A Thermal Emission Spectrometer for Field Use

Gordon Hoover and *Anne B. Kahle*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

ABSTRACT: A field portable spectrometer has been built at the Jet Propulsion Laboratory which is suitable for collecting data relevant to remote sensing applications in the 4.7- to 5.6- and 8- to 12-micrometre atmospheric windows. The instrument employs a single cooled HgCdTe detector and a continuously variable filter wheel analyzer. The spectral range covered is 5- to 14.5- micrometres and the resolution is approximately 1.5 percent of the wavelength.

A description of the hardware is followed by a discussion of the data processing steps leading to emissivity and radiance spectra. A section is devoted to the evaluation of the instrument performance with respect to spectral resolution, radiometric precision, and accuracy. Several examples of spectra acquired in the field are included.

INTRODUCTION

A FIELD-PORTABLE SPECTROMETER for operation in the 5- to 14.5- micrometre region of the infrared spectrum has been built at the Jet Propulsion Laboratory (JPL). This instrument, the Portable Field Emission Spectrometer (PFES), was built for the purpose of measuring the ambient spectral thermal emission of geologic materials *in situ*, avoiding the disturbance of the natural setting which occurs when samples are transported to the laboratory.

Spectra provided by this instrument will aid in the interpretation of data acquired by the airborne Thermal Infrared Multispectral Scanner (TIMS) (Kahle and Goetz, 1983). The instrument will also be used to help define the design requirements for future remote sensing instruments to be operated in the thermal infrared.

Some years before the PFES was built, Goetz of JPL's Geologic Remote Sensing Group developed a portable spectrometer for the 0.4- to 2.5-micrometre region, designated the PFRS, for Portable Field Reflectance Spectrometer (Goetz *et al.*, 1975). The PFES was designed to be compatible with this already-existing system, making use of the same data recorder and power supplies.

GENERAL DESCRIPTION

The complete PFES system consists of two main parts, the sensor head and the data recorder. Each of these is mounted on a packframe for easy carrying. Accessories include a gas bottle, signal monitoring box, reference blackbody, and connecting cables. Figure 1 shows the system in use at a field site.

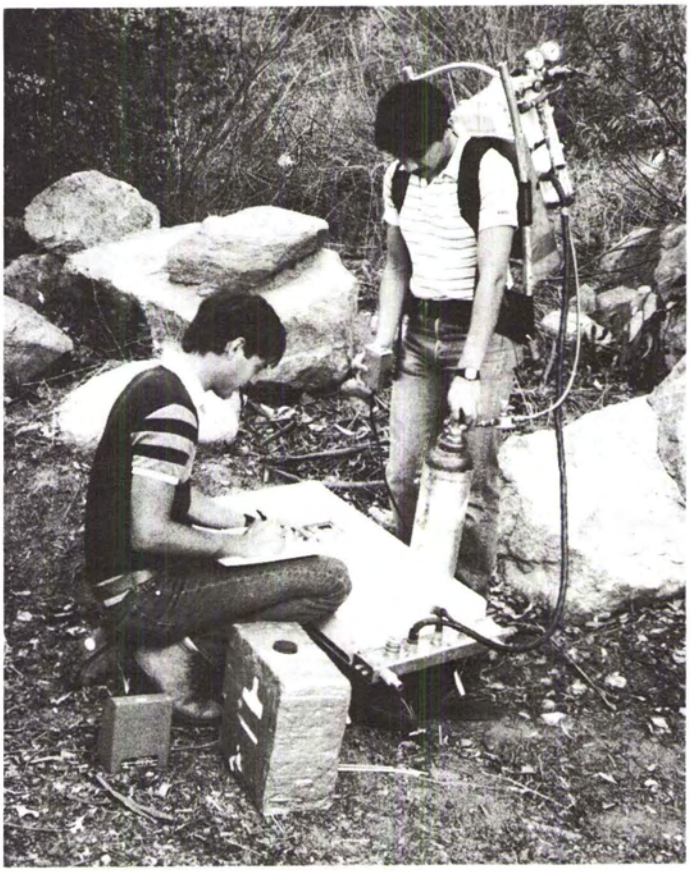

FIG. 1. Portable field emission spectrometer (PFES) in use.

The sensor head (Figure 2) contains the optics, the detector, and preamplifiers. During operation, the sensor head is connected by a hose to a tank that supplies high pressure argon gas for cooling the detector. The head and its pack frame together weigh 11.4 kg.

The data recorder consists of a number of electronic subassemblies attached to an aluminum sheet, which is bolted to a pack frame. A fiberglass cover provides structural rigidity and protection. Contained in the data recorder are the digital cassette tape recorder, signal processing circuitry, scan sequencing logic circuits, and the silver zinc battery with power converters for supplying the various voltages needed. Operator controls are located on the data recorder box and on a small monitor head connected to the data recorder by a cable. The data recorder weighs approximately 18.2 kg.

The head and the data recorder are connected together by a multi-conductor electric cable over which the spectral data are transmitted as analog voltages. The cable also carries sample identification codes in parallel digital form, chopper phase signals, and power of various voltages.

INSTRUMENT DESIGN

A schematic diagram of the sensor head appears in Figure 3. All lenses are of optical grade germanium and coated on both sides with a multilayer antireflection coating with a minimum transmission per element of 92 percent for the 5- to 14.5-micrometre range. The front surface of element 1 was coated with a monolayer of ZnO which was considered more abrasion resistant than the multilayer coating.

The detector is housed in a small dewar behind a window of uncoated IRTRAN 2. The 1- by 3.5-millimetre sensitive area of the detector is imaged by lenses 4 and 5 onto the filter wheel. Lenses 2 and 3 reimage the detector onto the plane of the chopper mirror. The focal plane of lens 1 coincides with the plane of lens 2 which forms the target defining aperture. The field of view is circular and 15 degrees in extent. The focus is set for a distance of 1 metre although the working distance is not critical when dealing with homogeneous targets.

The analyzing element of the spectrometer is a filter wheel containing three filter segments of the continuously variable multilayer interference type. Each filter segment is sandwiched

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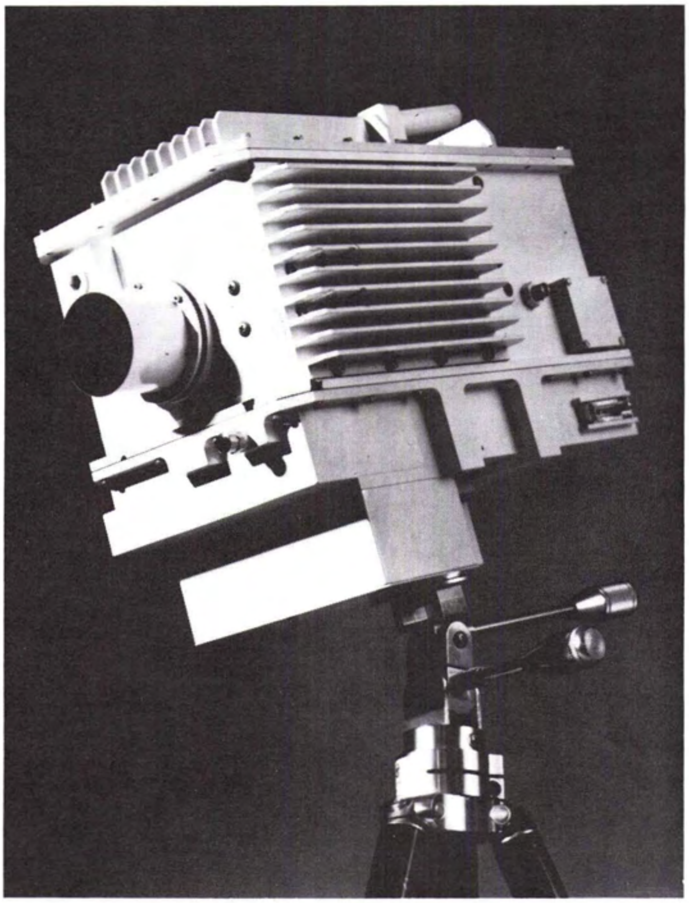

FIG. 2. Sensor head.

with a blocking filter that limits transmission outside its range to less than 0.5 percent.

The weakness of emission from natural surfaces in the 2.5- to 4.5-micrometre region and the confusion arising from the competition of reflected solar radiation have forced us to restrict our attention, to date, to the second and third segments only, covering the region from 4.4 to 14.5 micrometres.

During the scanning of a spectrum, the filter wheel is driven at a constant speed by a small AC motor. An absolute digital shaft encoder is mounted on the filter wheel shaft and transmits wavelength information to the data recorder. The output of the shaft encoder also triggers sampling and recording and controls the sequence of operations during a scan.

The use of a filter wheel lends the system a simplicity and ruggedness that would be more difficult to achieve with an analyzer based on diffraction gratings. A continuously variable filter has a somewhat limited spectral resolution, but it is adequate for most geological applications and is the logical choice here. Moreover, with such a filter it is easier to achieve the high throughput needed for measuring the relatively weak emission from ambient temperature targets.

A rotating chopper mirror, set at an angle of 45 degrees to the optical axis, alternatively passes radiation from the target and reflects radiation from an internal reference source. An LED-photodiode edge detector mounted at the rim of the chopper provides a phase signal which is used for chopper speed control and for synchronous demodulation of the spectral amplitude signal in the analog data processor.

The internal reference source consists of a disk of aluminum with a series of concentric, V-shaped grooves machined to its face and painted black. It is mounted on a massive heat sink, but no further provision is made for regulating its temperature. Reliance is placed on its thermal inertia to hold it at a steady temperature during a measurement. A thermistor is embedded in the disk to provide a temperature monitoring capability.

The detector is a mercury cadmium telluride photoconductor. HgCdTe was chosen because of its extended range of spectral response and its superior sensitivity. It requires cooling, however, and its response is critically dependent on its temperature. A small temperature sensor is mounted next to the detector inside the dewar to monitor the detector temperature. Cooling is by a Joule-Thompson cryostat using high pressure argon gas. The gas bottles we use hold 22 cubic feet of argon and weigh about 7 kg. One tank of gas is sufficient for a cool-down and about 45 minutes of operation.

The data recorder receives the amplified analog signal from the sensor head. It converts the signal to digital form, assembles a data word for each sample point, and records the data words into a tape cassette of the familiar Philips type. The data recorder box also contains the operator controls and the power supplies.

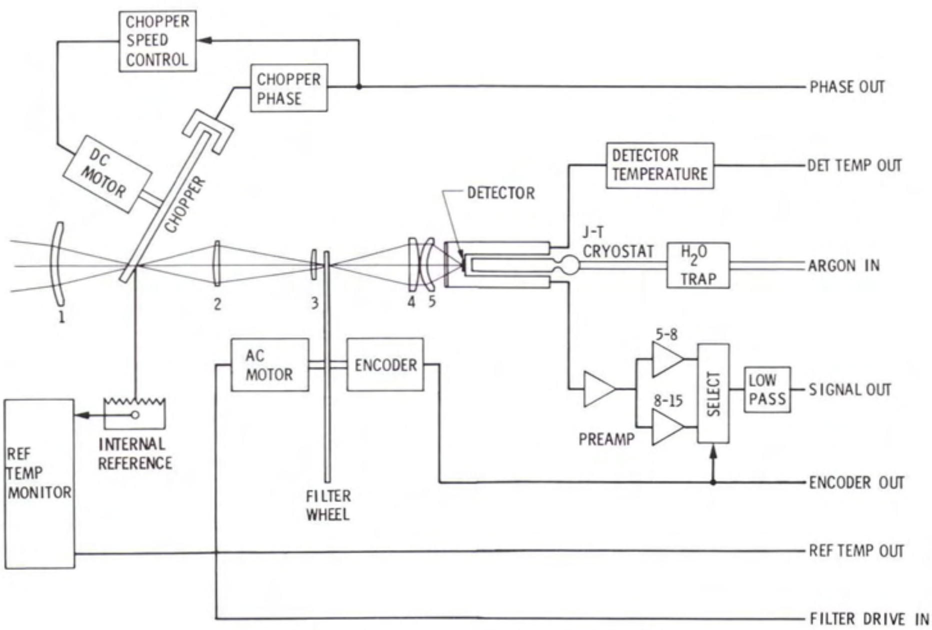

FIG. 3. Functional diagram of the sensor head.

Considering the design in retrospect, after several seasons of field testing, we have pinpointed several areas for improvement. The most important of these is to substitute a conventional liquid nitrogen cryogenic cooling system for the Joule-Thompson. The logistic difficulties associated with providing the tanks of high pressure argon outweigh the threat of spilling liquid nitrogen. In any subsequent instrument, we will incorporate some method of viewing the spectra in the field as a check on data quality. Also a greater effort should have been made to reduce the weight.

For further details concerning the hardware design, including specifications of the detector, preamplifier, optics, filter wheel, etc., interested readers should request from the authors a copy of Hoover and Kahle (1986).

DATA ACQUISITION AND PROCESSING

The instrument requires a two- or three-person team for field operation. One member wears the sensor pack frame on his back and stands stationary, pointing the sensor at the target. A second member of the team selects the proper amplifier gain, and watches the signal level monitor and the flashing light that indicates proper recording. A third member may be employed in collecting samples and keeping a written log of site description, instrument settings, time of day, and other particulars.

All spectral measurements are made relative to the spectrum of a reference blackbody. This blackbody is a sheet metal horn made of aluminum and painted black inside. It is foam insulated to insure temperature stability. Its temperature is measured using an attached thermistor. For recording a reference spectrum, the sensor is made to look down the throat of the reference horn at close range.

Usually about four spectra of each target are measured to provide a check of consistency and to reduce noise by averaging. The same number of reference spectra are made using the reference blackbody. The temperature of the reference must be measured and logged each time. Each spectrum takes about 30 seconds to scan; a complete set of four target spectra and four reference spectra can be completed in about 5 minutes.

Treatment of Data

The following discussion refers to a simplified model of the spectrometer, shown in Figure 4. This model is restricted to those aspects of the spectrometer that have a bearing on the data analysis.

The detector produces an AC signal of amplitude proportional to the difference between the radiance from the target and the radiance from the internal reference, which are alternately selected by the chopper. The AC signal which results is rectified and converted to digital form for recording on tape. The digital output, N, is related to the input by the following equation:

$$N = K(L_t T_\ell - L_{ref}\rho_m + L_\ell - L_m) \qquad (1)$$

where

- N = digital output
- L = radiance,
- ρ = reflectivity,
- T = transmission, and
- K = responsivity of the detector

and the subscripts used are

- t = pertaining to target,
- m = pertaining to mirror,
- ref = pertaining to reference source,
- ℓ = pertaining to lens, and
- bb = pertaining to blackbody.

The transmission of the lens and the reflectivity of the mirror are assumed to be constant over the temperature range encountered in practice.

Applying this relationship to measurements of the target and an external reference blackbody, we get

$$N_t = K(L_t T_\ell - L_{ref}\rho_m + L_\ell - L_m) \qquad (2)$$

$$N_{bb} = K(L_{bb} T_\ell - L_{ref}\rho_m + L_\ell - L_m) \qquad (3)$$

Provided the two measurements are made close together in time, the thermal inertia of the lens, chopper, and internal reference will allow us to assume that their contributions are essentially constant. Taking the difference between Equations 2 and 3, we get

$$N_t - N_{bb} = KT_\ell\,(L_t - L_{bb}) \qquad (4)$$

from which we can get L_t, the radiance of the target; i.e.,

$$L_t = L_{bb} + (N_t - N_{bb})/KT_\ell. \qquad (5)$$

In this equation L_{bb} is calculated from the Planck formula and the KT_ℓ divisor is drawn from a table which has been generated from measurements made on blackbodies of different temperatures. For example, applying Equation 5 to blackbodies BB1 and BB2 and solving for KT_ℓ, we get

$$KT_\ell = (N_{bb1} - N_{bb2})/(L_{bb1} - L_{bb2}), \qquad (6)$$

where L_{bb1} and L_{bb2} are calculated and N_{bb1} and N_{bb2} are the digital responses.

When the digital responses at a given wavelength are plotted versus the temperatures of the blackbody for various temperatures, the points lie very close to a straight line. The slope of the line best fitting the points is accepted as the responsivity of the instrument for the wavelength in question.

Deriving the responsivities, which correspond to the KT_ℓ divisor in Equation 5, constitutes the response calibration of the instrument. Blackbody temperatures are used ranging from 0 to 55 degrees Celsius.

For the identification and comparison of materials, emissivity is the property sought, because it is specific to the material and independent of temperature. Emissivity can be calculated by dividing the radiance of the material by the radiance of a blackbody at the same temperature. There is a further condition that the surface must be in radiative equilibrium with its surroundings.

In practice it is very difficult to measure the temperature of the radiating surface, and the condition of equilibrium is always violated to some extent. Therefore, we have adopted the expedient, when calculating the emissivity, of using as the target temperature the smallest temperature which produces a calculated

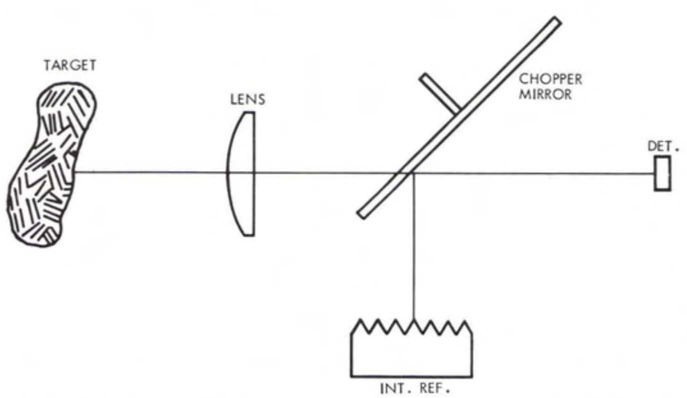

FIG. 4. PFES conceptual model containing only those elements relevant to the data processing discussion.

blackbody curve that is everywhere greater than or equal to the curve of the target radiance. An example of such a fit can be seen in Figure 5. There is some theoretical justification for this procedure, particularly as applied to the spectra of geologic materials (Conel, 1969), but we are offering it merely as a practical compromise.

SYSTEM PERFORMANCE

SPECTRAL RESOLUTION

The spectral resolution of the instrument is largely determined by the filters in the analyzer. According to the manufacturer, the resolution of segment 2, which covers the region from 4.5 to 8.0 micrometres, is 1.5 percent and that of segment 3, covering 7.9 to 14.5 micrometres, is 1.8 percent. The resolution curve displayed in Figure 6 is based on the manufacturer supplied information with allowance made for the effective slit width.

In order to check the total system resolution, scans were made of CO_2 laser light scattered from a diffusing surface of gold coated 600 grit sandpaper. The spectral line selected was that at 10.588 micrometres. The line profile produced is shown in Figure 7. The width of the response profile at half height is 0.2 micrometres, which is approximately 2 percent of the wavelength.

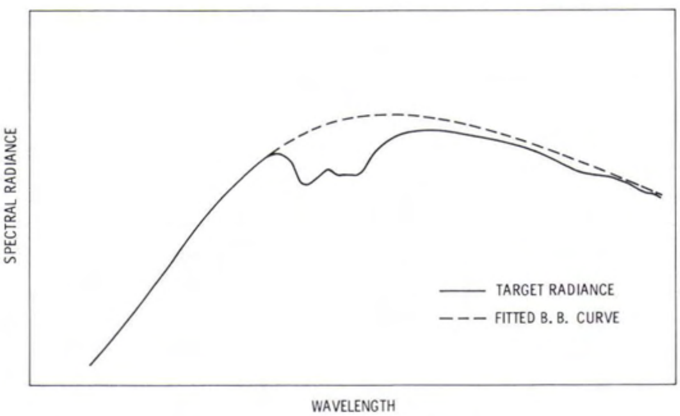

FIG. 5. Fitting a blackbody curve to target spectrum for the purpose of determining the target temperature.

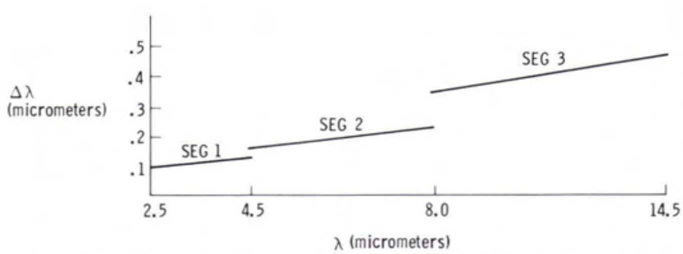

FIG. 6. Spectral resolution (calculated from optical specifications).

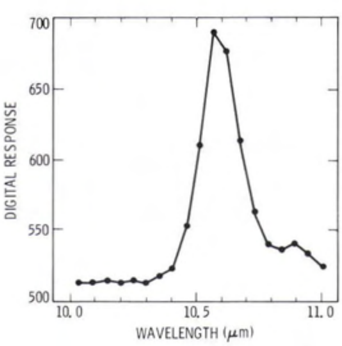

FIG. 7. Response profile to CO_2 laser line at 10.588 micrometres.

An indication of the performance with a complicated spectrum containing many narrow features can be obtained by examining Figure 8 which consists of two separate curves, each of which was produced by looking at a blackbody target through a thin absorbing layer of polystyrene. The upper curve is from the PFES while the lower one was made on a laboratory fourier transform spectrometer (Analect model 6200). The resolution of the Analect is approximately four wavenumbers, which equates to 0.25 percent at 10 micrometres.

RADIANCE RESOLUTION

To determine the radiance resolution of the total system, a number of spectra were made using a laboratory blackbody maintained at a constant temperature approximating that of the spectrometer, 24 degrees Celsius. Using the spectra by pairs, with one spectrum as the target and the other as the reference, one can calculate radiances for the black body. The standard deviation of the set of spectra then gives a fair measure of the minimum detectable radiance for one spectrum. Twenty-three consecutive pairs were considered. Multiplying the standard deviation of the radiance measurements by Δtemp/Δradiance for a blackbody at 24 degrees Celsius gives the noise equivalent ΔT, NEΔT, and ratioing the standard deviation of the radiance to the calculated radiance for the blackbody produces the signal-to-noise ratio. Plots of the standard deviation of the radiance, the NEΔT, and the signal-to-noise ratio are contained in Figure 9.

ABSOLUTE SPECTRAL CALIBRATION

For the purpose of absolute spectral calibration, reference was made to the accepted values for the absorption peaks in the polystyrene spectrum already referred to. The maximum error anywhere observable was one half of a sample. This corresponds to one sixth of a spectral resolution element. To date, we have no reason to suspect the stability of the wavelength calibration, either from deterioration of the filters or from slippage between the filter wheel and the angle encoder.

ABSOLUTE RADIANCE CALIBRATION

Absolute errors in radiance come primarily from two sources, changing responsivity of the detection system and errors in measuring the temperature of the reference blackbody.

The temperature of the reference blackbody is measured using a thermistor and a commerical meter, the YSI Model 42SC. Temperature readings from the thermistor coincided with those from a mercury thermometer to within 0.2 degree Celsius when

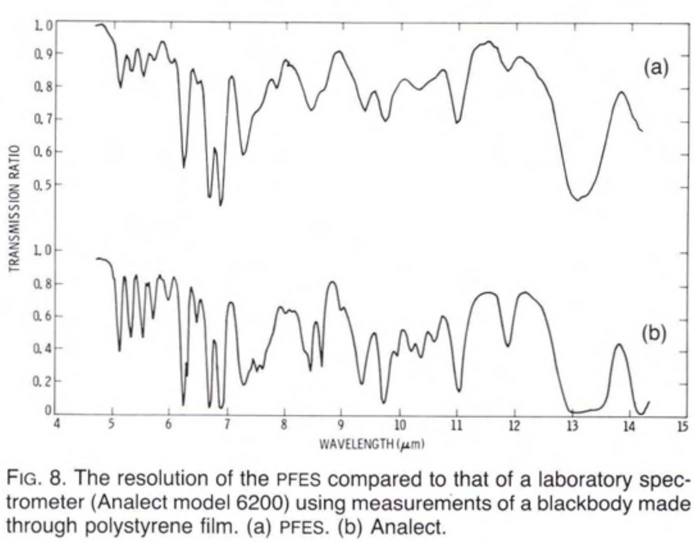

FIG. 8. The resolution of the PFES compared to that of a laboratory spectrometer (Analect model 6200) using measurements of a blackbody made through polystyrene film. (a) PFES. (b) Analect.

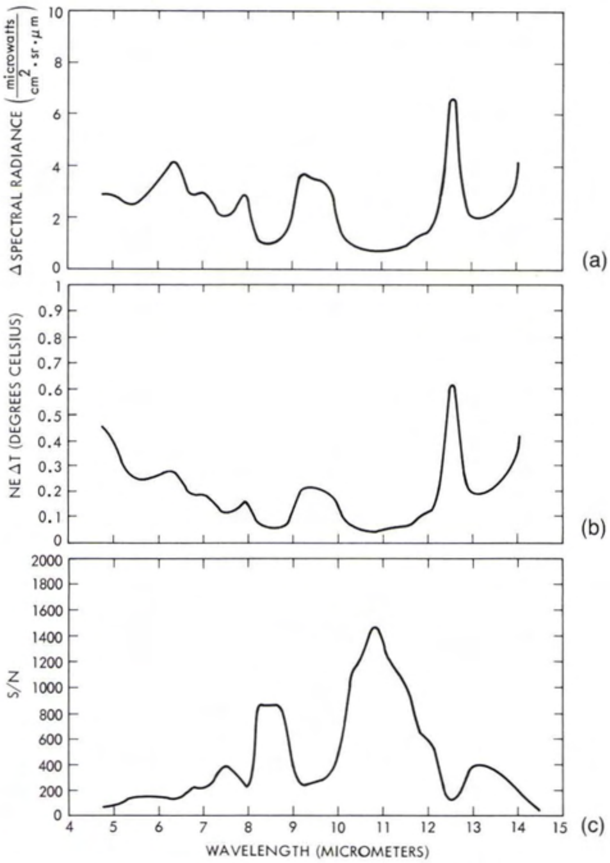

FIG. 9. Radiometric precision of the PFES displayed in three different ways, based on measurements of a blackbody at 24 degrees Celsius. (a) Standard deviation of spectral radiance. (b) Noise equivalent temperature difference (NEΔT). (c) Signal to noise ratio (Δradiance/total radiance).

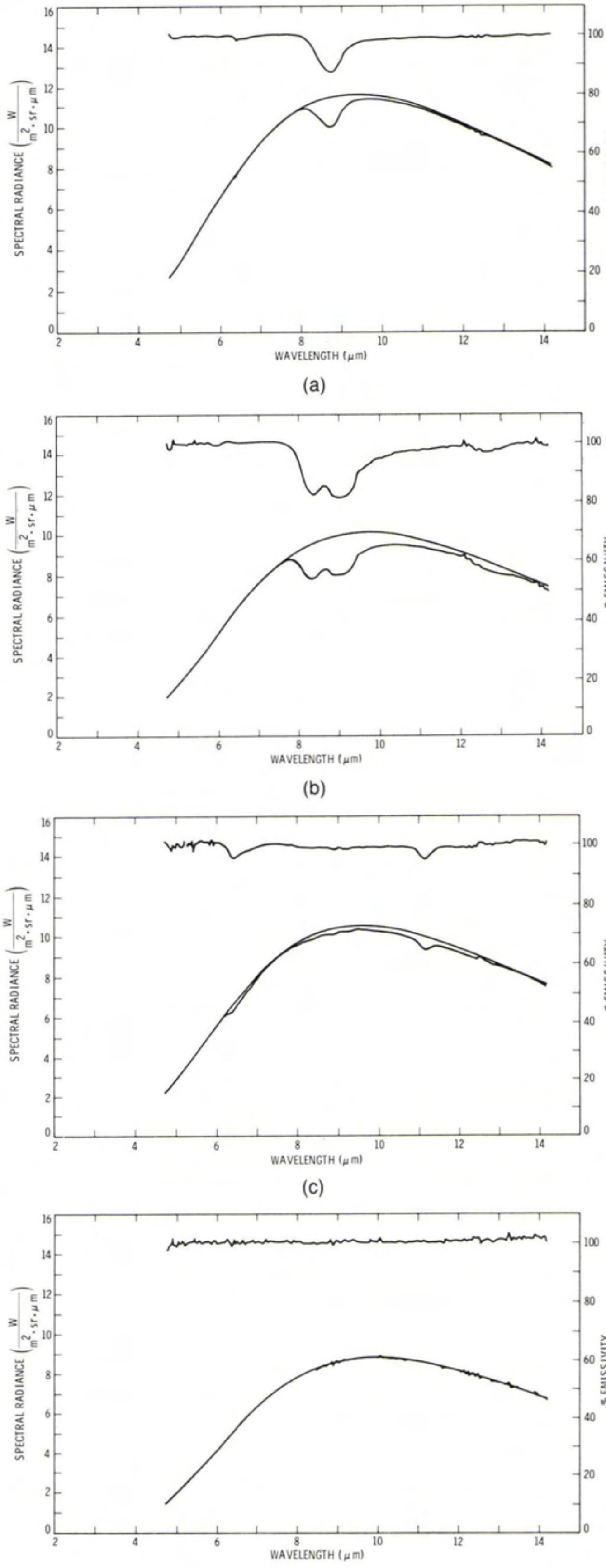

FIG. 10. (a-d) Field data obtained using the PFES. Each figure contains a plot of radiance and the blackbody curve fitted to the radiance. The upper curve shows the emissivity ratio. (a) Gypsum Bearing Soil. (b) Quartzite Outcrop. (c) Dolomite Boulder. (d) Desert Holly Bush.

both were immersed in a stirred water bath at various temperatures ranging from 0 to 55 degrees Celsius. Measurements made simultaneously at different points on the reference horn indicated that an isothermal condition can be maintained to within 0.5 degree Celsius if care is taken not to expose the horn to direct sunshine or the warmth of the operator's hands. A smooth variation of 0.5 degree Celsius from point to point within the horn could give rise to an error in measured radiance as great as 0.8 percent at 4.5 micrometres or 0.3 percent at 14 micrometres.

Variation in the responsivity of the detection system can be caused by aging of the optical and electronic components. So far, the system appears reasonably stable over a time span of a few weeks. Periodic recalibration using the method outlined in the discussion of data handling earlier in this paper, however, has been proven necessary. We should point out that any errors arising from changes in responsivity are going to be proportional to the difference between the radiance of the target and the external reference. The fact that target and reference both follow roughly the temperature of the environment mitigates the problem.

EXAMPLES OF SPECTRA

Figures 10 (a-d) are examples of data acquired in the field. Each figure contains a plot of radiance, a blackbody curve fitted to the radiance, and the emissivity ratio. Each of these spectra are of naturally occurring materials identified *in situ* by inspection. They should not be considered as spectra of pure samples.

These spectra were chosen as typical of the hundreds we have measured. The gypsum-bearing soil, quartzite, and dolomite all show the spectral features we would expect for these materials based on published laboratory measurements (Lyon, 1964; Hunt and Salisbury, 1976; Hunt, 1980) and our own laboratory reflectance measurements using the Analect 6200. The spectrum of the desert holly plant is typical of all the spectra of desert plants that we have measured, resembling a black (or possible gray) body.

SUMMARY

The PFES (Portable Field Emission Spectrometer) is an instrument capable of characterizing the spectral nature of the Earth's surface in the thermal infrared. It can also be used to measure the temperatures of emitting surfaces provided the emissivity is known. The system is portable and has, on a number of occasions, been carried several miles from the nearest road over rough terrain to collect data at remote sites. We think this instrument fills a very important niche among the tools of geologic remote sensing.

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