NIRS in Space?

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Proponents of near infrared reflectance spectroscopy have been exceptionally successful in applying NIRS techniques to many instances of organic material analyses. While this research and development began in the 1950s, in recent years, stimulation of advancements in instrumentation is allowing NIRS to begin to find its way into the food processing systems, into food quality and safety, textiles and much more. And, imaging high spectral resolution spectrometers are now being evaluated for the rapid scanning of foodstuffs, such as the inspection of whole chicken carcasses for fecal contamination[1]. The imaging methods are also finding their way into medical applications, such as the non-intrusive monitoring of blood oxygenation in newborns[2]. Can these scientific insights also be taken into space and successfully used to measure the Earth's condition? Is there an analog between the organic analyses in the laboratory and clinical settings and the study of Earth's living biosphere? How are the methods comparable and how do they differ?

The earth science community has become engaged in a study of the Earth's climate, ecological, lithological and hydrological processes on a truly planetary scale. This enormous effort is called Global Change involving internationally integrated programs such as the International Geosphere Biosphere Program. More recently, much of the astronomical as well as evolutionary and ecological communities are beginning an interdisciplinary study of life in the Universe, called Astrobiology. The search for a living planet other than Earth asks some of the same questions being addressed in Global Change. For example, how does one determine that a planet is potentially living? Part of this question has to do with the transformational power of the biosphere's metabolism. On Earth it involves the regulatory strength of the greenhouse gas, carbon dioxide, and its role in keeping Earth's climate within narrow limits of temperature suitable for life. Can NIRS be used to help assess the status of Earth's metabolism and monitor changes in it in response to changing climatic conditions? The success with which the biosphere can assimilate CO2 and respire it is regulated by the nutritional and water availability of an ecosystem. Can NIRS be used to assess these key biogeochemical cycling properties? NIRS is being used to study these and related "health" properties of Earth's biosphere, including the measurements of the greenhouse gases themselves and the response of the ecosystems to various stresses. How is this being done and what unique requirements does this place on the science of planetary biospheric analyses?[3]

A hyperspectral imaging device is simply an extension of multispectral devices which are common in Earth remote sensing. In general, as one adds more and more wavebands to an imaging instrument, one eventually ends up with a contiguous set of wavebands which exhaustively sample a spectral space. The advent of detector arrays enabled the invention of dispersive optical designs to achieve pushbroom sensors capturing a contiguous sample of as many as 400 narrow wavebands. The original scientific rationale for hyperspectral imaging sensors was geologic. Absorption features characteristic of many minerals have fairly broad absorptivities located uniquely throughout the 400-2400 nm spectral range. Silicon arrays are suitable for the visible to near infrared region while various infrared detector materials are suitable for arrays in the shortwave infrared. Because of the interest in detecting the presence of many different minerals in an image of the Earth's surface, the first imaging spectrometers for remote sensing were general purpose designs, covering a very broad spectral range. As one of the principal goals of geology is the detection and geographic mapping of minerals, the contiguous sampling of spectral space allows for the discrimination of the shape and location of these features and the unmixing of mixed mineralogic features using lookup tables and relative analytical techniques such as isolation of absorption profiles. By inclusion of the visible, the geobotany community could begin to look at the disruption of vegetation reflectance signals which might be indicative of geochemical processes such as gas seepages, hydrothermal vents and so forth.[4]

Probably the most successful hyperpsectral instrument to date is an airborne one, the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) produced by the NASA's Jet Propulsion Laboratory which operates from NASA's high altitude ER-2 aircraft at 20 km.[5] This instrument uses order sorting filters to segment spectral space into four regions for dispersive measurement using gratings. This instrument can achieve spectral resolutions of less than 10 nm covering the 400-2400 nm region. Through intensive attention to calibration, AVIRIS can now achieve signal to noise data as high as several hundred to one. While this is substantially less than values typical of the laboratory, the signals are nevertheless quite exceptional for remote sensing and have produced useful mapping results in the geological sciences. Soon after the appearance of AVIRIS, other dispersive designs were advanced including a prism spectrometer called HYDICE produced by an American agency, a spectral wedge produced by Santa Barbara Research Institute, an all reflective optics design of SAIC, and other grating designs from Canada and the United States. The first satellite hyperspectral sensor was to have been the antecedent of AVIRIS called the High Resolution Imaging Spectrometer (HIRIS), again by JPL and destined for the first EOS platform but which proved to be too costly, among other concerns. Finally TRW succeeded in building the Lewis satellite which employed a grating design and was launched, only to be lost in space. TRW is now using the spare parts from that design to fly a smaller version of the Lewis design on the first New Millenium satellite called EO-1.

In the early 80s, this author proposed to use imaging spectrometer data to analyze ecosystem reflectance properties for some of the variables related to the metabolism, nutritional status and water status of the Earth's biosphere[6]. This introduced a new challenge to the field of hyperspectral remote sensing. While mineralogy and biology share similar spectroscopic phenomena, i.e., the absorption of radiation is due to harmonics, overtones and combination bands of fundamental stretching frequencies of bonds, the goals of the research are different. The variables of interest to ecosystem analyses and biogeochemical cycling are properties such as the biochemical composition of plant canopies, the photosynthetic pigments and the water status of leaves. For example, the chlorophyll content of leaves provides a measure of the capacity for absorption of photosynthetically active radiation. The abundance of other accessory pigments is also useful in this determination. However, the ability of plants to convert this radiation into photosynthate and to use it for growth is regulated by the availability of nutrients and water in the soil. Can imaging spectrometric data provide a clue to these processes? The variables of interest are, first, the nitrogen content (proteins) of the leaves giving some direct insight to the nitrogen cycling in ecosystems, and the lignin content which determines the rate at which organic material in senesced leaves can be mineralized and made available for future plant uptake. These and other biochemical fractions are sensible by measuring the bonds associated with the absorption by C-O, N-H, O-H and C-N bonds in the organic molecules. This knowledge comes straight out of the outstanding laboratory research in the agricultural community. The difference between geology and biology thus comes down to whether one can use hyperspectral data to perform a quantitative prediction of biochemical content, since virtually all plants components have the same general chemical makeup only in continuously varying proportions. It is not sufficient to simply "detect" proteins, for example; one must be able to determine how much protein there is per unit of ground area.

This need to produce quantitative information places a heavy burden on the analysis of the data. For one thing, unlike the lab situation, one must deal directly with an ever-changing atmosphere. Not only does the atmosphere scatter radiation into and out of the field of view of the sensor, but it also absorbs radiation as a function of wavelength. In several regions of the infrared, in fact, water vapor in the atmosphere makes it impossible to even penetrate the atmosphere, regions near 1400 and 1900 nm, two regions with valuable biochemical absorption bond locations. However, the broad and high resolution data have proven useful in determining some of the water vapor characteristics of the intervening atmosphere and help to reduce these effects. The contiguous spectra, though coarser than lab spectra, are still usable to calculate first derivatives even though this degrades the signal to noise performance. The remote sensing field has long used band ratios of multispectral data to derive important ecosystem parameters such as leaf area index. These band ratios are crude approximations of the first derivative and hyperspectral data allow for much more meaningful calculations[7]. For example, the first derivative can reduce the influence of the prominent reflectance features of plant canopies (strong absorption in the visible and strong reflectance with powerful water absorption bands in the infrared) while emphasizing subtle shifts in absorption edges such as the chlorophyll red edge which can be shown to shift as a result of stress. Derivative spectroscopy has been a popular choice in the lab.

Calibration is another matter, however. Unlike the lab environment in which variations in sample preparation which induce variations in scattering can be beaten down with large sample sizes and efforts to produce uniformity to minimize uncertainty due to scattering, this situation does not prevail when studying ecosystems from space. Scattering varies initially as a function of cell size and number as well as changes in index of refraction at cell wall air interfaces internal to the leaf; additional scattering occurs at the leaf level (specular as well as diffusely), between leaves in the canopy and in the canopy as a whole. While the instruments themselves are carefully calibrated and recalibrated to reduce instrument noise, one cannot get away from the scattering in the image scene. There is also variation introduced by spatial variations in species type, plant condition, biochemical variations within a canopy and so forth. While the first results using imaging spectrometry were based on the same multiple regression techniques perfected by the NIRS community, it is clear that one must ultimately turn to complex radiative transport models to explain both scattering and absorption, with the hope to eventually invert these models to predict biochemical composition from a given spectrum. Researchers in Europe and the United States have begun to tackle this daunting problem with some success. One model, based on first principles of radiative transfer, has been developed by researchers at Ames and the University of Arizona, called LEAFMOD. Analyses with this model indicate that the effects of scattering can be separated from those due to absorption. Researchers in France have produced PROSPECT and a group in England have derived a version from PROSPECT called LIBERTY. These models are a potential means to deal with the scattering uncertainty and to derive absolute absorptivities of biochemical compounds in leaves and canopies.[8]

The demanding requirements of remotely sensing biochemical composition have also led to some new and innovative instrument designs. One of the most intriguing is imaging interferometry. In these instruments, using no moving parts, a spatially resolved interferogram is generated and measured by an array . Just as with grating designs, one axis of the array is used to sample a range of pixels in a frame (a linear set of pixels imaged on the ground) while the array is pushed through space by the moving platform (aircraft or spacecraft) to produce an image by successive sampling along the flight direction. The huge throughput advantage of these instruments lend them to miniaturization and the simple optical train give them ruggedness. While these instruments can produce hyperspectral images over a broad range with performance comparable to the grating spectrometers, they actually measure the spectral continuum and can do so for a small fraction of the weight and volume. However, imaging interferometers, such as the Digital Array Scanned Interferometer being built by Washington University -St. Louis and Ames[9], have some unique measurement capabilities better suited to more specific measurement goals such as derivative spectrometry and very high resolution measurement at specific spectral regions related to specific biochemical properties such as protein. At this point, the value of the radiation transport models is to establish the specifications for accurate measurement of these second order phenomena.

While a lot of progress has been made in the past 15 years developing hyperspectral imaging sensors and demonstrating their value for a wide range of applications, the future holds the promise of even more advancements, such as miniaturization and specialization.

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