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THE REMOVAL OF ATMOSPHERIC EFFECTS FROM REMOTELY-SENSED NEAR-INFRARED SPECTRAL DATA

P.L. BLAKE, R.B. SINGER

University of Hawaii
Hawaii Institute of Geophysics
Honolulu, Hawaii

ABSTRACT

A method is presented for removing the effects of atmospheric absorption from remotely-sensed near-infrared (0.3 μ m to 2.6 μ m) spectral data. The raw spectral data are used as a sounding mechanism to determine the degree to which the intervening atmosphere has affected these same spectral data, thereby providing calibration information without reference to an external standard. The specific form of the atmospheric contribution is determined through comparison to a set of synthetic atmospheric transmission spectra generated using the LOWTRAN model developed by McClatchey *et al.* and Kneizys *et al.* Results are presented for the application of this calibration process to four samples: two basalts, a carbonate, and a white standard.

I. INTRODUCTION

Although the "broadband" instruments such as Landsat and the Thematic Mapper are widely used and valuable sensors, the advent of advanced forms of multispectral instrument such as the mapping spectrometer, which would obtain data at high spatial and spectral resolution, requires a new approach to multispectral analysis. Remotely obtained data of the earth's surface from any of these instruments necessarily contain the effects of absorption and scattering by the atmosphere. Unless these effects are accounted for, spectral signatures of the target data may be so altered that quantitative (and often even qualitative) comparisons of remote data may be impossible, thereby precluding any compositional analysis.

Much work has been devoted to developing methods for removing atmospheric effects from broadband spectral data; this paper presents a technique for removing atmospheric effects from high-resolution ($\Delta\lambda/\lambda < 3-5\%$) near-infrared spectral data. The method proposed is unique in that the remote spectra are, themselves, used to provide an estimate of atmospheric conditions. Thus, atmospheric and target data are obtained under exactly the same set of conditions and the problem of removing atmospheric effects is reduced to one of deconvolving target data from atmospheric data; it is a technique for performing that deconvolution which is considered here.

II. DATA SET

The data set used to test this model consisted of high resolution ($\Delta\lambda/\lambda=1.5\%$) near-infrared (0.65 μ m - 2.55 μ m) reflectance spectra of several rock samples measured both remotely in the field and in the laboratory using the same indium antimonide (InSb) spectrophotometer. This is a state of the art low-noise infrared instrument (described by McCord *et al.* 1978, 1980) utilizing a circularly variable filter (CVF). The filter and detector are cooled to liquid nitrogen temperature. The field of view of the instrument can be varied, by varying the aperture used, from 0.013° to 0.067°. In the laboratory this instrument is mounted on a spectrogoniometer; this range in field of view then corresponds to a range of 0.025 cm to 0.125 cm on the object surface. Imaging optics for the field instrument consist of a specially designed 10.8 cm diameter, f/10 cassegrain, telescope (focal distance ~36 cm) to accommodate what is basically an astronomical instrument designed for a much larger telescope.

The samples measured in the laboratory were measured in the field at a distance of approximately 0.5 km. The samples consisted of two basalts (a nepheline basalt and an olivine-rich basalt), a carbonate, and a non-geologic white reflectance standard, which was used as a calibration standard in earlier experiments (Singer *et al.*, 1981).

III. TECHNIQUE

The calibration technique developed in this research uses the raw spectral data, themselves, as a "sounding" mechanism to determine the atmospheric contribution to the spectral data. The atmospheric spectrum is then removed from the raw spectral data through comparison with a set of synthetic atmospheric transmission spectra generated with the LOWTRAN model developed by McClatchey *et al.* (1972) and Kneizys *et al.* (1980). However, before such a comparison is possible the raw spectral data and the synthetic atmospheric transmission data must be in a similar form. The primary difference between these two data sets is that the LOWTRAN spectra represent percent transmissions of electromagnetic radiation through the atmosphere with, effectively, no introduction of a detector system into the data. Spectral data gathered by any instrument, however, will necessarily include the response of that instrument. In addition, the synthetic spectral data assumes a source of illumina-

tion whose intensity is independent of wavelength, whereas actual spectral data also inherently includes the spectral shape and features of some light source. This light source is the Sun in the case of the field observations employed in this study.

Thus, in order to bring the raw spectral data into a form comparable to the synthetic data two initial adjustments are required: The effect of the solar spectrum must be accounted for and the response of the detector system must be removed. Additionally, of course, the raw data also include the spectral response of the objects being measured. Naturally, it would be tautological to suggest that the object spectral response should be removed before the raw data are calibrated, but it has been found in this research that at least the general effect of the object's response may be approximated by defining a continuum for the data and dividing out that continuum. If a similarly defined continuum is also removed from the synthetic spectra, then in theory the two data sets should become fully comparable and the synthetic atmospheric transmission spectrum (representing the atmospheric component) can be divided out of the data. This calibration procedure may be expressed by the following relationship:

$$R_{lab} \propto R_{cal} = S_{fld} / (F_{sol} * S_{sys} * T_{atm})$$

where R_{lab} = the spectral reflectance of an object measured in the laboratory and calibrated to laboratory standards; R_{cal} = the remotely-obtained reflectance of an object calibrated to match laboratory standards; S_{fld} = the uncalibrated remotely-obtained spectral radiance of an object, in units of flux relative to the instrument; F_{sol} = the solar spectrum, in units of relative flux; S_{sys} = the system response curve, in units of flux relative to the system; and T_{atm} = the atmospheric transmission spectrum, in terms of percent transmission.

The following sequence of operations summarizes the various components of the calibration procedure:

1. Obtain remote near-infrared spectrum.
2. Remove spectral characteristics of illumination source.
3. Remove instrumental system's response.
4. Define and remove continuum from observed spectrum to temporarily remove surface spectral properties and bring data into a form directly comparable with synthetic (calculated) atmospheric transmission spectra.
5. Iteratively fit calculated atmospheric transmission spectra to observed spectrum across wavelength region of two unsaturated water-vapor bands.
6. When a good fit is obtained, divide each observed spectrum by the appropriate calculated atmospheric transmission spectrum, across entire near-infrared spectral range.

7. Factor continuum back into observed spectrum to re-introduce surface spectral features.
8. Output calibrated spectra.

This procedure is discussed in detail below.

IV. COMPONENTS OF DATA AND PRELIMINARY ADJUSTMENTS

A. Field And Laboratory Spectra

The final laboratory-obtained spectra, calibrated relative to the Halon white standard, are shown in Figure 1a-d. An example of the raw data, obtained in the field, for one of these samples is shown in Figure 2. The strong absorption bands centered near 0.935 μ m, 1.13 μ m, 1.4 μ m, 1.9 μ m and 2.6 μ m are the result of atmospheric absorption (Kondratyev, 1969). These samples clearly show that the atmospheric absorptions are among the most prominent features of the spectra, tending to be more pronounced than most of the features characteristic of the minerals' reflectance behavior. Since the positions of these atmospheric absorptions are well-known, it is possible to identify in the observed spectra the bands present as a result of atmospheric absorption.

B. Adjustments to Field Spectra

The solar spectrum. In order for the field spectra to be comparable to the synthetic spectra, as well as to laboratory-obtained spectra, the inherent effects of the light source--in this case the Sun--must be removed. One generally accepted solar spectrum, used for calibrations of astronomical data, was published by Arveson *et al.* (1969). An alternative to this spectrum was published by Labs and Neckels (1968, 1981); the difference between these two spectra is everywhere less than 10%, and across most of the spectral region of interest is less than 1%. Hence, the more widely used of the two, the Arveson *et al.* spectrum, was used here.

The system response. The detector and optical system introduce into the raw data an undesired wavelength-dependent behavior. This system response curve is removed in the laboratory automatically when the data are referenced to a standard star set or to a calibrated area of the lunar surface. However, for the present application, an explicit characterization of the system's response was required; this response curve was determined as part of this research. Figure 3 shows an example of the raw data for one of the object spectra with both the solar spectrum and the system response curve divided out.

Continuum definition and removal. Removal of a continuum was the final operation performed on the field data in order to bring these data into a mode comparable with the synthetic spectra. The rationale for this continuum removal is twofold: First, if a similarly-defined continuum is also divided out of the synthetic spectra, this brings both data sets into the same data range, varying from zero to one. Secondly, it was found as part of this research that a continuum, defined as described below, contains spectral information about the object surface. While this spectral information is essential and is, in fact, factored back into the object spectra at a later point in

the calibration procedure, its temporary removal serves to segregate further the atmospheric absorption bands present in the object spectra.

The continuum for a given spectrum is defined with reference to the relative reflectance maxima which fall between the atmospheric (principally H₂O) absorption bands. These maxima occur at approximately 0.86 μm , 1.05 μm , 1.24 μm , 1.60 μm , and 2.13 μm in the calculated atmospheric transmission spectra.

When the solar and system-response spectra are calibrated out of the raw observed data, the atmospheric absorptions dominate the resulting spectra to such an extent that the above intensity maxima also correspond roughly to maxima in the observed data. The points in a spectrum which correspond to the wavelengths above are connected by linear splines and the curve so generated is defined as the continuum. (Cubic spline continua were initially fit to the data, but the resulting curves exhibited the "ringing" behavior often associated with this type of spline.) The end segments of the continuum, for which there are no maxima to use as a guide, are defined as a straight-line extension of the nearest segment of the curve.

An example is shown in Figure 4 of the continuum defined for one of the object spectra (with the solar and system-response spectra removed) along with the object spectrum. This same spectrum with the continuum removed (divided out) is shown in Figure 5. It is in this form of the spectra to which synthetic atmospheric absorption spectra are compared.

C. Synthetic Atmospheric Transmission Spectra

The LOWTRAN model for atmospheric absorptions, which is basically a technique to calculate the transmission and radiance of the atmosphere as a function of wavelength, was developed by McClatchey *et al.* (1972), and modified extensively by Kneizys *et al.* (1980). Included in the LOWTRAN model are data for six standard atmospheric configurations. The difference between these configurations is in the profiles (as a function of altitude) for temperature, pressure, water-vapor density, and ozone density. Five of these six cases correspond to atmospheric models for different latitude and seasonal regions: tropical, mid-latitude summer, mid-latitude winter, sub-arctic summer, and sub-arctic winter. A sixth model corresponds to the 1962 U.S. standard model atmosphere (Valley, 1965). Additionally, LOWTRAN contains the option of including the effects of aerosol scattering in the transmission spectra, for four different aerosol configurations: urban, rural, maritime, and tropospheric (the tropospheric model is inherent in the other three as well). These different aerosol models were developed by Kneizys *et al.* (1980) and corresponds to different species and concentrations of species. For the present data, obtained on Oahu, Hawaii, the tropical profile model and the maritime aerosol model were chosen as most likely to be representative.

A further aspect of the measuring technique also has to be considered. For the present field observation geometry, two paths were followed through the atmosphere: a slant-path from the sun onto the object, and a roughly horizontal path from the object to the sensor. Accordingly, the synthetic spectra obtained with LOWTRAN are the pro-

duct of a slant-path from sea-level to space and a horizontal path at sea-level.

D. Adjustments to Synthetic Spectra

Convolution. LOWTRAN calculations were performed at a resolution of 10 cm over the wavelength range 0.56 μm to 2.8 μm (18000.0 cm⁻¹ to 3571.0 cm⁻¹). In order for these data to correspond to the field spectra, the synthetic spectra were convolved to correspond to the same resolution and wavelengths as the object spectra. All further LOWTRAN-produced spectra presented below have been so convolved.

Continuum definition and removal. Continua were calculated for the LOWTRAN-produced synthetic atmospheric transmission spectra using the same procedure as described above for the observed object spectra and divided out of the atmospheric transmission spectra. In the case discussed above for the observed spectra, it was found that the continua for those spectra contained information pertinent to the spectral properties of the object's surface. Similarly, it was also found that the continua defined for the atmospheric transmission spectra closely resembled the spectra resulting from aerosol scattering in the atmosphere (as modeled by LOWTRAN). Thus, the continua defined for the synthetic transmission spectra were factored back into these data, prior to dividing the synthetic spectra out of the object spectra in the final calibration step, as an approximation to removing from the field data the effects of aerosol scattering by the atmosphere.

V. CALIBRATION PROCEDURE

As stated earlier, the hypothesis underlying this calibration technique was that the raw near-infrared spectral data, themselves, contain sufficient information to establish the contribution of the intervening atmosphere to these same near-infrared spectra. Further, it was assumed that an existing atmospheric model, LOWTRAN, could be used to extrapolate across the whole wavelength region of interest the atmospheric information contained in the near-infrared spectra. The technique developed based upon these hypotheses has a two-fold objective: 1) To obtain, through LOWTRAN, the appropriate atmospheric transmission spectra; and 2) To use these calculated spectra to remove the atmospheric components from the object spectra, i.e., to calibrate the object spectra. In order to accomplish these two objectives, it was necessary to establish criteria for identifying the "appropriate" transmission spectra and then to determine a method for applying these criteria.

A. Definition of Appropriate Transmission Spectra

Simplistically, what is required are the transmission spectra which, when divided out of the object spectra, will best remove the atmospheric components from those object spectra and in doing so yield the desired, calibrated spectra; these spectra would then be in a form comparable to laboratory-calibrated spectra obtained of the same objects. The practical implementation of this definition required identifying certain limited criteria for the "best-fit" transmission spectra. Because atmospheric water vapor is by far the most significant contributor to the atmospheric spectrum, the portion of the spectrum encompassing two of the unsaturated water-vapor absorption bands of intermediate depth was used as the region to test

for goodness-of-fit. The procedure used to calibrate the object spectra was based upon the assumption that by varying the water content of the model atmosphere in a systematic way, the best-fit atmospheric transmission spectra could then be determined.

As the amount of water vapor in the atmosphere varies, both the shape and depth of the H₂O absorption bands vary as well. At first the change in band depth is nearly linear, becoming more asymptotic as the band center saturates and the wings of the band begin to broaden (Goody, 1964). If an atmospheric band is saturated, then this indicates that no information pertaining to the target is reaching the sensor in the wavelength region near the center of that band because the light in that region has been fully absorbed by the atmosphere. The three deepest atmospheric bands, centered near 1.4 μm , 1.9 μm , and 2.6 μm , will, at sea level, reach saturation in virtually all cases. Thus, remotely obtained spectra of objects on or near the earth's surface will always have at least three regions over which effectively no additional spectral information is available. The four smaller atmospheric bands centered near 0.72 μm , 0.81 μm , 0.94 μm and 1.13 μm will not, however, in most cases be fully saturated, and spectral information across these bands as well as in the regions between the large bands should therefore be recoverable. Accordingly, the wavelength region across two of these smaller absorption bands (centered near 0.94 μm and 1.13 μm) was used to determine when the synthetic spectra sufficiently matched the object spectra.

B. Measures of Goodness-of Fit

Several specific measures of goodness-of-fit (with regards to the two bands at 0.94 μm and 1.13 μm) were tested. The most diagnostic of these measures—that is, the parameter giving the most useful information as to how to vary the assumed water content of the atmosphere so as to yield the appropriate synthetic spectra—was the average band depths of the band minima for the above two bands. This value exhibited a predictable relationship with changes in the water-vapor density of the bottom (horizontal) layer of the atmosphere. The exact point defining the band minimum was identical in all cases for the object and synthetic spectra.

C. Iterative Technique

As discussed above, the different synthetic atmospheric transmission spectra were obtained by varying the water-vapor content (in terms of density) of the model atmosphere. Naturally, varying the density, within the LOWTRAN model, of the water vapor in the bottom, horizontal layer of the atmosphere had a greater effect on the resultant transmission spectrum than varying the density in other layers; in fact, varying this parameter alone would have been sufficient to obtain the appropriate synthetic transmission spectra. However, in order to maintain the integrity of the atmospheric water density profile within LOWTRAN, the water vapor density within the bottom three layers of the model atmosphere was varied. Although the resultant water density profile for each case is probable, no suggestion is made here that the profile so achieved corresponds to the actual structure of the atmosphere at the time the spectral measurements were obtained—it is merely one of many possible models.

The procedure to obtain the best-fit atmospheric transmission spectra was iterative, where the variable used to drive the iterative process was the water-vapor density of the model atmosphere. The following four steps formed the basis for the iteration:

1. Assume some set of initial values for the water-vapor density and calculate atmospheric transmission spectra.
2. Test for goodness-of-fit between object spectra and calculated atmospheric transmission spectra, using the criteria described above.
3. If the goodness-of-fit is sufficient (i.e. if the difference in band depths between object and calculated spectra are below a specified value), divide calculated atmospheric spectra out of object spectra, multiply object continua back in and output calibrated spectra; otherwise go to step 4.
4. If the goodness-of-fit is not good enough, increment or decrement, as appropriate, the assumed water-vapor density, recalculate the synthetic atmospheric transmission spectra, and return to step 2.

VI. RESULTS

The foregoing iterative calibration process was applied to the four near-infrared samples discussed earlier. An example of an object spectrum (with the solar spectrum, system's response curve, and continua removed) is presented in Figure 6 along with the appropriate LOWTRAN-computed transmission spectra (with continua removed). The final, calibrated spectra were obtained by dividing the object spectra (without continua removed) by the appropriate atmospheric transmission spectra (including the computed aerosol contribution); these calibrated spectra, along with their respective laboratory counterparts, are shown in Figure 7a-d.

The success of the calibration technique may be evaluated by comparing the calibrated field spectra to their laboratory equivalents. Two basic features should be apparent in both data sets: the overall shape of the spectra and any diagnostic absorption features. For the white standard, the spectral shape is a rather smooth downward-sloping line; principal absorption features are the result of the white paint on this standard and occur at about 1.4 μm , 1.7 μm , 1.9 μm and 2.3 μm . Because the two atmospheric absorption bands near 1.4 μm and 1.9 μm are saturated, any features near these positions will not be recoverable. However, as seen in Figure 7a, the basic shape of this spectrum as well as the absorption feature near 2.3 μm are preserved in the calibrated spectrum. It should be noted that minor differences in the field and lab spectra may be due to inaccuracies in the calibration—but differences (such as the different shape of the absorption feature near 2.3 μm) may also be due to the inherent differences in obtaining field and laboratory spectra. In particular, laboratory spectra are obtained over relatively small areas on the object surface, whereas field spectra represent a much larger surface area.

The carbonate sample (Figure 7b) is characterized by a spectral shape that is largely flat in the visible region with a slight negative slope in the near-infrared region. Diagnostic absorption features occur near 1.4 μ m, 1.9 μ m, 2.3 μ m and 2.5 μ m. The calibrated field spectrum preserves the overall spectral shape and the absorption bands near 2.3 μ m and 2.5 μ m. Again, absorption features near the two major atmospheric absorptions in this region of the spectrum are not well-indicated.

The characteristic spectral shape of the olivine basalt sample (Figure 7c) is a "check" shape caused by a relatively strong absorption near 1 μ m and a relatively flat shape in the near-infrared. The basic shape is largely preserved in the calibrated spectrum; while the 1 μ m band is apparent, the atmospheric removal was not ideal across the atmospheric absorption band near 1.13 μ m and consequently the shape of this band is imperfectly preserved.

The nepheline basalt sample (Figure 7d) is characterized by an absorption band near 1 μ m resulting from pyroxene, with little indication of the 2 μ m pyroxene absorption feature and thus a relatively flat shape into the near-infrared. The calibration procedure preserves the basic shape of this spectrum, but, as in the previous sample, the 1.13 μ m atmospheric absorption is not well-removed. In general, as for more traditional techniques utilizing an external standard for calibration, darker samples were more difficult to calibrate using the technique developed in this research.

In summary, this technique proved successful for removing atmospheric effects from remotely-obtained single-point spectra. Future research will be directed towards expanding the technique so that it may be used to calibrate high-spectral resolution images, such as would be obtained from a mapping spectrometer.

REFERENCES

- Arveson, J.C., R.N. Griffin, Jr. and B.D. Pearson, Jr. (1969), "Determination of Extraterrestrial Solar Spectral Irradiance from a Research Aircraft", Applied Optics, **8** (11):2215-2232.
- Goody, R.M. (1964), Atmospheric Radiation I: Theoretical Basis. Oxford University Press, London.
- Kneizys, F.X., E.P. Shettle, W.O. Gallery, J.H. Chetwynd, Jr, L.W. Abreu, J.E.A. Selby, R.W. Fenn and R.A. McClatchey (1980), Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 5, AFCRL Environmental Research Paper, No.697, AFCRL-80-0067.
- Labs, D.T. and J.A. Neckel (1968). Z. Astrophysik, **69** (1):15-22.
- Labs, D.T. and J.A. Neckel (1981), Solar Physics, **74**: 231-249.
- McClatchey, R.A., R.W. fenn, J.E.A. Selby, f.E. Volz and J.S. Garing (1972), Optical Properties of the Atmosphere (3rd ed). AFCRL Environmental research paper, No.411, AFCRL-72-0497.
- McCord, T.B., R.N. Clark and R.L. Huguenin (1978), "Mars: Near-Infrared Spectral Reflectance and Compositional Implications." Journal of Geophysical Research, **83**: 5433-5441.
- McCord, T.B., R.N. Clark and R.B. Singer (1982), "Mars: Near-Infrared Reflectance Spectra of Surface Regions and Compositional Implications." Journal of Geophysical Research, **87**: 3021-3032.
- Singer, R.B., P.L. Blake, P.G. Lucey and T.B. McCord (1981). "Application of Reflectance Spectroscopy to Geologic mapping on Earth: Stratigraphic Units in Kilauea Caldera", Annual progress Report, JPL contract #955722, Planetary Geosciences Division unpublished report.
- Valley, S.L., ed. (1965) Handbook of Geophysics and Space Environments, Airforce Cambridge Research Labs (AFCRL), Office of Aerospace Research, U.S. Air force, Cambridge, MA.
- Pamela L. Blake Ms. Blake is a doctoral candidate at the Hawaii Institute of Geophysics, University of Hawaii. Her PhD topic is concerned with the application of multi-sensor remote sensing data sets to the study of the earth's surface. The present paper is largely the outcome of her MS thesis.
- Robert B. Singer Dr. Singer is an Associate Researcher in the Planetary Geosciences Division of the Hawaii Institute of Geophysics, University of Hawaii. He received his PhD in Planetary Sciences from the Massachusetts Institute of Technology in 1980. His primary research interests are in the use of multispectral data to study planetary surfaces, with particular emphasis on Mars and Earth.

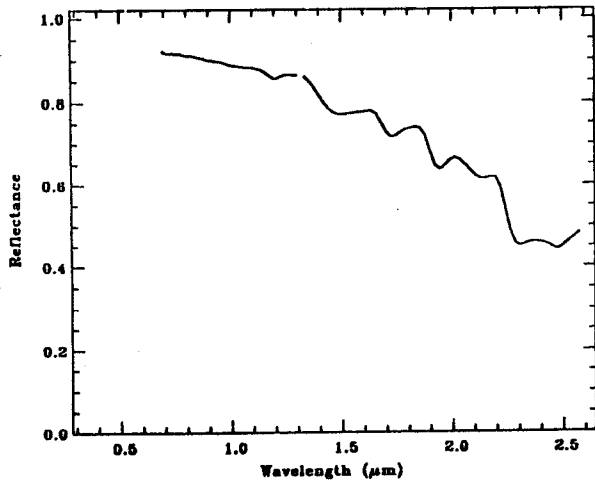


Figure 1a. Laboratory Spectrum for White Reflectance Standard

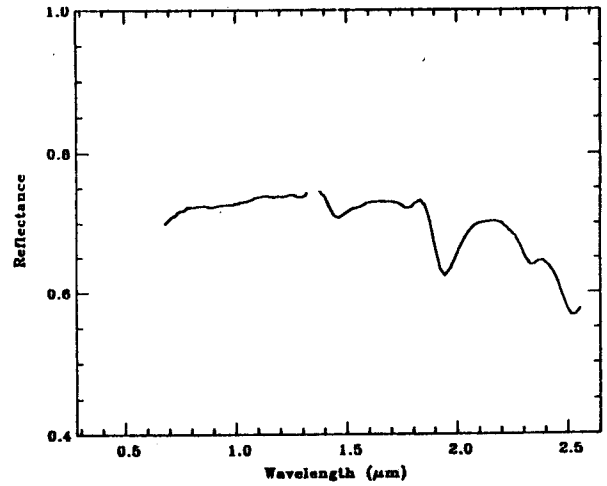


Figure 1b. Laboratory Spectrum for Carbonate Sample

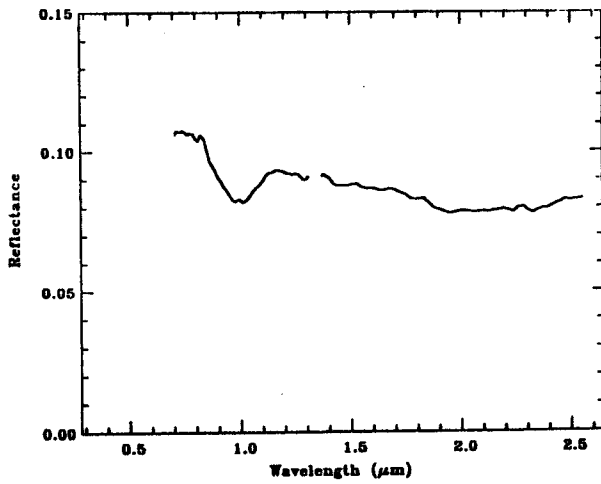


Figure 1c. Laboratory Spectrum for Nepheline Basalt

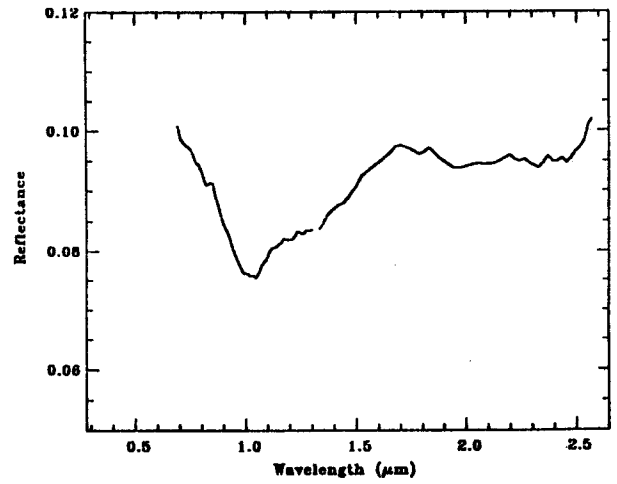


Figure 1d. Laboratory Spectrum for Olivine Basalt

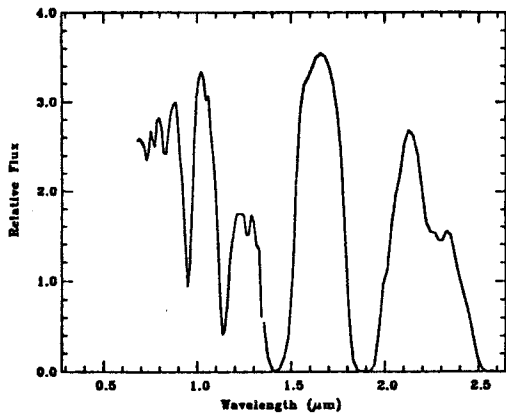


Figure 2. Raw Field Data for Carbonate Sample

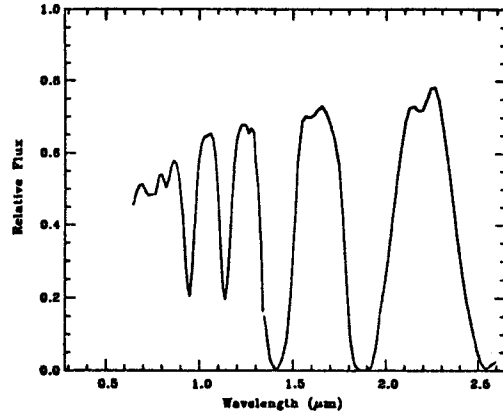


Figure 3. Raw Field Data for Carbonate Sample with Solar Spectrum and Systems' Response Factored Out

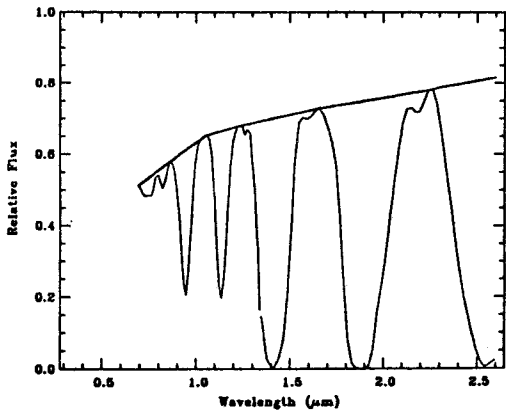


Figure 4. Continuum Defined for Carbonate Sample

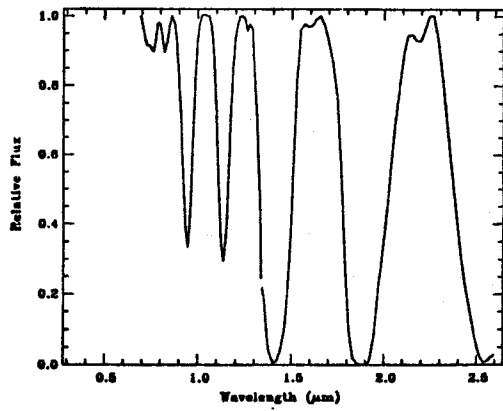


Figure 5. Carbonate Sample with Continuum Factored Out

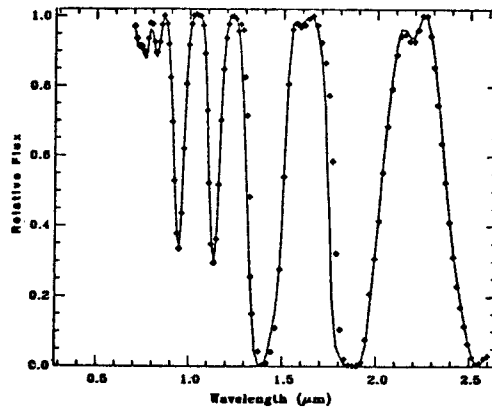


Figure 6. Carbonate Sample Overlaid with Appropriate LOWTRAN Atmospheric Transmission Spectrum

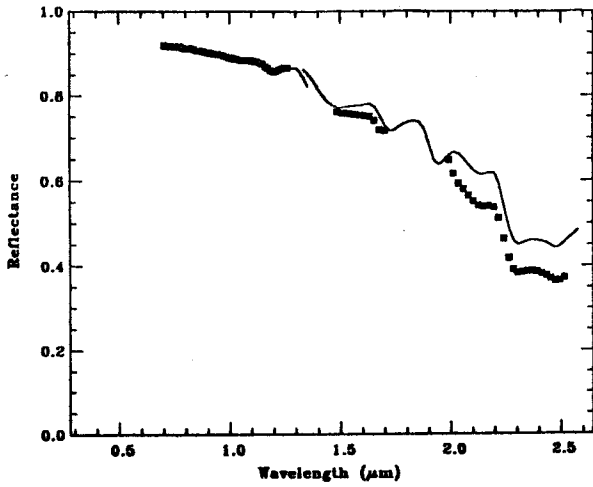


Figure 7a. Calibrated Spectrum for White Reflectance Standard

Points are Calibrated Field Spectrum.
Solid Line is Laboratory Spectrum.

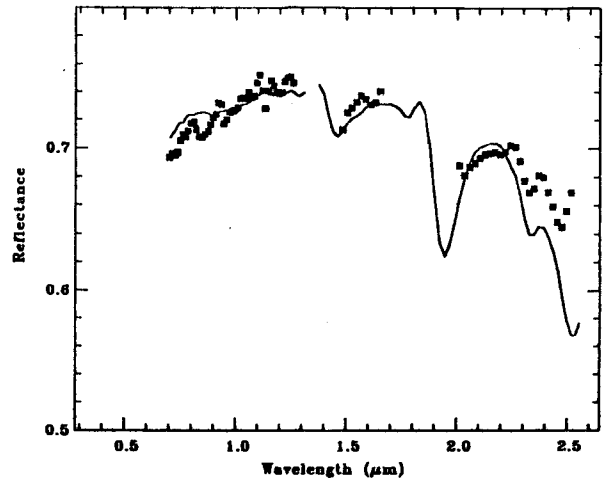


Figure 7b. Calibrated Spectrum for Carbonate Sample

Points are Calibrated Field Spectrum.
Solid Line is Laboratory Spectrum.

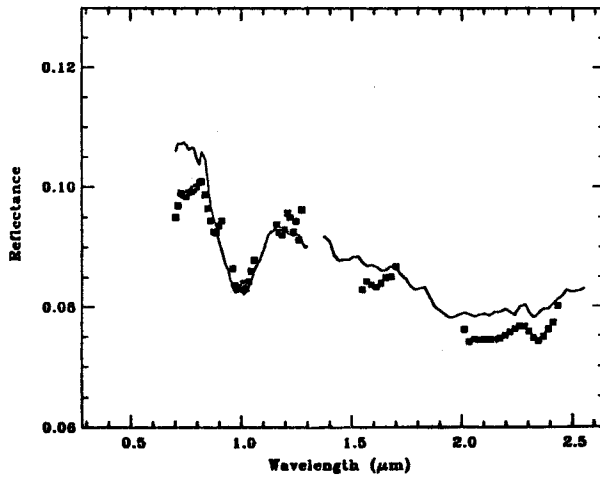


Figure 7c. Calibrated Spectrum for Nepheline Basalt Sample

Points are Calibrated Field Spectrum.
Solid Line is Laboratory Spectrum

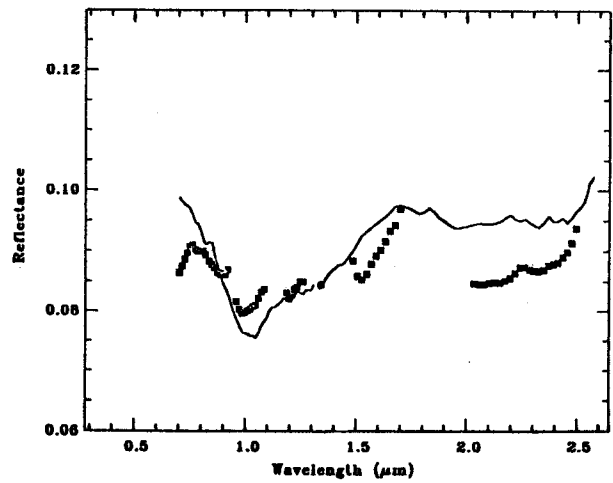


Figure 7d. Calibrated Spectrum for Olivine Basalt Sample

Points are Calibrated Field Spectrum.
Solid Line is Laboratory Spectrum.