CALIBRATION RESULTS FOR THE FIELD PORTABLE THERMAL INFRARED SPECTROMETER (THIRSPEC).

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ABSTRACT

A thermal infrared grating spectrometer was developed by the Institute for Space and Terrestrial Science (ISTS) and Barringer Research Inc. for field studies in the earth sciences. The design is based on a reflection grating and a 60 element HgCdTe detector array. The useful spectral range of the instrument covers 7.9-11.3 µm with a resolution of 0.09 ± 0.01 µm. The instrument averages over a 12^{o} field of view and compares the exitance of the target to that of an internal black body at ambient temperature. The noise equivalent temperature is approximately 0.05^{o}K over the useful spectral range. Background radiance reflected from the surface of the target can seriously impede the determination of emissivity. This effect is removed from the spectra of geological samples by the use of reference samples.

Key words: thermal infrared, portable spectrometer, calibration, emissivity.

INTRODUCTION

A thermal infrared grating spectrometer was developed by ISTS and Barringer Research Inc. for field studies in the earth sciences. This prototype instrument, the THermal InfraRed SPECtrometer (THIRSPEC), is a 60 channel array spectroradiometer operating in the 8 to 12 micrometer region of the electromagnetic spectrum. THIRSPEC is battery powered, tripod mounted, transportable by backpack, and was designed to collect *in situ* measurements of ambient spectral thermal emission of targets without disturbing their natural setting (Nerry et al. 1988, Zhang et al. 1986). The field of view of THIRSPEC is circular and of approximately 12 degrees at full angle. A noise equivalent temperature difference of 0.05^{o}K is obtained using a 10 second integration time.

THIRSPEC provides *ground truth* data at the spatial resolution necessary to construct radiative transfer models for the interpretation of airborne and satellite remote sensing data. This study summarizes the calibration results for THIRSPEC and the methodology developed to determine the spectral emissivity of rock samples using this instrument.

SPECTROMETER DESIGN

THIRSPEC consists of four units, an optical head, a datalogger, a pack frame, and a tripod. The optical head contains a chopper, reference blackbody, grating, collimation and focusing optics, detector, detector cooler, and electronics. The pack frame contains the battery pack and has attachment features for the optical head, datalogger and tripod. Two, 3-meter long cables provide power from the battery pack to the optical head and serial communication between the head and the datalogger. In use, the head is usually mounted on the tripod, with the long axis approximately horizontal, and an external beam-steering mirror is pivoted about this axis to view any target between nadir and zenith.

The optical head and datalogger are shown schematically in Figure 1. Thermal radiation entering the head through the entrance slit is reflected off the beam-steering mirror, passed through a field stop, reflected off a parabolic mirror which collimates the light and illuminates the blazed reflection grating. The parallel beam is then focused through a Germanium triplet lens that images the slit onto the detector array - a 60 element HgCdTe Common Module detector with integral cryocooler. THIRSPEC compares the exitance of the target, to that of an internal black body source at ambient temperature, by means of a chopper. Synchronous rectification is performed at the 1 kHz chopping frequency to eliminate electrical biases and signals from outside the instrument field of view. The voltage difference for each detector element is amplified, synchronously rectified, and multiplexed onto four analogue output lines together with temperature readings for the reference blackbody, the detector array and the THIRSPEC enclosure. Finally the analog signals are passed to an external data logger for digitization (12 bits), display and storage.

Optics

An entrance slit and an off-axis parabolic mirror produce a parallel beam to illuminate the grating. The clear aperture of the grating defines the field stop, and the spectrum is imaged onto the detector array by a lens. The path of the principal ray at the blaze wavelength is folded, in the form of a letter 'N', in a plane parallel to the base of the spectrometer, and the orientation of the grating rulings is such that the plane of dispersion is almost perpendicular to the base. The entrance slit has dimensions of 0.2 by 3.0 mm and is laser-machined in 0.013mm thick stainless steel. The slit width images, at the array, to the width of a single detector element.

Since it is hoped to commercialize the THIRSPEC, only stock components are used. All reflecting surfaces are vacuum gold coated. A diamond-turned, gold-coated, off-axis parabolic mirror is used as the collimator optic because, with the entrance slit at the focus, it is free of spherical and chromatic aberration. The parabola is a 50mm diameter, 125mm EFL, with the principal ray at an angle of 30degrees to the axis. These dimensions, combined with the 25mm diameter of the aperture at the grating, give the system an external field of view of 0.2radian (11.4 degrees) and allow a compact optical layout.

The line spacing and blaze for the grating, and the focal length of the lens, should be such that the wavelength range of the detector Common Module just fills the 6.06mm length of the array, with the blaze wavelength close to the centre. Because the closest stock values did not produce an exact fit, the dispersion was adjusted by rotating the grating rulings out of the plane of incidence, and adjusting the angle of incidence. Such an 'out-of-plane' arrangement results in a large angle between the incident and diffracted beams at the blaze, and permits a more compact optical layout.

The lens is a 25mmEFL, f/0.8, Germanium triplet, diffraction limited over the $\pm$ 6.7 degree field angle subtended by the array, giving an effective blur of about 12micron or 25% of the detector element dimension.

THIRSPEC operates with modulated radiation and narrow-band AC electronics. The modulator, a rotating, aluminum chopper disc with twelve uniformly spaced circular openings, is positioned just outside the entrance slit. Consequently the spectrometer alternately sees the internal reference blackbody, by reflection on the chopper, and the target, by reflection on the external beam-steering mirror. If the mirror and chopper have identical emissivities and temperatures, the modulated signal depends only on the radiance difference between the target and reference. Because both elements are vacuum coated with gold in the same lot (reflectance >98%), the emissivity differences, and the resultant radiance errors, are small. In practice the mirror and chopper may have temperature differences of several degrees but the temperatures of both elements are monitored, so a correction can be computed. The chopping frequency is 1kHz. An optical pickup senses the holes in the disc and provides a tachometer waveform for the motor drive, and a phase reference for the synchronous rectifiers. The relative sizes of the chopper holes and the input beam (in the plane of the chopper) give a trapezoidal signal waveform, with transition regions (when the edge of a hole is passing through the beam) lasting 14% of a period. The detector signals during transitions are ignored, giving a duty cycle of 0.72.

Internal reference blackbody

The internal reference is an isothermal, ambient-temperature blackbody cavity of the cylindro-inner-cone form described and analyzed by Bedford et al. (1985). Cavities of this shape have both high (>0.99) and uniform effective emissivities along the cone and adjacent cylindrical surface, and allow a short cavity length. Bedford et al. (1985) have demonstrated that changes in surface emissivity from 0.5 to 0.7 have little effect on the emissivity of the cavity (<0.002). The temperature of the cavity is measured but is not actively controlled which has the advantage of reducing weight, size, power, dynamic range, as well as the accuracy with which the system responsivity must be determined.

The radiometric accuracy is dependent on the accuracy of the temperature of the internal reference blackbody. THIRSPEC uses Platinum Resistance Thermometers (PRT's) to provide an overall temperature accuracy of better than $\pm$ 0.1K. These devices are nominally 100ohms and 4000ppm/degree K at 273K and are individually calibrated to $\pm$ 0.0025K. The bridge circuitry is thermally compensated and designed to have an absolute accuracy of $\pm$0.02K @ 273K and $\pm$ 0.05K from 263 to 308K. The bridge output is normalized so that the range 263 to 308K just fills the 12-bit range of the data logger, giving a digitizer resolution of 0.01K.

Detector and cryocooler

The detector is a 60-element version of the Military Common Module HgCdTe array/dewar package. This is a mature technology, providing the multiplex advantages of an array at much lower cost than a custom package. Also, compatible light-weight closed-cycle coolers are available. The spectral band of the array is

7.7± 0.25 to 11.75± 0.25 micron. The temperature of the array is measured via the voltage across a transistor attached to the focal plane.

The detector array employs a Stirling-cycle cooler designed to be used with military FLIR systems. The working fluid is helium. The cooling capacity is 0.35W @ 80K and the unit can draw approximately 30W @ 17VDC. Use of helium eliminates the logistical requirements imposed by compressed gas and provides a weight reduction of approximately 5kg relative to a Joule-Thompson cooler with a five-hour gas supply.

ELECTRONICS AND SIGNAL PROCESSING

Analogue electronics

The output from each of the 60 detector channels is amplified with a high-gain preamplifier followed by a switchable-gain amplifier, a synchronous rectifier, and a low-pass filter. Nominal noise figure for the preamplifiers is 2.5 nV/Hz at 1 kHz. The gain and bandwidth of each channel is set by selection of the gain resistors and with precision trimming potentiometers. All sixty switchable amplifiers are controlled by two common digital lines from the datalogger. While the preamplifier stage is broadband, the synchronous rectifier operates at a nominal frequency of 1 kHz as determined by the speed of the mechanical chopper. The system is relatively insensitive to drift in the chopping frequency. The output of the synchronous rectifier passes through a low pass filter with a bandwidth of 1 Hz. The analogue outputs of the 60 detector channels, along with temperature signals from the detector, the beam steering mirror, and the reference blackbody, are multiplexed onto 4 analogue lines that are accessible to external devices at a chassis-mounted connector. Control of the multiplexer is through four digital lines from the datalogger.

Datalogger

The datalogger (Omnidata Polycorder Model PC-706) provides six digital control lines to the optical head, to set the gain of the switchable amplifiers and to switch the analogue multiplexers, and digitizes, stores, and transmits the signal voltages from each channel of THIRSPEC. The digitizer has 12 bits of resolution with a 100 kHz update rate and 0.15% long-term accuracy. An internal 420 kbyte memory allows up to 900 readings to be stored before transmission via an RS232 serial link to an external computer for further analysis. The datalogger allows a limited amount of manipulation and display of the digital information, at a level that is useful during field data acquisition sessions to verify data and procedures.

SYSTEM PERFORMANCE

Spectral calibration

The spectral range is largely determined by the spectral band of the entrance window of the detector array which is specified by the manufacturer to be 7.7 ± 0.25 to 11.75 ± 0.25 μm. The optical design of THIRSPEC matches the spatial extent of the 60 element array to the spectral range. The relation between detector number and wavelength was determined by looking at a blackbody target through a thin absorbing film of polystyrene. The transmittance spectrum obtained for this measurement is shown in Figure 2. This spectrum displays five well characterized infrared absorption features of polystyrene. As can be seen in Figure 3 the known wavelengths of the five absorptions define a straight line when plotted against the detector number for the observed absorptions. Additional calibration points were obtained using a CO_2 laser tuned (Table 1). Detectors 1 and 60 lie at 7.34 and 12.08 μm respectively, and the spectral sampling interval is 0.08 μm/element. The maximum deviation of a calibration point from the best linear fit is approximately 0.1 μm.

Spectral resolution

The spectral resolution of THIRSPEC is limited primarily by the angular size of the discrete detectors on the array. Each detector element has an area of 58 μm by 41 μm and is separated from neighboring detectors by 43 μm. The common module array holding the 60 detectors is 6.06 mm in length. Measurements for CO_2 laser light reflected from a diffuse gold panel were used to check the total system resolution. The laser was tuned to a spectral line at 10.52 μm whose intrinsic wavelength was less than 0.001 μm The voltage output from THIRSPEC is shown on Figure 4. Resolution taken as full width at half maximum is approximately 0.09 ± 0.01 μμ.

Radiometric calibration

THIRSPEC receives radiation from emission targets within its field of view and from sources whose radiation is reflected from these targets. The reflections can be either diffuse or specular, depending on the surface characteristics of the targets. The transfer function of THIRSPEC relates the voltage signal to radiant power striking the detector when the instrument looks at the external target. The signal voltage for any spectral channel, denoted by λ, can be related to the input power using the following expression:

$$S(\lambda) - S_o(\lambda) = R(\lambda, T_{det}) * G(T_{amb}) * \left[- P_{bb}(\lambda, T_{bb}) + \sum_{j=1}^{N} \{P_{Ej}(\lambda, T_{sampj}) + R_{sampj} \sum_{k=1}^{M} P_{Rkj}(\lambda, T_{envj})\} \right] \quad (1)$$

where $S(\lambda)$ is the measured voltage, $S_o(\lambda)$ is the offset, $R(\lambda, T_{det})$ is the responsivity in V/W of the detector element. The temperature of the entire detector array is T_{det}. The gain of the amplification stages is $G(T_{amb})$ at enclosure temperature T_{amb}. The optical powers, P_{Ej}, P_{Rkj}, and P_{bb}, come from emission sources (within the field of view), reflection sources (outside the field of view), and an internal black body, respectively. R_{sampj} is the reflectivity of the j^{th} region of the emission source while T_{bb}, T_{sampj}, and T_{envk} are the temperatures of the internal blackbody and the external sources. The optical power, $P_{Ej}(\lambda, T_{sampj})$ at detector 1 from emission source j, is assumed to be a generalized blackbody:

$$P_{Ej}(\lambda, T_{sampj}) = \tau_{atm}(\lambda) * \tau_{opt}(\lambda) * \tau_{grat}(\lambda) * \varepsilon_j(\lambda) * A_j * \frac{\Omega_j}{\pi} * \Delta\lambda * M(\lambda, T_{sampj}) \quad (2)$$

where t_{atm}, t_{opt}, and t_{grat} are the transmission of the atmosphere, the optical elements, and the THIRSPEC grating respectively. The emissivity of source region j is $\varepsilon_j(\lambda)$, the effective area of the local homogeneous source region is A_j, the optical bandwidth per wavelength channel is $\Delta\lambda$. The collection solid angle is:

$$\Omega_j = \frac{A_{slit}}{D^2} \cos\theta_j \quad (3)$$

where A_{slit} is the area of the entrance aperture of THIRSPEC, D is the distance from the THIRSPEC aperture to the sample, and q_j is the angle between the aperture normal and the line between the aperture and the sample region A_j. $M(\lambda, T_j)$ is the radiant exitance of the source in units of $W/cm^2/\mu m$. A similar expression can be developed for each reflection source and for the internal blackbody source.

Because the reflection sources are usually not known and mask the desired signal from the emission source, the basic measurement strategy is to use multiple measurements on external samples to subtract out the effects of reflection sources. For purposes of radiometric calibration we used as a sample a well characterized blackbody panel, of known emissivity, measured at two temperatures. Changing the temperature of the emission source, T_{samp}, while keeping other parameters constant, allows subtraction of emission from the internal reference blackbody and reflections from external sources. For two sample temperatures, T_b and T_a, the signal difference is:

$$S_b(\lambda) - S_a(\lambda) = K'(\lambda, T_{det}, T_{amb}) * \varepsilon_{samp}(\lambda) * A_{samp} * [M(\lambda, T_b) - M(\lambda, T_a)] \quad (4)$$

The area A_{samp} of the blackbody panel is the full area of the field of view of the instrument. The radiation equilibrium condition, $R_{samp} = 1 - \varepsilon_{samp}$, has been assumed, and

$$K'(\lambda) = R(\lambda, T_{det}) * G(T_{amb}) * \tau_{atm}(\lambda) * \tau_{opt}(\lambda) * \tau_{grat}(\lambda) * \frac{A_{slit}}{\pi D^2} \cos\theta_j * \Delta\lambda \quad (5)$$

in units of V * μm/W. During measurements, T_{det} and T_{amb} are measured and the observed signals are corrected for temperature variations. For small temperature differences,

$$S_b(\lambda) - S_a(\lambda) = K'(\lambda, T_{det}, T_{amb}) * \varepsilon_{samp}(\lambda) * A_{samp} * \frac{\partial M(\lambda, T_a)}{\partial T} * (T_b - T_a) = K_1 * (T_b - T_a) * \varepsilon_{samp}(\lambda) * A_{samp} \quad (6)$$

The use of a high emissivity target filling the field of view of THIRSPEC minimizes the effect of variations of the reflection sources during the measurements. The K_1 term for each detector was regressed using three sets of small temperature differences $(T_b - T_a)$ near 28 ^oC for the blackbody panel (Figure 5). Drift in the temperature of the internal blackbody was compensated for in the analysis. Wavelength variations in K_1 are largely caused by the detector response and the transmission of the optical elements. The noise equivalent temperature difference (NETD) was determined by 16 repetitions of 10 second measurements of the voltage signal from an external reference blackbody. The "NETD per channel", plotted on Figure 5, is the standard deviation of these 16 measurements, expressed in temperature units through equation (6). An average of NETD of 0.06 ^oK was measured between 7.9 and 11.3 μm with the detector array operating at 119 ^oK. The noise can be reduced by a longer integration time or a cooler detector array.

RETRIEVAL OF TARGET EMISSIVITY

The primary objective of the data analysis is the retrieval of spectral emissivity for unknown geological targets. The measurement strategy has been to use two homogeneous samples of known spectral emissivity to model the emission contribution by the environment and to apply the results for retrieval of emissivity for unknown targets. The difference measurement eliminates the need for detailed calibration of the internal blackbody as long as a correction is made for drift in its temperature. The signal difference for two reference samples of known spectral emissivity that fill the field of view is:

$$\frac{S_b' - S_a'}{K' * A_{samp} * M_{samp}} = (\varepsilon_b - \varepsilon_a) * \left(1 - \left[\sum_{k=1}^{N} \varepsilon_{envk} * \frac{A_k}{A_{samp}} * \frac{M_{envk}}{M_{samp}}\right]\right) \quad (7)$$

where A_k is the effective area of the sample for reflection of a particular source in the environment, and may be less than A_{samp}. The term in square brackets accounts for environmental emission reflecting off the target. The environment emissivity, ε_{envk}, includes any atmospheric effects prior to reflection from the target. S'_a and S'_b are the measured voltage corrected for drift in the temperature of the internal blackbody reference and of the sample temperature.

For cases where the targets do not fill the entire field of view, the more complete formalism of equation (1) must be used. In a typical situation, the rock sample is placed on a large diffuse gold mirror. The dimensions of the mirror are selected to ensure that it completely fills the field of view. For this case, equaton (7) holds, with ε_b and ε_a replaced by "effective emissivities" ε_{effb} and ε_{effa}:

$$\begin{aligned} \varepsilon_{effb} &= \varepsilon_q f_q + \varepsilon_g (1 - f_q) \\ \varepsilon_{effa} &= \varepsilon_l f_l + \varepsilon_g (1 - f_l) \end{aligned} \quad (8)$$

Here, ε_q = known emissivity of quartzite rock sample
ε_l = known emissivity of limestone rock sample
ε_g = known emissivity of diffuse gold mirror
f_q= fraction of the field of view that is filled by the quartzite sample
f_l= fraction of the field of view that is filled by the limestone sample

A quartzite and a limestone sample were used to determine the background characteristics, while the "unknown" was a hornblende gabbro. The measurements were performed both in the laboratory and under field conditions. Figure 6 shows the reflection term derived from the fit of the quartz-limestone signal difference to the known quartz and limestone emissivity spectra using the model parameters listed in Table 2. The known emissivity spectra were derived from directional reflectance spectra acquired at a 10^o incidence angle using an Analect Fourier Transform Infrared (FTIR) spectrometer and a heated nichrome wire source. Spectral resolution within the 7-12 μm spectrum is 4 cm^{-1} for the FTIR spectra.

The reflection term computed from the quartz-limestone signal was then used in equation 7 to derive the emissivity of an unknown target measured under the same environmental conditions. Results are shown on Figure 7. The uncorrected outdoor difference signal, for the unknown and the quartzite, shows a blend of emission and reflection that masks the emissivity profile. Between 7.9 and 11.3 μm, where the responsivity of THIRSPEC is high, the computed spectral emissivity of the unknown sample is comparable to that obtained under well controlled conditions using FTIR spectroscopy. Residual differences are attributed primarily to the spatial variablility of the emissivity over the sample.

SUMMARY

In summary, measurements of spectral emissivity have been obtained from rock samples both in the laboratory and under field conditions, using THIRSPEC, a sensitive field portable thermal infrared spectrometer. The use of reference samples allows the effect of reflected background radiation from the instrument and from the environment to be removed.

ACKNOWLEDGEMENTS

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Table 1: Tunable CO_2 laser wavelengths used for the spectral calibration

Detector	Wavelength (μm)
25	9.24
26	9.33
28.5	9.57
35.5	10.18
37	10.32
41	10.63

Table 2: Parameters used to model the reflection contribution by the environment

Typical values measured	Typical values estimated
$T_{det} = 115\,°K, T_{amb} = 282.2\,°K, T_{bb} = 282.2\,°K$	$T_{env} = 279.5\,°K$
$T_{sampa} = 280.5\,°K, T_{sampb} = 280.5\,°K$	$\varepsilon_{env}(\lambda) = 0.6$

FIGURES

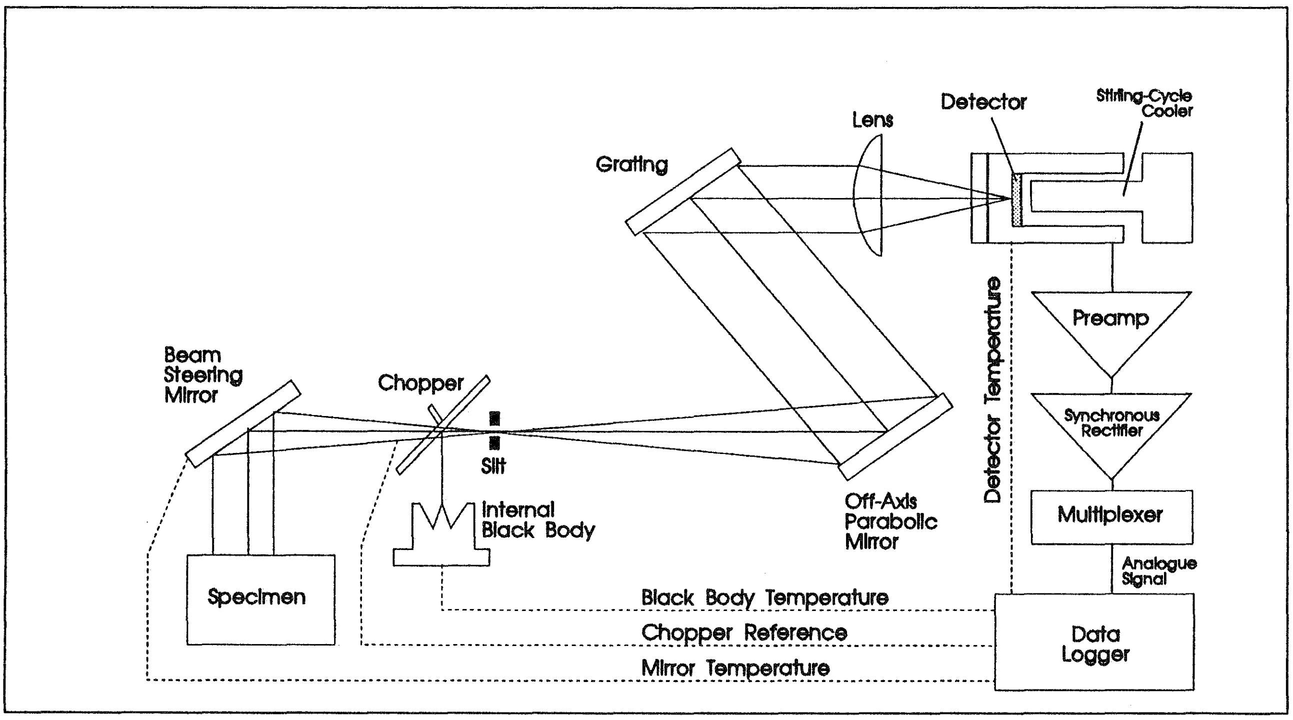

Figure 1: Schematic diagram of THIRSPEC.

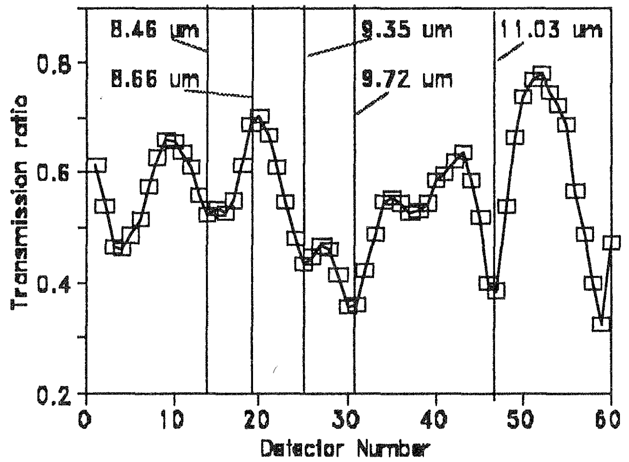

Figure 2: Transmittance spectrum of polystyrene using THIRSPEC measurement of a blackbody viewed through a thin film of polystyrene. Wavelengths of the labeled polystyrene absorptions are from Plyer and Peters (1950).

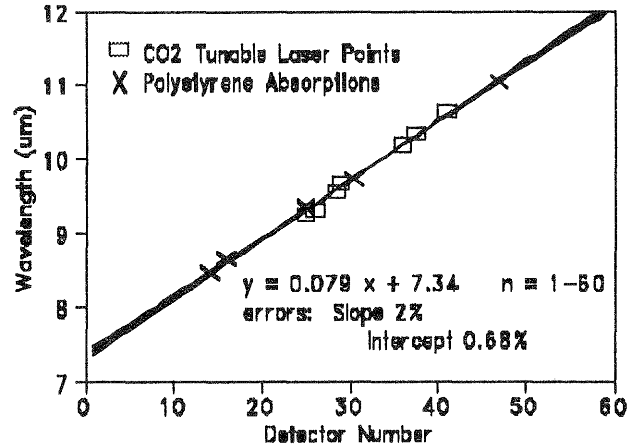

Figure 3: Spectral calibration of THIRSPEC. Experimental results for absorption wavelengths of polystyrene and reflection wavelengths of CO_2 laser lines.

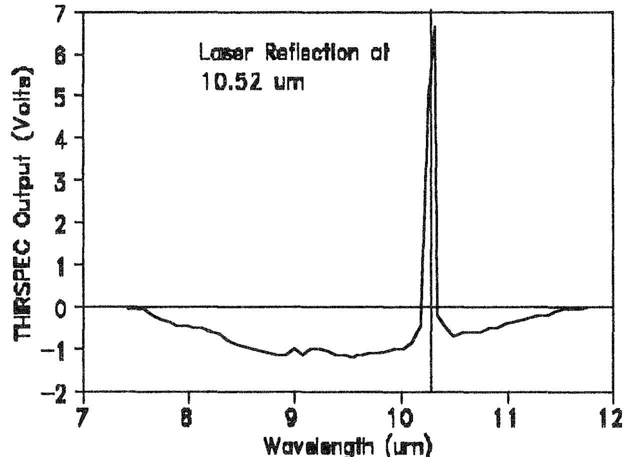

Figure 4: THIRSPEC signal for CO_2 laser light at 10.52 µm.

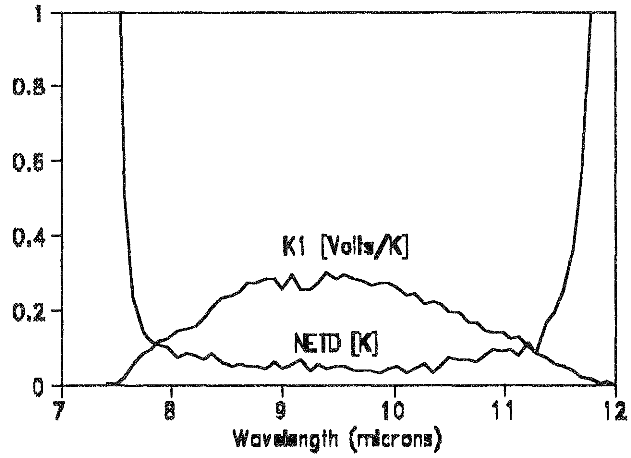

Figure 5: Radiometric calibration of THIRSPEC. K_1 is the instrument transfer function in Volts per degree Kelvin (cf. equation 6). NETD is the noise equivalent temperature difference in degree Kelvin.

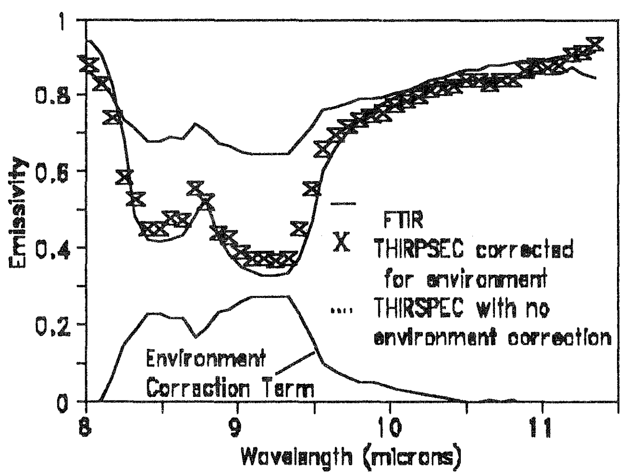

Figure 6: Fitting the THIRSPEC quartz emissivity spectrum to the FTIR reference spectrum, to obtain the environmental unknowns e_{envk} and T_{envk}. The dotted curve represents the quartzite spectrum if environmental reflections are neglected. The solid curve was obtained from the difference of the reflection-corrected and uncorrected curves, illustrating the modulation of the environment by the target sample. The quartzite and limestone signals were obtained from one 10 sec reading of each target. Parameters used in the fit are listed in Table 2.

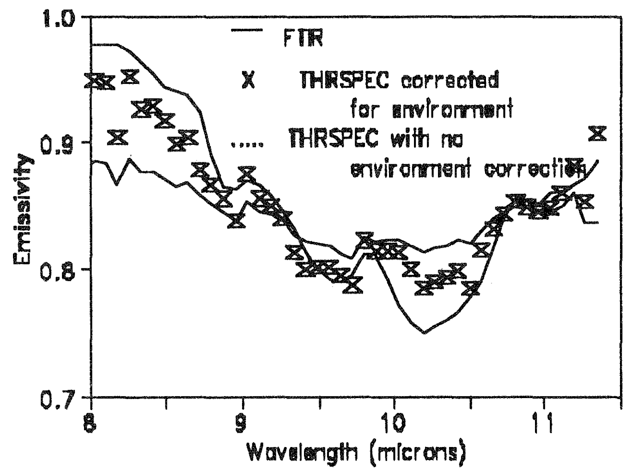

Figure 7: Comparing the hornblende gabbro emissivity spectra, corrected for reflections from the environment, with the FTIR reference emissivity spectra for the hornblende gabbro. e_{envk} and T_{envk} were determined using the quartzite and limestone spectra as described in Figure 6.