temperature profile, dust and water-ice opacity, and water vapor abundance in the lower atmospheric boundary layer. The Mini-TES is a Fourier Transform Spectrometer covering the spectral range 5-29 μm (339.50 to 1997.06 cm^{-1}) with a spectral sample interval of 9.99 cm^{-1}. The Mini-TES telescope is a 6.35-cm diameter Cassegrain telescope that feeds a flat-plate Michelson moving mirror mounted on a voice-coil motor assembly. A single deuterated triglycine sulfate (DTGS) uncooled pyroelectric detector with proven space heritage gives a spatial resolution of 20 mrad; an actuated field stop can reduce the field of view to 8 mrad. Mini-TES is mounted within the Rover's Warm Electronics Box and views the terrain using its internal telescope looking up the hollow shaft of the Pancam Mast Assembly (PMA) to the fixed fold mirror and rotating elevation scan mirror in the PMA head located ~1.5 m above the ground. The PMA provides a full 360° of azimuth travel and views from 30° above the nominal horizon to 50° below. An interferogram is collected every two seconds, and transmitted to the Rover computer where the Fast Fourier Transform, spectral summing, lossless compression, and data formatting are performed prior to transmission to Earth. Radiometric calibration is provided by two calibration V-groove blackbody targets instrumented with platinum

thermistor temperature sensors with absolute temperature calibration of ±0.1° C. One calibration target is located inside the PMA head, the second is on the Rover deck. The Mini-TES temperature is expected to vary diurnally from –10 to +30° C, with most surface composition data collected at scene temperatures >270 K. For these conditions the systematic calibration error for two-spectra summing is ~1.8 x10^{-8} W cm^{-2} str^{-1} /cm^{-1} between 450 and 1500 cm^{-1}, increasing to ~4.2 x10^{-8} W cm^{-2} str^{-1} /cm^{-1} at shorter (300 cm^{-1}) and longer (1800 cm^{-1}) wavenumbers. The absolute radiance error will be <5 x10^{-8} Watt cm^{-2} str^{-1} /cm^{-1}, decreasing to ~1 x10^{-8} Watt cm^{-2} str^{-1} /cm^{-1} over the wavenumber range where the scene temperature will be determined (1200-1600 cm^{-1}). The worst-case sum of these random and systematic radiance errors correspond to an absolute temperature error of ~0.4 K for a true surface temperature of 270 K, and ~1.5 K for a surface at 180 K. The Mini-TES will be operated in a 20-mrad panorama mode and an 8-mrad targeted mode, producing 2-dimensional rasters and 3-dimensional hyperspectral image cubes of varying sizes. The overall Mini-TES envelope size is 23.5 x 16.3 x 15.5 cm and the mass is 2.40 kg. The power consumption is 5.6 W average. The Mini-TES was developed by Arizona State University and Raytheon Santa Barbara Remote Sensing.

1 INTRODUCTION

The Miniature Thermal Emission Spectrometer (Mini-TES) is intended to provide remote determination of the mineral composition of the rocks and soils, surface temperature, and atmospheric properties in the scene surrounding the Mars Exploration Rovers. The Mini-TES collects high resolution infrared spectra over the wavelengths where distinctive vibrational spectral bands are best observed, providing a direct means of identifying crystal structure, and hence mineralogy, of all geologic materials including silicates, carbonates, sulfates, phosphates, oxides, and hydroxides. The scene around the rover will be imaged by Mini-TES at two different spatial scales, creating 3-dimension hyperspectral image cubes (**Figure 2**) These remote mineralogic measurements, together with the morphologic and color data from the Panoramic Camera (Pancam), will be used to direct the Rovers to specific targets of interest for detailed study by the full suite of Rover instruments (**Figure 2**). Mini-TES will also measure the temperature of the lower atmospheric boundary layer, and provide information on suspended dust, water-ice, and water vapor opacity.

The Mini-TES (**Figure 1**) is a miniaturized version of the Thermal Emission Spectrometer (TES) built by Arizona State University (ASU) and Raytheon Santa Barbara Remote Sensing (SBRS) for the Mars Observer (MO) and Mars Global Surveyor (MGS) missions (Christensen, et al, 1992). Mars Observer was launched in 1992 and the MO TES successfully returned flight data. Unfortunately, a spacecraft anomaly occurred as the spacecraft was about to begin orbital operations in 1993. Mars Global Surveyor was launched in 1996, and the MGS TES has been returning excellent data since the spacecraft arrived at Mars in September, 1997 [*Christensen et al.*, 2001b; *Christensen et* *al.*, 2001a; *Bandfield et al.*, 2000; *Bandfield*, 2002; *Smith et al.*, 2001b; *Smith et al.*, 2001a; *Kieffer et al.*, 2000; *Kieffer and Titus*, 2001].

ASU and SBRS began developing an advanced and miniaturized version of the TES in 1995 under NASA Planetary Instrument Definition and Development (PIDDP) and internal SBRS funding (Schueler, et al, 1997). This effort resulted in a hardware demonstration in late 1996, and in mid-1997 the Mini-TES was included as a component of the proposed Athena Precursor Experiment (APEX) for NASA's Mars 2001 Lander mission. Following the cancellation of the 2001 Lander, the Athena payload, including the Mini-TES, was selected for the Mars Exploration Rover (MER) mission.

The specific scientific objectives of the Mini-TES investigation are to:

1) determine the mineralogy of rocks and soils
2) determine the thermophysical properties of selected soil patches
3) determine the temperature profile, dust opacity, water-ice opacity, and water vapor abundance in the lower boundary layer of atmosphere

2 MEASUREMENT REQUIREMENTS

2.1 Science Requirements

The Mini-TES science objectives can be successfully addressed if the instrument meets a specific set of measurement requirements. Mineralogic mapping has three measurement requirements: (1) radiometric accuracy and precision necessary to uniquely determine the mineral abundances in mixtures to within 5% absolute abundance; (2) spectral resolution sufficient to uniquely determine the mineral abundances in mixtures to within 5% absolute abundance; and (3) spatial resolution of ≤25 cm at 10 m distance (25 mrad) necessary to resolve and identify individual rocks 0.5 m in size or larger in the rover near field. The thermophysical objective requires determining the thermal inertia to within ±10 J-m^{-2}-K^{-1}-s$^{-1/2}$. The determination of atmospheric temperature profiles, aerosols, water vapor, condensates has two measurement requirements: (1) radiometric accuracy and precision necessary to determine the opacities of atmospheric dust and ice to ±0.05 and temperature to ±2 K; and (2) spectral resolution sufficient to uniquely identify dust, water-ice, water-vapor, and sound the atmosphere, and monitor their physical and compositional properties.

2.2 Radiometric Requirements

The radiometric requirements for determining mineral abundances to 5% accuracy in mixtures depend critically on the specific minerals in question. However, in general it is necessary to resolve the relative depths of mineral absorption bands to ~2% and the absolute mineral band depths to ~10% of their typical band depth (0.15 emissivity). This produces a relative (precision) emissivity requirement, stated as the Noise Equivalent Delta Emissivity (NEDε) of 0.003 and an absolute requirement of 0.015. At typical daytime temperatures of 270 K and a reference wavenumber of 1000 cm^{-1} (10 μm), these requirements correspond to an absolute spectral radiance accuracy of 9×10^{-8} W cm^{-2} str^{-1} /cm^{-1} and a 1-sigma (σ) radiometric precision, stated in terms of the noise equivalent spectral radiance (NESR), of 2×10^{-8} W cm^{-2} str^{-1} /cm^{-1}. The accuracy and precision necessary to sound the atmospheric temperature profile with a <1 K temperature error and to determine the opacity of dust and ice aerosols are comparable to the mineral requirements. Determination of thermal inertia to ±10 J-m^{-2}-K^{-1}-s$^{-1/2}$ requires an absolute accuracy of the surface temperature determination to within ±2 K for typical night (170 K) and day (270 K) temperatures.

The 1-σ NESR of an individual spectral sample in a single MGS TES spectrum has been demonstrated using both pre-launch and in-flight observations to be ~1.5 $x10^{-8}$ W cm^{-2} str^{-1} $/cm^{-1}$ for wavenumbers from ~300 to 1400 cm^{-1}, increasing to ~2 $x10^{-8}$ W cm^{-2} str^{-1} $/cm^{-1}$ at longer (1650 cm^{-1}) wavenumbers [*Christensen et al.*, 2001a]. Experience with MGS TES has shown that an absolute accuracy of 2% can be achieved with the Mini-TES provided that the internal and external calibration targets meet their requirements of an emissivity of >0.98, known to within ±0.005 over the mini-TES spectra range, and absolute knowledge of the target temperature to within ±0.2° C [*Ruff et al.*, 1997].

For proper calibration, Mini-TES must be able to view two beam-filling blackbody calibration references whose temperatures are well known. The primary calibration target is placed within the PMA head, where it can be viewed easily by the instrument and where it is protected from martian dust. The secondary target is on the rover deck. Because the outer surface of the PMA is painted white and the target on the rover deck is black, the temperature difference between the targets is expected to be substantial (>20° C).

2.3 Spectral Requirements

The spectral requirements are determined by the width and position of the key spectral features in the materials and mixtures of materials. Determining mineral abundances within mixtures to 5% requires the capability to sample mineral spectral band to ~10% of their width. For geologic materials, the full width at half maximum (FWHM) width of typical spectral bands is ~100 cm^{-1}, and the minimum in the Si-O stretching band undergoes a shift of over 150 cm^{-1} for differing crystal structures from low-to high-silica content, and an offset of up to 500 cm^{-1} from the fundamental C-O, S-O, and P-O stretching bands [*Farmer*, 1974; *Salisbury et al.*, 1992; *Christensen et al.*, 2000a]. Therefore, a spectral sampling of 10 cm^{-1} is sufficient for identifying key minerals and deconvolving mineral mixtures [*Ramsey and Christensen*, 1998; *Feely and Christensen*, 1999; *Hamilton and Christensen*, 2000].

2.4 Fore-Optics and Field of View Requirements

Mini-TES is mounted within the rover's Warm Electronics Box (WEB) and views the terrain around the rover using its internal Cassegrain telescope, looking up the hollow shaft of the Pancam Mast Assembly (PMA) to the fixed fold mirror and rotating elevation scan mirror in the PMA head. The PMA provides a full 360° of azimuth travel, but limitations on the size of opening in the mirror assembly atop the PMA restrict the total elevation range to 80°. The mirrors were oriented to provide a 30° elevation view above the nominal horizon, allowing observation of the sky, and 50° below the nominal horizon, allowing the terrain with ~2 m of the rover to be observed. The PMA's mirror assembly is located ~1.5 m above the ground. The offsets between the Mini-TES and the Pancam were measured pre-flight to within 2 mrad, allowing data from these two instruments to be co-registered to within a single Mini-TES pixel.

The Mini-TES the integration time required to achieve a given signal-to-noise ratio (SNR) is inversely proportional to the fourth power of the angular resolution. This strong dependence drove the selection of two spatial resolution modes: a 20-mrad (full width half maximum (FWHM) mode for rapid surveys of large areas, and an 8-mrad mode for detailed study of limited high-priority regions. The Mini-TES telescope aperture size results from a trade between the integration time required to obtain an adequate SNR (large telescope), and the mass of the PMA and the shadowing of the rover's solar array (small telescope). A telescope aperture of 6.35 cm (2.42 inches) was selected, resulting in a PMA that is manageable and achieves the required SNR under all daytime conditions in the 20-mrad mode by co-adding two spectra. The required SNR can be obtained with just one spectrum for the warmest mid-day conditions.

3 VIBRATIONAL SPECTROSCOPY

3.1 Overview

Vibrational spectroscopy is based on the principle that vibrational motions occur within a crystal lattice at frequencies that are directly related to crystal structure and elemental composition (i.e. mineralogy) [e.g. *Wilson et al.*, 1955; *Farmer*, 1974]. The fundamental frequencies of geologic materials typically correspond to wavelengths greater than ~5 μm, and provide a diagnostic tool for identifying virtually all minerals.

An extensive suite of studies over the past 35 years has demonstrated the utility of vibrational spectroscopy for the quantitative determination of mineralogy and petrology [e.g. *Lyon*, 1962; *Lazerev*, 1972; *Vincent and Thompson*, 1972; *Farmer*, 1974; *Hunt and Salisbury*, 1976; *Salisbury et al.*, 1987b; *Salisbury et al.*, 1987a; *Salisbury and Walter*, 1989; *Bartholomew et al.*, 1989; *Salisbury et al.*, 1991; *Salisbury*, 1993; *Christensen and Harrison*, 1993; *Lane and Christensen*, 1997; *Feely and Christensen*, 1999; *Christensen et al.*, 2000a; *Hamilton*, 2000; *Hamilton and Christensen*, 2000; *Wyatt et al.*, 2001; *Hamilton et al.*, 2001]. The fundamental vibrations within different anion groups, such as CO_3, SO_4, PO_4, and SiO_4, produce unique, well separated spectral bands that allow carbonates, sulfates, phosphates, silicates, and hydroxides to be readily identified (**Figure 3**). Additional stretching and bending modes involving major cations, such as Mg, Fe, Ca, and Na, allow further refinement in mineral identification, for example the excellent discriminability of minerals within the silicate and carbonate groups (**Figure 4**). Significant progress also has been made in the development of quantitative models to predict and interpret the vibrational spectra produced by emission of energy from complex, natural surfaces [e.g. *Conel*, 1969; *Henderson et al.*, 1992; *Hapke*, 1993; *Salisbury et al.*, 1994; *Moersch and Christensen*, 1995; *Wald and Salisbury*, 1995; *Mustard and Hays*, 1997].

The fundamental vibrations of geologic materials typically occur between ~5 and 100 μm. In addition to these modes, overtone and combination vibrations, such as the 2.35 μm ($3\nu_3$) and 2.55 μm ($\nu_1+2\nu_3$) combination tones in carbonates [*Gaffey*, 1984] and the 4.5 μm ($2\nu_3$) overtone in sulfate [*Blaney and McCord*, 1995], also occur. These vibrations typically occur between ~2 and ~6 μm [*Roush et al.*, 1993]. While they also contain important diagnostic information, these modes are typically much less populated than the fundamental vibrations [*Wilson et al.*, 1955], and the overtone and combination band absorptions in the 2-6 μm region tend to be relatively weak compared to the fundamental absorptions in the 5-100 μm region.

3.2 Mineral Groups

3.2.1 Hydrothermal Minerals

Hydrothermal systems produce characteristic mineralization that is dominated by microcrystalline quartz (chert, chalcedony, opal, etc.) and carbonates. The silica minerals have a major 8-10 μm absorption [e.g. *Hunt and Salisbury*, 1970]. Carbonates precipitate in thermal spring environments, and are the key constituents of the martian meteorite samples examined by McKay et al. [*McKay et al.*, 1996]. The fundamental C-O absorption occurs near 6.7 μm [e.g. *Farmer*, 1974; *Nash and Salisbury*, 1991; *Lane and Christensen*, 1997] in a region that is distinct from other mineral classes (**Figures 3** and **4**), thereby greatly facilitating carbonate identification. **Figure 5** shows examples of the degree to which minerals within the carbonate [*Lane and Christensen*, 1997] and clay [*Piatek*, 1997; *Van der Marel and Beeutelspacher*, 1976] mineral groups can be distinguished using vibrational spectroscopy.

Figure 6 shows laboratory thermal emission spectra of travertine and hydrothermal silica samples collected from the Castle Hot Springs Volcanic Field of central Arizona. The distinctive spectral character of both types of hydrothermal deposits in the thermal infrared are apparent. Travertine samples are characterized by the broad absorption features typical of carbonates (calcite). The hydrothermal silica spectrum clearly exhibits the major absorption features typical of quartz. The basalt sample is an excellent analog for hydrothermal alteration on Mars. It contains small (<1 mm) calcite-bearing vesicles and veins, similar to those found in the SNC sample ALH84001 [*McKay et al.*, 1996]. The spectrum of this rock demonstrates that a small amount of carbonate (<5%) can be detected in volcanic rocks using thermal-IR spectra.

3.2.2 Evaporite Minerals

This broad class of minerals includes the following important groups: carbonates, sulfates, chlorides, and phosphates that are precipitated by the evaporation of marine or non-marine waters. As such, they are the most obvious and direct mineralogical evidence for standing water. In the search for candidate sites for sample return, locating evaporite minerals is a high priority. The abundance of any one of these minerals in an evaporite basin is a function of the dissolved chemical constituents contained in the water as well as the history of the basin inundation/denudation. Therefore, the identification and quantification of the different evaporite minerals can yield information about the environment in which they were produced. Thermal-infrared spectra provide distinguishing characteristics for the different groups. Sulfates (gypsum) and phosphates (apatite) have deep, well-defined features in the 8.3 to 10 μm region that vary with position based on composition (**Figure 3**).

3.2.3 Hydrous Silicates

Minerals that incorporate hydroxyl $(OH)^-$ anions into their structure give clues about the availability of water during their formation. The majority of such minerals occur in the silicate class and most of these are in the phyllosilicate group (**Figure 5**). Within the phyllosilicates, the clay, mica, serpentine, and chlorite groups are all important. Serpentine minerals form through the activity of H_2O and ultramafic igneous rocks, so they may provide additional evidence of hydrothermal activity on Mars. Though all the hydrous silicates have the hydroxyl anion as their common trait, they range widely in their mode of occurrence. Some form as primary constituents of igneous rocks, giving clues about the magmatic conditions under which the rock was formed. Most hydrous silicates crystallize as secondary products of metamorphism and hydrothermal alteration and their composition provides insight into the pressure and temperature where they formed. The hydrous silicates all have characteristic mid-IR features (e.g. **Figure 5**) due to fundamental bending modes of $(OH)^-$ attached to various metal ions, such as an AL-O-H bending mode near 11 μm in kaolinite clay [e.g. *Farmer*, 1974; *Van der Marel and Beeutelspacher*, 1976].

3.2.4 Igneous Silicates

The primary silicate minerals associated with igneous rocks are the most abundant mineral class found on Mars [*Christensen et al.*, 2000b; *Bandfield et al.*, 2000; *Christensen et al.*, 2001a; *Bandfield*, 2002]. The majority of martian rocks likely will vary by only relatively subtle differences in bulk mineralogy, represented by the common rock forming minerals. An ability to distinguish and quantify olivines, pyroxenes, and feldspars is crucial to describing the geological character of the planet. Without this overview, the locations of hydrous activity are without context. All silicates have Si-O stretching modes between 8 and 12 μm that vary in position with mineral structure (e.g. **Figure 4**). This absorption shifts to higher frequency (shorter wavelength) as bond strength increases for isolated, chain, sheet, and framework tetrahedron structure. These shifts allow for detailed identification of the igneous silicates, including variations within the solid solution series.

3.3 Quantitative Analysis of IR Spectra

A key strength of mid-infrared spectroscopy for quantitative mineral mapping lies in the fact that mid-infrared spectra of mixtures are linear combinations of the individual components [*Thomson and Salisbury*, 1993; *Ramsey and Christensen*, 1998; *Feely and Christensen*, 1999; *Hamilton and Christensen*, 2000]. The mid-IR fundamental vibration bands have very high absorption coefficients and therefore much of the emitted energy only interacts with a single grain. When absorption coefficients are low, as is the case for overtone/combination bands, the energy is transmitted through numerous grains and the spectra become complex, non-linear combinations of the spectral properties of the mixture. The linear nature of the thermal spectral emission of mineral mixtures has been demonstrated experimentally in particulates for mixtures of up to five components [*Thomson and Salisbury*, 1993; *Ramsey*, 1996]. In these experiments the mineral abundance could be quantitatively retrieved using linear deconvolution techniques to within 5% on average.

The linear mixing of mineral components in rock spectra has also been confirmed [*Feely and Christensen*, 1999; *Hamilton and Christensen*, 2000; *Wyatt et al.*, 2001; *Hamilton et al.*, 2001], with retrieved mineral abundances that are accurate to 5-10% in laboratory spectra. Mineral composition and abundance were determined both spectroscopically and using traditional thin-section techniques for a suite of 96 igneous and metamorphic rocks [*Feely and Christensen*, 1999]. The rocks were used in their original condition; no sample cutting, polishing, or powdering was performed, and weathered surfaces were observed where available to best simulate remote observations. Comparison of the mineral abundances determined spectroscopically with the petrographically estimated modes for each sample gave an excellent agreement using high-resolution data. The spectroscopically determined compositions matched the petrologic results to within 8-14% for quartz, carbonates, feldspar, pyroxene, hornblende, micas, olivine, and garnets. These values are comparable to the 5-15% errors typically quoted for traditional thin section estimates.

3.4 Environmental Effects

Variations in particle size and porosity produce variations in the spectra of materials at all wavelengths. Numerous quantitative models have been developed to investigate these effects [*Vincent and Hunt*, 1968; *Hunt and Vincent*, 1968; *Conel*, 1969; *Hunt and Logan*, 1972; *Hapke*, 1981; *Hapke*, 1993; *Salisbury and Eastes*, 1985;

Salisbury and Wald, 1992; *Salisbury et al.*, 1994; *Moersch and Christensen*, 1995; *Wald and Salisbury*, 1995; *Mustard and Hays*, 1997] and have demonstrated the importance of specular reflectance and scattering. Two basic behaviors are observed with decreasing grain size: (1) strong bands (high absorption) tend to get shallower; and (2) weak bands (low absorption) increase in contrast, but appear as emission maxima and reflectance minima [*Vincent and Hunt*, 1968].

Dust coatings and weathering rinds present a potential problem for any optical remotely-sensed measurements of Mars. However, the thickness of material through which sub-surface energy can escape increases linearly with wavelength. Thermal IR spectral measurements through coatings have been studied using mechanically deposited dust [Ramsey, 1992 #1622; Johnson, 2002 #2410] and terrestrial desert varnish [*Christensen and Harrison*, 1993] as analogs to martian rock coatings. These results have shown that thermal-IR spectral observations can penetrate relatively thick (mean thickness up to ~40-50 μm) layers of these materials to reveal the composition of the underlying rock.

Downwelling radiation is reflected off of the surface materials and this reflected component is included in the total radiance received by the Mini-TES. The downwelling radiance will be measured directly using Mini-TES sky observations. It will also be modeled using MGS TES downward-looking observations of atmospheric temperature and dust, water-ice, and water-vapor abundances acquired simultaneously or at identical seasons from similar atmospheric conditions during previous Mars years [*Smith et al.*, 2001b].

4 INSTRUMENT DESCRIPTION

4.1 Instrument Overview

The design of the Mini-TES is intentionally conservative. A major aspect is the use of uncooled detectors, substantially reducing the complexity of the fabrication, testing, operation, and rover interface of the instrument, while meeting the scientific requirements for the investigation. Mini-TES covers the spectral range from 5 to 29.5 µm (1997.06 to 339.50 cm^{-1}) with a spectral sampling of 9.99 cm^{-1}. The telescope is a compact 6.35-cm diameter Cassegrain telescope with an intermediate stop before the afocal section that provides excellent stray light rejection and efficient baffling. The flat-plate Michelson moving mirror is mounted on a voice-coil motor assembly that provides the optical path difference necessary for the Michelson interferometer with excellent tilt performance. A single deuterated triglycine sulfate (DTGS) uncooled pyroelectric detector with proven space heritage gives a spatial resolution of 20 mrad; a actuated field stop reduces the field of view to 8 mrad . The overall envelope size is 23.5 x 16.3 x 15.5 cm and the mass is 2.40 kg. The power consumption is 5.6 W average. Mini-TES I, (**Figures 1 and 6**), was delivered to JPL on Aug. 16, 1999, initially for integration into the 2001 Mars Lander; Mini-TES II was delivered on June 7, 2002. A summary of the instrument characteristics are given in Table 1.

The Mini-TES spectrometer provides data to the rover computer at a fixed rate of one interferogram every two seconds (1.80 second Michelson scan, 0.20 second retrace) whenever it is powered. The rover flight software accepts these data when appropriate, and performs the Fast Fourier Transform (FFT) processing, spectral co-adding, and lossless compression. The FFT algorithm transforms the raw interferograms, containing up to 1120 16-bit interferogram samples, into 16-bit spectra during the 200 ms retrace period.

The Mini-TES Zero-Path-Difference (ZPD) algorithm locates ZPD using a selectable choice of the positive-, negative-, or mid-point of the interferogram peak-to-peak amplitude, and selects the central 1024 points of the interferogram. The FFT generates a spectrum of 512 16-bit samples, from which the 167 with useable response are selected. Co-addition of two subsequent spectra reduces the data rate by an additional factor of two. Based on these post-processing steps, the result is an average data rate of approximately 400 bits per second.

4.2 Optical Design

The Mini-TES optical system (**Figure 7**) uses a compact Cassegrain telescope configuration with a 6.35 mm diameter primary mirror that defines the system's aperture stop. Light reflects off the secondary mirror, forming the f/12 focal ratio. The 1.12 cm diameter secondary obscures the clear aperture reducing the effective collection area. The use of baffles around the telescope housing and secondary mirror and the use of diffuse black paint around the optics and within the cavity minimizes stray light affects. An anti-reflection coated Cadmium Telluride (CdTe) window is located between the exit of the telescope's optical path and the entrance of the interferometer optical system. This window was chosen for its excellent high transmission characteristics and is tilted so that an internal etalon is not created between this surface and the beamsplitter. The light passes through this window and strikes the main fold mirror which folds the rays into the plane of the interferometer. All mirror surfaces are diamond-turned and gold-coated for ease of manufacturing and high reflectance in the IR. The very low wavefront error and surface roughness allows for optimal performance and the lowest scatter.

Mini-TES utilizes the identical Michelson interferometer design as the TES instruments. The radiance from the main fold mirror passes through a 0.635 cm thick Potassium Bromide (KBr) beamsplitter and its amplitude is split in two and reflected/transmitted to each arm of the interferometer. This beamsplitter is installed in a radial 3-point mount that allows the beamsplitter to undergo a 100^{o} C temperature change (-50^{o}C to + 50^{o}C). Due to the hydroscopic nature of KBr, a dry nitrogen purge during ground testing is required to maintain its transmission properties. In order to maintain positive purge without over-pressurization, the Mini-TES housing has a CdTe window, described above, an exhaust port, and check valve.

A reference fixed mirror is in the reflected path of the interferometer, while a constant velocity moving mirror is in the transmission path. The moving mirror is attached to a compact and reliable voice-coil motor that provides precise motion control. Each wavefront recombines at the beamsplitter and passes through an equivalently thick compensator to preserve the optical path difference (OPD). The difference in the distance traveled between the two arms of the interferometer is equal to the known distance of the moving mirror.

The Mini-TES optical bandpass of 5-29.5 microns was chosen to include that of the MGS TES observations from orbit. The moving mirror optical path difference (OPD) is set to ±0.25 mm to achieve the spectral sampling requirement of 10 cm^{-1}, as derived by the requirements to allow unique identification of the atmospheric components. The recombined energy from the interferometer is directed by the interferometer fold mirror through the 20-mrad field stop towards the parabolic focus mirror. This mirror re-images the optical pupil onto the on-axis detector element. Aspheric mirror surfaces are used for the powered elements in order to offer the best image quality. Mini-TES uses an uncooled Deuterated Triglycine Sulphate (DTGS) pyroelectric detector to measure the time-varying radiance from the scene. A thin (0.05 cm) chemical vapor deposited (CVD) diamond window is used on the detector package.

A monochromatic fringe counting interferometer is used to precisely track the motion of the moving mirror assembly. The counting interferometer uses a redundant set of matched wavelength narrowband 978 nm laser diodes. The laser diodes are wavelength and temperature stabilized by the use of a Distributed Bragg Reflector (DBR) in a 1-meter fiber optic. There is a small thermal region where DBR lasers go unstable thus a small heater is provided on each laser to push the laser out of that mode. The ends on each fiber optic are mated with a micro-lens to control the f-cone transmitted energy. The output of the laser diode fibers is directed through a small window in the beamsplitter/compensator pair. The laser diode interference signal is measured at a silicon fringe counting detector, which has a neutral density filter over the detector element. The fringe counting interferometer was designed to provide 5 times oversampling of the shortest scene bandpass wavelength, resulting in a minimum of 964 samples for the total moving mirror distance.

4.3 Mechanical Design

The mechanical design of the Mini-TES uses fold mirrors in and out of plane and a convergent optical beam allows for very a highly integrated optical system. The instrument housing, interferometer optical bench, telescope and all optical mirrors are made of aluminum for light weight and strength, while meeting the Delta II launch load and MER pyro- and landing shock requirements. The Mini-TES housing has four mounting feet that serve as the mounting interface to the nadir deck of the Rover WEB structure. The alignment of Mini-TES to the rover reference frame was performed using a removable alignment cube that was aligned to the Mini-TES optical axis and utilized precision registration surfaces to allow removal and installation to within the tolerance errors.

4.4 Electronics Design

The block diagram of the Mini-TES flight electronics is shown in **Figure 8**. The flight electronics of Mini-TES I are shown in **Figure 9**. Mini-TES uses two Datel DC to DC power converters that accept +11 to +36 volts unregulated input voltage and supply ±5 and ±15 volts regulated output voltage. The Datel converters went through significant screening by Raytheon and NASA to validate them for use on the MER Mini-TES instruments. The power converters are mounted on the same circuit card as the two SDL 80 mWatt 978 nm laser diode assemblies. These laser diodes have also been through significant screening for the Mini-TES instruments. The laser diodes are coupled into the optics via 1m fiber optic cables. The power connections to the spacecraft power bus are through the 21-pin Cannon micro-D flight connector located at the base of the Mini-TES interferometer baseplate.

Mini-TES uses an uncooled DTGS pyroelectric detector with an integrated FET detector package. The bias voltage applied to the FET by the pre-amplifier ensures that the DTGS detector's crystals are properly "poled" when power is applied to the instrument. Pre-amplification and front-end filtering is performed on the preamplifier circuit board amplify the signal and to AC couple the detector output to block high frequency oscillations. A ±12 volt regulator supplies power the detector and preamplifier electronics.

The spectrometer circuit board performs the bulk of the analog electronics processing. The analog detector signal is passed through dual post-amplifier chains, performing the high-frequency “boost”, 3-pole Bessel filtering, amplifier gain, and analog signal track/hold. The interferogram signal due to the scene is “boosted” to account for the “1/f” roll-off of the detector response and is amplified to fill the 16-bit analog to digital converter. The filtering is performed to achieve the desired IR signal bandpass of 5 to 220 Hz. In addition, the analog signals from the two Hammamatsu silicone photo-diode fringe signal detectors are passed through the fringe post-amplifier and fringe detection circuitry on the spectrometer board. The fringe detection electronics use a zero crossing comparator to generate the sampling pulse and the constant velocity servo feedback fringe clock. The amplified and filtered IR signal, fringe analog signal amplitude and the internal instrument analog telemetry is then fed into a 16:1 analog multiplexer followed by a 16-bit analog to digital converter. The 16-bit digital IR data are then transferred to the data buffer on the command and control circuit board for formatting and transfer to the Mini-TES interface electronics.

The low level command, control and data flow tasks of Mini-TES are controlled by logic in the command and control Field Programmable Gate Array (FPGA). These are the same tasks that were developed to support the original Mini-TES RS-422 interface to the MER. The uplinked Mini-TES commands are processed by the new interface electronics board. The interface electronics parse out the low level instrument command parameters that control various Mini-TES hardware functions. These low level RS-232 protocol Mini-TES commands are then transferred through the RS-422 differential line receivers to the command and control logic in the command and control board FPGA. The Mini-TES command parameters that are being inherited by Mini-TES are: interferometer motor on/off, amplifier gain high/low, amplifier chain primary/redundant, target (shutter) open/close, laser diode1 on/off, laser heater2 on/off, start-of-scan optical switch primary/redundant, and laser heaters on/off.

The flow of the digital interferometer data is controlled by additional logic in the command and control board FPGA. After each interferometer scan, the 16-bit interferogram data and 16-bit telemetry data are moved from the A/D to the input memory buffer on the 16-bit parallel data bus. These 16-bit parallel data are then sent to the digital multiplexer and serializer electronics where the three header words and fourteen digital telemetry words are serialized with the 16-bit IR data. The multiplexer, serializer and data formatting logic are included in the command and control FPGA. The three data header words include: 8-bit sync, 8-bit commanded parameter status, 16-bit scan count, and 16-bit interferogram sample count. The fourteen 16-bit telemetry words include: +5V power, -5V power, +15V power, -15V power, +10V power, -10V power, +12V power, -12V power, detector temperature, motor temperature, beamsplitter/optics temperature, laser diode1 temperature, laser diode2 temperature, and fringe signal amplitude.

The Mini-TES timing sequencing electronics are implemented in the command and control board FPGA. These electronics generate the timing waveforms necessary to control and synchronize instrument operation. The timing electronics provide the control and synchronization of the amplification, track/hold, multiplexing, and analog to digital conversion of the analog signals. They also control and synchronize the interferometer servo electronics with the data acquisitions. The timing sequencing electronics include the fringe delay electronics which are used to correct the sampling error due to the phase delays between the fringe and IR analog channels. All clocks in the timing sequencer are generated from the master clock crystal oscillator which operates at a frequency of 14.5152 MHz.

The Mini-TES interferometer servo electronics are located on the command and control board and include the digital motor control logic and the analog servo drive electronics. The interferometer digital drive electronics, located in the FPGA, receive scan timing clocks from the timing sequencer electronics and the fringe clock from the fringe detection electronics. The motor control logic uses these clocks to synchronize the mirror movement with the spectrometer data acquisitions. The interferometer analog servo drive electronics generate the analog signals that control the movement of the TES interferometer moving mirror actuator. The moving mirror uses a direct drive Schaeffer linear motor with tachometer feedback. The moving mirror tachometer signal is returned to the interferometer control electronics to allow active feedback control of the actuator. The start of scan is monitored using primary and redundant single and double scan optical-interrupters that are connected to the moving mirror assembly.

4.5 Fabrication and Test Program

The top-level sequence of events for the fabrication and test of Mini-TES are shown in **Figure 10**. The optical system is comprised of the interferometer beamsplitter, fixed mirror, and moving mirror, and the telescope assembly, fold mirror, and imaging mirror. The electronics system is comprised of the spectrometer pre- and post-amplifier, analog to digital conversion, multiplexing, digital signal processing, servo control, start-of-scan, fringe detection, laser diode, calibration target, heater control, command, control, interface and power supply electronics. The Mini-TES instrument was completed with the addition of the PMA assembly, including the internal PMA fold mirror, the azimuth and elevation actuators, the PMA elevation scan mirror, the PMA internal calibration target, and the external calibration target mounted on the rover deck.

The Mini-TES instruments were assembled and tested at SBRS in a class 10,000 facility, subject to NASA Planetary Protection requirements, and integrated with the PMA and rovers at JPL in a class 10,000 clean room facility. The first Mini-TES instrument was subjected to protoflight levels for each of the environmental tests to qualify the unit; the second unit was only subjected to flight acceptance levels. A series of performance tests are performed before and after each of environmental test to verify successful completion of each test. Thermal vacuum testing and initial radiometric calibration was performed in a vacuum chamber at SBRS (**Figure 11**). Mini-TES I was operated for a total of 166 hours and Mini-TES II was operated for 594 hours at SBRS prior to initial delivery to JPL.

5 INSTRUMENT CALIBRATION

5.1 Calibration Overview

The initial Mini-TES calibration and test was performed at SBRS prior to delivery to JPL, and a subset of these tests was performed on the integrated Mini-TES/PMA assembly. The objectives of these tests were to determine: (1) the field-of-view definition and alignment; (2) the out-of-field response; (3) the spectrometer spectral line shape and spectral sample position; and (4) the spectrometer radiometric calibration.

For each planet observation the Mini-TES acquires an interferogram signal, measured in voltage, that is transformed to a signal as a function of frequency. This signal is given at each wavenumber (ν; subscripts omitted) by:

$$V_s = (R_s - R_i) * f \tag{1}$$

where:

V_s is the fourier-transformed voltage signal generated by the Mini-TES looking at the scene

R_s is the radiance of the scene (W cm^{-2} str^{-1} /cm^{-1})

R_i is the radiance of the instrument

f is the instrument response function (V / W cm^{-2} str^{-1} /cm^{-1})

Solving for the radiance of the scene gives:

$$R_s = \frac{V_s}{f} + R_i \tag{2}$$

The instrument radiance and the response function are determined routinely using simultaneous observations of the internal (I) and external (E) calibration targets ("IE-pairs"). The response function is slowly varying except for small variations due to changes in instrument temperature, whereas R_i can vary continuously throughout the day. Thus, IE-pairs are acquired only at the start and end of each observing sequence to determine the response function, while the internal calibration target is observed approximately every 3-5 minutes to determine R_i.

The objectives of the in-flight calibration are: (1) to develop an effective means for interpolating the instrument response function and instrument radiance between calibration observations; and (2) to minimize the noise on these functions by taking advantage of their repetitive and predictable forms. Initially the response function for each scene observation will be determined using a linear interpolation between the response functions for bounding IE-pairs. However, the noise in the response function from a single IE-pair can be reduced by combining multiple determinations over a period of time, taking into account the changes due to variations in instrument temperature. At the end of the mission, the data will be recalibrated using a low-noise response function determined by fitting a function to the complete set of instrument response data over long (~10 day) periods.

Once the instrument radiance is determined for each internal calibration target observation, it will be interpolated over time for all of the intervening scene observations and used with the response function to determine the calibrated radiance for each scene spectrum (Eq. 2). Initially a linear interpolation between bounding values will be used; with time a more complex function will be determined to account for repetitive, periodic variations in instrument temperature.

5.2 Test Overview

5.2.1 Internal Instrument Temperature Instrumentation

Five internal temperature telemetry points are instrumented in the Mini-TES and can be transmitted upon ground command. The digitization of these telemetry points is typically 0.1°C at an instrument temperature of 0°C. The sigmas for these telemetry points, determined for thermal vacuum conditions with the instrument at its nominal operating temperature (0° C), are <0.05°C, and are within the digitization levels.

5.2.2 Internal Reference Surface Properties and Instrumentation

The Mini-TES internal reference surfaces are formed with parallel groves machined with 15° inclined surfaces (30° Vs) with a depth of 1.73 mm and a spacing of 1.2 mm. The reference surface was machined from aluminum alloy and painted with Aeroglaze Z302 blank paint to a thickness of ~6 mil. The internal and external reference surfaces are each instrumented with two platinum thermistors that are bonded to the underside of each surface. These thermistors were delivered from the manufacturer with a measured absolute accuracy of better than 0.1° C for temperatures from –130° to 110°.

Resistances from the reference surface thermistors are digitized through the rover telemetry and converted to temperature. The digitization of the resultant temperatures is ~0.02° C at 0° C. The temperature differences between the two independent temperature readings for each calibration target were determined during JPL thermal vacuum tests to be <0.5° C over the full range of operating temperatures. The in-flight calibration algorithm uses the average of these two temperatures for each calibration target.

Immediately prior to launch one the internal reference thermistors in one of the PMA heads failed. It was determined that the thermistors had been bonded incorrectly prior to delivery of the PMA to JPL in a manner that enhanced fracturing of the thermistor element. In response, both PMAs were disassembled and one of the two thermistors on each assembly was replaced. This action preserved the pre-launch calibration for the remaining thermistor, while providing improved reliability.

5.2.3 External Target Properties and Instrumentation

The two precision calibration reference blackbodies (BCU-1 and BCU-2) used in the SBRS and JPL thermal vacuum testing were identical, 7.25" diameter, 15° half-angle cones machined at ASU and assembled and painted with "CAD-A-LAC black" paint at SBRS. Each blackbody was instrumented with two pairs of platinum thermistors, with one pair placed near the apex of the cone and the second pair approximately half-way between the apex and the opening of the cone [*Christensen*, 1999; *Christensen et al.*, 2001a]. These thermistors were calibrated prior to shipment from the manufacturer to an absolute accuracy of 0.1 °C (±0.5% resistance).

The digitization of the reference blackbody telemetry points varies from ~0.01 °C at -190°C to 0.02 at 35 °C [*Christensen*, 1999; *Christensen et al.*, 2001a]. The means and sigmas of the front and back thermistors in the blackbodies were determined in vacuum for the five target temperatures with the instrument temperature at 0 °C. The temperature stability was within the digitization level over >1 minute time periods. The front and back temperatures agree to within 0.7 °C for cold temperatures, increasing to 1.5 °C for hot temperatures.

5.2.4 Bench-Level Test Overview

Bench-level testing of the Mini-TES instrument was performed at SBRS in two phases. The first phase consisted of piece-part and system-level testing of the spectral performance of each sub-section. These tests were performed under ambient conditions. The second phase consisted of field of view and out-of-field tests conducted before and after vibration and thermal-vacuum testing to determine and confirm the instrument field-of-view and alignment.

5.2.5 Thermal Vacuum Test Overview

The Mini-TES spectrometer, without the PMA, was tested and calibrated in vacuum at SBRS at instrument temperatures of –30, -10, 10, and 30 °C. A matrix of calibration tests were performed viewing one of the precision calibration reference blackbody sources set at 223 K, 243 K, 263 K, and 283 K. while the second reference blackbody source was varied at temperatures of 145 K, 190 K, 235 K, 280 K, and 325 K °C.

The Mini-TES/PMA system was calibrated in 6 mbar of nitrogen at JPL at instrument temperatures of –30, 0, and 30 °C over a range of temperatures of the two calibration reference blackbodies. Mini-TES I was calibrated at –30° C with one reference blackbody set at 223 K while the second was set to 145, 190, 235, 280, and 325 K. At an instrument temperature of 0° C one target was set to 253 K while the second was set to 145, 235, and 325 K; at an instrument temperature of 30° C the targets were set to 190 and 325 K. Mini-TES II was calibrated at –30° C viewing one target set to 223 K, while the second was set at 145, 235, and 325 K, at 0° C viewing one target set to 253 K, while the second was set at 145, 235, and 325 K, and a 30° C viewing one target set to 283 K, while the second was set at 145, 235, and 325 K,

5.3 Field of View

5.3.1 Pre-launch Measurements

Field of view characterization data were acquired at SBRS for the Mini-TES spectrometer using a precision collimator. Thermal and visual sources were projected through a 1 mrad wide, 40 mrad long slit into the Mini-TES aperture [*Christensen*, 1999]. The Mini-TES was manually rotated to move the slit at 1-mrad spacing across the focal plane; 31 points were measured from –15 to +15 mrad in elevation, 31 points were measured from -15 to +15 mrad in azimuth. The results from the final pre-shipment bench alignment tests for Mini-TES I in both 20- and 8-mrad mode in elevation and azimuth are shown in **Figure 12**. The FWHM of the Mini-TES I 20 mrad field of view mode is 17.5 mrad in azimuth and elevation. The FWHM of the 8 mrad field of view mode is 6.6 mrad in azimuth and 6.9 mrad in elevation (**Figure 12**)

After the Mini-TES was delivered to JPL, it was aligned on the rover using the Mini-TES alignment cube for reference. Bench level testing was performed to verify that the Mini-TES field of view is not vignetted by any elements of the PMA over the expected range of rover tilt angles.

5.3.2 Out-Of-Field Response

Near-field out-of-field response was measured at the bench level using a 2.4 mrad square slit that was stepped in 2.45 mrad increments from -14.7 to +14.7 mrad in azimuth and -19.6 to +19.6 mrad in elevation. At each grid point, 5 spectra were collected with the aperture open and 5 spectra with the aperture blocked to correct for the background. No measurable out-of-field energy was observed. The far-out-of-field response was determining over an extended area using a 40 x 32 mrad slit that was stepped in increments of 32.7 mrad in azimuth and 40 mrad in elevation from -196 to +196 mrad in azimuth and from -200 mrad to +200 mrad in elevation. At each grid point, 5 spectra were collected with the aperture open and 5 spectra with the aperture blocked to correct for the background. Again, no measurable out-of-field energy was detected.

5.4 Radiometric Calibration

5.4.1 Overview

The Mini-TES I instrument was radiometrically calibrated in thermal vacuum at JPL between December 16 and December 23, 2002; Mini-TES II was calibrated at JPL between February 25 and March 3, 2003. These tests determined: 1) the emissivity and effective temperature of the internal reference surface; 2) the instrument response function and its variation with instrument temperature; 3) the absolute radiometric accuracy; 4) the spectrometer noise characteristics; and 5) the spectrometer gain values.

The measured transformed interferometer voltage ($V_{measured}$) from the TES spectrometer as a function of wavenumber is given by:

$$V_{measured} = \{(R_{emitted} + R_{reflected}) - R_{instrument}\} * f \tag{3}$$

where $R_{emitted}$ is the radiance emitted by the target, $R_{reflected}$ is the radiance emitted by the environment and reflected off of the target, $R_{instrument}$ is the radiance emitted by the instrument, and f is the instrument response function. High emissivity targets (>0.995) were used for all of the calibration tests and the $R_{reflected}$ term can be ignored.

During the system-level Mini-TES/PMA thermal-vacuum tests, observations were acquired of the two precision reference blackbody targets, one cold and one hot, and the flight external and internal calibration targets. The relationships between the measured instrument signal (V) and the instrument and target radiance for the cold, hot, and external reference views are given by:

$$V_{cold} = (R_{cold} - R_i) * f \tag{4}$$

$$V_{hot} = (R_{hot} - R_i) * f \tag{5}$$

$$V_{internal\ reference} = (R_{internal\ reference} - R_i) * f \tag{6}$$

$$V_{external\ reference} = (R_{external\ reference} - R_i) * f \tag{7}$$

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

$$V_{cold} = (\varepsilon_{cold} B_{cold} - R_i) * f \tag{8}$$

$$V_{hot} = (\varepsilon_{hot}B_{hot} - R_i) * f \tag{9}$$

$$V_{internal\ ref} = (\varepsilon_{internal\ ref}B_{internal\ ref} - R_i) * f \tag{10}$$

$$V_{external\ ref} = (\varepsilon_{external\ ref}B_{external\ ref} - R_i) * f \tag{11}$$

All of the values are determined at each spectral wavenumber (subscript omitted).

The instrument response function (f) has been shown through testing on the TES [*Christensen et al.*, 2001a] and Mini-TES to be independent of signal magnitude, but is a function of instrument temperature. The spectra from each target were acquired over a relatively short period of time (<3 min) under highly stable conditions with a constant instrument temperature, so R_i and f are assumed to be constant in Equations 8-11. The temperature of the external targets and reference surface was determined to be constant to within 0.1 °C using the thermistors located in or on each target surface, and the average temperature of each target over the time interval of data collection was used in the calibration.

Equations 8 and 9 give two equations and four unknowns (ε_h, ε_c, R_i, and f). The calibration blackbodies have equal emissivities ($\varepsilon_h = \varepsilon_c$) that are >0.995 [*Christensen et al.*, 2001a; *Christensen*, 1999], and are assumed to be unity. With this substitution Equations 8 and 9 give:

$$f = \frac{V_h - V_c}{B_h - B_c} \tag{12}$$

and

$$\text{Sample Spacing} = \frac{1}{\left(0.978 * 10^{-4}\right) * \text{Npts}} \tag{13}$$

5.4.2 Reference Surface Emissivities and Temperature

The emissivity and temperature of the internal and external calibration targets can be determined for each target observation acquired during the stable thermal vacuum tests by first computing the calibrated radiance from each target using Equation 2 and the computed R_i and f . A Planck function was fit to the calibrated radiance and the temperature of this best-fit function was assumed to be the kinetic temperature of the target. The target emissivity was determined using the ratio of the measured calibrated radiance to a blackbody at this kinetic temperature. The emissivity of the external target was also measured in the ASU Thermal Spectroscopy Lab. The temperature sensors on both targets were calibrated by comparing the derived kinetic temperature with the telemetry reading for each target. Analysis of these data is on-going.

5.4.3 Instrument Response Function Versus Instrument Temperature

The instrument response varies with instrument temperature due to changes in detector response and interferometer alignment with temperature. The variation of instrument response with temperature for is shown in **Figure 13** for the system-level calibration tests done at JPL for Mini-TES I. The actual instrument response function will be determined in flight using observations of the internal and external calibration targets and Eq. 12.

5.4.4 Noise Performance

The noise equivalent spectral radiance (NESR) of the Mini-TES was determined in thermal vacuum testing by converting standard deviation in signal to radiance using the instrument response function. This approach produces an upper limit to the noise levels (a lower limit to the SNR) because other sources of variance may be present that are not related to the instrument itself. The most likely of these are variations in the target signal due to minor variations in target temperature.

Figure 14 gives a representative NESR for Mini-TES I at an instrument temperature of 0 °C observing the internal reference surface. The 1-σ radiance noise level of an individual spectral sample in a single Mini-TES spectrum varied from ~3 x10^{-8} W cm^{-2} str^{-1} /cm^{-1} for the central wavenumbers from ~500 to 1400 cm^{-1}, increasing to ~6 x10^{-8} W cm^{-2} str^{-1} /cm^{-1} at shorter (300 cm^{-1}) and longer (1800 cm^{-1}) wavenumbers (**Figure 14**). For the planned observing scenario in which two spectra are summed, these values reduce to 2.1 and 4.2 x10^{-8} W cm^{-2} str^{-1} /cm^{-1} respectively. As shown in **Figure 13** the instrument response function decreases with decreasing temperature. However, the noise also decreases with temperature, so that there is only an approximately 35% increase in the noise level between the highest (30° C) and lowest (-30 °C) instrument temperatures.

5.4.5 Absolute Radiometric Accuracy

The absolute calibration of the Mini-TES spectrometer was determined during thermal vacuum testing at SBRS in the following manner:

1) The instrument response and instrument spectral radiance were determined using observations of the two precision calibration reference blackbodies whose spectral radiances were determined using the average of the two temperature measurements and assuming unity emissivity.

2) Mini-TES observations of a V-groove targets were converted to calibrated spectral radiance using Eq. 2 and the instrument response function and instrument radiance.

3) The calibrated spectral radiance was converted to the brightness temperature of the V-groove blackbody at each wavenumber and averaged from wavenumber 400 to 1100 cm^{-1} to determine the "best-fit" target temperature.

Figure 15 shows an example of the comparison between the V-groove target calibrated radiance and the blackbody radiance computed using the measured V-groove temperature for Mini-TES II at an instrument temperature of -10°C. **Figure 15b** shows the difference between the calibrated radiance and Planck function radiance at the measured V-groove temperature. At low scene temperatures (<220 K) there are errors of up to 2×10^{-7} Watt cm^{-2} str^{-1} /cm^{-1} when comparing the derived calibrated radiance to the measured V-groove target temperature. However, the errors are less than 5×10^{-8} Watt cm^{-2} str^{-1} /cm^{-1} when compared to the best-fit derived V-groove target temperature. Based on the quality of the best-fit Planck curves, we estimate that the primary error is in the calibration of the V-groove thermistors at low temperatures [*Christensen*, 1999; *Christensen et al.*, 2001a]. We conclude that the absolute radiance error of the Mini-TES instrument is $<5 \times 10^{-8}$ Watt cm^{-2} str^{-1} /cm^{-1}. Systematic errors in radiance can occur in the calibration process where noise in the internal and external calibration target observations is mapped into the calibrated scene spectra as a function of the instrument temperature and the temperature difference between the scene and the instrument. This noise will be reduced by acquiring and averaging ~5 consecutive observations of both calibration targets.

5.4.6 Derived Temperature and Emissivity Error

The Mini-TES temperature is expected to vary from –10 to +30° C over the course a day, with most surface composition data collected at instrument temperatures

>10° C and scene temperatures >270 K. For this combination of temperatures, and assuming the nominal operational mode of the Mini-TES in which two spectra are collected for each observation, the resulting systematic calibration error is ~1.8 x10^{-8} W cm^{-2} str^{-1} /cm^{-1} between 450 and 1500 cm^{-1}. The absolute error will be ~1 x10^{-8} Watt cm^{-2} str^{-1} /cm^{-1} over the wavenumber range where the scene temperature will be determined (1200-1600 cm^{-1}) (**Figure 15b**). The worst-case sum of these random and systematic radiance errors correspond to a best-fit absolute temperature error of ~0.4 K for a true surface temperature of 270 K, and ~1.5 K for a surface at 180 K. This temperature error is mapped into a smoothly varying offset in the emissivity spectrum that varies from 0.001 at 400 cm^{-1}, to a maximum of 0.005 at ~1000 cm^{-1}, to essentially 0 at 1400 cm^{-1} for a scene temperature of 270 K. This subtle curvature has a negligible effect on the derived surface composition.

5.4.7 Sample Position and Spectral Line Shape

In an ideal interferometer with an on-axis point detector, the spectral samples are uniformly distributed in wavenumber and the full-width, half maximum (FWHM) of each sample is simply determined by the optical displacement of the Michelson mirror. The Mini-TES uses a laser diode with a line at 0.978 μm in the visible interferometer to sample the IR interferometer. The ideal sample spacing of the interferometer is given by:

$$\text{Sample Spacing} = \frac{1}{\left(0.978 * 10^{-4}\right) * \text{Npts}}$$

where Npts is the number of points in the FFT; Mini-TES collects 1024 points.

5.4.8 In-flight Calibrated Radiance Algorithm

The following sequence of operations is carried out for spectral calibration:

1) Identify all of the Internal/External calibration target (IE) pairs and Internal target observations (I) in the given set of observations.
2) At each IE-pair, compute the radiance of the instrument (R_i), the instrument response function (f), and the temperature of the instrument (T_i) (for reference only) using Equations 12 and 13.
3) At each Internal observation, compute R_i by using the measured spectrum and f determined by interpolating over time between bounding IE-pairs.
4) At each scene observation, determine f and R_i by interpolating over time between the bounding IE-pair or I observations, and compute R_s for each detector using:

$$R_s = (V_s / f) + R_i.$$

5.5 Rock Calibration Target Observations

A rock calibration target containing 14 samples was constructed provide mineral detection calibration and validation data for each of the MER science instruments. The rocks ranged in size from 6.5 x 7.2 cm to 14.8 x 14.8 cm and were cut and polished. Both of the Mini-TES instruments viewed this target during system-level thermal vacuum testing at JPL. The target was placed 2.5 m from the Mini-TES telescope aperture, resulting in a projected, out-of-focus Mini-TES field of view of ~11.3 cm in size. A 41 x 33 raster image was obtained by Mini-TES I of roughly 3/4 of the target, but test anomalies and time limitations only permitted the last column of rock targets to be observed with a single Mini-TES elevation scan.

The calibrated spectral radiance from the rock targets was determined using the instrument response and instrument radiance obtained viewing the two calibration reference blackbodies immediately prior to the rock target observations. This spectral radiance consists of the emitted radiance from the rocks and the radiance emitted by the environment and reflected off of the rocks (Eq. 3). The reflected component was removed by approximating the emitted radiance from the environment (B_{env}) assuming Planck function emission at the temperature of the vacuum chamber walls (~0° C), and simultaneously solving for the emissivity (ε_{rock}) and reflectivity ($1-\varepsilon_{rock}$) of each rock. With these substitutions Eq. 3 becomes:

$$V_{rock} = \{(\varepsilon_{rock}B_{rock} + (1-\varepsilon_{rock})B_{env}) - R_i\} * f \qquad (14)$$

Solving for the emissivity of the rock gives:

$$\varepsilon_{rock} = \frac{\frac{V_{rock}}{f} + R_i - B_{env}}{B_{rock} - B_{env}} \qquad (15)$$

A similar procedure will be performed at Mars using the measured or modeled atmospheric downwelling radiance as B_{env} and solving for the emissivity of the surface rocks and soils.

Examples of the rock emissivity spectra with the environmental radiance removed are given in **Figure 16**. These spectra represent averages of ~5 Mini-TES spectra acquired at an instrument temperature of 0° C viewing rock targets heated to ~35° C (310 K).

Each of the rock targets was analyzed by a linear deconvolution method developed and used extensively for TES data analysis [Adams, 1986 #1047; Ramsey, 1998 #1967]. A subset of 57 mineral spectra from the ASU thermal emission spectral library [Christensen, 2000 #2117] were selected for deconvolution of the rock target spectra. In addition, a high-silica glass spectrum was obtained along with additional goethite, magnesite, hematite, and chert samples. Two other endmembers allowed in the subset were: 1) a linear slope, to account for the variable brightness temperatures of the rock and rock mounting surface contained within the Mini-TES field of view; and 2) blackbody (emissivity =1.0) to account for spectral contrast differences between the particulate endmembers in the ASU library (700-1000 μm) and polished rock slabs. Finally, the average emissivity spectrum from the first rock target was used as an endmember (Al Oxide) due to a lack of mineral spectra that modeled this target well (corundum and blackbody were the best fit to this target, with RMS errors of ~12%).

The average emissivity spectrum from each rock target was deconvolved using this endmember set. The extreme ends of each spectrum (339-399 cm^{-1} and 1727-1997 cm^{-1}) were excluded from the deconvolution, due to lower SNR in these spectral regions in both the measured and endmember emissivity. The band range used for each target was varied, based on model fits. Although different subsets of the endmember library were found to provide better fits for each target, the results reported here used the same 64-endmember set for each rock.

Results for the average emissivity spectrum from each target are given in **Table 2**, normalized to remove the blackbody component. The individual model results have been grouped into the sum of each major mineral group. The slope endmember was used at the 1-2% level for all targets except Rock 4 (8%) and Rock 5 (3%). At the distance to the rock target the Mini-TES field of view was too large to completely resolve any individual target, and the emissivity includes components from surrounding targets and the background black paint. Examples of the measured and best-fit mineral mixture are shown in **Figure 17.** Future work will compare these analyses with mineral abundances measured using laboratory techniques as well as the composition of these rock targets determined from each of the other MER instruments.

6 MISSION OPERATIONS

The Mini-TES is a versatile instrument that will be used in a number of different modes. One of the most important will be to acquire full 360° 20-mrad panoramas that will be co-registered with image panoramas to provide merged mineralogic and morphologic information. A complete panorama will be acquired while each rover is still on its lander, and other panoramas will be obtained as appropriate as the rovers traverse the surface. In addition, Mini-TES will be operated in the 8-mrad field of view mode to obtain detailed spectra of small raster scans of specific rock and soil targets.

Even with the substantial effort that has been devoted to allow Mini-TES to acquire high-quality spectra in four seconds, some compromises are necessary when acquiring a 360° pan. The elevation range can be restricted, typically to the region between the horizon and about 30° below. A single spectrum per pixel in 20-mrad mode can be used, leading to a $2^{1/2}$ lower SNR that will still acceptable at some times of day. It is also possible to use a raster step size of more than 20 mrad in one or both axes, undersampling the scene but providing more rapid coverage. All of these techniques may be used in order to make panorama acquisition time manageable.

Partial panoramas (*i.e.*, rasters smaller than 360° in azimuth) will be the most common use of Mini-TES. They typically will be targeted at regions of high scientific interest, based on Pancam or Navcam observations. Where appropriate, very small rasters or even single Mini-TES spots, targeted carefully to address specific scientific hypotheses, will be used. In all these instances the Mini-TES observations will be optimized to the extent possible, concentrating measurements in the hottest part of the day when signal is strongest, taking advantage of illumination geometry to view targets when they receive the most solar input, and using one spectrum/pixel when the SNR will be adequate.

The instrument's 8-mrad mode will be used sparingly. The minimum size of the Mini-TES beam is limited by the 6.35-cm diameter of the instrument's telescope aperture. In the near-field the Mini-TES spot size is the aperture size plus the angular divergence. Therefore, near the rover the difference in diameter between the 20-mrad beam and the 8-mrad beam is small. Because 8-mrad observations require a long integration time, this mode will not be useful close to the rover. The 8-mrad mode will be used on mid-range to distant targets when the 2.5× improvement in spatial resolution will help to answer a question that cannot be addressed at lower resolution.

Whenever the *in situ* instrument suite is used on a rock or soil target, Mini-TES coverage of the target will be obtained before the rover leaves it. In many instances this will require driving the rover backwards a short distance and acquiring Mini-TES data on the target, since much of the *in situ* instrument suite work volume is not visible to Mini-TES. For such observations spatial resolution will be of particular importance. This is especially true when the Rock Abrasion Tool (RAT) has been used on the target, because the region exposed by the RAT is only 45 mm in diameter, or about half the size of the Mini-TES beam directly in front of the rover. These targets will be observed using substantial oversampling, stepping the pointing mirror at a fraction of the projected Mini-TES field of view and using spatial deconvolution techniques to sharpen the effective resolution.

Mini-TES directly determines the temperature of points in a scene and these data will be used to produce thermal inertia images. Spectra obtained at multiple times of day will be used along with a thermal model [e.g. \Kieffer, 1977 #519] for thermal inertia determination. An attempt will be made to coordinate these diurnal observations with the times of TES or THEMIS direct overflights, providing simultaneous temperature observations that will be extended to broader regions surrounding the rovers.

The Mini-TES will also view upward at angles up to 30° above the horizon to provide high-resolution temperature profiles of the martian boundary layer [Smith, 1996 #1974]. This upward-viewing mode will yield high-resolution temperature profiles through the bottom few km of the atmosphere. Temperatures are retrieved from the wings of the 15-µm CO2 band. This lowest region of the atmosphere has been difficult to measure on Mars because of the thicker nature of the weighting functions as seen from orbit, and because of the difficulty of determining surface contributions to radiance.

Atmospheric water abundance will be obtained by vertical and horizontal viewing of rotational H_2O lines. Separate measurements of water near the ground will be obtained by viewing distant surface obstacles. The broad water-ice feature centered near 800 cm^{-1} [Curran, 1973 #210; Pearl, 2001 #2131] will allow monitoring of ground ice hazes. Together, these measurements will illuminate the behavior of water in lower atmosphere and of water transport between the atmosphere and surface. Atmospheric dust abundance will be obtained using the redundant temperature information in both sides of the 15 µm CO_2 band, together with differential absorption across the dust band in that region.

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Figure Captions

Figure 1 The Mini-TES I spectrometer following completion of testing at SBRS. (a) The instrument with its cover on and the optical aperture facing upward. (b) The Mini-TES with its protective cover off, showing the highly integrated packaging of the electronics and optics required to meet the size and weight constraints of the rover mission.

Figure 2. The size and spacing of representative Mini-TES observational grids. Both the 20-mrad (coarse) and 8-mrad grids are shown, superimposed on a simulated Pancam scene.

Figure 3. Thermal infrared spectra of representative mineral groups. Major mineral groups are readily separated.

Figure 4. Examples of individual minerals within the silicate and carbonate mineral groups, illustrating the degree to which these minerals can be identified using Mini-TES spectra. The individual spectra have been scaled and offset for clarity. These spectra are representative of the spectral sampling and radiometric precision that will be obtained from the Mini-TES. The emissivity minima in the absorption bands in these minerals vary from 0.5 to 0.8.

Figure 5. Individual minerals with the key carbonate and clay mineral groups, illustrating the degree to which individual minerals within these groups can be identified. The individual spectra have been scaled and offset for clarity. The band depths in these coarse particulate mineral samples have a band depth (emissivity minima) relative to the nearby local emissivity maxima of

~0.4 to 0.8. (a) Selected examples of minerals in the carbonate mineral group. (b) Selected examples of minerals in the clay mineral group. (c) Selected examples of the pyroxene mineral group.

Figure 6. Thermal emission spectra of hydrothermal rocks. The travertine and hydrothermal quartz samples are from a hot-spring system within a volcanic environment. The hydrothermally altered basalt sample contains small (<1 mm) calcite-bearing vesicles, demonstrating that <5% carbonate can be detected in volcanic rocks. Individual spectra have been offset and scaled for clarity.

Figure 7. The Mini-TES optical system. (a) The Mini-TES 3-D perspective optical layout. Folding optics permit the full capabilities to be contained in a small lightweight package. (b) The Mini-TES optical design schematic. Schematic shows the unfolded optical system, including the Cassegrain collimating telescope, the interferometer, reimaging mirror and detector assembly, with a ray trace through all the elements.

Figure 8. Block Diagram of Mini-TES. Mini-TES takes advantage of strong TES and PIDDP heritage (shaded components).

Figure 9. Interior View of Mini-TES electronics. (a) The Mini-TES is shown with the Control Logic/Spectrometer circuit card assembly (CCA) in its folded up position where is was mated to the mechanical assembly and tested prior to final installation. Also shown are the smaller interferometer fringe detection (Fringe) CCA, the detector pre-amplifier (Preamp) CCA, and the Power Converter CCA. The inset shows an expanded view of the spectrometer

mechanical componetns (b) Details of the individual mechanical components within the Mini-TES that were shown in the insert in **Figure 9a**.

Figure 10. Mini-TES Fabrication and Test Flow.

Figure 11. Mini-TES thermal vacuum test setup at Santa Barbara Remote Sensing. The Mini-TES instruments were tested at vacuum using precision calibration reference blackbodies. (a) The cylindrical aluminum exterior of the thw reference blackbodies can be seen in this image, along with Mini-TES (black box) that is pointing downward toward a pointing mirror (not shown) that permitted the two reference blackbodies, the V-groove target (not shown) and a quartz crystal to be viewed. (b) The final configuration of blackbodies and the Mini-TES instrument can be seen covered in insulating thermal blankets immediately prior to vacuum chamber closing and pumpdown.

Figure 12. Mini-TES field of view. The Mini-TES I field of view. The response was mapped viewing a thermal source through a collimator and a 1x40 mrad slit that was stepped at 1-mrad increments across the aperture. (a) 20 mrad mode; elevation direction. (b) 20 mrad mode; azimuth direction. (c) 8 mrad mode; elevation direction. (d) 8 mrad mode; azimuth direction.

Figure 13. Variation in instrument response with temperature. The instrument response determined for the integrated Mini-TES I/PMA is shown for the three instrument temperatures (-30° C, 0° C, and +30° C) measured in 6 mbar nitrogen at JPL. Also shown are the instrument response functions determined for the Mini-TES I spectrometer alone at SBRS

Figure 14. The noise equivalent spectral radiance (NESR) for the integrated Mini-TES I/PMA measured in 6 mbar nitrogen at JPL. Values are computed for a single spectrum. During operations at Mars two spectra will typically be averaged together, reducing the NESR by $2^{1/2}$.

Figure 15. Absolute spectral radiance error. A representative example of the absolute radiance error for the Mini-TES I spectrometer is shown for an instrument temperature of 0° C measured in vacuum at SBRS. (a) Comparison of the derived calibrated spectral radiance viewing a V-groove target in thermal vacuum at SBRS and a Planck function fit to the calibrated radiance. (b) The difference between the V-groove calibrated spectral radiance and the best-fit Planck function.

Figure 16. Mini-TES I spectra of selected rock targets. In all cases the Mini-TES field of view was larger than the rock target. The spectra shown here are averages of ~5 individual spectra. The reflected background radiance has been removed. These spectra illustrate the quality of spectra that will be obtained of the rocks and soils at the MER landing sites.

Figure 17. Mineral deconvolution results for selected rock targets. The modeled spectra were determined using a linear deconvolution technique and a library of 62 spectra (see text for details). The model spectra fit the measured spectra to within the noise of the Mini-TES instrument. The derived mineral abundances are given in Table 2. (a) Rock Sample 11. (b) Rock Sample 12. (c) Rock Sample 13.

Table 1. Mini-TES Design and Performance Parameters

Parameter	Description
Spectral Range	339.50 to 1997.06 cm^{-1} (5.01 – 29.45 μm)
Spectral Sampling Interval	9.99 cm^{-1}
Field of View	8 and 20 mrad
Telescope Aperture	6.35 cm diameter Cassegrain
Detectors	Uncooled Alonine doped Deuterated Triglycine Sulphate (AlDTGS) Pyroelectric detector $D^* > 6 \times 10^8$ at 20 Hz
Michelson Mirror Travel	-0.25 – 0.25 mm
Mirror Velocity (physical travel)	0.0325 cm/sec
Laser Fringe Reference Wavelength	978 ± 2 nanometers
Interferometer Sample Rate	645 samples/sec
Cycle Time per Measurement	2 seconds (1.8 seconds Michelson mirror forward scan; 0.2 second retrace)
Number of Scans to Achieve 400 SNR at 1000 cm^{-1}; 270 K Scene Temperature; 0° C Instrument temperature	2 (20 mrad); 80 (8 mrad)
Number Samples per Interferogram	1024
Number Bits per Sample - Interferogram	16
Number Samples per Spectrum	167
Number Bits per Sample – Spectrum	12
Dimensions	9.25 x 6.4 x 6.1 inches (23.5 x 16.3 x 15.5 cm)
Mass	2.40 kg
Power	5.6 Watts (operating), 0.3 Watt (daily average)
Operational Temperature Range (Instrument Temperature)	Survival and Operability -45, +50C; Performance within Spec -10, +30C

Table 2. Mini-TES Rock Target Results

Rock Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Mineral Abundance (%)*													
Feldspar		44	76	2		81	9	69	51	10	39		55
Pyroxene		2	5		8	6		2	3	1		2	17
Amphibole		2						16	3	11	39		
Olivine		12	6				10		6		9		9
Silica				9	61				4	4		36	
Oxide	100	12	9	61	16	9	13	6	7	54	1	58	8
Carbonate		1	1	1	2	1	67	1	1	16	2	4	1
Sheet-silicates		12	2		10	1		2	2	1	5	1	7
Apatite		1		12					5				
Al2SiO5				5				1					
Pyroxenoid											2		
High-Si Glass									16				
Garnet		2	1			1					2		3
Epidote		6				1		4	3	2			
Sum	100	94	100	90	97	100	99	101	101	99	99	101	100
Blackbody	0	-97	-45	-15	28	-136	-55	-94	19	-15	-85	-169	-76
RMS Error	0.000	0.714	0.470	0.549	1.290	0.691	3.225	0.494	0.355	0.520	0.748	1.694	0.720
*Abundances are normalized for blackbody and rounded to the nearest whole percentage.													