

versity of Hawaii/NASA 2.2-m (88-inch) telescope, using either a f10 or f35 secondary mirror. The highest spatial resolution (~3 km) required exceptionally still atmospheric conditions, using a small spectrometer aperture at f35 near full moon when the reflected flux is highest. Only about 5% of the data were obtained under these optimal conditions. About a third of the spectra were measured using a 60-cm (24-inch) telescope. These lower spatial resolution data, obtained early in the program, concentrated on soils in the maria which are relatively homogeneous at the observed scale.

The near-infrared spectrometer used for these measurements was developed by T. B. McCord in the mid-1970s explicitly for planetary spectroscopy needs and has been described by *McCord et al.* [1981]. The detector used is a liquid nitrogen-cooled InSb (indium antimonide) single detector. Spectral coverage is obtained by sweeping through a circular variable filter in 120 steps, providing a spectral resolution of about 100 Å from 0.6 to 1.4 μm and 200 Å from 1.35 to 2.5 μm. Each such sweep, or "data run," takes a little less than 2 min and must be repeated many times on the object being measured as well as on a calibration standard (star or lunar landing site). For each data measurement a dark background, or sky, measurement is obtained. During data acquisition a photograph is obtained of the lunar area, as it is seen on the mirrored aperture, to be used as documentation for area location. Raw data are viewed on a monitor during data acquisition and stored on magnetic tape with observational parameters for later processing. Most processing routines are contained in an interactive software package (SPECPR) initially developed by *Clark* [1980] for efficient manipulation of spectroscopy data.

For lunar data the calibration standard used is normally the Apollo 16 landing site. Prior to 1980 an area in Mare Serenitatis (MS2) was used as a lunar standard with earlier instruments [*McCord et al.*, 1972a, b; *Pieters*, 1978] because there are no nearby albedo features that can add unwanted spurious data if the area is not properly located through the telescope. With this infrared spectrometer on the MKO 2.2-m telescope, the spatial resolution is sufficiently high to allow accurately repeated measurements of a homogeneous area of Cayley Formation continuous with, but located about 10 km to the west of, the Apollo 16 site. This Apollo 16 standard is measured every 15 to 25 min to monitor atmospheric extinction and calculate appropriate signal adjustments with time.

The raw data are converted to reflectance measurements through a data processing sequence that includes the use of laboratory reflectance measurements of a carefully chosen returned mature soil from Apollo 16 (62231). The use of lunar soil as a calibration standard has been found to be more accurate for telescopic reflectance measurements than using "solarlike" stars or stellar models [*Nygaard*, 1972]. Data processing to derive the spectral reflectance of area X can be summarized as

$$\frac{\text{area X}}{\text{Apollo 16}_{\text{telescope measurements}}} \times \frac{\text{Apollo 16}}{\text{halon}_{\text{laboratory measurement}}} = \frac{\text{area X}}{\text{sun}} = \text{reflectance}_{\text{area X}}$$

The first flux ratio of this sequence, a relative reflectance measurement, provides atmospheric and instrumental calibration but still includes observational and statistical errors of repeated measurements. The precision of the reflectance data

depends on this ratio, which in turn also depends on the observing conditions and the number of times an independent measurement is made. The second ratio, laboratory measurements of 62231, is quite precise ( $\leq \frac{1}{2}\%$ ). The laboratory standard, halon, has been calibrated by the National Bureau of Standards (NBS) as an absolute reflectance standard with reflectance values of 97% to 99% in the near infrared (1975 NBS test 232.04/213908). Since albedo data are not derived in this process, lunar reflectance data are scaled to unity at an appropriate wavelength, usually at 1.02 μm for the near-infrared data since there are no major atmospheric absorptions at that wavelength.

There are three major sources of error that are not easy to separate for these reflectance measurements. The first is statistical and is dependent on the sensitivity and stability of the detector. Normally, this source of error is the smallest and is less than 1% after averaging four to six measurements. The second is atmospheric transparency and stability. This is not only often the largest source of error, it is also the least predictable and controllable. The procedure described above eliminates most of the systematic atmospheric variations, but nothing can effectively be done about the smaller-scale atmospheric turbulence that earth-based telescopes must tolerate. The third source of error arises from the difficulty in repositioning the telescope at precisely the same lunar location for each observation and keeping it pointed at that same location (within a fraction of an arcsecond) throughout the measurement. For surfaces that contain significant small-scale albedo variations these pointing errors can create signal variations that mimic spectral variations (since they are measured sequentially). The error bars normally plotted with a measured reflectance spectrum are the statistical variation (standard deviation) between repeated measurements of the object area and the standard area during the night. The error bars thus only measure the random nature of the errors and are not sensitive to any slightly systematic or discontinuous variations that occurred over the period of the measurements (about 1.5 hours). For complex surface areas it is thus important to have more than one completely independent measurement of the spectrum.

Data analysis utilizes the scaled reflectance values from this processing. Virtually all lunar telescopic spectra exhibit a continuum that increases toward longer wavelengths. Since most lunar mineral absorption bands are weak and superimposed on this continuum, an early step in data analysis includes the estimation and removal of the overall continuum slope, allowing the residual absorption features to be examined in more detail. For all the data presented here (and in publications since 1980) the continuum around the 1-μm absorption features is estimated as a straight-line tangent to the spectrum (usually near 0.73 and 1.60 μm). The ratio of the reflectance spectrum to this continuum provides a residual reflectance spectrum that enhances the mineral absorption features near 1.0 μm.

Most lunar spectra from the highlands exhibit a change of continuum slope near 1.6 μm. A second less steep continuum normally should be estimated to examine the nature of features near 2.0 μm. Although this can easily be done for laboratory samples, the telescopic measurements may include a minor ( $\leq 10\%$ ) thermal component of radiation increasing beyond about 2.2 μm when the lunar area and the standard area are observed at greatly different illumination (heating conditions). This thermal component can mimic variations on the weak 2.0-μm pyroxene absorption band and must be pre-