Reflectance spectra from eutrophic Mono Lake, California, measured with the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS)

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ABSTRACT

An AVIRIS image was obtained for Mono Lake, California, on 26 May 1989, a day with excellent visibility. Atmospherically-corrected reflectance spectra derived from the image indicate a spectral signature for chlorophyll a, the dominant photosynthetic pigment in the phytoplankton of the lake. Chlorophyll a concentrations in the lake were about 22 mg m^{-3}, and the upwelling radiance was low with a peak reflectance at about 570 nm of about 5%. Coherent noise appeared in the image as regular variations of 0.1 to 0.2 $\mu W\ cm^{-2}\ str^{-1}$ oriented diagonally to the flight line. A simple ratio of two spectral bands removed the conspicuous undulations, but modifications of the shielding within the instrument are needed to improve the signal, especially over dark targets such as lakes.

1. INTRODUCTION

Lakes have several distinctive characteristics which require for their study by remote sensing the spatial and spectral resolution offered by imaging spectrometers such as the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS). In particular, most lakes are moderate to small-sized, have long interfaces with land and often have strong horizontal gradients in biological and physicochemical conditions. Furthermore, a very wide range of optical conditions occurs among lakes.

Recent satellite-borne sensors have permitted some success in the examination of lakes. While identification of open water and sediment-laden water is straightforward[1,2,3], quantitative detection of chlorophyll by the Landsat Multispectral Scanner and Thematic Mapper has had only modest results[4,5,6,7,8]. While the Coastal Zone Color Scanner (CZCS)[9] has proven valuable in mapping chlorophyll distributions in oceanic environments[10,11,12,13], its application to large lakes has been less common and less successful[14] and its application to small or moderate-sized lakes is precluded by its pixel size.

Accurate measurement of primary productivity is a major scientific problem in lakes and is amenable to significant improvement with application of imaging spectrometry. Primary productivity is generally estimated from measurements of the quantity of photosynthesizing material and the rate of carbon fixation per unit biomass. Much of the variance in such estimates is owed to temporal and spatial variability in the distribution of the photosynthetic organisms[8,15]. Synoptic coverage provided by remote sensing offers a considerable reduction in errors associated with spatial heterogeneity. Furthermore, phytoplankton species vary in pigment composition as a function of taxonomic group and nutritional status. Hence, additional improvements in estimates of primary productivity are possible if spectral signatures are obtained that permit discrimination of taxa or nutritional condition. Recent bio-optical modeling of oceanic primary productivity[16,17] shows promise for use in lakes when combined with data obtained from imaging spectrometers.

The principal problem with application of airborne imaging spectrometers to lakes is the weak upwelling signal, especially when narrow spectral bands with high spatial resolution are sought. Furthermore, atmospheric path radiance dominates the signal received from dark targets such as lakes. An additional potential concern is the adjacency effect[18], i.e. diffuse radiation scattered into the line-of-sight of the sensor from neighboring, bright terrain. Once atmospheric effects have been removed from the radiance received at the sensor, semi-empirical relationships can be developed to extract information about phytoplankton pigment concentrations for different underwater optical conditions[19,20,21,22]. In lakes where concentrations of dissolved organics and suspended detritus may not co-vary with phytoplankton pigments, the many spectral channels of an imaging spectrometer such as AVIRIS are likely to be required to distinguish the various aquasols.

AVIRIS utilizes silicon and indium antimonide line array detectors to cover the spectral region from 0.395 µm to 2.45 µm with 224 contiguous, 10-nm wide bands[23]. When flying at an altitude of 20 km aboard NASA's ER-2 aircraft, the instrument images a 614-pixel swath with ground instantaneous field-of-view of 20 m and a swath about 10 km wide. Ten-bit data are recorded onto 14-track high-density digital tapes at a rate of 17 Mbit s^{-1}. Signal-to-noise specifications for a surface albedo of 0.5 viewed through a standard LOWTRAN atmosphere with 23-km visibility are 100 to 1 at 0.7 µm. The electronics are packaged by major function in an attempt to isolate signal chains from other noisier circuitry.

The objectives of this paper are three fold: (1) To present reflectance spectra with the atmospheric path radiance removed for a lake with moderate phytoplankton abundance; (2) To estimate the chlorophyll content of the lake by applying CZCS-type algorithms to AVIRIS data; (3) To examine the spatial variability of reflectances from the lake. These objectives are prerequisites to an application of AVIRIS data for modeling of primary productivity in lakes.

2. METHODS

2.1. Study site

Mono Lake is a large (150 km^2), moderately deep (mean depth, 17 m), hypersaline (total dissolved solids, ca. 90 g L^{-1}) lake lying in the North American Great Basin just east of the Sierra Nevada, California (38°N, 119°W; elevation ca. 1942 m above sea level)[24]. A decade-long, ongoing limnological study has included examination of spatial variability of the plankton[5,25] and primary productivity[26]. The phytoplankton is dominated by very small (2-3 µm diameter) coccoid cells that vary in abundance from <1 to ca. 60 mg chlorophyll a m^{-3}. The offshore waters are largely uncontaminated by suspended particles from inflows.

2.2. Sampling and measurements

Two flight lines were flown over Mono Lake on 26 May 1989. Only the flight segment that covered the western and southern portions of the lake was used in the analyses reported here because the field sampling was limited to this region. The five segments acquired combine to include most of the lake.

Twenty locations (Figure 1) were sampled for phytoplankton on 26 May 1989. Integrated samples of the top 2 m were collected with a plastic tube at each location. The material was kept cool and in the dark during transport to the field laboratory, where the water was filtered onto 47 mm Gelman A/E glass fiber filters or 47 mm Whatman GF/F glass fiber filters; the filters were kept frozen (ca. -40°C) until pigments were analyzed. The filters were homogenized in 90% acetone, and the pigments extracted at room temperature in the dark for about 30 minutes. Following clarification by centrifugation, absorption was measured at 750, 665, 663, 645, 630, 570 and 480 nm. The samples were then acidified (0.1 ml of 0.1 N HCl per 3 ml of extract) in the spectrophotometer cuvette, and absorption was determined at 750 and 665 nm. Absorbances were converted to chlorophyll a, b and c and carotenoid concentrations[27] and to phaeophytin-corrected chlorophyll a concentrations[28]. At four locations underwater attenuation of photosynthetically available irradiance (PAR, 400 nm-700 nm) was measured with a submersible LiCor quantum sensor.

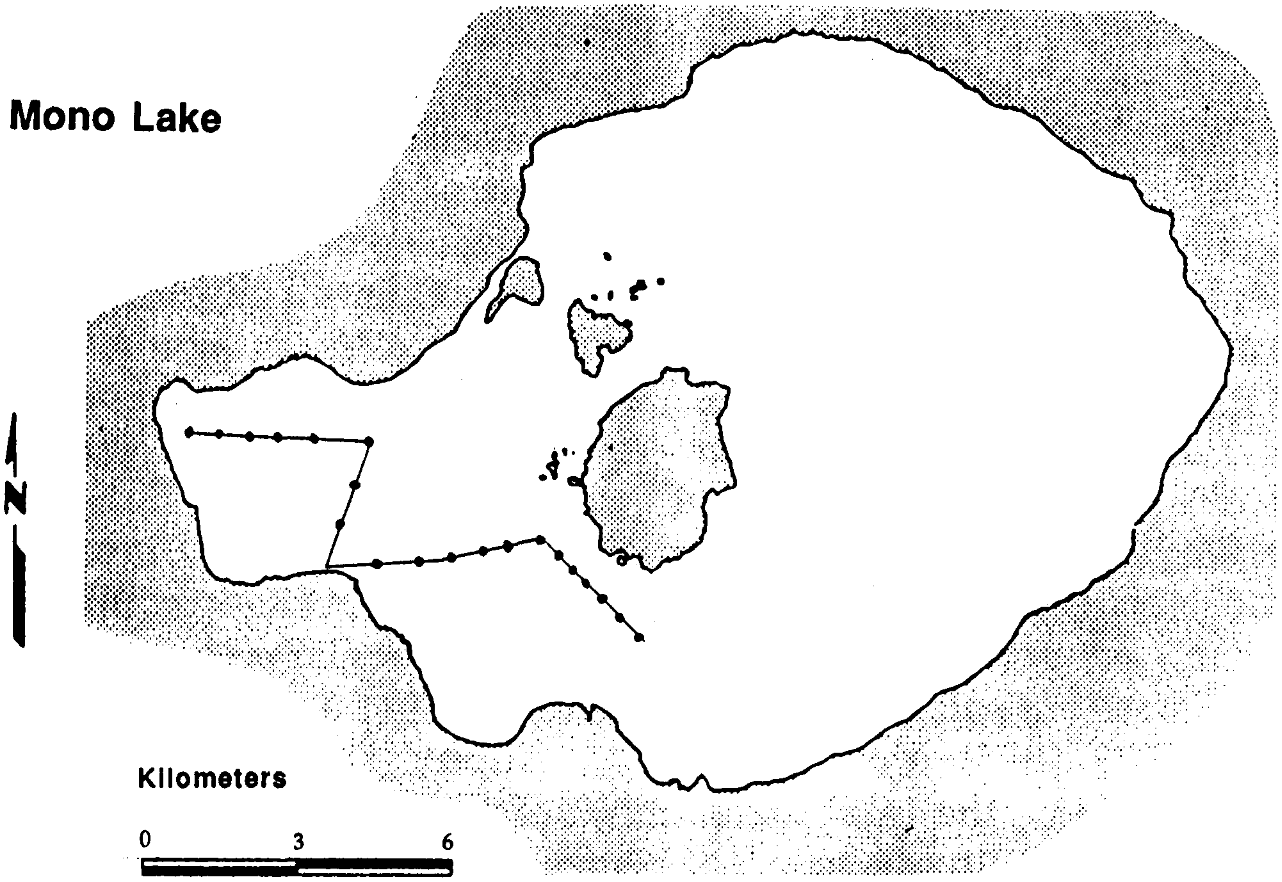

Figure 1 Mono Lake shoreline at lake level of 1945 m above sea level. Stippling is land. Line with dots is sampling transect; station numbers are consecutive from west (1) to east (20) along line.

On 26 May 1989, measurements were made with a Reagan radiometer of atmospheric conditions, and measurements of the spectral reflectance of dark, volcanic debris and bright deposits were made with the Portable Instant Display and Analysis Spectrometer (PIDAS)[29]. These measurements were used to calculate atmospheric corrections of the spectral imagery with LOWTRAN 7[30] and the empirical line algorithm[31].

3. RESULTS AND DISCUSSION

Visibility, as measured with the Reagan radiometer, was excellent on 26 May 1989; hence, conditions were ideal for imaging Mono Lake with AVIRIS.

Attenuation of PAR was 0.84 m^{-1}; hence the 10% light level was 2.7 m and the 1% light level was 5.5 m. Chlorophyll concentrations in Mono Lake were moderate (Figure 2, Table 1) compared to the seasonal range in Mono Lake. As expected, chlorophyll a is the dominant photosynthetic pigment in the phytoplankton. The minor amounts of chlorophyll b indicate the presence of chlorophytes, and the chlorophyll c indicates diatoms and/or chrysophytes.

Table 1. Pigment concentrations in Mono Lake, 26 May 1989; Mean ±1 standard deviation (SD) for 20 stations from Gelman A/E filters. Chlorophyll a concentrations determined from Whatman GF/F filters are about 10% higher. All but the first chlorophyll values are calculated according to Strickland and Parsons[27].

Pigment	Mean ± SD $mg\ m^{-3}$
Chlorophyll a[28]	22.3 ± 3.4
Chlorophyll a	21.6 ± 3.1
Chlorophyll b	5.3 ± 1.3
Chlorophyll c	5.7 ± 2.2
Carotenoid 1	10.5 ± 2.5
Carotenoid 2	8.4 ± 1.9

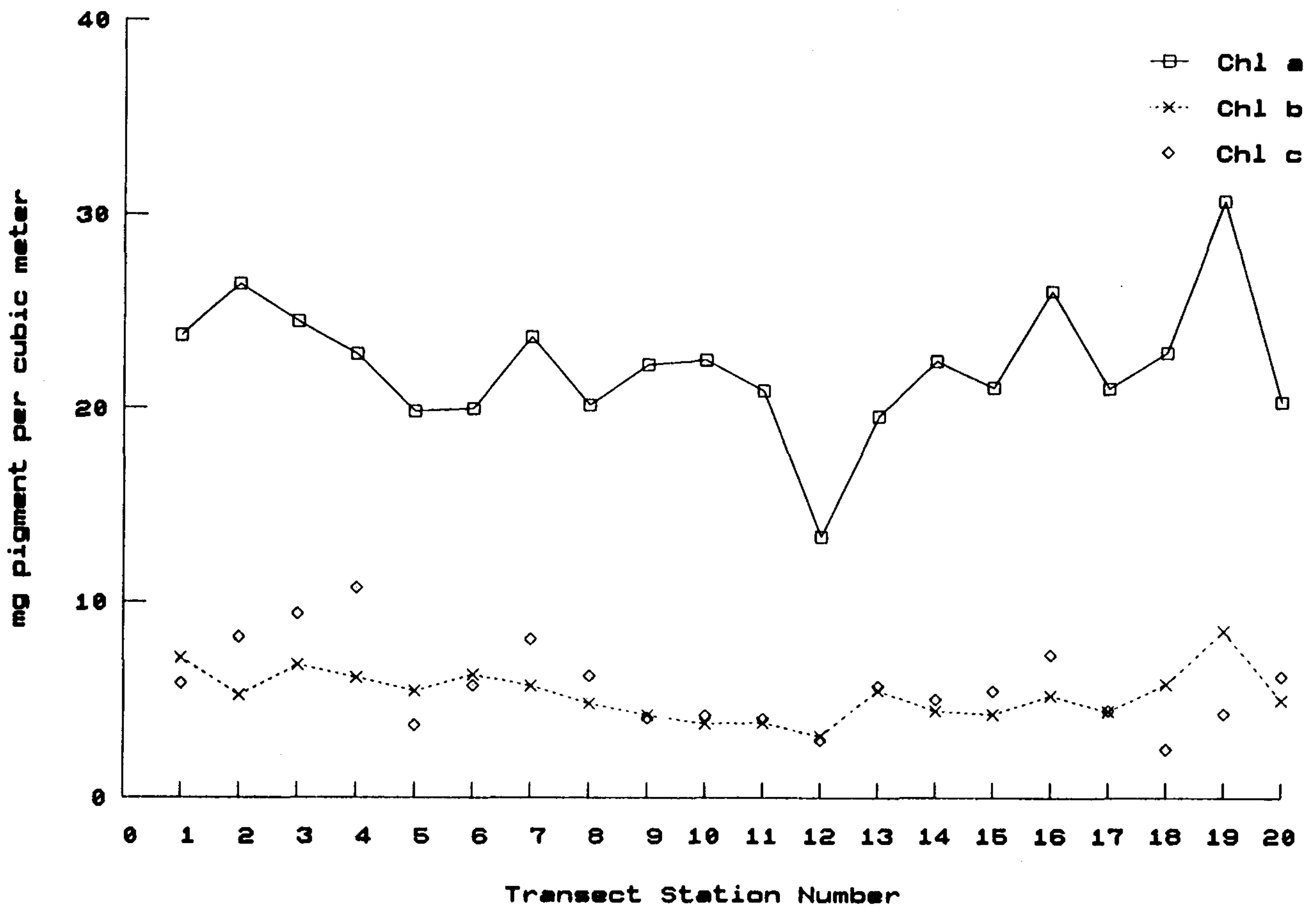

Figure 2 Chlorophyll (chl) a, b, c concentrations at 20 stations in Mono Lake, 26 May 1989. Chl a is phaeophytin corrected using the method of Golterman[28]; chl b and chl c are calculated using the method of Strickland and Parsons[27].

As an initial attempt to calculate chlorophyll concentrations in Mono Lake from AVIRIS data, the CZCS algorithm developed for oceanic waters with about 1 mg chlorophyll m^{-3} was applied. CZCS spectral bands at 520 and 550 nm were simulated by a weighted summation of the four AVIRIS bands closest to each of the two CZCS bands. The weighting factors were derived from applying a normal distribution to the 20 nm full width-at-half maximum locations of the two CZCS bands. The chlorophyll concentration was calculated using the equation:

$$\log_{10} \text{chla} = 0.522 + 2.44 \left(\log_{10} \left({}^{L_w550}/{}_{L_w520}\right)\right) \quad (1)$$

where L_w550 and L_w520 are the upwelling radiances at 550 nm and 520 nm. This algorithm produced chlorophyll values of about 10-12 mg m^{-3}. These values are about half those measured in the lake (Table 1). However, the actual values in Mono Lake exceeded by about an order of magnitude the values used to develop the CZCS algorithm. Moreover, the lake probably contains other aquasols that behave different optically from those typically found in offshore oceans. Further research, now in progress, will utilize more of the spectral information from AVIRIS to develop new algorithms appropriate for inland waters.

Atmospherically-corrected reflectance spectra from Mono Lake indicate a signature of chlorophyll a (Figures 3 and 4). Both the empirical line method and LOWTRAN served well for atmospheric correction as judged by visual inspection; further comparison is warranted. Maximal reflectance broadly peaked at about 570 nm; a secondary peak occurred between 400 and 450 nm. Reflectance minimum occurred at about 680 nm and 480 nm, the regions of chlorophyll absorbance peaks. These reflectance spectra are among the first good spectra obtained for inland waters with AVIRIS.

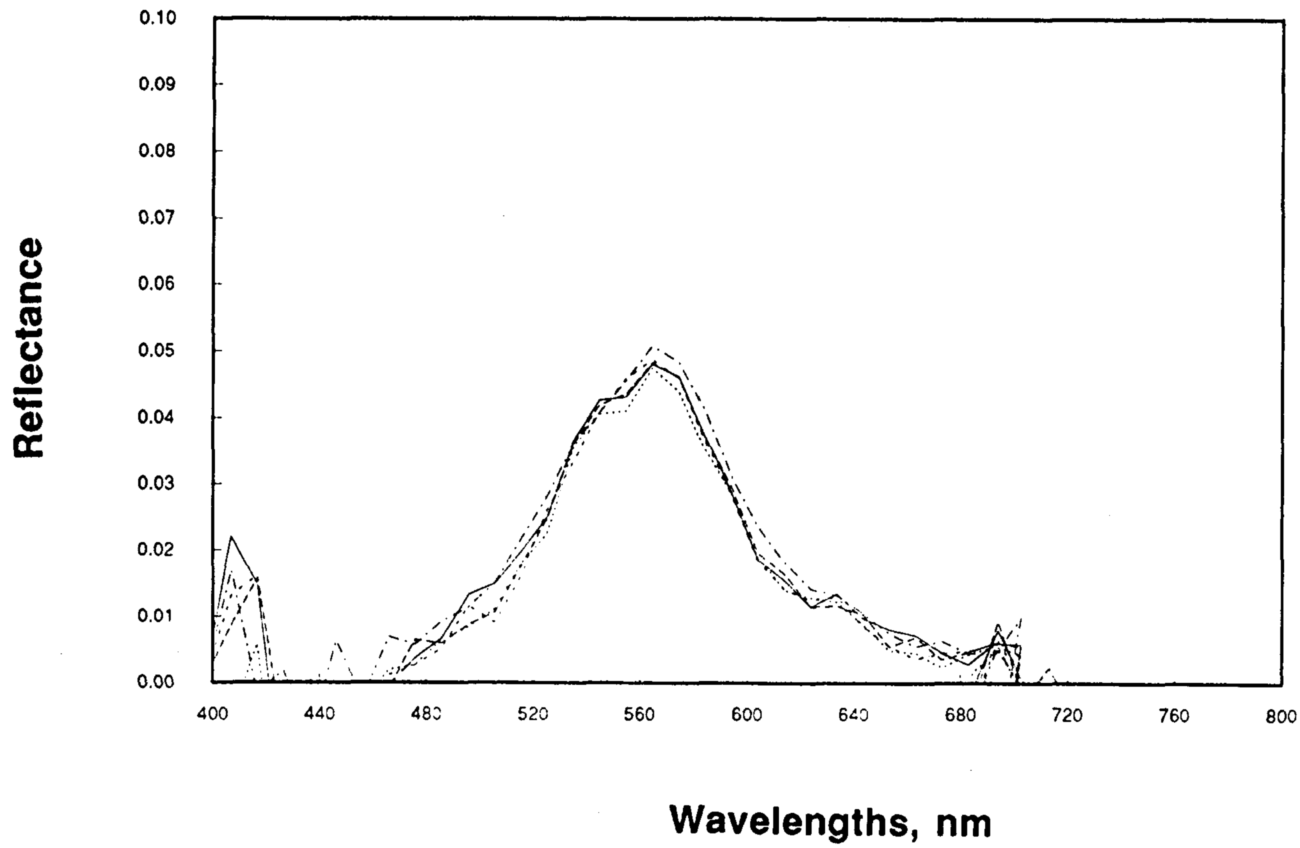

Figure 3 Reflectance spectra, atmospherically corrected with empirical line method[30], for five pixels in south-central Mono Lake, 26 May 1989.

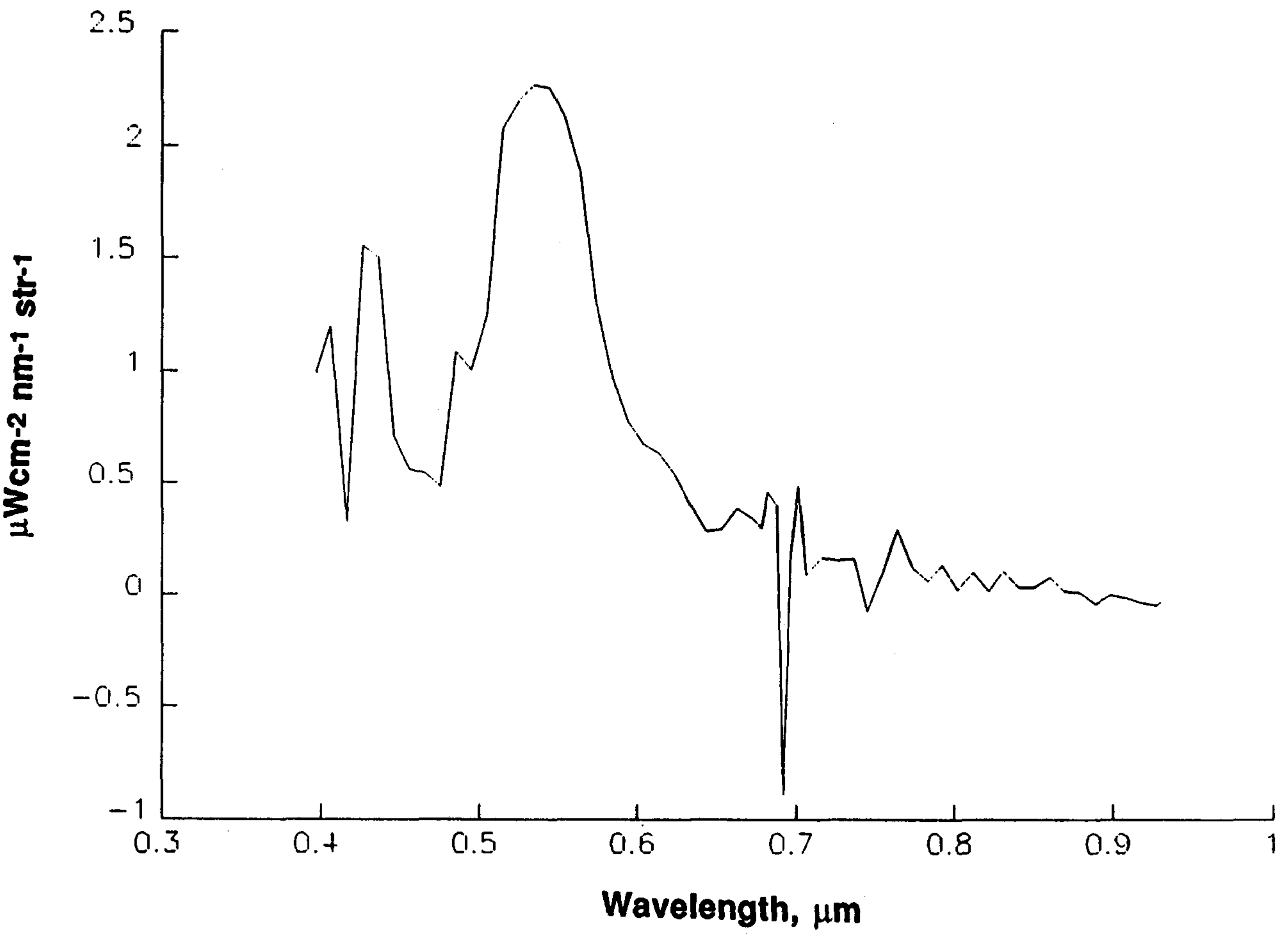

Figure 4 Reflectance spectrum, atmospherically corrected with LOWTRAN 7, for a 15 x 15 pixel averaged region in west-central Mono Lake, 26 May 1989. Spike at about 0.69 μm is an artifact of switch from spectrometer A to B.

As expected for a dark target such as an eutrophic lake, the reflectances are low. Maximal values are about 5%, and the low upwelling radiances (0.5 to 2.5 μW cm^{-2} nm^{-1} str^{-1}) impose high signal to noise requirements on the instrument. During the period in which these data were taken, the instrument detection capability varied from approximately 0.35 to 0.1 μW cm^{-2} nm^{-1} str^{-1} over the wavelengths from 410 to 550 nm. In addition, coherent noise was evident in the imagery (Figure 5). The largest of these effects appears in the form of 0.1 to 0.2 μW cm^{-2} nm^{-1} str^{-1} undulations oriented diagonally to the flight line (Figure 6).

Deciphering spectral signatures of even broad classes of absorbers such as chlorophyll, phaeopigments, and suspended sediments, will require the ability to distinguish 0.1 to 0.05 μW cm^{-2} nm^{-1} str^{-1} differences in upwelling radiance. In order to obtain this goal it will be necessary to remove a large portion of the coherent noise patterns and make use of spatial, and possibly spectral, data binning. Most of the coherent noise is now known to be due to aircraft operation, which may be improved by planned modifications to the shielding of the instrument.

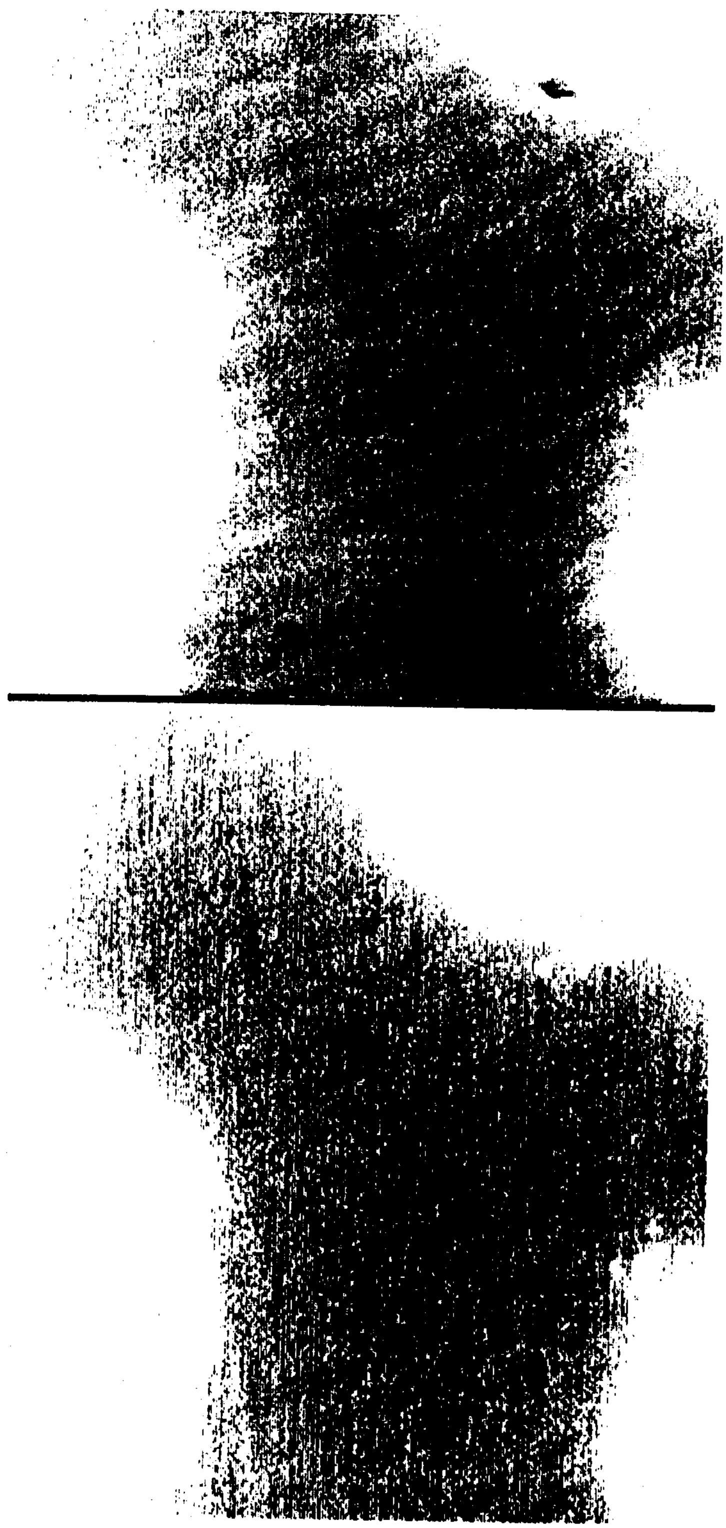

Figure 5 AVIRIS images (26 May 1989, flight 5, run 3, segment 4) of western and southern Mono Lake. Top panel is 937 nm-centered band and bottom panel is 535 nm-centered band. Images are masked to remove land and stretched to ±2 standard deviations of within lake reflectances.

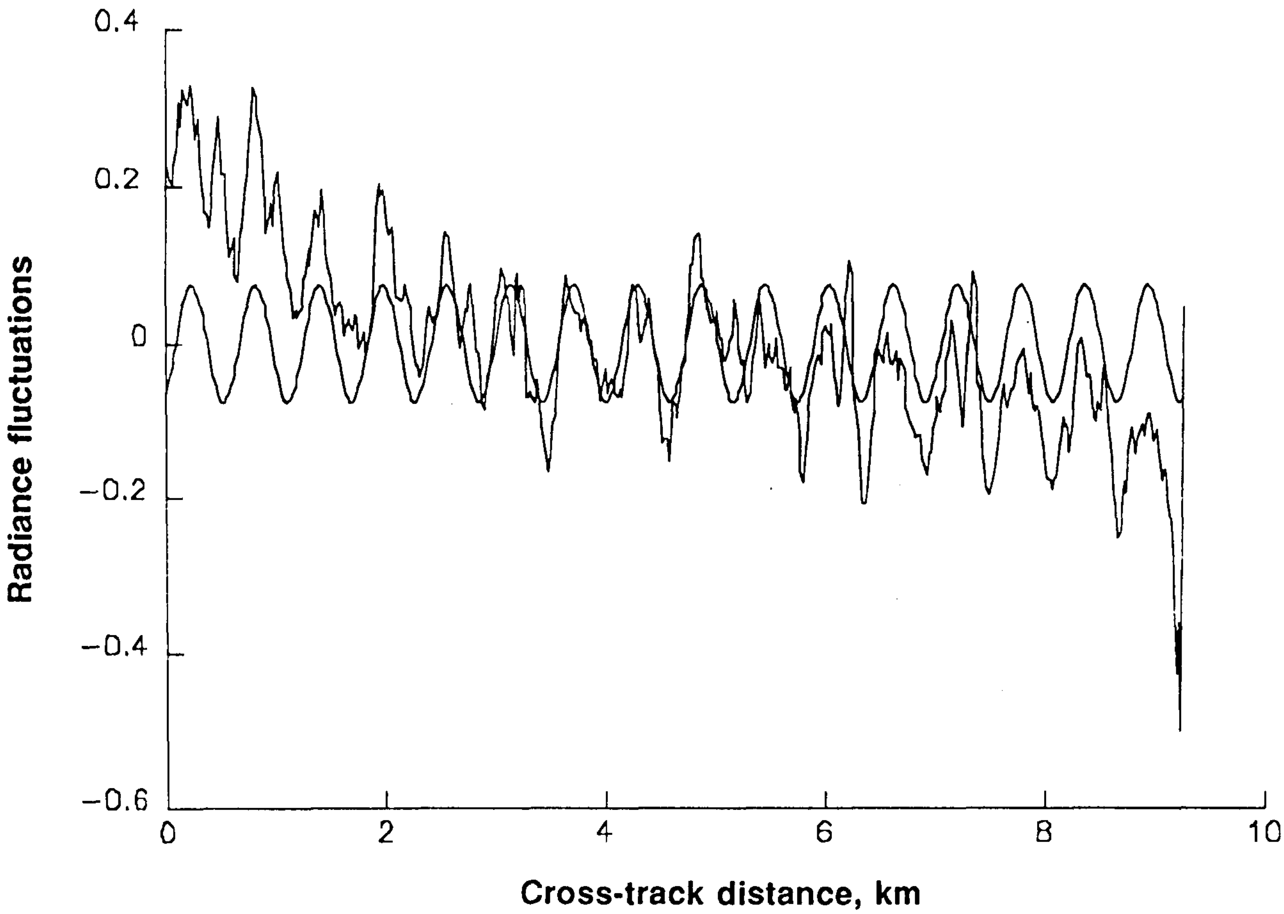

Figure 6 Transect of averaged radiance fluctuations ($\mu W cm^{-2} nm^{-1} str^{-1}$) from east to west across the scene shown in Figure 5, plotted together with the inverse Fourier transform of the most significant peak from the power spectrum. The data represent an average over bands 2 to 29 (415 to 682 nm), and part of the large scale slope is probably due to faulty vignetting correction.

To remove the coherent noise a simple ratio of two spectral bands was calculated after confirming that the undulations were in the same location in the different spectral bands. AVIRIS channels with midpoints of 515 and 545 nm were ratioed because these are approximately the bands used with the CZCS algorithm. After calculating ratios, masking the land using the AVIRIS channel centered at 937 nm, stretching the image and averaging 5 x 5 pixels, an across lake variation was evident. Slightly brighter regions one half to one km wide appeared around the perimeter of the lake. These regions are not caused by vignetting because the lake shore was not on the edge of the image, and are unlikely to be an adjacency effect because of the extreme clarity of the atmosphere on the day of the overflight. The underwater attenuation of light was too great for the bottom to be influencing the signal. Hence, the pattern may indicate differences in phytoplankton abundance, but limnological sampling was insufficient to test this possibility.

To further examine spatial variability in the image, an unfiltered fast Fourier transform was performed on the deviations from the mean of the ratio of the reflectances at 545 and 515 nm for an east to west transect of 360 pixels (Figure 7). While this preliminary analysis must be considered cautiously, a conspicuous minimum in variance occurred at a spatial scale of 240 m and maxima in variance occurred at 80 m and 1500 m and perhaps at 50 m and 360 m. Interpretation of these features is premature until further filtering of the coherent noise and additional analysis of the spatial patterns in variance are performed.

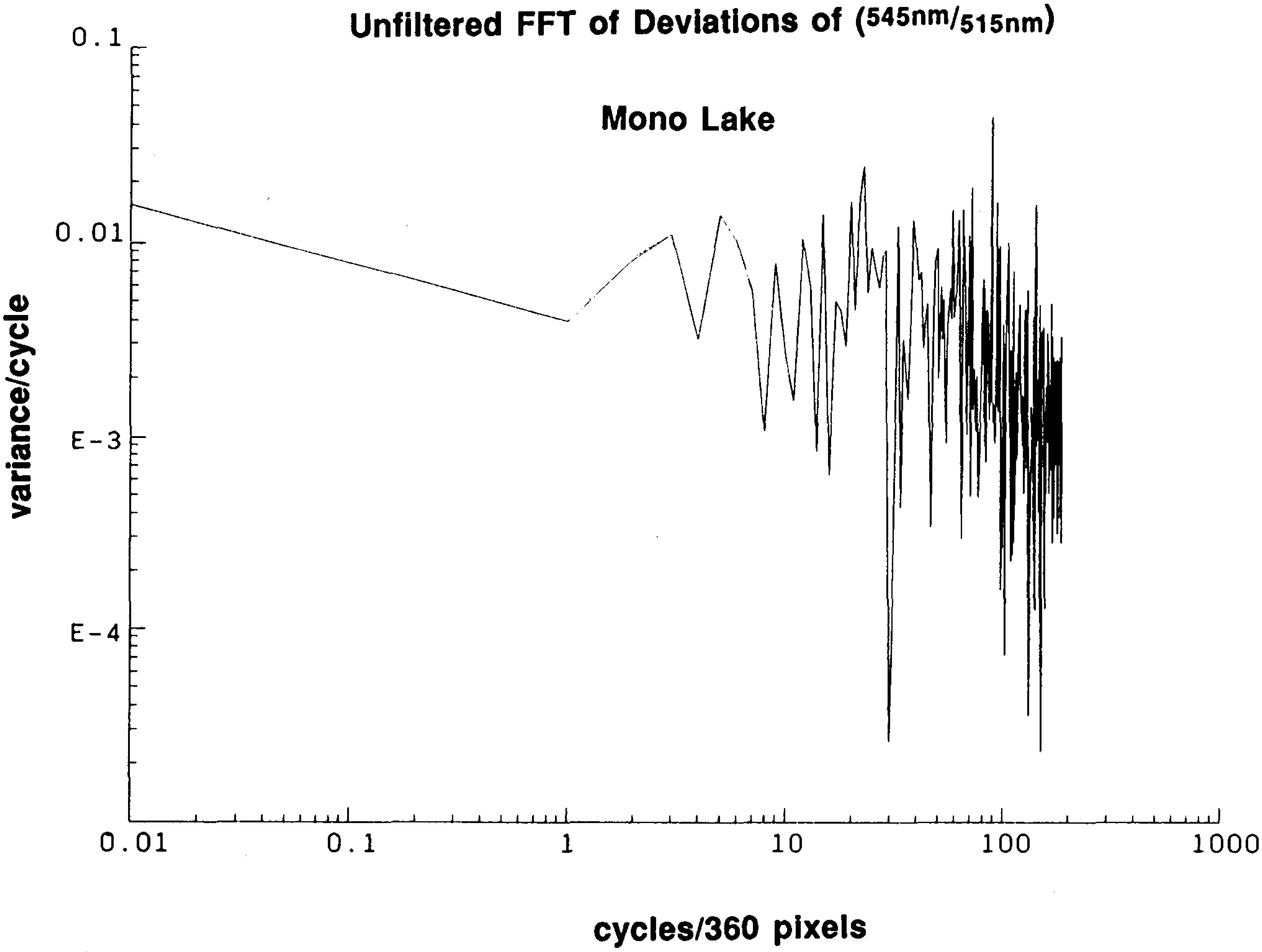

Figure 7 Unfiltered fast Fourier transform (FFT) of deviations from mean of ratios of upwelling radiance at 545 nm and 515 nm; E-3 is 0.001; E-4 is 0.0001.

During 1990, AVIRIS imagery will be obtained from Mono Lake during two seasons and from neighboring lakes with different optical properties. If the coherent noise can be reduced, which is likely, this imagery promises to permit ecological interpretation of spatial patterns in upwelling radiances. Improvements in the algorithms to calculate chlorophyll concentrations, which utilize more of the spectral signature provided by AVIRIS, will permit examination of phytoplankton distribution and better estimates of primary productivity.

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