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Initial data from the Mars Global Surveyor thermal emission spectrometer experiment: Observations of the Earth

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Abstract. The thermal emission spectrometer (TES) on the Mars Global Surveyor spacecraft acquired observations of the Earth from a distance of 4.7 million km for instrument performance characterization on November 24, 1996. The data were calibrated using an internal reference surface and deep space in a manner identical to that which will be used in Mars orbit, and scaled to account for the fact the Earth filled only 9.3% of the field of view. These first, calibrated, in-flight spectra from the TES confirm the expected instrument performance and radiometric accuracy and precision. The data provide the first known whole-disk thermal infrared spectral observations of the Earth. These spectra represent how an Earth-like planet would appear during a search for "extrasolar" planets. Spectral features in the Earth's atmosphere are readily apparent; CO_2 (centered at 668 cm^{-1}), ozone (1000–1075 cm^{-1}), and water vapor (200–550 and 1260–1650 cm^{-1}) absorptions are evident. Radiation at the center of the CO_2 band arises mainly from the lower stratosphere; near 650 and 700 cm^{-1} from near the tropopause; and further into the band wings from the troposphere and surface. Thus, in the disk-averaged sense, the spectrum indicates a warm stratosphere above a tropopause somewhat colder than 215 K, in good agreement with results from similar instruments previously flown in low Earth orbit. The atmospheric window between approximately 800 and 1200 cm^{-1} is relatively featureless, as expected, given the observing geometry centered over the Pacific Ocean and the partial obscuration by clouds. The derived window brightness temperature, assuming an emissivity of unity, is 270 K, a reasonable average temperature of the ocean surface, the polar regions, and the cloud tops, especially given the uncertainties in the exact scaling to account for the fact that the Earth did not fill the field of view.

Introduction

The thermal emission spectrometer (TES) instrument was launched toward Mars aboard the Mars Global Surveyor (MGS) spacecraft on November 7, 1996. This mission is to address a wide range of objectives, including the determination of surface mineralogy, volatile abundance and history, and atmospheric dynamics [*Albee et al.*, 1992]. The specific objectives of the TES experiment are (1) to determine and map the composition of surface minerals, rocks, and ices; (2) to study the composition, particle size, and spatial and temporal distribution of atmospheric dust; (3) to locate water-ice and CO_2 condensate clouds and determine their temperature, height, and condensate abundance; (4) to study the growth, retreat, and total energy balance of the polar cap deposits; and (5) to measure the thermophysical properties of the Martian surface materials [*Christensen et al.*, 1992]. These objectives will be addressed using spectral observations between 6 and 50 μm (~1650–200 cm^{-1}) with 5 and 10 cm^{-1} spectral resolution and high radiometric accuracy and precision. In addition, the instrument has bore sighted bolometric thermal radiance (4.5–100 μm) and solar reflectance (0.3–2.7 μm) channels. Each instrument subsection has six instantaneous fields of view (IFOV) of ~8.3 mrad, which will provide a spatial resolution of 3 km from the MGS mapping orbit altitude of 350 km.

In this report we present a unique set of observations obtained by the TES instrument during its initial power on and check out. These observations used the Earth as an approximate point source to verify instrument performance, alignment, and out-of-field response, as well as to acquire whole-disk spectra of the Earth from 6 to 50 μm.

Observation Sequence and Data Collection

The TES instrument was turned on 16 days after launch on November 23, 1996, and pointed toward Earth on November 24 between 1702 and 1755 UT. At this time the spacecraft was 4,776,000 km from the Earth, which had an angular diameter of 0.153° (2.67 milliradians (mrad)). The TES Earth data were collected between 1714 and 1742 UT centered over a sub-Earth point at approximately 152°W, 18°N. The view of the Earth from the spacecraft is shown in Figure 1 near the midpoint of the data collection period (1730 UT). Figure 2 shows a GOES 9 infrared (11.5–12.5 μm) image of the Earth taken from a similar vantage point (135°W, ~0°N) at 1800 UT (0900 local time at the GOES 9 location).

The Earth was observed by slowly rolling the spacecraft to sweep its z axis, which normally will point at nadir from the Mars mapping orbit, across the Earth. The TES instrument contains an internal pointing mirror that was stepped perpen-

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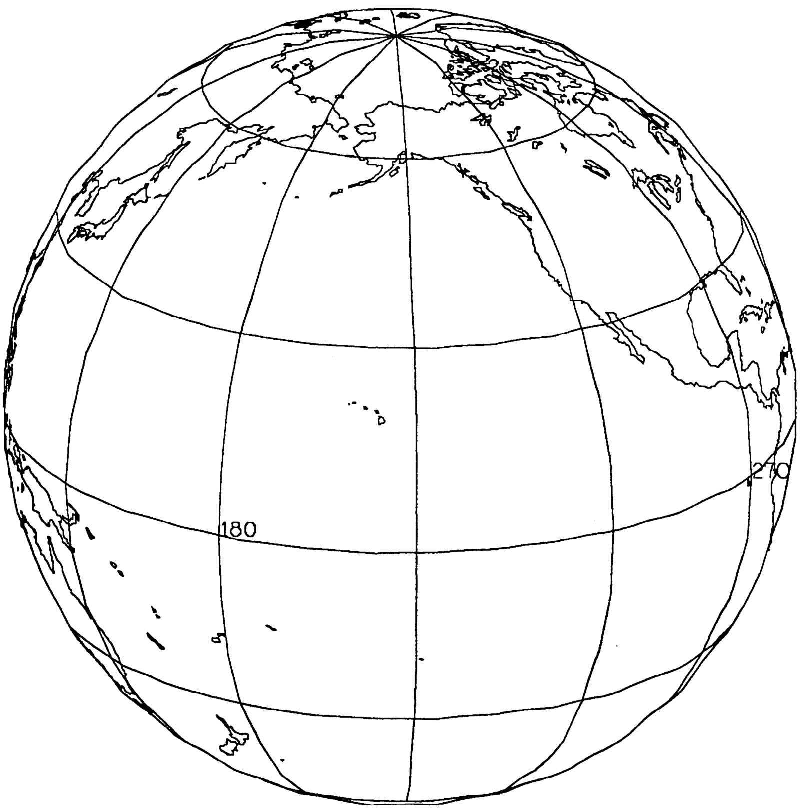

Figure 1. View of the Earth at 1730 UT on November 24, 1996, from the Mars Global Surveyor at the midpoint of the TES Earth observations.

dicular to the spacecraft motion from a planned position $+1.128°$ (19.68 mrad) "above" the Earth in the $+x$ direction to 1.128° "below" in increments of 0.094° (1.64 mrad) for a total of 25 positions. Two 10 cm^{-1} resolution spectra were collected at each position for a total of 100 spectra per scan. Thirty-two scans were obtained, as illustrated in Figure 3. Data rate limitations prevented full spectral resolution data from being obtained continuously, so five positions (10 spectra) at the beginning and end of each scan had to be obtained in a spectral integrated mode (see Figure 3). Unfortunately, a minor offset in the spacecraft pointing biased the start of each scan, so that full spectral resolution data of the Earth were only obtained for detectors 4, 5, and 6 (Figure 3). The Earth passed through the central response area of each detector on five scans, and in each scan 7–10 individual spectra were obtained. The calibrated radiance spectra in each scan were averaged together to produce five final spectra from each of three detectors (15 total).

Calibration

The TES instrument is designed to obtain absolute calibrated radiance using periodic views of an internal blackbody reference and of space. Because the TES operates in the thermal infrared, it measures the difference in radiance between the scene and the instrument with the resulting calibration equation given by

$$V_{\text{measured}} = (R_{\text{scene}} - R_{\text{instrument}})f \tag{1}$$

where V_{measured} is the voltage measured by the detector, R_{scene} is the desired radiance emitted from the scene, $R_{\text{instrument}}$ is the instrument radiance, and f is the instrument response function [*Christensen and Harrison*, 1993]. Observations of the reference surface and of space are used to determine $R_{\text{instrument}}$ and f, allowing R_{scene} to be determined. The reference surface has an emissivity of >0.99 based on prelaunch calibration measurements, and its temperature is determined using three platinum thermistors that are calibrated to ±0.1°C. This knowledge of the reference surface allows absolute calibration of the scene radiance to better than 1.0×10^{-7} W cm^{-2} sr^{-1}/cm^{-1} based on prelaunch calibration measurements.

Ten consecutive observations of the reference surface were collected at the beginning of the observation sequence, and 10 more were collected at the end 53 min later. Space observations were collected in conjunction with these data, allowing the instrument response function and instrument radiance to be derived using the two-temperature method described above.

During the 28 min Earth observation, the detector temperature, measured using a thermistor mounted on the detector housing, decreased uniformly with time from 22.1 to 20.8°C. This cooling occurred because the spacecraft had been reoriented from a 100 min rotation during which the TES was alternatively in full sunlight and shadow, to a condition where the TES was in shadow for the entire duration of the Earth observation. The instrument spectral response is a weak function of instrument temperature, and was found to decrease by ~7% during the observation period. This variation was corrected for by linearly interpolating the instrument response function to correspond to the acquisition time of each spectrum.

A precise value of the instrument temperature was required in order to determine the instrument radiance term. This calibration was made using (1) with observations of deep space before and after each of the Earth scans, together with the

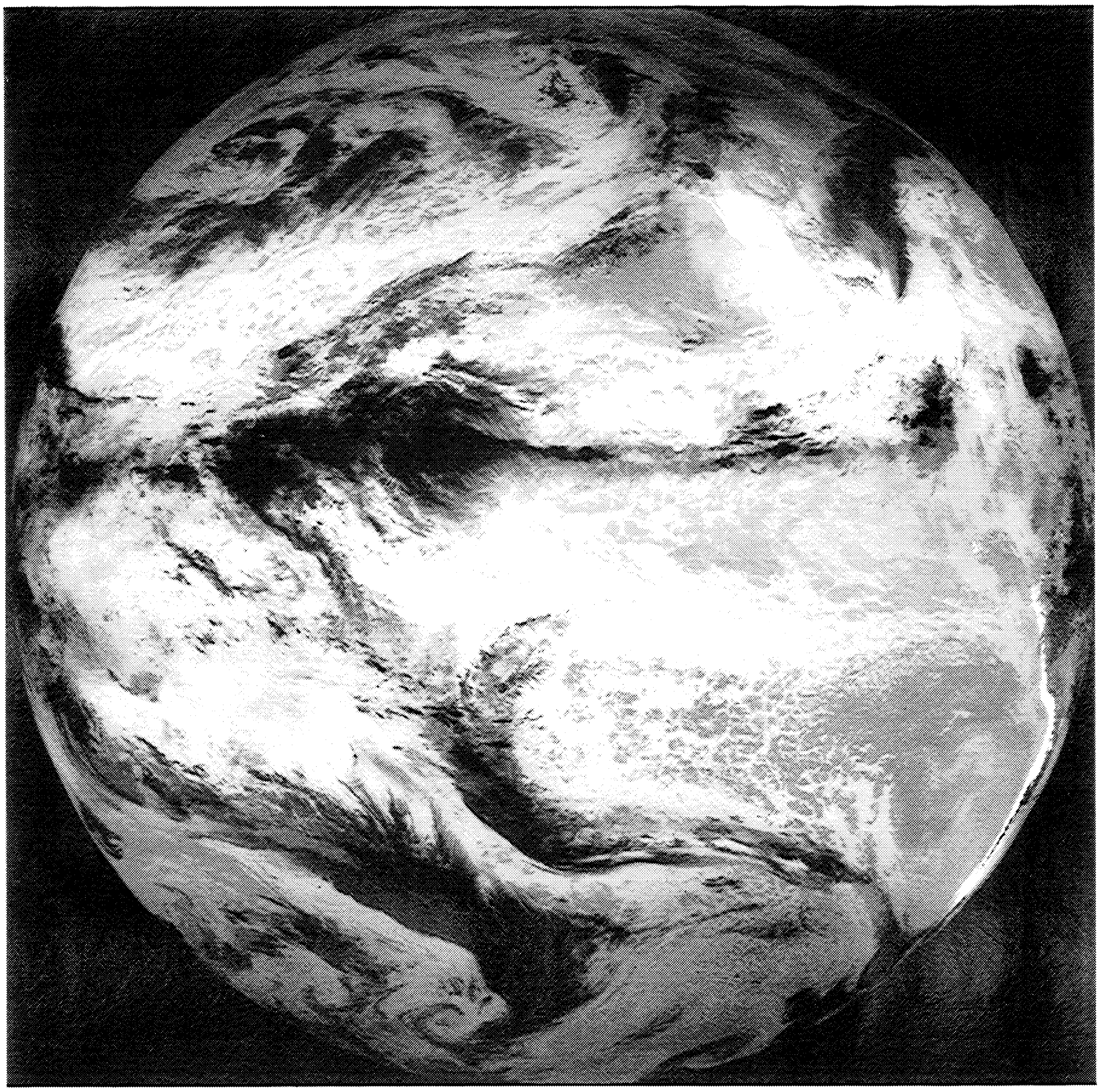

Figure 2. The Earth as seen from GOES 9. This infrared (11.5–12.5 μm) image was acquired at 1800 UT on November 24, 1996, from the GOES 9 spacecraft at a sub-Earth longitude of 135°W.

interpolated instrument response and an assumed space radiance of zero. The derived instrument temperature varied from 24.6°C at the start to 23.2°C at the end of the Earth observations. These derived temperatures are higher than those measured by the detector thermistor, due to the fact that the thermistor is on the outside of the detector package. However, the change in temperature was remarkably consistent between the measured and derived values. This consistency suggests that the TES data could be calibrated using only the measured instrument temperature and views of space, without the need of the internal blackbody, i.e., by a "single temperature" calibration method. This approach has been successfully used for a similar spectrometer on Voyager [*Hanel et al.*, 1980].

Figure 4 shows the noise equivalent spectral radiance (NESR) for each of the six TES detectors determined using 10 consecutive observations of space. The standard deviation of the measured voltage was computed and converted to spectral radiance using the calibration procedure outlined above. The typical noise value of 1.5×10^{-8} W cm^{-2} sr^{-1}/cm^{-1} is consistent with measurements obtained prior to launch. These levels are consistent with an SNR of 400 at 1000 cm^{-1} for typical Martian daytime temperatures of 270 K.

The primary uncertainty in determining the overall calibrated radiance of the Earth comes in estimating the total fraction of the detector instantaneous field of view that the Earth occupied. The diameter of the Earth at the time of these observations was 2.67 mrad. The spatial response for each detector was measured prior to launch using a 1×40 mrad slit passed across the detectors in two orthogonal directions. Figure 5 shows representative responses for detectors 4, 5, and 6 measured in the direction perpendicular to the TES pointing mirror motion. The effective IFOV was determined using the prelaunch data in two ways: (1) using the half-power points and (2) integrating the area under the response functions and determining the equivalent field size for an ideal square-wave response. Averaging the field size in the two orthogonal directions gives IFOV sizes for detectors 4, 5, and 6 of 7.78, 8.04, and 7.87 mrad using the half-power points, and 7.54, 7.77, and

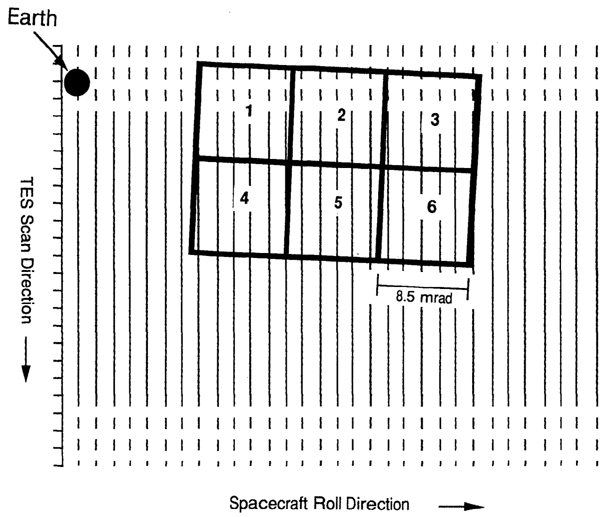

Figure 3. Path of the Earth relative to the TES detector array. The six individual TES detectors, each with a field of view of ~8.3 mrad, are shown with the path of the Earth, shown at its scaled size. Each individual scan was obtained using the TES internal pointing mirror; 32 scans were obtained by rolling the spacecraft at 0.015 mrad/s. The scan lines are canted relative to the TES detector array due to the spacecraft rotation. The locations of each observation point are indicated by tick marks on scan 1. Full-spectral data were acquired for 15 locations in each scan (solid line); spectrally integrated data were acquired for five locations at the start and end of each scan (dashed line).

7.56 mrad using the integrated energy. Using the average value of the field of views from the two laboratory methods, the Earth filled only 9.3% of the field of view. Each of the 15 average spectra was scaled by this factor in order to estimate the total radiance of the Earth. Confirmation of the field of view data was obtained using the Earth as a target. Figure 6 shows a two-dimensional map of detector response for detectors 4, 5, and 6 made using the integral of the spectrum of the Earth at each position and normalizing these values to unity.

Figure 7 shows the five average spectra obtained by detector 5. The spatial response of each detector varies slightly with position (Figures 5 and 6), which accounts for the variability between the individual spectra. This variability cannot be calibrated out precisely because the reference and space views are of extended targets and no information on the spatial variability of the detector is obtained. Therefore the final processing step was to normalize each spectrum to the maximum radiance spectrum using the integrated radiance between 245 and 1640 cm^{-1}. Even for the observations furthest to the edges of the detector field of view, only a 15% adjustment was required. It is important to note that this field normalization will not be necessary for the planned use of TES at Mars, where the planet, space, and reference targets will all fill the field of view. The average of all normalized spectra are shown in Figure 8.

Results

Figure 8 presents the first, calibrated, in-flight spectrum obtained from the TES instrument. The uniform spectral shape and lack of any slope artifacts confirms that the calibration method worked well, even in the presence of larger instrument temperature changes than are expected in Mars orbit. The data provide the first known whole-disk thermal infrared spectral observations of the Earth and confirm the expected instrument performance and calibration accuracy. The spectrum represents what would be seen if residents of another stellar system were to discover the Earth during a search for "extrasolar" planets.

Spectral features in the Earth's atmosphere are evident in Figure 8. In particular, the CO_2 absorption band centered at 668 cm^{-1} is readily apparent, ozone is easily detected between 1000 and 1075 cm^{-1}, and water vapor absorptions are obvious from 200 to 550 and 1260 to 1650 cm^{-1}. The substantial fraction of the spectrum spanned by these features is largely responsible for the greenhouse effect at the Earth's surface.

Radiation at the center of the CO_2 band arises mainly from the lower stratosphere; near 650 and 700 cm^{-1} from near the tropopause; and further into the band wings from the troposphere and surface. Thus, in the disk-averaged sense, the spectrum indicates a warm stratosphere above a tropopause somewhat colder than 215 K. This is in good agreement with results from a similar instrument previously flown in Earth orbit [*Conrath et al.*, 1970]. The heating of the stratosphere is caused by absorption of solar ultraviolet radiation in the ozone layer. The structure apparent in the water vapor regions of the spec-

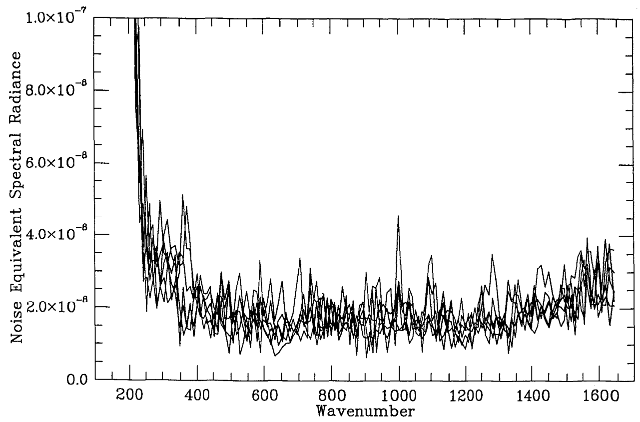

Figure 4. TES noise equivalent spectral radiance shown for all six TES detectors.

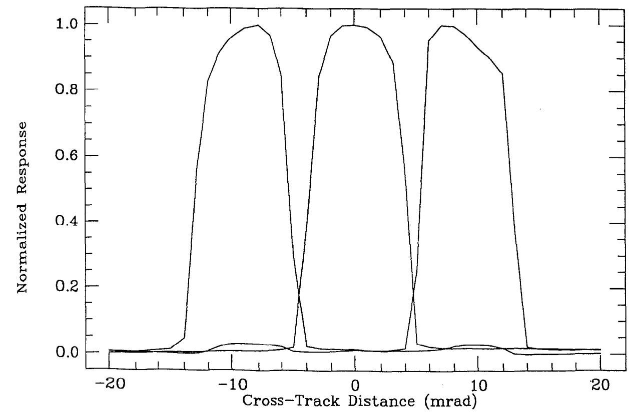

Figure 5. Prelaunch field of view map. The field of view response determined using a 1 mrad slit is shown for detectors 4, 5, and 6 in the direction perpendicular to the TES pointing mirror scan direction.

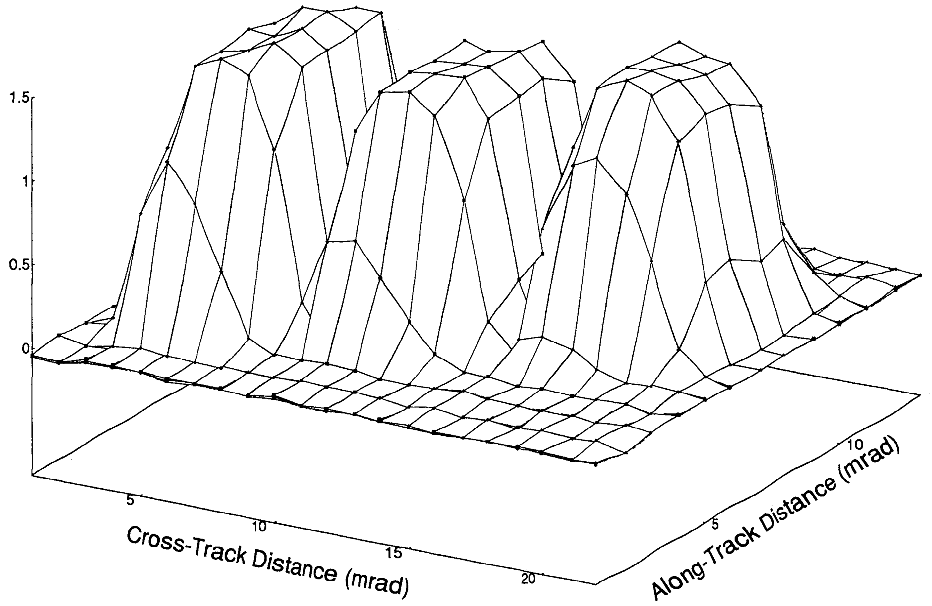

Figure 6. Two-dimensional field of view map of detectors 4, 5, and 6 using the Earth as a calibration target. The map represents the normalized, integrated spectral radiance of each observation.

trum is not noise but is due to the many strong, widely spaced spectral lines of H_2O.

The atmospheric window between approximately 800 and 1200 cm^{-1} is relatively featureless. This is expected, given the observing geometry centered over the Pacific Ocean (Figures 1 and 2). Even the small portion of North America that was potentially visible was largely obscured by clouds (Figure 2). Thus the surface observed was dominated by water (emissivity ~0.988) and clouds. The spectral contribution of water clouds is broad and featureless in this part of the spectrum but will tend to lower the brightness temperature in this part of the spectrum. An estimate of the cloud/surface temperature was determined assuming an emissivity of unity. The radiance between 800 and 950 cm^{-1} was converted to temperature, filtered by seven samples, and averaged, with a resultant value of −2.45°C. Given the small size of the Earth and uncertainties in the exact scaling factor to account for the fact it did not fill the field of view, this value is within the expected average temperature of the ocean surface, the polar regions, and the cloud tops.

To date, only massive extrasolar planets have been detected, through the use of Doppler techniques [e.g., *Marcy and Butler*, 1996]. To discover smaller, terrestrial-scale planets capable of harboring life may require alternative methods. The deep O_3 and H_2O signatures in the Earth's IR spectrum not only are indicative of life [*Owen*, 1980], but suggest that a spectroscopic search in the infrared may be possible. Though the immense ratio of stellar to planetary fluxes poses a formidable challenge, large interferometers designed to null out the star have been proposed [*Bracewell*, 1978; *Léger et al.*, 1996]. Such instruments

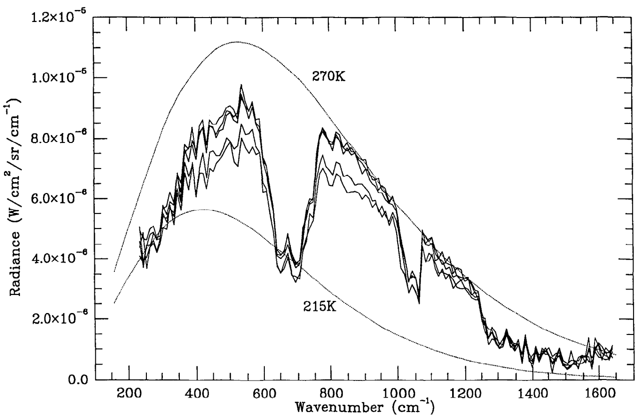

Figure 7. Calibrated spectral radiance of Earth. The five spectra from detector 5 are shown scaled by the fraction of the Earth in the TES field of view. Blackbody curves at 215 and 270 K are also shown.

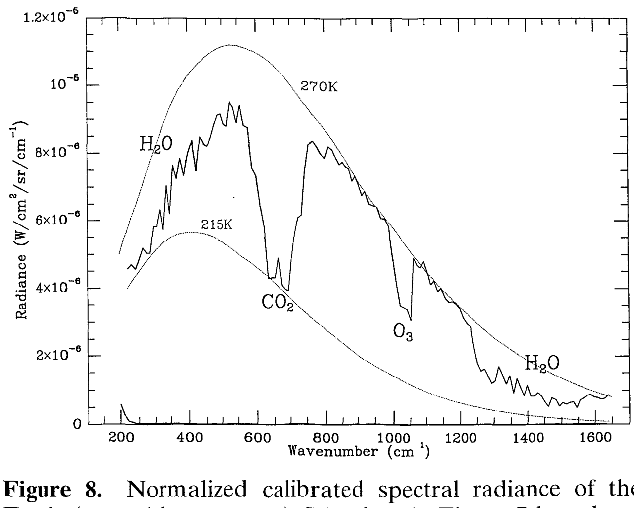

Figure 8. Normalized calibrated spectral radiance of the Earth (central heavy curve). The data in Figure 7 have been normalized to the highest signal. The noise equivalent spectral radiance is the lower heavy curve near the *x* axis. Dotted curves show blackbodies at 215 and 270 K. Note the presence of CO_2, O_3, and water vapor absorption features. The signal-to-noise ratio is ~400 at 1000 cm^{-1}. The structure in the water vapor bands is real.

may provide the best means for discriminating the small planetary signal from that of the central star.

Conclusions

The first data acquired by the TES instrument demonstrate that the instrument is performing as expected and producing data with high radiometric precision and accuracy. The calibration methods accurately account for the instrument response and the variation in instrument radiance with temperature. Spectra acquired of the Earth reveal the major atmospheric gases, with derived surface and atmospheric temperatures that are consistent with expected values, given the uncertainties in measuring an object that fills <10% of the field of view. These data indicate that the TES will perform as designed with the expected arrival of the spacecraft at Mars on September 12, 1997. The spectra also provide the first known whole-disk thermal infrared spectral observations of the Earth and provide the first direct measurement on how an Earth-like planet would appear during a search for "extrasolar" planets.

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