Performance of the Miniature Thermal Emission Spectrometer (Mini-TES) for Mars 2001 Lander

Duane Bates*, Steven Silverman, James Jeter, and Karl Blasius
Raytheon Santa Barbara Remote Sensing
75 Coromar Dr.
Goleta, CA 93117
*805-562-7620
dbates@west.raytheon.com

Phil Christensen and Greg Mehall
Arizona State University
Tempe, AZ 85284

Abstract—This paper describes the science rationale, design, and the measured performance of the Miniature Thermal Emission Spectrometer (Mini-TES) [1] developed by Raytheon Santa Barbara Remote Sensing (SBRS) under contract to Arizona State University (ASU). Mini-TES is a single detector Fourier Transform Spectrometer (FTS), covering the spectral range 5-28 microns (μm) at 10 cm^{-1} spectral resolution. The primary mission of Mini-TES will be to obtain mineralogical data for rocks and soil surrounding the 2001 Lander. Mini-TES also plays a key role in the Mars sample return missions in 2003 and 2005.

The Mini-TES design is based on proven heritage from the successful Mars Global Surveyor (MGS) TES which is currently providing excellent science data from Mars orbit. Mini-TES has only 15% of the volume and 17% of the mass of MGS TES. The use of TES design heritage and commercial technology in a few key areas has led to a low-cost, robust design.

Additional applications are anticipated for the Min-TES in the exploration of other planets, moons, asteroids, and comets.

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1. INTRODUCTION

The Miniature Thermal Emission Spectrometer (Mini-TES) is, as the name implies, a miniaturized version [Silverman, et al, 1999] of the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) currently in orbit about Mars. MGS TES was actually the second TES built and flown to Mars. The Mars Observer (MO) TES [Christensen, et al, 1992] was launched in 1992, and successfully returned flight data shortly before a spacecraft anomaly occurred as the Mars Observer was about to begin orbital operations in 1993. Following that setback, NASA initiated an ambitious, lower-cost and shorter schedule Mars Global Surveyor (MGS) follow-up mission. Just four years later, MGS arrived successfully at Mars carrying the TES instrument.

Raytheon Santa Barbara Remote Sensing (SBRS), under contract to Arizona State University (ASU) and the Jet Propulsion Laboratory (JPL), built both the MO and MGS TES sensors. The MGS TES was built in less than two years, and was delivered ahead of schedule and under budget. The Mini-TES was built on an even tighter development schedule and was still delivered early and under budget this summer (1999).

As described in an earlier paper [Schueler, et al, 1997], Raytheon SBRS has been developing an advanced and miniaturized version of MGS TES since early 1995 under NASA Planetary Instrument Definition and Development (PIDDP) and internal company funding. The PIDDP-sponsored effort resulted in a hardware demonstration in late 1996, and in mid-1997 the Mini-TES was selected by a Cornell University led science team to become a component of the proposed Athena Precursor Experiment (APEX) for NASA's Mars 2001 science mission.

2. APEX Science Mission

APEX is part of the Mars 2001 Lander mission, scheduled for launch in April of 2001, with a planned landing in February of 2002. The primary APEX mission objectives are summarized in Table 1. APEX is designed to explore Mars' terrain and atmosphere with maximum science return at minimum cost, and the science gain is expected to be synergistic with the overall Lander science payload. For example, APEX and the Mars Environmental Compatibility Assessment (MECA) can be used on the same soil samples to provide an extremely comprehensive picture of the Martian soil at the landing site. The term "precursor" in the mission name refers to the fact that the 2001 Lander mission is the testbed for large scale Mars Athena rover missions, as part of the Mars Sample Return (MSR) missions, scheduled for 2003 and 2005.

Table 1. Athena Precursor Experiment (APEX) Mission Objectives

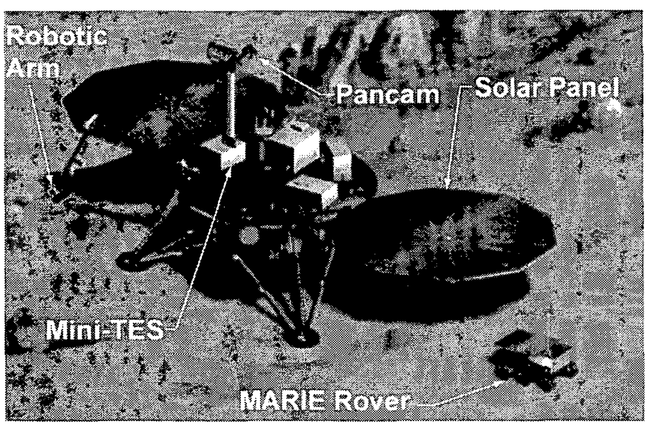
1	Provide remotely-sensed point discrimination of mineralogical composition
2	Determine elemental and mineralogical composition of Martian surface materials
3	Determine fine-scale textural properties of these materials
4	Provide temperature profiles (sounding) in the atmospheric boundary layer
5	Determine the thermophysical properties of rocks and soils
6	Identify samples for return to Earth for detailed scientific analysis (Athena mission)

Raytheon SBRS developed the Mini-TES design details and has since converted them to hardware under a NASA contract awarded in 1998. Integration of the hardware into the Mars 2001 Lander package must occur early in calendar 2000, to meet an April 2001 launch date. Generally, complex space instrumentation requires a four-year development from contract go-ahead. By comparison, Mini-TES was completed on a 19-month schedule.

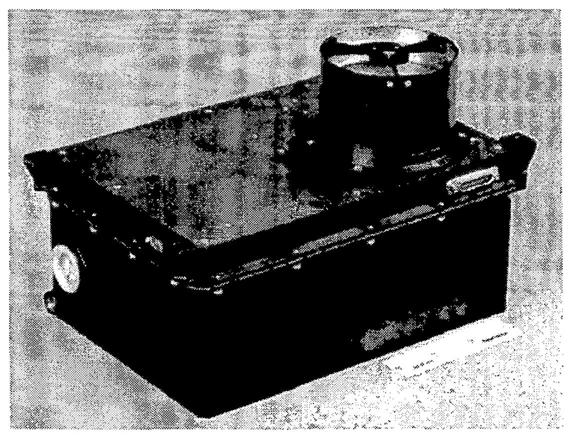
Mini-TES will be carried on board the Mars 2001 Lander as illustrated in Figure 1, and is part of a suite of sensors and other specialized miniature space-qualified equipment to be delivered to NASA by the Cornell team. The 2.4 kg Mini-TES views the scene around the Lander through a periscope assembly shared with visible panoramic camera equipment, "Pancam."

To address APEX Mission Objective 1 in Table 1, the Pancam will provide color stereo pictures of the terrain around the Lander, and the Mini-TES will provide remotely-sensed point discrimination of mineralogical composition in the same field-of-view (FOV). Mini-TES senses fundamental emission features in the thermal spectra of minerals, allowing a characterization of the Martian terrain mineralogy on a pixel-by-pixel basis. Guided by the data provided by Mini-TES, the science team will then command the specialized remote sensing instruments contained on the Lander Robotic arm and on the MARIE Rover (shown in Figure 1) to perform direct in-situ measurements to further satisfy Mission Objectives 2 and 3 (Table 1).

This paper briefly reviews how the Athena mission objectives drove the selection of thermal Infrared (IR) spectrometry and the Mini-TES performance and design characteristics. An overview of the Mini-TES design is provided, including a detailed parameter summary and hardware description. The measured sensor performance is presented based on hardware acceptance testing. Finally, some possible future applications of Mini-TES beyond the Mars 2001 mission are described.



(a)



(b)

Figure 1. a) Mini-TES Packaged on Mars 2001 Lander as depicted by Spacecraft Provider Lockheed Martin Astronautics, and b) Mini-TES Shown With Optical Aperture Facing Up. *Mini-TES was delivered ahead of schedule.*

3. MINI-TES DESIGN REQUIREMENTS

The Mini-TES design and hardware details described in this paper can only be appreciated if the sensor's purpose and requirements listed in Table 2 are understood. The overall purpose of Mini-TES for the APEX mission is to remotely determine site mineralogy around the Mars 2001 Lander. Additional science objectives with Mini-TES include measuring the thermophysical properties of rocks and soils as well as temperature profiles in the atmospheric boundary layer. A further objective is to complement and be synergistic with the global data sets to be obtained by the MGS TES and the MSP '01 Orbiter's Thermal Emission Imaging System (THEMIS). (The THEMIS instrument is currently under development by Raytheon SBRS under contract to ASU, and is scheduled for launch in March, 2001.) By obtaining similar spectral measurements from both Lander and Orbiter instruments, it will be possible to place the Lander results in a global context and to improve the understanding of compositional units.

The science team decided that the Lander site, to be selected based upon information gathered from the orbiting MGS mission using the TES and other MGS instrumentation, would be reasonably well characterized and explored if samples could be examined to a distance of about 10 meters from the Lander. This requires the Mini-TES to separate samples roughly 8 centimeters across from other samples at a range of 10 meters. Thus, Mini-TES requires a spatial resolution of 8 mrad. In addition, acquisition of panoramic data must be obtained in timely manner, so a larger 20 mrad FOV was required. This drove the basic optical and mechanical configuration and size of the sensor by defining the minimum optical aperture, the focal length, and detector dimensions at the focal plane. An aperture flag within the optical train allows selection of the 20 or 8 mrad FOV.

Secondly, science requirements dictated that major mineralogical types be discernible through coatings of dust expected to be found on the Martian surface. This dictated operation in the thermal IR beyond 5 microns, as shorter wavelengths would be substantially scattered or absorbed by dust coatings, and the actual mineralogy would therefore be occluded. Terrestrial desert IR observations [Ramsey and Christensen, 1992] have shown that thermal IR penetration of relatively thick 50 micron dust layers is quite good.

Additionally, diagnostic features in the thermal IR beyond 5 microns are fortunately also stronger than the features at shorter wavelengths [Wilson, et al, 1955]. Furthermore, the 8 mrad resolution means there will be combinations of mineral content in a single Mini-TES pixel, so it is important to be able to apply spectral decomposition to the retrieved spectra to estimate the percentage of various component minerals in a given pixel. This technique works best if the spectra of mineral mixtures is a linear combination of the individual spectra, which is approximately the case in the thermal IR [Ramsey, 1996], while non-linear mixing effects are strong at shorter wavelengths.

Extensive studies of thermal IR spectra of minerals, rocks, and soils [Farmer, 1974; Hunt and Salisbury, 1976; Lazerev, 1972; Salisbury and Walter, 1989; Salisbury, et al, 1991; Salisbury, 1993] have shown that mineral structures are primarily characterized by the presence and polymerization of anion groups such as CO_3, SO_4, PO_4, and SiO_4. Therefore, carbonates, sulphates, phosphates, silicates, and other minerals have thermal IR spectra that are identifiable using FTS data similar to those to be recovered by Mini-TES, as illustrated in Figure 2.

Figure 2(a) shows spectra obtained from salts and other evaporites, typically expected near hydro-thermal springs, which would, if seen, indicate a prior abundance of surface water on Mars. Notice that the features of these various spectra are readily distinguishable without fine radiometric resolution or calibration, or even high spectral resolution. At this level of application, the spectroradiometric requirements for Mini-TES could be fairly coarse.

Figure 2(b), on the other hand, shows that although carbonates can easily be distinguished from other mineral types (as shown in Figure 2(a)), resolving specific carbonates from one another requires 10 cm^{-1} spectral resolution [Salisbury, 1987]. This can be estimated by inspecting the variation in position among the various carbonates of the two absorption lines near 6 and 11 microns identified in the graph.

Therefore, the mineralogy requirement drove the spectral resolution to 10 cm^{-1}, and consequently set the Fourier Transform Spectrometer (FTS) moving mirror optical path difference (OPD) to 0.5 mm. This allows for compact and reliable voice-coil mirror activation based on the MGS TES, which required a full millimeter OPD to obtain its required 5 cm^{-1} spectral resolution. Furthermore, the compactness of the Lander and low power requirements dictated the use of uncooled detectors. Uncooled Alonine Deuterated Triglycine Sulphate (AlDTGS) detectors, already demonstrated on MGS TES for this same purpose, were again selected for Mini-TES.

Table 2. Mini-TES Mission Requirements Drove Sensor Characteristics

Mission Requirements	Sensor Characteristics
Discern 8 cm features at a distance of 10 meters	• 8 mrad FOV (selectable- aperture flag)
Provide timely panoramic coverage	• 20 mrad FOV
See through dust and other coatings on rocks	• Thermal IR operation 5-28 microns
Discern mineralogical types remotely	• 10 cm^{-1} spectral resolution FTS • Signal-to-Noise Ratio (SNR) 400 @ 10 μm for a 240K scene • 2% relative/5% absolute Blackbody Calibration
Mass < 3.1 kg, Power < 7 Watts, Volume < 3.5 liters	• f/9.3, 59 cm effective focal length reimaging optics; • Folded ray path; • Uncooled AlDTGS Detectors
Low Data Rate	• On-board FFT; • Downlink buffered, compressed spectra; • <5 hours daily operation

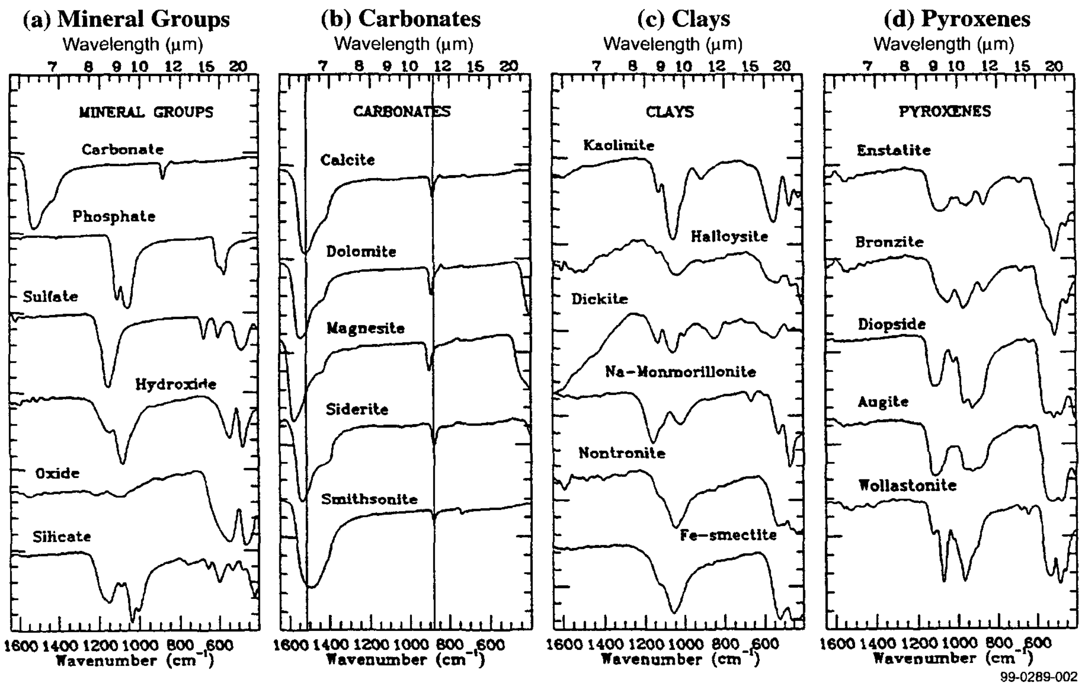


Figure 2. Thermal IR emission spectra of relevant minerals. (a) shows that minerals from various oxyanionic groups can be identified with ease. (b) shows that different carbonates can be distinguished from one another. This group drives the spectral resolution requirements for Mini-TES. (c) shows that clays can be readily identified. (d) shows that pyroxenes may be distinguished from one another within their solid solution series.

Additional Design Considerations

In general, the diurnal variation of temperature on Mars precludes night operation when the temperature is too low to obtain adequate SNR. Figure 3 shows the diurnal variation of temperature on Mars. At latitudes where the Lander might be located there is only about a six-hour window of time when the temperature rises above 240K. The present plan is to limit Mini-TES operation to the hours between 10 a.m. and 3 p.m., local Martian time.

Figure 4 shows the measured SNR performance for a single spectrum (i.e., without the benefit of co-adding spectra) at a target temperature of 240K over the wavenumber range of 2200 to 200 cm-1 (4.5 to 50 microns), using the 20 mrad FOV. [NOTE: The data is collected over this full range even though the instrument bandpass is limited to the 5 to 28 μm range.] As can be seen, performance peaks at about 13 microns because the blackbody emission peaks at about that point and falls off at other wavelengths. To obtain sufficient radiometric resolution at the zero path difference (ZPD) interferogram maximum, and to limit quantization noise, 16-bit quantization was selected for the Mini-TES design.

The optical collecting aperture was selected to roughly match the spatial resolution requirements and to keep the instrument volume, as well as that of the periscope mast and fore optics, as small as possible. However, this limits the SNR for a single spectrum, so that co-adding of spectra is required in order to obtain the required SNR of 400 at 10 µm for a scene at 240K.

To avoid aliasing of spectral information at the shortest wavelength of five microns, a factor of greater than five in spectral oversampling was selected, requiring one sample per 0.98 micron of interferometer moving mirror travel. Therefore, a total of 964 samples per interferogram were required, as a minimum. It is more cost effective, however, to use standard fast Fourier transform (FFT) algorithms, so 1024 point interferograms are used.

To keep the power consumption low and to obtain sufficient integration time (and therefore signal) for each interferogram sample, the A/D converters need to run at less than 500 Hz. Therefore, a 2-second period was selected for each interferogram scan.

To minimize the data transmission requirements, the interferograms for a given sample are first converted to spectra via an on-board FFT algorithm, which provides a factor of forty data reduction, before being co-added. Co-adding provides a data reduction factor proportional to the number of spectra averaged. The resulting spectrum is then compressed by approximately a factor of 1.6 using lossless Rice data compression. For relay to earth, the Lander transmits the data to the Orbiter during two passes each Sol. Each data burst from the Lander is accomplished in approximately 10 minutes.

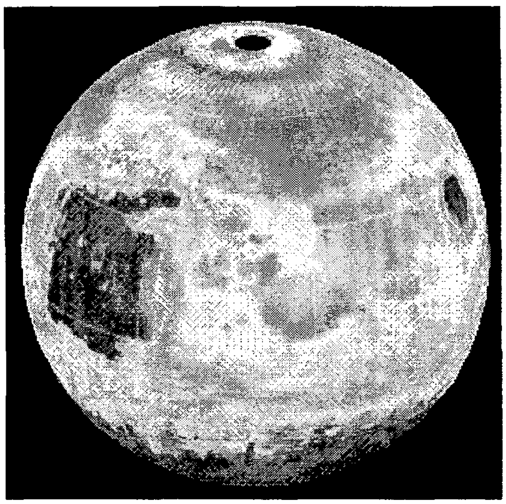


Figure 3a. Martian Temperature Distribution. *Global Temperature plot created with data derived from MGS TES, currently in orbit around Mars.*

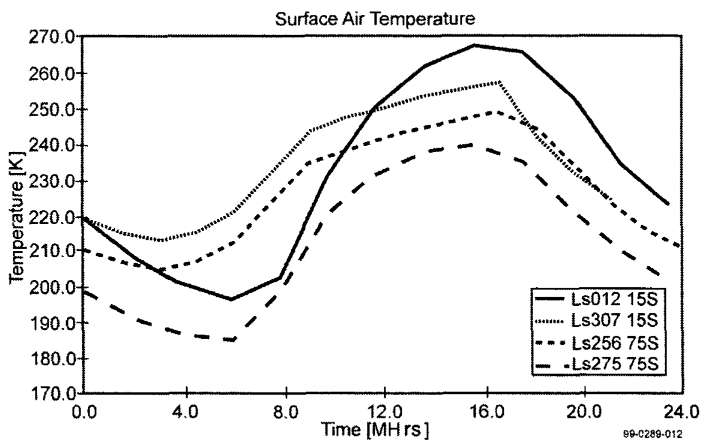


Figure 3b. Martian Diurnal Temperature Variation. *Diurnal variation at different latitudes and conditions.*

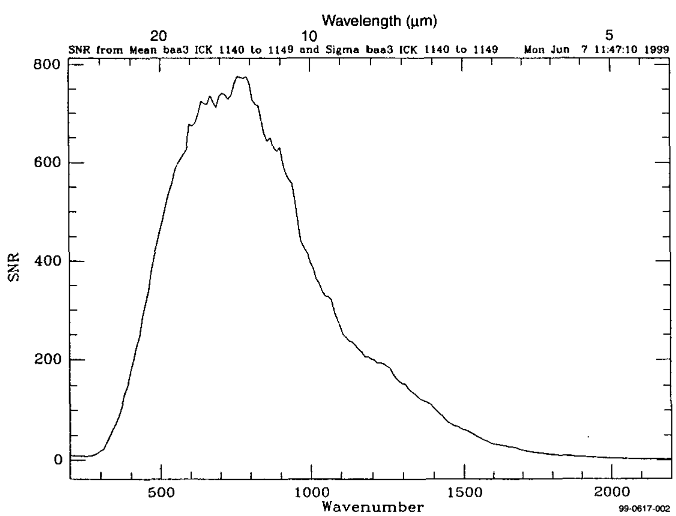


Figure 4. Measured SNR for Mini-TES. *Final acceptance test laboratory measurements indicate better than expected performance for the Mars 2001 mission's Mini-TES instrument.*

4. Instrument Design

Figure 5 represents a schematic, unfolded optical ray-trace through the telescope to the detector assembly. Figure 6 displays the folded, 3-dimensional optical path through the entire instrument. Figure 7 shows a functional block diagram of the Mini-TES instrument. With reference to Figures 5, 6, and 7, a short walk-through the elements of the instrument reveals the key design features and explains the functional operation.

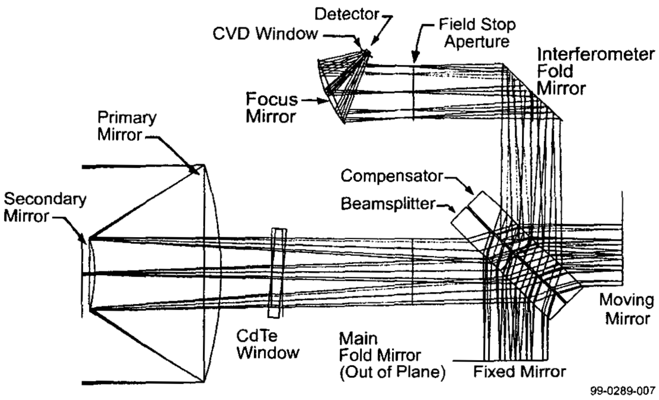


Figure 5. Mini-TES Optical Design Schematic. *Schematic shows the unfolded optical system, including the Cassegrain collimating telescope, the interferometer, reimaging mirror and detector assembly, with a ray trace through all the elements.*

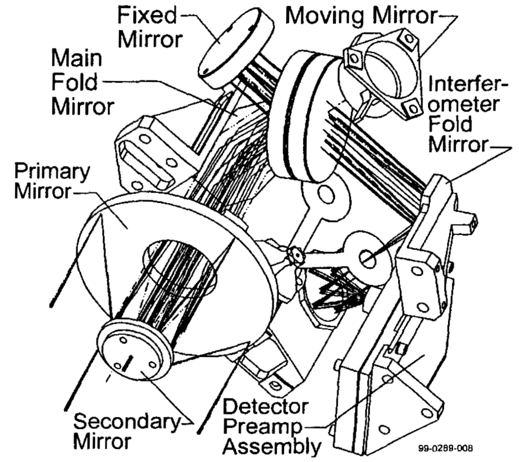


Figure 6. Mini-TES 3-D Perspective Optical Layout. *Folding optics permit the full capabilities to be contained in a small, lightweight package.*

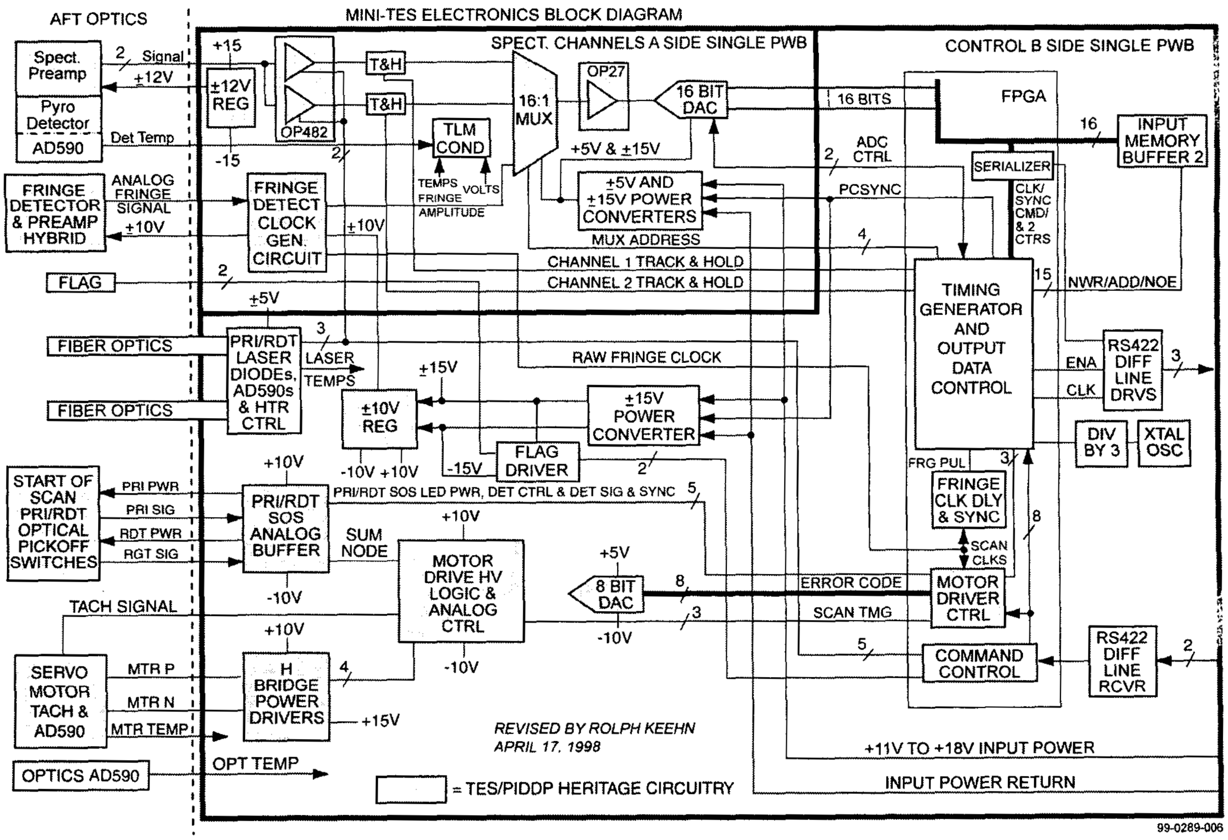


Figure 7. Block Diagram of Mini-TES. Mini-TES takes advantage of strong TES and PIDDP heritage (shaded components).

As shown in Figures 5 and 6, light enters the aperture, striking the primary mirror of the 63 mm aperture Cassegrain obscured telescope. The obscuration by the secondary mirror reduces the effective collecting aperture to 52 mm (for the purpose of computing signal radiance). After reflecting off the primary mirror, the scene radiance reflects off the secondary and is converging as it passes through the optical bench Cadmium Telluride (CdTe) window, which provides environmental protection.

This light strikes the main fold mirror on its way to the interferometer beamsplitter. The beamsplitter and mount was modified from the one used on MGS TES. The new design uses KBr vs. CsI, and has radial vs. axial mounts. The beamsplitter splits the light into the two interferometer paths. The light reflects off the fixed mirror (for one path) and off the moving mirror (for the other path), and then back to the beamsplitter, as shown in the ray-trace in Figures 5 and 6. The resulting combined light beam from both paths is directed by the interferometer fold mirror to the parabolic imaging mirror, which focuses the light onto the detector/preamp assembly. The final optical element is a chemical vapor deposited (CVD) diamond window covering the AlDTGS pyroelectric detector.

The resulting signal detected during the full moving mirror scan then comprises an interferogram. The conversion of the interferogram into a spectrum is done via a Fast Fourier Transform (FFT). In order to do this, it is necessary to sample the interferogram at fixed positions of optical path difference. The precise position information is determined by a laser fringe counting assembly which provides redundant narrowband laser input light sources to the interferometer, and is illustrated and labeled "pri/rdt laser diodes" in Figure 7. Narrow band temperature stabilized radiation is achieved by using commercial Distributed Bragg Reflector (DBR) lasers. The 980 nm laser energy is delivered through an optical fiber which has a 10 cm focal length lens fused to the end. This light follows a path through the interferometer parallel to the scene radiance, but bypasses the interferometer fold mirror at the left of the beamsplitter to reach the fringe counting detector assembly. This position sampling information is used by the servo control electronics to control the motion of the moving mirror. It is also used to format the data so that the complex FFT calculation can be performed on the scene interferogram data to obtain the complex spectrum. Once the complex spectrum is obtained, it is converted to an intensity spectrum, compressed, buffered, co-added as predetermined by ground instructions, and then stored in Lander memory until it can be transmitted to the Earth during the next pass of one of the Mars orbiters.

The electronics that perform these computations are shown in Figure 7, along with the control functions that operate the moving mirror. The digitized output is then processed by the Lander computer which performs the FFT, compression, and buffering. Figure 8 is a photograph of the Mini-TES showing the integration of the electronics into the instrument.

Table 3 provides a listing of the principal Mini-TES parameters that characterize the design and performance of the instrument at a level of detail substantially finer than Table 2.

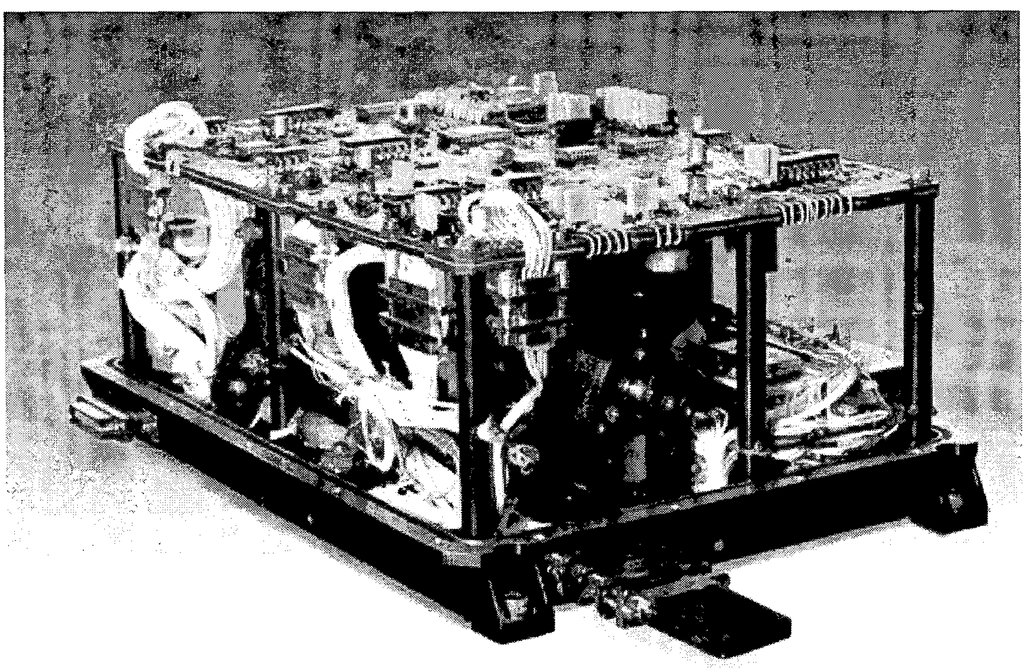


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Figure 8. Interior View of Mini-TES Instrument. *Highly integrated and tightly packaged electronics and optics allowed minimum size and weight for this interplanetary instrument.*

Table 3. Mini-TES Design and Performance Parameters

Parameter	Description
Interferometer Spectral Range	2,000 to 350 cm^{-1} (5 – 28 microns)
Interferometer Spectral Resolution	10 cm^{-1}
Field of View	8 mrad (fine) and 20 mrad (coarse)
Telescope Aperture	63.5 mm diameter Cassegrain
Detectors	Uncooled Alonine doped Deuterated Triglycine Sulphate (AlDTGS) Pyroelectric detector $D^* > 6 \times 10^8$ at 20 Hz
Michelson Mirror Travel	0.5 mm
Mirror Velocity (physical travel)	0.0325 cm/sec
Laser Fringe Reference Wavelength	980 ± 2 nanometers
Sample Rate	645 samples/sec
Cycle Time per Measurement	2 sec (1.8 sec forward scan, 0.2 sec retrace)
Number of Scans (co-adds) needed to Achieve 400 SNR at 10 μm for a 240K scene	2 (20 mrad); 80 (8 mrad)
Number Samples per Interferogram	1024
Number Bits per Sample	16
Number Spectral Samples	165
Data Rate (bits/second, averaged over 1 Sol)	240
Dimensions	8.75 x 6.4 x 4 inches (22 x 16 x 10 cm)
Mass	2.4 kg
Power	5.4 Watts (operating), 0.3 Watt (averaged over 1 Sol)
Operational Temperature Range (Instrument Baseplate Temperature)	Survival and Operability -45°C, +50°C; Performance within Spec -30°C, +30°C

The perspective 3-D view of the optical design shown in Figure 6 provides a clear illustration of not only the optical design, but also the layout of the components and the optical ray path through the Mini-TES telescope and interferometer (laser counting interferometer is not shown).

The optical design was performed using Code V. Key features of the design include:

1. Focused at infinity, with minimal blur at typical observational range of 4 to 10 meters from Lander
2. All Aluminum Optical Bench and Mirrors for light weight and strength and uniform CTE properties
3. CdTe optical window for contamination control and high transmission out to 28 microns with tested anti-reflection coating

Figure 9 shows the CdTe window transmittance over the spectral range, dropping off at longer wavelengths. CdTe was chosen in part because of the saturated water vapor condition of the Martian atmosphere.

Figure 10 shows the Mini-TES object size on the focal plane in inches as a function of range from the Lander when the focus is set to 6 meters. For the 8 mrad fine-resolution case, the object size is about 12.5 cm at 10 meters range

5. Mini-TES Build and Test Flow

The top-level sequence of events for the build and test of the Mini-TES unit are depicted in Figure 11. The Optical system consists of the beamsplitter subassembly, the fixed mirror, the moving mirror assembly, the telescope assembly, the fold mirror and the imaging mirror. The interferometer assembly adds the aperture flag, the fringe detector, and the pyrodetector and associated preamp. The electronics subsystem is comprised of the following functions: control logic, spectrometer signal processing, power conversion, start-of-scan electronics, and the (redundant) fringe lasers.

Performance tests were conducted before and after each of the environmental tests. These environmental tests were performed at protoflight levels in order to qualify this miniaturized design for space flight and Martian surface use. The thermal vacuum testing included servo optimization as part of the integration and electrical component value selection finalization.

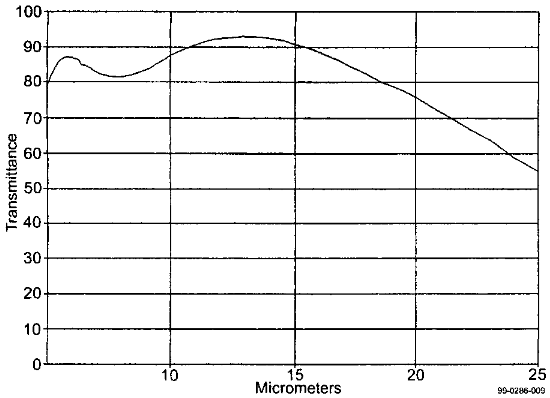

Figure 9. CdTe Window Measured Transmittance. *This window provides a highly transmitting contamination shield for the optics enclosure.*

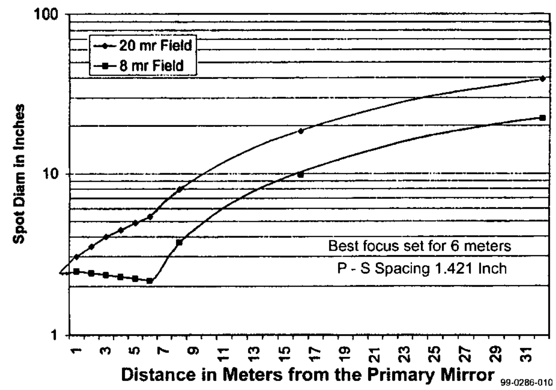

Figure 10. Mini-TES Object Size as a Function of Range From the Lander. *Mini-TES optical focus tradeoff with operational use showed that infinite focus offered a reasonable resolution within 7 meters range from the Lander, where most observations are expected to occur.*

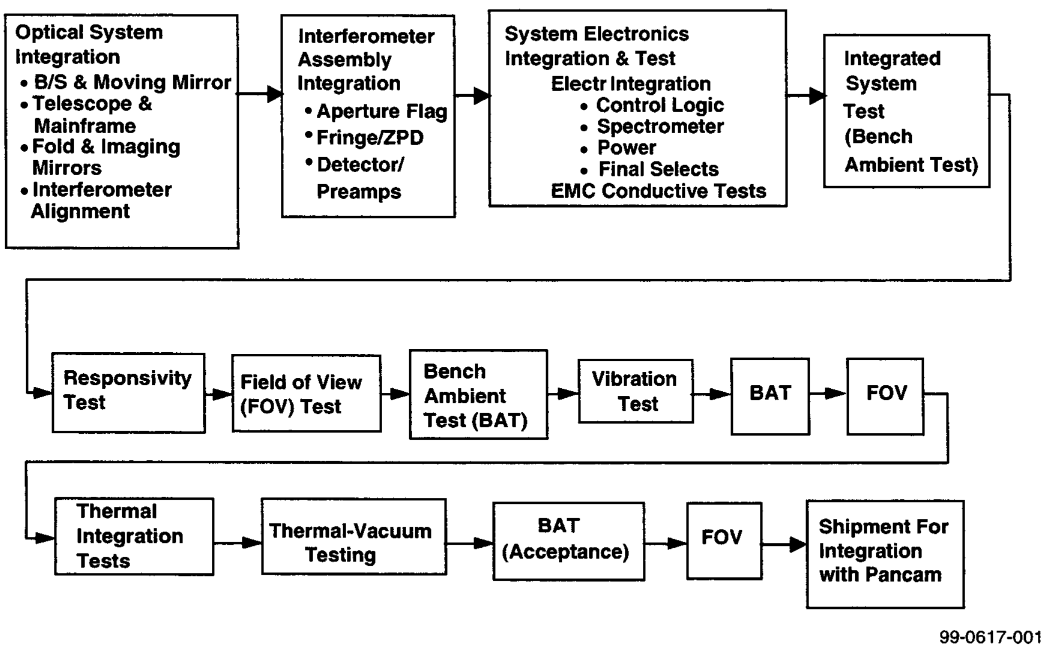

Figure 11. Mini-TES Build and Test Flow. *This approach optimized performance vs. risk vs. cost for this planetary instrument.*

6. Mini-TES Performance Results

Some of the key Mini-TES instrument performance measurements are shown in Figures 12 through 15. These results indicate that Mini-TES will meet the mission objectives over the full expected range of environments expected at Mars.

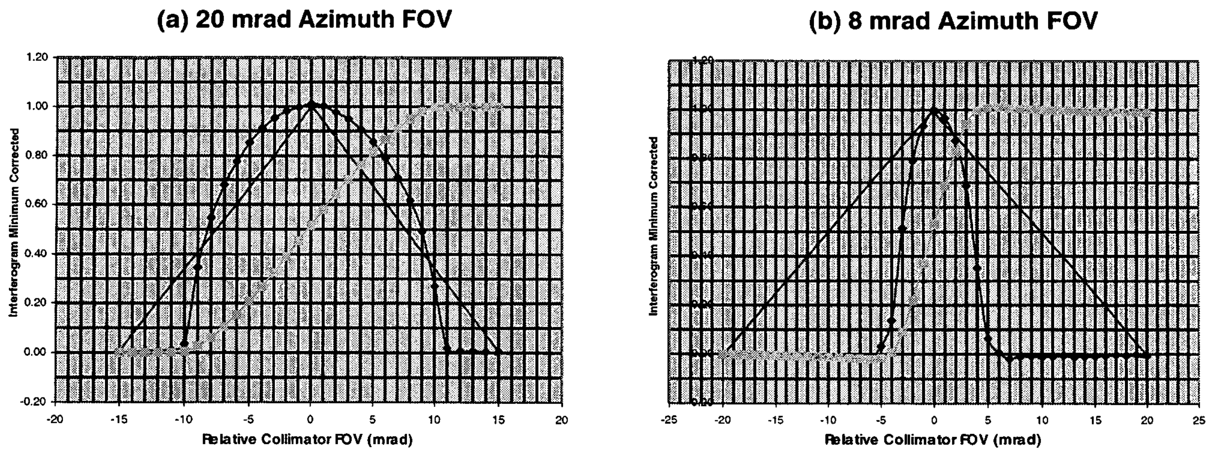

Figure 12. Measured Field of Views. Measurements of the field of view for (a) the large, and (b) the small FOV. *Diamonds represent the signal vs. angle, beginning and ending at the center (and hence creating the triangle line). The half-tone squares represent the integrated energy, and are used to calculate encircled energy performance.*

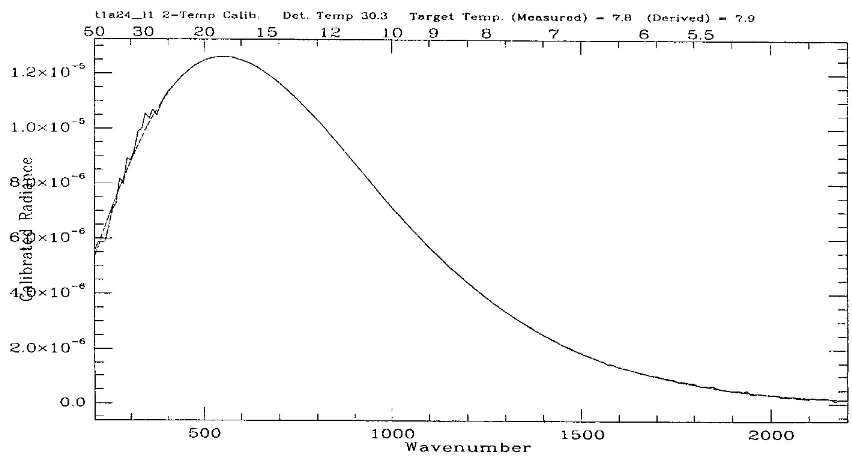

Figure 13. Scene Radiation Prediction. *The predicted scene radiance as a function of wavenumber for conditions where Mini-TES is at or above the nominal mission temperature indicate better-than-expected performance.*

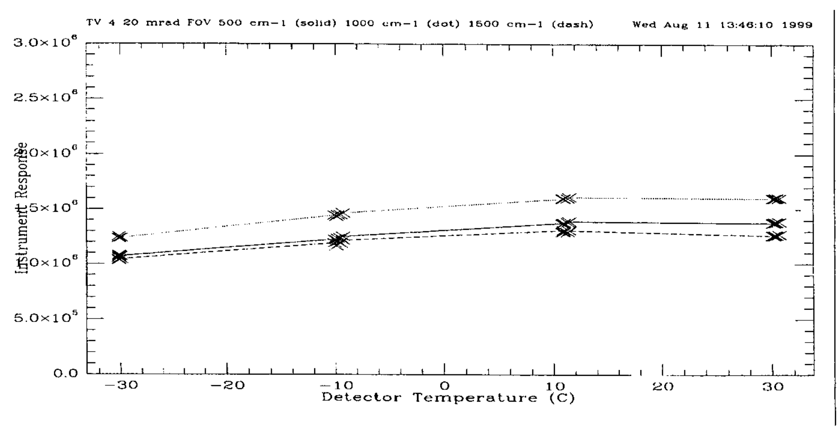

Figure 14. Response vs. Temperature. *Response is relatively flat over temperature, minimizing the amount and degree of signal correction software.*

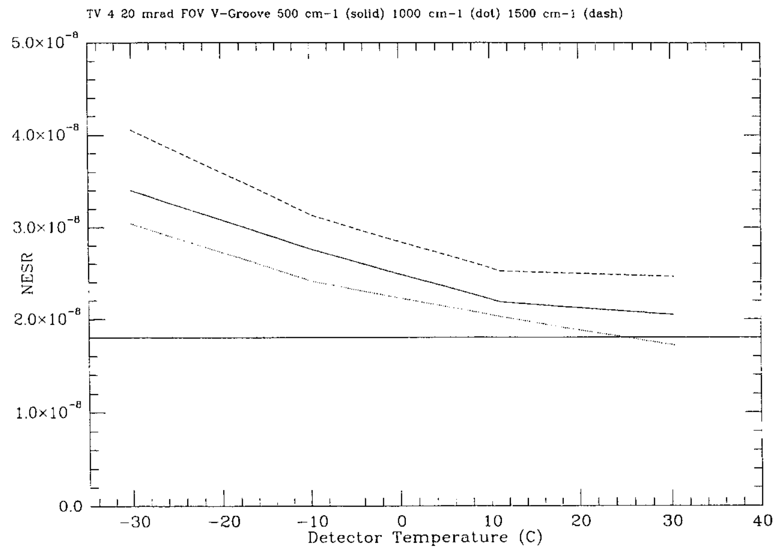

Figure 15. NESR vs. Temperature. *Measurements over temperature indicate acceptable unit performance even under the low temperature conditions expected on the Martian surface.*

7. Potential Future Mini-TES Mission Concepts and Requirements

The Mini-TES modular design can meet varying mission requirements. Four mission types are considered in order of decreasing distance from the planetary surface: flyby, orbital, low-altitude, and surface. The characteristics of these mission types are summarized in Table 4 and illustrated in Figure 16. Each mission has surface and atmospheric applications which Mini-TES is either being built to address or could be modified to address.

Part of NASA's overall plan for the early 21st century is to fully explore the solar system [National Commission on Space, 1986; Stafford, 1991]. The four mission types of Table 4 are potential elements of an overall mission concept to characterize specific atmosphere and surface composition and dynamics of asteroids, planets, and their moons. Two of these mission concepts have been or are being implemented for Mars: the orbiting mission that MGS is currently completing with the TES instrument and the Lander mission for which Athena is being developed with Mini-TES.

Science goals include obtaining detailed knowledge to test long-standing hypotheses regarding solar system and Earth properties and behavior. Pragmatic goals include economic resource identification; the planets may eventually become "outposts" for further space exploration, and even sources of enhanced commerce and trade. These objectives require a cost-effective program, starting with proven remote sensing payloads to assist decisions regarding more expensive steps, including human exploration.

Table 4. Mission Concept Definition

Mission Type	Characteristics	Science Objectives	TES Implications
Flyby	> 2000 km altitude 10-50 km resolution	Atmosphere/surface general assessment	Coarse resolution Small and light
Orbital	300-500 km altitude 3-10 km resolution	Global survey of surface and atmosphere	Modest resolution (atmospheric sounding emphasis)
Low-Altitude	1-10 km altitude 100 m resolution	Lander site selection	Modest resolution Small and light
Surface	20-100 meter range 1 - 20 cm resolution	Surface examination Sample examination	Very small and light

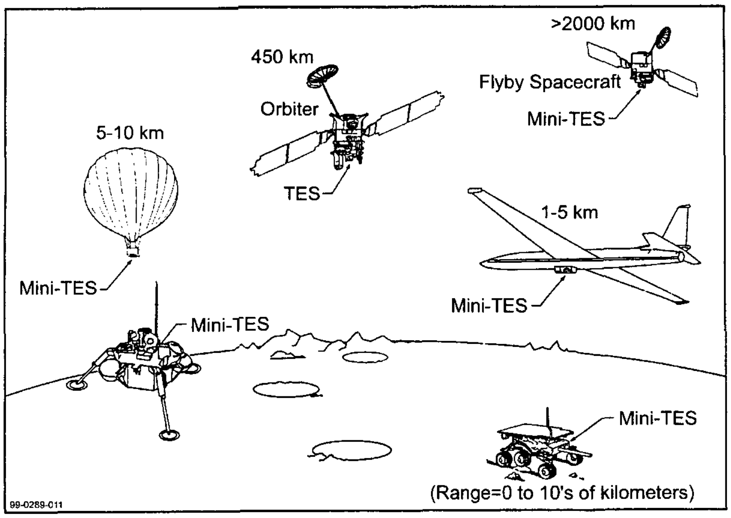

Figure 16. Mission Scenarios From Planetary Composition to Site Selection and Surface Examination. *The Mini-TES design provides detailed thermal and spectral remote sensing in a small, lightweight package for a variety of mission scenarios*

Flyby Mission

The classic "flyby" mission uses small, instrumented robotic spacecraft to evaluate solar system bodies from asteroids to planets and their moons. Early flyby Mars Mariner missions in the late sixties [Conrath, et al, 1973; Curran, et al, 1974] led to orbiting Viking missions in the mid-seventies, with surface landings, spectacular photographs of the Martian landscape, and substantive atmospheric and geologic findings [Pollack, et al, 1977; Binder, et al, 1977; Tillman, et al, 1979]. The flyby spacecraft would not approach a planet close enough to be drawn into orbit. This limits the spatial resolution and extent of ground coverage of a planetary flyby evaluation, however, smaller objects, such as asteroids, could be examined more closely. Therefore, flyby missions should characterize atmospheric and surface features of planets and their moons, as well as provide a detailed catalog of asteroid and comet characteristics. Data from flyby missions allow selection of specific planets, their moons, or other bodies for orbital missions, wherein instrumented spacecraft are dedicated to global examination of particular planets or their moons.

The flyby mission would entail a distant approach to a planet, probably exceeding several thousand kilometers. Closer flyby approaches may be planned for asteroids. A flyby mission would focus on basic compositional measurements. The spatial resolution requirements would be perhaps 1% of the diameter of small bodies, such as asteroids, and 10-50 km for planets. At these spatial scales, sub-pixel mixing of multiple components becomes a significant issue. Fortunately, mixing of the outgoing thermal IR (TIR) radiance is approximately a linear portion of the surface area of each component because of the very high TIR absorption coefficients. This minimizes probability of multiple grain interactions of the emitted photons [Ramsey, 1996].

Spectrally, Mini-TES should operate over the interval from 6 to 35 μm to cover a significant range of vibrational frequencies present in solid materials and water vapor. A spectral resolution of 5-10 cm^{-1} is sufficient to identify geologic materials using emission observations to determine the pressure-temperature relation in a planetary atmosphere, and to resolve water vapor rotational bands [Salisbury, et al, 1987]. An SNR of 300 at 10 μm viewing a target at 240 K is adequate. The relative radiance calibration should be 2% over the spectral range and stable for 30 days. Absolute calibration should be 4% to provide sufficiently accurate temperature measurements for atmospheric sounding and total energy balance modeling. The spatial resolution requirement translates to instrument spatial resolution of roughly 10 mrad.

Orbital Mission

Renewed interest in planetary exploration, but at low cost using miniature spacecraft and robotic sensor technologies, has led to the current MGS orbital mission and the advanced-technology New Millennium Program (NMP) to reignite solar system exploration efforts. Anticipated MGS results include characterization of the Martian atmosphere and surface, with photographs and altimetry, as well as TES spectroscopic surface analysis. These results should lead to selection of geographical regions for more detailed examination.

Low-Altitude Mission

To further explore the orbiter-identified geographic regions in a cost-effective manner, the low-altitude site survey mission follows. This mission could employ robotic aircraft or balloon-borne remote sensing instrumentation within 10 km to 1 km of the planetary surface. Balloon instruments would move with the local winds. Aircraft instruments could operate at selected speeds guided by on-board maps based on orbital data such as from MGS.

The Mini-TES science requirements for the low-altitude mission would include both surface and atmospheric characterization. For example, down-welling or up-welling radiances could be measured from a balloon platform to study local atmospheric horizontal and vertical structure and dynamics. The spectral performance requirements are similar to those for the other mission scenarios. A spatial resolution of 1 to 10 meters would be desirable to study potential landing sites for interesting rock and mineral features for examination over a spatial range of perhaps a hundred-meter radius. A 10 mrad nominal spatial resolution would allow 10 meter resolution from 1 km, and 1 meter resolution from 100 meters. For the aircraft case, a combination of image-motion compensation, used on TES, and longer integration times would be necessary to accommodate these resolutions.

Surface Landing Mission

The final step in robotic exploration is the surface mission which Athena is designed to perform on Mars and for which Mini-TES has currently been built, wherein instrumented Landers containing miniature mobile robotic vehicles are placed at selected sites for detailed surface examination. Centuries of field geological expertise developed on Earth for mineral and petrologic exploration can be programmed into surface systems to enable rapid evaluation of surface materials for both scientific and economic objectives.

The surface landing mission is the basic subject of this paper, and the focus of the APEX program. The program was originally focused on placing the Mini-TES on the Rover vehicle, as illustrated in Figure 16, but was then refocused on the Lander scenario. Mini-TES is an ideal instrument for the Rover-based Athena mission.

8. Conclusions

A description of the science, rationale, design, and performance of the Athena Precursor Experiment Mini-TES has been presented. The use of design heritage, and modest use of commercial technology has led to a low-cost, robust, miniature design of a Fourier transform spectrometer. Numerous applications are available for the Mini-TES in addition to its primary use as a key instrument in the Mars Sample Return Program.

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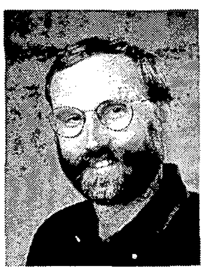
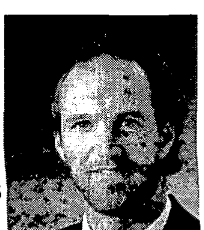
10. BIOGRAPHIES

Dr. Karl Blasius *is the Manager, Earth and Planetary Sensors, for Raytheon Santa Barbara Remote Sensing (SBRS). Since joining SBRS in 1993 he has lead sensor concept definition projects for Earth and planetary remote sensing missions. He is a member of the Instrument Technologies and Architectures Team of NASA's New Millennium Program. Prior to joining SBRS he developed visual and IR image simulation techniques for Hughes Training and Support Systems, worked in oil exploration as a geophysicist and instrument developer for Getty Oil Co. and Magnavox, respectively, and held the position of Senior Research Scientist with SAIC. He has been a Principal Investigator for NASA's Planetary Geology Program and a member of the Mars Viking Orbiter Imaging Team. He holds a BS degree in Physics and Astronomy from Michigan State University and MS and PhD degrees in Planetary Science from Caltech.*

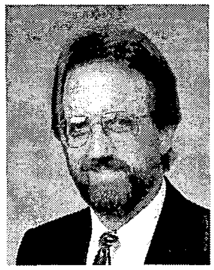


Philip Christensen *is a recognized expert in geophysics and space physics, particularly with respect to the Martian environment. A professor in the Department of Geology at Arizona State University, he has served since 1986 as Principal Investigator for NASA's Planetary Geology and Thermal Emission Spectrometer Programs, and, since 1996, as Principal Investigator on NASA's Planetary Instrument Definition and Development Program. He currently serves on the National Academy of Science Committee on Planetary and Lunar Exploration (COMPLEX) and participates in NASA's Mars Sample Return Working Group and Mars Observer/Surveyor Project Science Group. Previously, he served as Principal or Co-Investigator on several NASA efforts related to planetary geology, as well as on a number of associated working groups and panels. His professional affiliations include the American Geophysical Union, the American Astronomical Society (Division of Planetary Science), the Geological Society of America, and the Optical Society of America.*



Steven Silverman *is a systems engineer specializing in the design, development, and test of space-qualified electro-optical instru-ments. He is currently the technical director on the Mars Surveyor 2001 Project's Thermal Emission Imaging System (THEMIS) and Miniature Thermal Emission Spec-trometer (Mini-TES) Programs. Most recently, he completed more than 12 years of work as systems engineer on the Mars Observer/ Mars Global Surveyor Thermal Emission Spectrometer, on which he was responsible for overall technical performance of the TES, including all system-level testing. He was also the point of interface with the spacecraft contractor, the science team, and JPL. Other assignments have included serving as proposal manager and system engineer on various proposals and studies for satellite-based remote optical sensors, and as program manager on the airborne Wedge Imaging Spectrometer. He has an MS from the University of California at Santa Barbara, specializing in microwaves, optics, and acoustics, and a BSEE with Honors from California Polytechnic State University.*

Greg Mehall *has 12 years of engineering experience with space flight missions including both mission operations and flight hardware development. He is currently an associate research specialist in the Department of Geology at Arizona State University. Since 1992 he has been the instrument manager, mission manager, and systems engineer for the Mars Observer (MO) and Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) Programs, as well as for the Mars Surveyor 2001 Project's THEMIS and Mini-TES Programs. As the mission manager for the MO and MGS TES instruments, he has managed the daily mission operations activities for the TES instruments and has worked closely with the spacecraft team at Lockheed Martin and the mission operations team at JPL. During the 5 years prior to his employment at ASU, he was an integral member of the engineering team that designed and built the TES instruments at Santa Barbara Remote Sensing. His fields of expertise include electronics, optics, and systems engineering. He received a BS in electrical engineering from the University of Michigan and a MS in electrical engineering, with an emphasis in electro-optics, from Stanford University.*



Duane Bates *is currently the Mini-TES Program Manager at Santa Barbara Remote Sensing. He has 15 years of experience in space flight programs covering a wide variety of missions and technologies. He was the lead payload system engineer on the GOES (NASA) and GMS (NASDA) weather satellite programs and the spacecraft Operations Manager on the Multi-Mission Bus (MMB) program, responsible for all aspects of spacecraft operations and test, including ground support equipment development. Most recently he held a similar role on the Moderate Resolution Imaging Spectroradiometer (MODIS) for NASA's Earth Observing System. Other ongoing assignments include engineering line management and proposal management. He earned his BS, MS, and PhD degrees in Physics from the University of Southern California.*

James Jeter *is a project engineer specializing in advanced development programs for airborne and spaceborne remote sensing instruments. He recently served as system engineer for the Mini-TES program. He managed hyperspectral sensor development programs at Santa Barbara Remote Sensing (SBRS), including the second generation VNIR-SWIR airborne wedge hyperspectral sensor program. Prior to focusing on airborne/spaceborne remote sensing, he was responsible for development of non-contact sensors for manufacturing at SBRS and at the Albuquerque Engineering Laboratory (AEL). At the AEL, he was also responsible for active and passive vibration control for airborne and spaceborne sensor systems. He was the manager for active and semi-active automotive suspension control programs and has a patent in this area. He has over 25 technical publications.*

Previously, he taught mechanical engineering at the University of New Mexico and the Virginia Military Institute. He earned a BS degree in engineering from the Virginia Military Institute and MS and PhD degrees from the University of Virginia, where he specialized in applied mechanics.

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