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ANALYSIS OF AIRCRAFT SPECTROMETER DATA WITH LOGARITHMIC RESIDUALS

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ABSTRACT

Spectra from airborne systems must be analysed in terms of their mineral-related absorption features. The first part of this paper discusses methods for removing backgrounds and extracting these features one at a time from reflectance spectra. The second part discusses methods for converting radiance spectra into a form similar to reflectance spectra so that the feature extraction procedures can be implemented on aircraft spectrometer data.

INTRODUCTION

Aircraft and spacecraft based spectrometer data pose fundamentally different analytical problems to those we have found when working with multispectral imagery. These new problems are associated with the analysis of curve shape. The overall brightness variability which is the dominant feature in multispectral imagery is now taken for granted and we are interested in the detailed shape of the reflectance curve as a function of wavelength. In this paper we shall deal with spectra in the SWIR region 1.9-2.5 μm and treat the problems involved in analysing both reflectance curves, such as those obtained in the laboratory, and the more difficult problem of radiance curves acquired by remote sensing systems.

ANALYSIS OF REFLECTANCE SPECTRA

Reflectance spectra in the SWIR region are usually composed of a flat or generally convex background with superimposed sharper absorption features due to the chemical groups which are of interest for remote sensing. The information content of these curves lies primarily in the wavelength position of these absorption minima and to a lesser extent in the relative intensity and shape of the absorption features. The extraction and parametrization of absorption features in a spectrum is the first step in the recognition of the chemical species which are causing the absorption spectrum. In order to extract these features we must first remove the overall convex background.

This may be done by ratioing the spectrum to its "upper convex hull (or envelope)", defined as the lowest convex curve lying above the given spectrum. The resulting curve - called the "hull-quotient" of the input curve - appears as a horizontal line of height unity interrupted by absorption features extending down towards the horizontal axis. Figure 1 illustrates a raw spectrum, its hull, and hull-quotient. Note especially the enhancement of features beyond 2.2 μm, where removal of the sloping background has brought out sharp minima not identifiable in the raw data.

The technique is easily extended to permit the isolation and extraction of individual features. Thus, the "first featuregram" is obtained as the union of hulls for the parts of the hull-quotient to

left and to right of the lowest point on that curve. The ratio of hull-quotient to first featuregram is a curve coinciding with the hull-quotient, except for the absence of its dominant feature. Remaining features may be extracted successively until the residual spectrum is reduced to mere noise fluctuation of no significance.

If implemented as described above the algorithm produces V-shaped absorption features which do not match well with the usual inverted Gaussian shape of most absorption features. Improved performance is obtained by making the featuregram coincide with the curve (from which it is to be removed) between the points of inflection closest to the minimum and on either side of it. The rest of the featuregram is made up of the two hulls computed beyond those points. Figure 2 illustrates the features extracted from a simple reflectance spectrum.

Feature extraction can provide the basis for automatic classification of spectra. Classification of two types is possible.

The first type compares the wavelength position, relative depth and shape of each extracted feature with a list of characteristics of reference materials, and makes an assignment in much the same way as would a human interpreter.

The second type of classifier relies on the signs of first and second derivatives of hull-quotients. The second derivative of a convex curve is always non-positive. On the other hand, the slope of a featuregram will be negative to the left of the feature-minimum, positive to the right. The ratio of a hull-quotient to its residual noise-spectrum equals the product of extracted features and so is characterized by long runs of channels with the same sign for the first or second derivative.

By encoding the sign as 0 or 1, and concatenating the strings for first and second derivative, we obtain the 2N-channel "binary signature" of an N-channel spectrum. The Hamming distance (equal to the number of mismatches in corresponding channels) between two such signatures provides an effective measure of their similarity. Input spectra could then be classified by comparison with stored, library spectra.

RADIANCE SPECTRA

Radiance spectra acquired in airborne systems bear little resemblance to the laboratory reflectance spectra that would result from sampling the surface materials along the flight path. Apart from the ambiguity introduced by the heterogeneous composition of each pixel, the difficulties are of two kinds. First, topographic effects, such as different inclination, affect the apparent brightness of different occurrences of the same material. Secondly, the solar illumination curve, unlike a laboratory light source, varies considerably in accordance with prevailing atmospheric conditions.

Using a very simple model we relate the radiance measurement $X_{i\lambda}$ to the reflectance $R_{i\lambda}$ in sample i, wavelength λ, by means of a multiplicative formula

$$X_{i\lambda} = T_i R_{i\lambda} I_{\lambda}, \qquad (1)$$

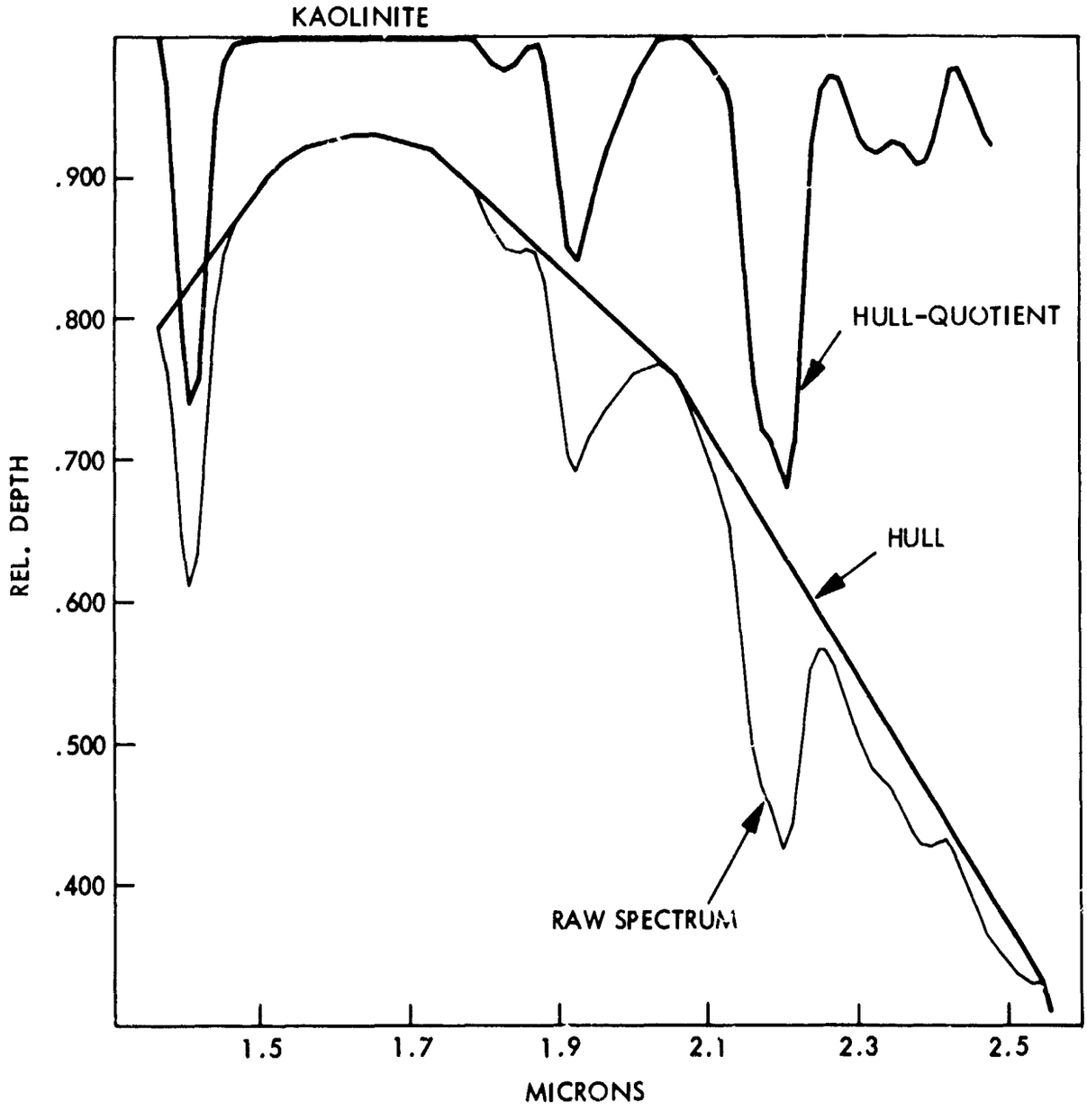


Figure 1. Raw spectrum, hull and hull-quotient for a kaolinite spectrum between 1.4 and 2.5 μm.

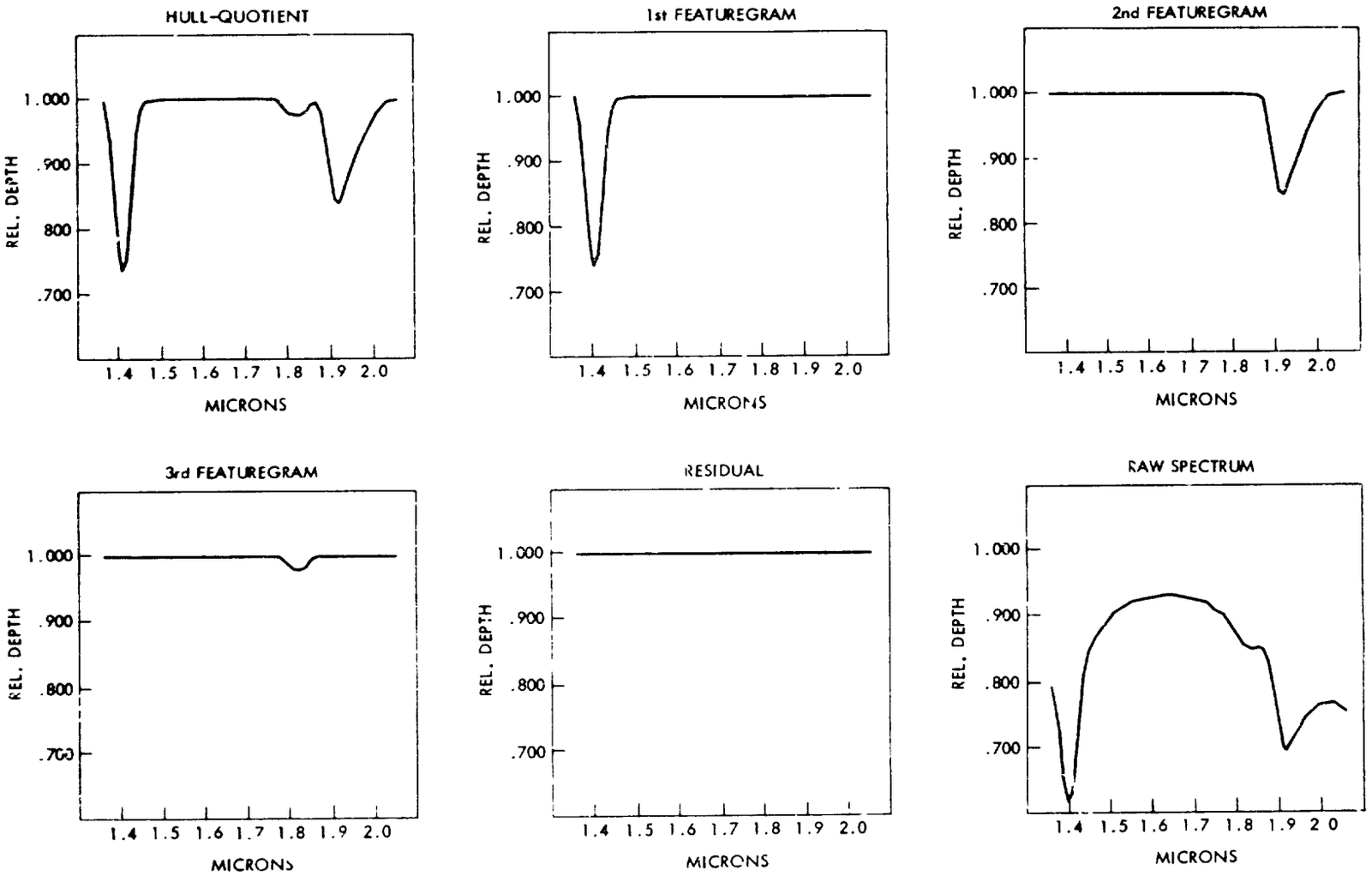


Figure 2. Progressive feature extraction from a hull-quotient spectrum (obtained from the raw reflectance spectrum at lower right). Each featuregram represents a separate absorption feature.

The "topographic" factor T_i accounts for surface variability with sample number and is constant for all wavelengths, while the "illumination factor" I_λ describes the unknown illumination curve, assumed the same for all points on a single flight line.

Write $X_{i.}$ to denote the geometric mean of $X_{i\lambda}$ taken over all channel wavelengths λ. With a similar convention regarding the other new symbols we have from (1)

$$X_{i.} = T_i R_{i.} I_{.} ,$$

hence by division

$$X_{i\lambda}/X_{i.} = (R_{i\lambda}/R_{i.})(I_\lambda/I_{.}), \qquad (2)$$

independent of the unknown factor T_i. The spectra represented by the two sides in (2) may be called the "topographically equalized" (or "albedo equalized") versions of the input spectra (1).

The simplest way of eliminating the unknown illumination factor is by taking the geometric mean over all samples in equation (2). With an obvious notation we find

$$X_{.\lambda}/X_{..} = (R_{.\lambda}/R_{..})(I_\lambda/I_{.}), \qquad (3)$$

giving upon division

$$(X_{i\lambda}/X_{i.})/(X_{.\lambda}/X_{..}) = (R_{i\lambda}/R_{i.})/(R_{.\lambda}/R_{..}). \qquad (4)$$

We have thus computed from the original radiance spectra $X_{i\lambda}$ a new set of spectra with the advantage that they are the same as would be obtained by applying the same process to the unknown reflectance spectra $R_{i\lambda}$.

The geometric means must, in practice, be computed from arithmetic means of logarithms; hence, it is the logarithm of the quantity in (4) which results from the processing. Such spectra are termed the "logarithmic residuals" of the original spectra $X_{i\lambda}$, the quantity in (4) giving then the "exponentiated log residuals" of the $X_{i\lambda}$. This residual method has some features in common with that used by Marsh and McKeon (1983) but it is also fundamentally different in the way it removes the I_λ factor.

Log residual spectra lack some of the information originally present. For example, a mineralogical absorption feature present in all samples, even if situated away from the known positions of atmospheric absorptions, will be treated as a component of I_λ and removed by the processing. On the other hand, a mineralogical feature whose presence in a few samples was obscured in the radiance spectra, due to its coincidence with a major atmospheric absorption, will become evident in the log residual data. Thus, despite its limitations, the log residual transformation of radiance spectra from airborne systems has shown itself to be a very useful aid to interpretation.

The log residual technique as described above requires modification to render it compatible with the processing described earlier for reflectance spectra. Suppose, for example, that a particular absorption feature, such as the clay/muscovite feature at 2.2 microns, is strongly represented within a flight line. That

feature will then persist in the geometric mean (3) of the albedo equalized spectra. Samples which do not have an absorption at 2.2 microns will give values at 2.2 μm which are high relative to the mean. The ratio (4) for such samples will thus exhibit what may facetiously be termed an "emission feature" at that wavelength.

Such features will of course defeat the algorithm for (absorption) feature extraction. To overcome the problem we need a replacement for the geometric mean (3) which likewise contains the factor $X_\lambda/I.$, but is never less than any value (2) which it is to divide. The required quantity is of course the least upper bound spectrum (LUB)

$$\mathrm{LUB}_i(X_{i\lambda}/X_{i.}) = \mathrm{LUB}_i(R_{i\lambda}/R_{i.})(I_\lambda/I.)$$

taken over all sample numbers i. We get in place of (4)

$$(X_{i\lambda}/X_{i.})/\mathrm{LUB}_i(X_{i\lambda}/X_{i.}) = (R_{i\lambda}/R_{i.})/\mathrm{LUB}_i(R_{i\lambda}/R_{i.}), \qquad (5)$$

which may be termed the least upper bound (or supremum) residual corresponding to $X_{i\lambda}$.

The least upper bound residuals may be computed as well from the earlier log residuals as from the radiance data. We have only to observe that the left member in (5) equals

$$[(X_{i\lambda}/X_{i.})/(X_{.\lambda}/X_{..})]/\mathrm{LUB}_i[(X_{i\lambda}/X_{i.})/(X_{.\lambda}/X_{..})].$$

This observation has allowed us to use, as input, an extensive library of early log residual back-up tapes, to generate least upper bound residuals with a minimum of computation.

EXAMPLES

Aircraft data were acquired over a number of Australian test sites with the GER spectrometer system (Collins et al., 1981) in September, 1982. The examples used here are taken from a flightline over the Mary Kathleen area in NW Queensland. The data were corrected for instrument response function and processed to log residual spectra and least upper bound spectra as described above.

Figure 3 shows the results of the two procedures when used on data averaged over three uniform areas of distinctly different terrain type.

DISCUSSION

The area covered by the flight line used in this example can, to a first degree of approximation, be thought of as being composed of two cover types. These are firstly, a mixture of soil with arid-land grass known as spinifex, and secondly, an anomalous Ca-rich clay which is exposed in the Mary Kathleen open pit. The spectra of both these species are incorporated into the mean reflectance spectrum of the flight line and so will be subtracted from each true spectrum to produce the log residual spectrum for any given sample in the flightline. The result for a region which is typical of the grass/soil mixture is shown in Figure 3(a). The log residual spectrum (upper curve) is what we call a "not - Ca-clay" spectrum.

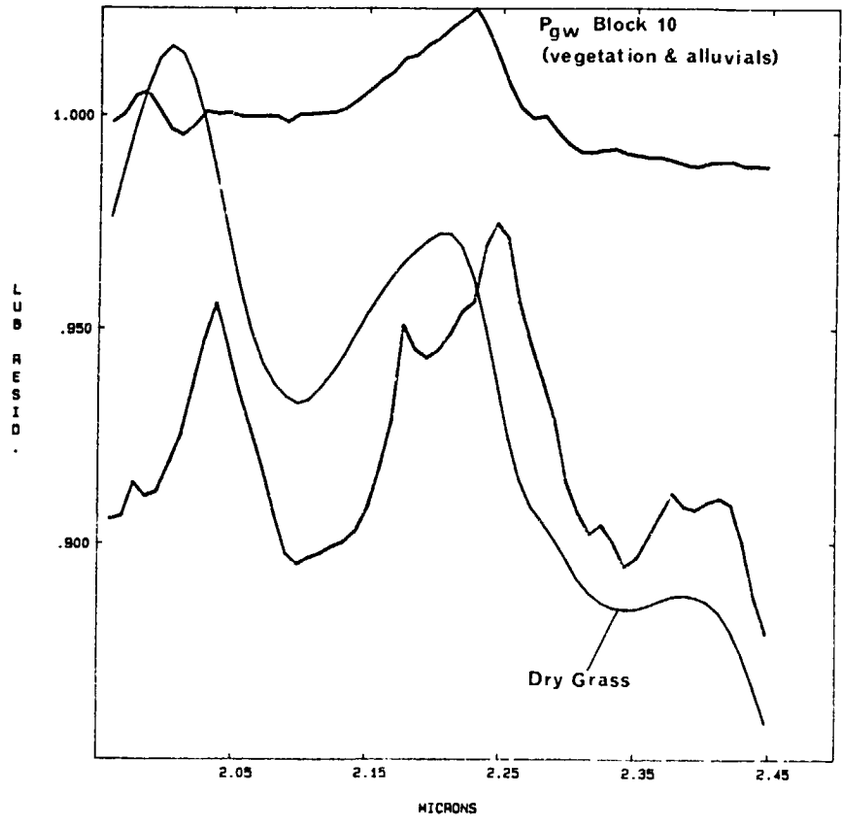
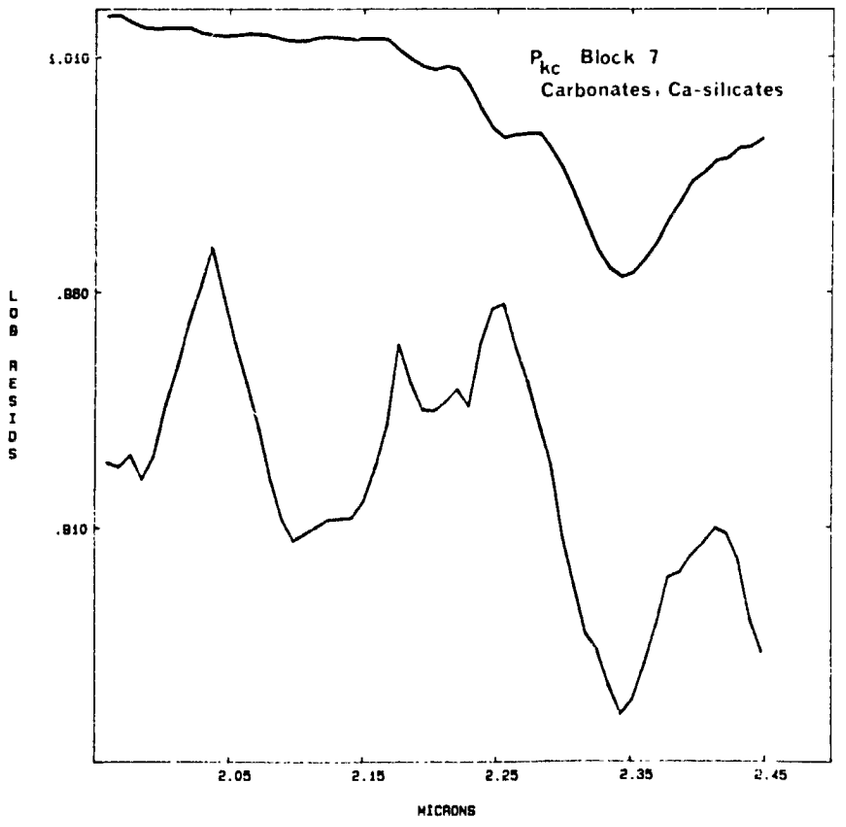
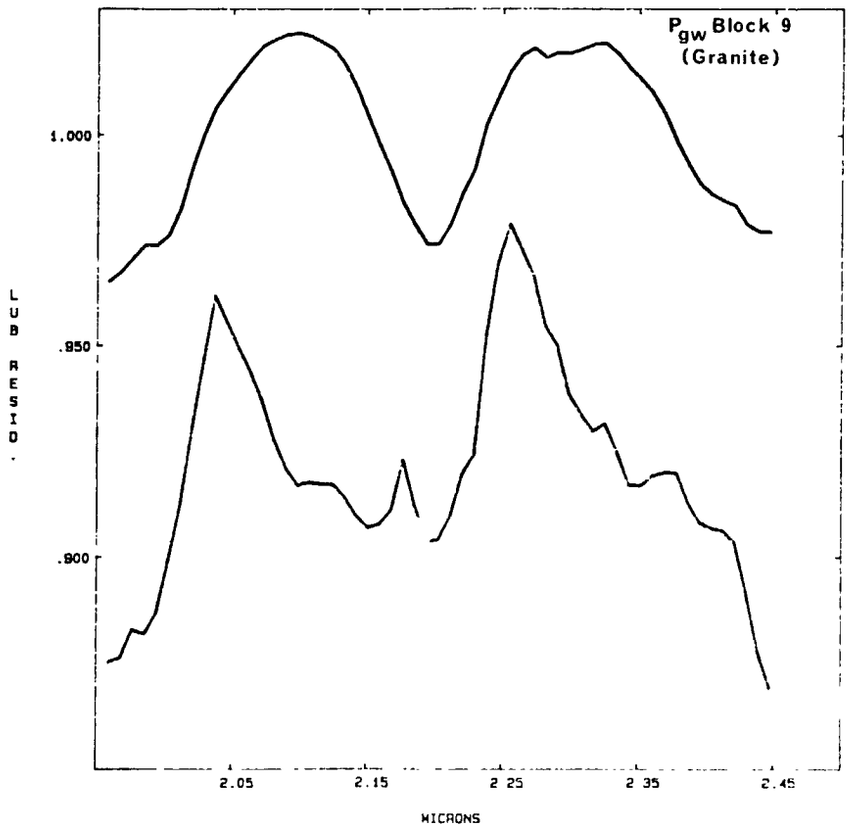


Fig. 3 (a). Log residual spectra (upper curve) and least upper bound residual (lower curve) for an area of dry grass and some soil near Mary Kathleen, Qld. The spectrum of dry grass alone is superimosed for comparison with the LUB curve.



3 (b). Log residual (upper) and LUB (lower) spectra for an area of carbonates and calc-silicates near Mary Kathleen in Qld. The log residual curve shows a typical spectrum for this type of terrain while the LUB residual spectrum shows a dominant vegetation curve perturbed by the carbonate feature at 2.35 μm.



3(c). Log residual (upper) and LUB (lower) spectra for an area of granite. The typical 2.2 absorbtion feature is much more visible on the log residual than the LUB residuals.

It contains an upward feature with the inverted shape of a Ca-clay absorption feature. In contrast, the least upper bound residual (lower curve) shows a typical spectrum for a mixture of dry grass and a 2.2-absorbing clay. Although the least upper bound procedure does remove obnoxious upward features it superimposes a very strong dry grass spectrum onto the spectra of all samples except those from the open pit. In doing this it is correctly reproducing the reflectance spectra of those samples but it is also masking subtle mineralogical features evident in the log residual spectra, Figures 3(b) and 3(c). From this we can see that, in areas of relatively uniform dry grass cover, the log residual spectra have certain advantages. They remove the unwanted dry grass spectrum, leaving a spectrum which can more easily be alloted to the mineralogy.

CONCLUSIONS

Successful analysis of airborne spectrometer data depends on an ability to extract absorption features and measure their wavelength, shape and intensity. Background removal and feature extraction procedures can perform this function on reflectance curves. Radiance spectra can often be converted into "reflectance-like" curves by log residual or least upper bound residual methods which then enable the application of feature extraction procedures.

REFERENCES

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