

# The Spectral Image Processing System (SIPS)—Interactive Visualization and Analysis of Imaging Spectrometer Data

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*The Center for the Study of Earth from Space (CSES) at the University of Colorado, Boulder, has developed a prototype interactive software system called the Spectral Image Processing System (SIPS) using IDL (the Interactive Data Language) on UNIX-based workstations. SIPS is designed to take advantage of the combination of high spectral resolution and spatial data presentation unique to imaging spectrometers. It streamlines analysis of these data by allowing scientists to rapidly interact with entire datasets. SIPS provides visualization tools for rapid exploratory analysis and numerical tools for quantitative modeling. The user interface is X-Windows-based, user friendly, and provides "point and click" operation. SIPS is being used for multidisciplinary research concentrating on use of physically based analysis methods to enhance scientific results from imaging spectrometer data. The objective of this continuing effort is to develop*

*operational techniques for quantitative analysis of imaging spectrometer data and to make them available to the scientific community prior to the launch of imaging spectrometer satellite systems such as the Earth Observing System (EOS) High Resolution Imaging Spectrometer (HIRIS).*

## INTRODUCTION

Maps of the distribution and composition of materials on the Earth's surface are an important source of information for scientific investigations of resources, environment, and man-made change on our planet. During the late 1980s and early 1990s, imaging spectrometry has emerged as an exciting technology that provides the potential for rapidly producing both traditional surface-cover maps and new maps based on quantitative measurement of Earth-surface properties. Imaging spectrometers acquire images simultaneously in many narrow, contiguous spectral bands (Goetz et al., 1985). The data can be thought of as a "cube" of the dimensions #lines × #samples × #bands. NASA's operational imaging spectrome-

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ter, the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), presently acquires data in up to 224 spectral bands (Vane et al., 1993). Data collected by these instruments can be displayed and analyzed as either images or as detailed spectra; one spectrum for each picture element in the image. High spectral resolution reflectance spectra collected by imaging spectrometers allow direct identification and characterization of individual materials including minerals, vegetation, water, ice and snow (Goetz et al., 1985; Vane and Goetz, 1985; 1986; Vane 1987; 1988; Green, 1990; NASA, 1987).

The strength of imaging spectrometry lies in the simultaneous use of spatial and spectral information for integrated analysis. Previous software packages, the Spectral Analysis Manager (SPAM) (Mazer et al., 1988) developed at the Jet Propulsion Laboratory (JPL) and the Integrated Software for Imaging Spectrometers (ISIS) developed at the U.S. Geological Survey in Flagstaff (Torson, 1989) utilized this concept to permit interactive analysis of subsets of imaging spectrometer data. While providing basic capabilities, these packages did not satisfy many of the user community's scientific requirements primarily because they did not provide utilities for preprocessing or calibration, only allowed analysis of a small part of the image cube, and were hardware-specific. Despite promising results from AVIRIS data using these and other software packages in the geological sciences, terrestrial ecology, hydrology, and oceanography, scientists have not yet tapped the full potential of the data. The volume and complexity of information contained in the imaging spectrometer data have made detailed analyses difficult, and only a small fraction of the data collected have ever been analyzed to extract quantitative information.

The Spectral Image Processing System (SIPS) is a software package developed by the Center for the Study of Earth from Space (CSES) at the University of Colorado, Boulder, using IDL (the Interactive Data Language, a proprietary programming language) (Research Systems Inc., 1991) in response to a perceived need to provide integrated tools for analysis of imaging spectrometer data both spectrally and spatially. Many of the ideas and techniques incorporated into SIPS are the result of nearly 10 years experience with imaging spectrometer analysis by principals at

Table 1. SIPS Version 1.1 Hardware Platforms and Required Software Versions

Hardware	Color	Operating System	Window Manager	IDL
DECstation 3100	8-bit	Ultrix 4.1	Motif 1.1	IDL 2.2.2
DECstation 5000	8-bit	Ultrix 4.1	Motif 1.1	IDL 2.2.2
IBM RISC 6000	8-bit	AIX 3.1	Motif 1.1	IDL 2.2.2
SUN	8-bit	SunOS 4.1	Openlook 2.0	IDL 2.2.2
SGI with xterm	8-bit	IRIX 4.0	4Dwm	IDL 2.2.2

CSES (Goetz, 1981; 1984; Goetz et al., 1985; Goetz and Calvin, 1987; Goetz and Boardman, 1989; Gao and Goetz, 1990; Goetz and Davis, 1991; Kruse et al., 1985; 1990; Kruse, 1987, 1988; Kruse and Dietz, 1991; Boardman, 1989; 1990; 1991). This manuscript describes the version 1.1 implementation.

SIPS was specifically designed to deal with data from AVIRIS and the High Resolution Imaging Spectrometer (HIRIS) (NASA, 1987), but has been tested with other data sets including the Geophysical and Environmental Research Imaging Spectrometer (GERIS), GEOSCAN images, and Landsat TM. It takes advantage of high speed disk access and fast processors running under the UNIX operating system (Table 1) to provide interactive analysis of entire imaging spectrometer data sets. SIPS is specifically designed to allow analysis of single or multiple imaging spectrometer data segments at full spatial and spectral resolution. It also allows visualization and interaction analysis of image cubes derived from quantitative analysis procedures such as absorption band characterization and spectral unmixing.

SIPS version 1.1 presently consists of three modules: SIPS Utilities, SIPS\_View, and SIPS Analysis (Fig. 1). The SIPS Utilities are programs for disk-to-disk processing of imaging spectrometry data and include tape reading, data formatting, calibration to reflectance, and cosmetic processing of the data. SIPS\_View provides interactive visualization and analysis capabilities for large imaging spectrometer data sets. It provides a user-friendly interface through the use of the X-Window system and "widgets" such as menus, buttons, and slider-bars. SIPS\_View provides the capability to interactively select and enhance bands to make color-composite images. It allows rapid extraction and display of individual spectra, or of spectra extracted from polygon regions. These spectra can be visually compared to library

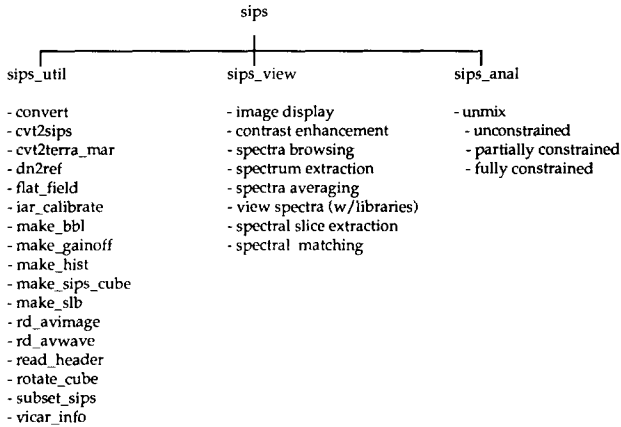


Figure 1. Tree diagram showing functions of the Spectral Image Processing System (SIPS). Brief descriptions of the SIPS Utility functions are given in Table 2.

spectra or automatically matched to spectral end-members. Extraction of spectral slices also allows display of spectral data as stacked, color-coded spectral images (Marsh and McKeon, 1983). SIPS Analysis is a set of programs for detailed, full-cube analysis of imaging spectrometry data. These are primarily programs that require extensive mathematical calculations and CPU time that are not amenable to interactive analysis on a complete data set. Together, these three modules provide the capabilities to proceed from raw radiance data to final analysis results and output.

## SIPS DESIGN CRITERIA

The following requirements for the next generation of imaging spectrometer software were defined based on an informal user survey and documented research needs of CSES scientists in a variety of disciplines.

- The system should allow routine analysis of imaging spectrometer data sets to minimally include AVIRIS, GERIS, and Eos HIRIS.
- It should be flexible enough to permit limited analysis of other multispectral data sets such as Landsat MSS, Landsat TM, and SPOT.
- The system should provide utilities for input of data, data formatting, data calibration, and other common image processing tasks.

- Data visualization tools should be provided for rapid, exploratory analysis.
- Numerical tools should be provided for quantitative modeling with the results displayed visually in real time.
- The tools and techniques provided should be generally useful across multiple disciplines.
- The software should have a user-friendly interface.
- The software should be independent of specific image display hardware.

## SIPS UTILITIES

The SIPS utilities module contains tools that prepare data for input to SIPS\_View, the analysis programs, and other image processing software. These tools are written in IDL, with the exception of the tape reading utilities. The tape utilities are either IDL programs that spawn processes written in the C programming language or are written entirely in C. SIPS utilities operate on images with standard headers conforming to the Planetary Data System (PDS) format (Jet Propulsion Laboratory, 1991). The utilities all have a command line interface and some also have an interactive graphical interface. A list and brief description of tools presently available is given in Table 2. Details of the header format including any variation from the PDS format and a complete list of parameters and detailed usage instructions for each tool are given in the *SIPS User's Guide* (CSES, 1992).

Most of the SIPS utilities format image data or create files for input to SIPS\_View. For example, when starting with AVIRIS data on tape, the *rd\_avimage* utility is used to create a band sequential (BSQ) and/or band interleaved by pixel (BIP) and/or band interleaved by line (BIL) cube from the raw radiance data on that tape. The *rd\_avwave* utility is used to create a wavelength table from the tape. To derive apparent reflectance values from the raw radiance values using the empirical line calibration (Roberts et al., 1985), the *make\_gainoff* and *dn2ref* utilities are executed using the BSQ cube as input. The data set for input into SIPS\_View is completed using *convert*, *make\_hist*, and *make\_bbl* to create the calibrated BIP image cube, a histogram file and a bad-band-list file.

Table 2. Description of SIPS Utilities

<u>Tape Utilities</u>	
rd_avimage:	Reads an image cube, with or without VICAR labels, from an AVIRIS tape; all present JPL AVIRIS tape formats are supported
rd_avwave:	Reads the wavelength and FWHM data from an AVIRIS tape and outputs wavelength file; this wavelength file is used as input to SIPS_View
vicar_info:	Displays the VICAR label information for each tape file
<u>File Utilities</u>	
convert:	Converts the storage order of an input cube that is in BSQ, BIP, or BIL to either BSQ, BIP or BIL format
cvt2sips:	Creates an output cube with a standard SIPS header from BSQ, BIP, or BIL formatted non-SIPS data with any size header
cvt2terra_mar:	Creates an output cube with a standard Terra-Mar header (used in Terra-Mar MICROIMAGE software) from a BSQ input cube
make_bbl:	Creates a bad-bands file; the bad-bands file can be used as input to SIPS_View to mask out bad bands during spectral processing
make_hist:	Creates a histogram file from an input BSQ cube file with a standard SIPS header; the output file is used as input to SIPS_View for rapid contrast stretching
make_sips_cube:	Creates a BSQ formatted output cube with a standard SIPS header from multiple non-SIPS input image files; the output cube can be used as input to most other utilities and to SIPS_View
make_slb:	Creates a SIPS spectral library file containing any number of ASCII spectra files
read_header:	Looks for a standard SIPS header in the input file and prints out the header information; if no header is found, it prints an error
rotate_cube:	Rotates the cube 90°, 180°, or 270°; this utility can be used to change the orientation of the image in the Image Window
subset_sips:	Extracts a subset of an input cube and writes it to a cube file with a standard SIPS header
<u>Calibration Utilities</u>	
make_gainoff:	Uses the empirical line method using selected areas on the ground to calibrate the data to reflectance (Roberts et al., 1985; Elvidge, 1988; Kruse et al., 1990). This calibration method requires choosing two or more ground target regions with diverse albedos and acquiring field or laboratory spectra to characterize them. <i>make_gainoff</i> uses the ground target reflectance spectra and the associated image radiance spectra to perform a linear regression for each band to determine the gains and offsets required to convert the DN values to reflectance. The output is a file containing the gains and offsets that can be used as input to <i>dn2ref</i>
dn2ref:	Applies gains and offsets calculated by <i>make_gainoff</i> to the entire imaging spectrometer cube; it uses a raw radiance image file and outputs a calibrated apparent reflectance cube
flat_field:	Removes a single spectrum for an area selected by the user with a uniform spectral response from the entire cube by division; it uses a raw radiance image file and outputs a calibrated apparent reflectance cube
IAR_calibrate:	Removes the global average spectrum for a cube from the entire cube by division to calibrate to Internal Average Relative Reflectance (IARR) (Kruse, 1988); it uses a raw radiance image file and outputs a calibrated apparent reflectance cube

The remainder of the SIPS utilities operate on image data to prepare them for input to various image processing software. For example, *make\_sips\_cube* and *cvt2sips* create an image file with a standard SIPS header. As another example, the *cvt2terra\_mar* utility converts an image file with any type of header to an image file that can be used with the Terra-Mar “MicroImage®” software (Terra-Mar, 1991).

## SIPS\_VIEW

### General

SIPS\_View is an interactive IDL program that allows the user to visualize and work with imaging spectrometer data both spectrally and spatially. It uses “widgets” along with mouse and keyboard

input to create a user-friendly interface. A widget is a simple graphical object, such as a pushbutton, slider, or menu that allows users easy interaction with the program. A more detailed description of widgets is given in Table 3. Interaction by the user on a given widget produces what is referred to as an “event” from that widget. When the user generates an event (by pushing a button, moving a slider, etc.), the software is then able to respond to the event by performing some function. An example of the SIPS\_View main window using IDL widgets under Motif (OSF, 1989) is shown in Figure 2.

In addition to the main window, SIPS\_View creates and manages many other windows throughout its execution. The “Status Window” is a normal text widget on the lower right hand corner of the SIPS\_View main window that dis-

Table 3. Definition of Widget Types and Actions

Button widget	Used to select a given option. It consists of a rectangular region with a label. "Pushing" the button by moving the mouse cursor over the button and pressing the left mouse button generates an event
Slider widget	Used to select a value from a range of possible values. It consists of a rectangular region inside of which is a sliding pointer that displays the current value. The slider is "grabbed" by placing the mouse cursor over the slider pointer and holding down the left mouse button. Moving the mouse while continuing to hold the mouse button down will change the slider value
Menu widget	Used to select one or more items from a given list. It consists of a rectangular region with a list of items, each with its own toggle button with an "on" and "off" state
Pull-down Menu widget	Used to select a given option from a list of options. It consists of a button widget that when pressed expands into the list of choices. The menu may be viewed (or the menu item executed) by moving the mouse cursor into the menu button and clicking the left mouse button
List widget	Used to select one item from a list of items. It consists of a rectangular region with a list of items, one item per line. Moving the mouse cursor over an item and clicking the left mouse button generates an event and selects the item
Editable Text widget	Used to receive user input from the keyboard. It consists of a rectangular region that when "activated" will display and act on characters typed from the keyboard
Normal Text widget	Used to display text in a window. It consists of a rectangular region, usually surrounded by a frame, where the program may display text
Draw widget	Used to display a standard IDL graphics window within a widget application. It consists of a rectangular region where plots and images are displayed

plays useful information about the current state of SIPS\_View, and the functions that the three mouse buttons will currently perform. The last two lines of the Status Window report processing status. The "Scroll Window" (not shown in Fig. 2) displays a subsampled image if a data set is larger than the standard 512 line  $\times$  614 pixel AVIRIS image and allows extraction of a full resolution image for a desired location. The "Image Window" contains the image at full resolution. The "Zoom Window" contains a subset of the image zoomed from 1 to 16 times. The "Current

Spectrum Window" and "Saved Spectra Window" are used for viewing, extracting and saving spectra. Other windows such as "View Spectra," "Spectral Slices," and the "SAM Viewer" are created only when accessed by the menu fractions.

SIPS\_View requires as a minimum one image cube in either BSQ, BIL, or BIP format to run. Optimum functionality and performance are obtained if both a BSQ and BIP file are present. The second copy of the data in BIP format allows quick access to individual spectra. Other optional files including a wavelength file, histogram file, bad-band file, and spectral libraries enhance the performance and utility of the program. The wavelength file allows the SIPS\_View to associate each band to a specific wavelength. The histogram file allows the program to quickly perform stretches of 16-bit data to byte data for display. The band-band file allows users to mask out unwanted bands when plotting and analyzing spectra. File characteristics and formats are described in detail in the SIPS User's Guide (CSES, 1992).

### SIPS\_View Display Functions

Nearly all of the available functions in SIPS\_View perform their operations in the Image, Zoom, Current Spectrum, and Saved Spectra Windows located within the main SIPS\_View window (Fig. 2). The display functions operate on the image data in its spatial format and are accessed by clicking on the pull-down "Image Menu." When SIPS\_View is started, a gray-scale image is displayed. If the image is larger than 512  $\times$  614, SIPS\_View will display the full image subsampled to fit into the Scroll Window. Scrolling is used to allow the user to view different portions of the image at full resolution. The Image Window displays the full resolution image in a 512 line  $\times$  614 sample window with a default 2% linear contrast stretch applied. The displayed image can be a gray-scale or density-sliced image of a specific band, a color composite image of three bands, or a gray-scale image of analysis results. An example of a typical SIPS user session screen is shown in Figure 3. Possible actions associated with the Image Window include:

- selecting which band is displayed
- selecting the display mode, zoom factor, and contrast stretch of the band displayed

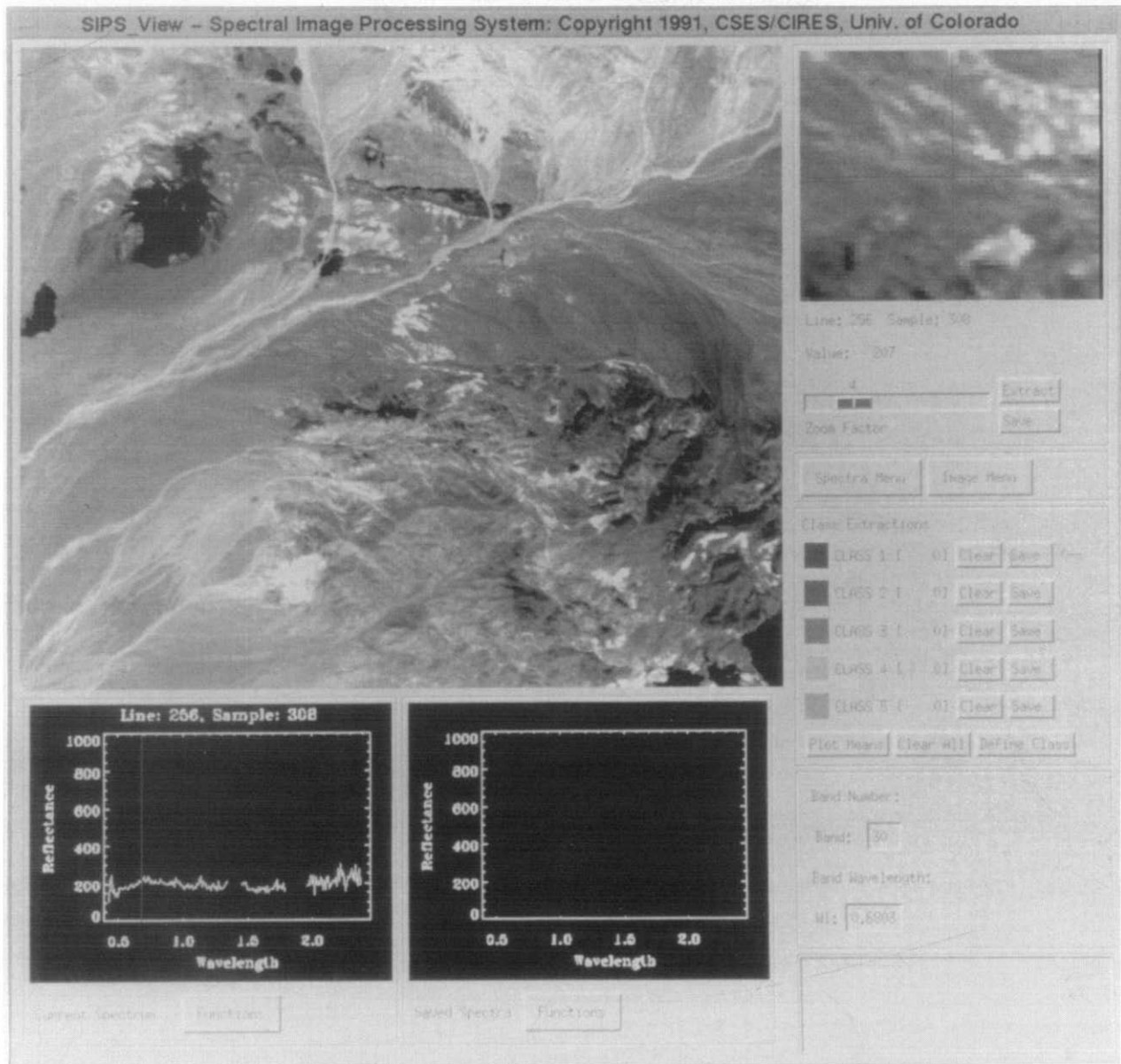


Figure 2. The initial view of the SIPS\_View main window using IDL widgets under Motif.

- saving the current image to a data file or a color PostScript file

#### Image Display

Individual bands can be selected by entering the band number or wavelength, or by using slider bars (Fig. 3). Grabbing and moving the slider changes its value and thus the band displayed. SIPS\_View can display the current band as a gray-scale or a density-sliced image, or display three bands as an RGB color composite. Selecting "Toggle Color On" on the pull-down Image Menu

causes SIPS\_View to replace the single slider used for selecting a single band number with three sliders used for selecting a red, green, and blue band number. Grabbing any of these sliders and selecting a new band number to display in that color causes SIPS\_View to read and display the new color composite image when the slider is released. Selecting "density-slice" on the menu provides an 18-color RGB ramp for a single image where low brightness values are represented by blacks and blues and high brightness values are represented by reds and whites. Individual ranges

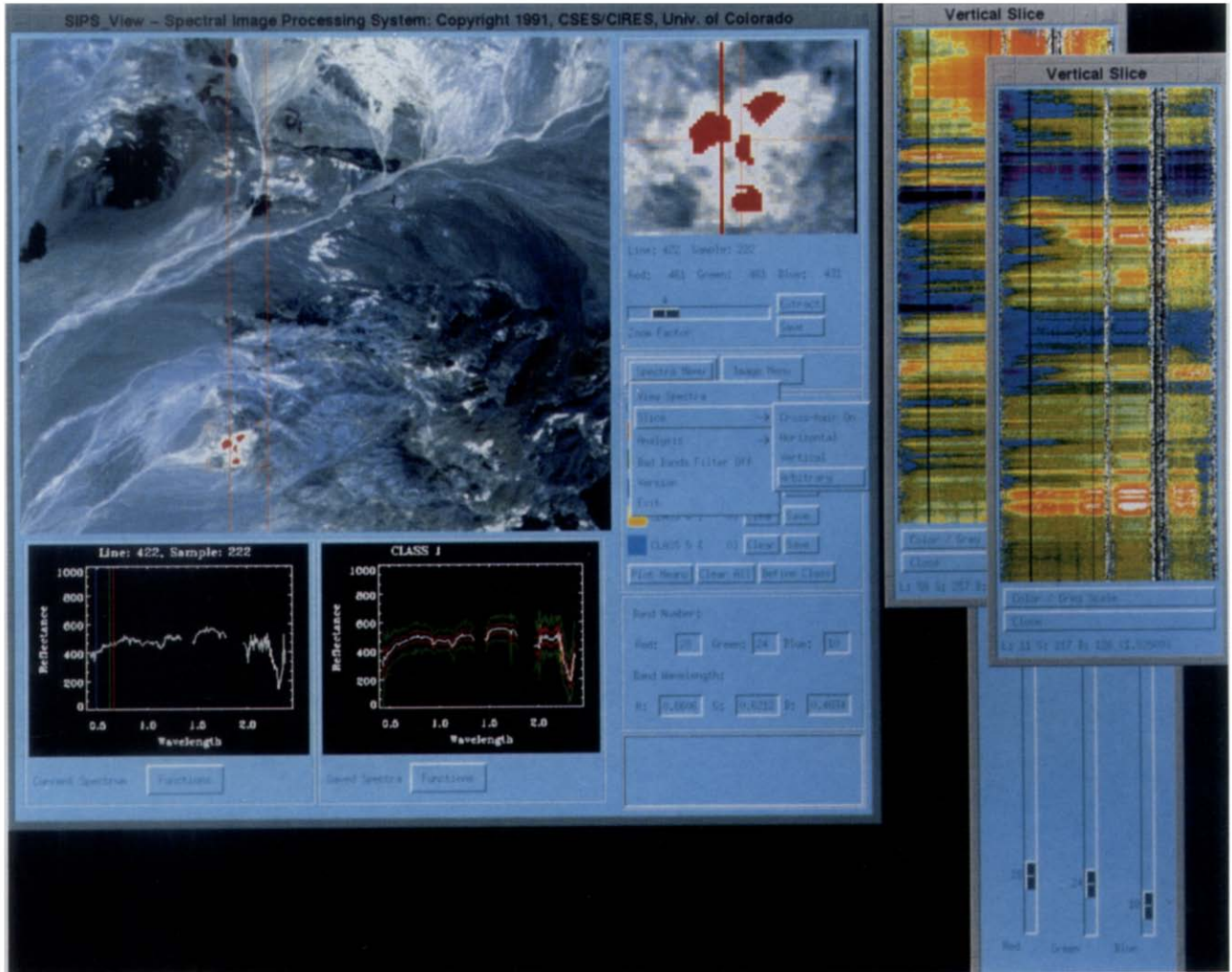


Figure 3. Typical SIPS user-session screen showing some of the functions used for spectral analysis of imaging spectrometer data.

can also be manually selected for each color of the density slice.

#### *The Zoom Window*

The Zoom Window, located to the right of the Image Window (Figs. 2 and 3) displays a small area from the Image Window with a user-definable zoom factor applied. The center of the zoomed area is defined by the position of the cursor in the Image Window. The pixels displayed can be magnified from 1 to 16 times their original size by grabbing the slider titled “Zoom Factor” and changing its value to the desired new zoom factor. The positions of the four red corner indicators in the Image Window change to reflect the new area displayed in the Zoom Window. The line and sample coordinates and data value of

the current pixel are displayed under the Zoom Window.

#### *Interactive Contrast Enhancement*

The user can change the contrast stretch for each band displayed by altering how the data fit into the 0 to 255 (8-bit) display range. The “Contrast Stretch” option is selected via the pull down Image Menu button. SIPS\_View creates a new window for the enhancement functions (Fig. 4). This window contains three draw widgets and plots the current histograms of the red, green, and blue bands. When the current image is a gray scale or density slice, only the first window is used. Next to each plot, SIPS\_View displays the band number, and the minimum and maximum values used for the current stretch. If there is a histogram file

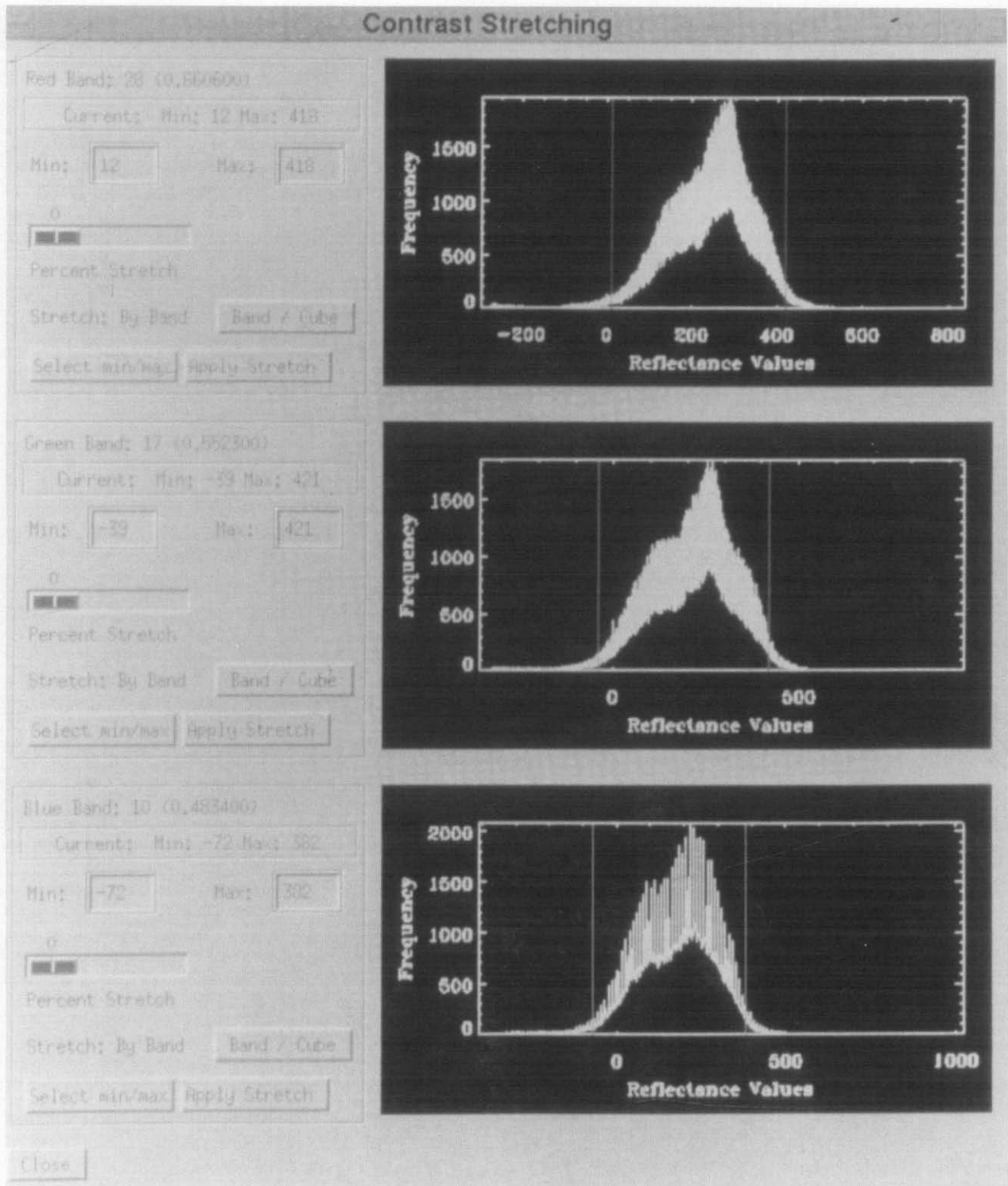


Figure 4. SIPS Histogram Window showing options for interactive contrast stretching of imaging spectrometer data.

associated with the input image, then a slider is also provided that allows the user to choose a specific percent of the data to stretch (0–15%). Two vertical bars within the plot display graphi-

cally where the current minimum and maximum values lie on the histogram. Whenever a change is made to the minimum and maximum stretch values, the position of the two vertical lines in the



histogram plot changes as well. The currently displayed image in the Image Window will not be updated with the new stretch, however, until one of the three “Apply Stretch” buttons is selected. When applied, all values less than or equal to the minimum stretch value are set equal to 0, and all values greater than or equal to maximum stretch value are set equal to 255. All values between the minimum and maximum are stretched linearly into the 0–255 range.

#### *Saving Images*

The displayed image can be saved to a file as byte-scaled images of either a single-band, gray-scale image or a three-band, RGB image with the current color tables applied. The output files are in BSQ format with the first band corresponding to the red values, the second band to the green values, and the third band to the blue values. This allows easy data interchange and also provides contrast enhanced images for use with color film writers or other output devices. SIPS\_View also gives the user the option of saving files in color PostScript format.

#### **SIPS\_View Spectral Functions**

SIPS\_View spectral functions are those items that deal with imaging spectrometer data primarily in its spectral format. These functions include spectra browsing, spectra averaging, spectral slice extraction, viewing spectra (with spectral libraries), and Spectral Angle Mapping (SAM).

#### *Spectra Browsing*

SIPS\_View allows the user to move the mouse cursor around the Image Window displaying the current spectrum in real-time. If SIPS\_View is being executed with either a BIL or BIP cube, then the spectrum at the current cursor position is displayed in the Current Spectrum Window and continuously updated as the cursor is moved using the mouse. Alternatively, if only a BSQ cube is present, then a click of the left mouse button causes the spectrum at the current cursor position to be extracted band by band and displayed in the Current Spectrum Window (a process that takes 5–15 s per spectrum on a DECstation 5000). At any time while browsing, a spectrum may be saved into the Saved Spectra Window by clicking the middle mouse button. Once a spectrum is in

the Saved Spectra Window, it may be saved to disk in an ASCII or binary library format, further examined in the View Spectra Window, or used as input for analyses.

#### *Spectra Averaging*

This function allows the user to interactively define and extract spectra for irregularly shaped polygon regions, vectors, and individual pixels. SIPS\_View provides five totally independent classes (Fig. 2). Any one class can contain up to 10,000 pixels from one or more separately defined regions. Only one class is “active” at a time, and the statistics for that class are totally independent of the other four classes. For example, if a polygon is defined when Class 1 is active, the spectra of the pixels contained within this polygon region will be averaged only with other regions defined for Class 1.

The region of interest is selected by positioning the Zoom Window coverage and setting the zoom factor. Selecting the “define class” button creates a new window with the same spatial coverage as the Zoom Window. Classes are defined by “drawing” polygons and/or vectors and/or selecting individual pixels within the selection window. After the class regions are defined, SIPS\_View extracts the spectra for all the pixels contained within the regions and calculates the mean, standard deviation, and minimum and maximum spectra. The results of the calculations are plotted in the Saved Spectra Window. This process may be repeated any number of times on separately defined regions in the image. Every time a new region is defined and extracted, the computed statistics for that region are averaged with the overall statistics for all the regions previously defined for that class. For each individual class, the control panel shows the class name and the total number of pixels contained in all the polygon regions defined for that class. The user can toggle between showing statistically-derived spectra for a single class or showing the mean spectra of all classes in the Saved Spectra Window. SIPS\_View also allows saving to disk files (as either ASCII spectra or binary spectral library files) the user’s choice of the following:

- the coordinates of all of the pixels in a given class
- the mean spectrum

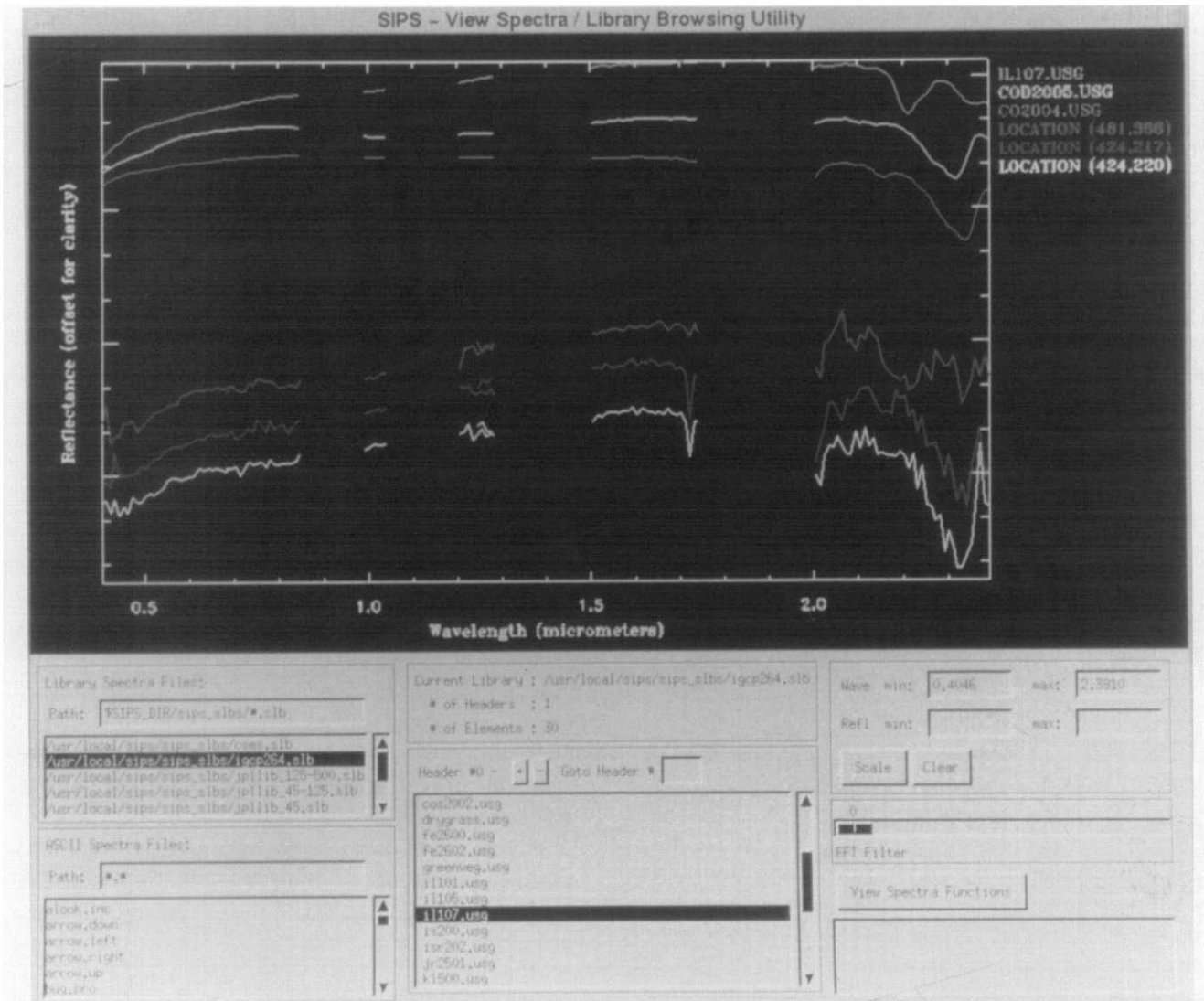


Figure 5. SIPS View Spectra Window showing three laboratory spectra (illite (il107.usg), dolomite (cod2005.usg), and calcite (co2004.usg)) and three spectra extracted from an imaging spectrometer cube for an area with sericite (muscovite or illite) (pixel 481, 366), calcite (pixel 424, 217), and dolomite (pixel 424, 220). The laboratory spectra are resampled to AVIRIS resolution. Windows for interactive selection of both ASCII and binary libraries are an integral part of this utility.

- one standard deviation spectrum above the mean
- one standard deviation spectrum below the mean
- spectrum of the cumulative maximum at each wavelength
- spectrum of the cumulative minimum at each wavelength

#### View Spectra

“View Spectra” is a utility used for spectral display and analysis. When the View Spectra function is selected, SIPS\_View creates a separate window

to plot the spectra currently in the Saved Spectra Window as well as access and plot other ASCII and library spectra saved in binary format (Fig. 5). The user can then manipulate this plot in a number of different ways, produce a PostScript output file of the plot, or import the plotted spectra back into the Saved Spectra Window for subsequent use in other SIPS functions.

The plot within the View Spectra Window initially displays the spectra that are in the Saved Spectra Window. Image spectra from the Saved Spectra Window are divided by a scale factor of 1000 (the same scaling factor used by SIPS Utili-

ties to preserve precision in reflectance calibration) so that both the image spectra and the laboratory spectra are the same magnitude (0–1.0) when plotted. SIPS\_View plots each spectrum in a different color (up to 16 colors), and the names of the displayed spectra are listed in matching color on the right side of the plot. If a bad-bands file is present and the bad-bands filter is on, then all spectra containing the same number of bands as the image data will be plotted with only the good bands showing. Any spectrum containing a different number of bands will ignore the bad-bands list.

The two areas in the left column below the plot titled “Library Spectra Files” and “ASCII Spectra Files” are used to select library files and ASCII spectra files to plot (Fig. 5). Both areas contain an editable text widget titled “Path:” and a list widget below listing the matched files of the path. Moving the mouse cursor over the desired file name in the ASCII Spectra Files list and clicking the left mouse button causes the selection to be highlighted and the spectrum to be read from disk and plotted. Moving the mouse cursor over the desired file name in the Library Spectra Files list and clicking the left mouse button highlights the selection and opens the library file. SIPS\_View displays this library as the Current Library, and lists the first 256 elements of this library in the middle column. Moving the mouse cursor over the desired element name in the list and clicking the left mouse button select and plots this spectrum with any spectra already plotted.

The View Spectra Window provides various mechanisms for manipulating the spectra once they have been plotted. The scale of the plot is automatically set to include all the spectra selected each time a new spectrum is selected. The user may also explicitly change the scale either by entering starting and ending wavelengths or reflectance values, or by clicking on the appropriate axes. SIPS\_View can either plot the spectra in the View Spectra Window overlaying one another, or stacked vertically offset from one another. Stacking the plot is useful for comparing spectra that have similar shapes and reflectance values (Fig. 5).

SIPS\_View can apply a fast Fourier transform filter to any plotted spectrum, allowing smoothing of noisy data. The FFT filter is used by grabbing the slider titled “FFT Filter” and changing the

value. Upon releasing the slider, the spectra are replotted with the filter applied. The higher the value of the slider, the fewer harmonics are used to draw the spectra, and, thus, the “smoother” the spectra appear. If there are very noisy bands in the data and these bands are not masked with a bad-bands list, then attempting to smooth the spectra using the FFT function may result in harmonic “ringing.” Also, filtering will only affect spectra with the same number of bands as the image data.

Color PostScript output can be produced of the View Spectra plot exactly as it appears. If the plotted spectra are stacked and smoothed with the FFT Filter, then that is how the plot will be saved to the PostScript file.

### *Spectral Libraries*

SIPS\_View spectral libraries are binary files that contain spectra and their associated wavelengths [see the *SIPS User's Guide* (CSES, 1992) for format information]. They also have an associated auxiliary information file. SIPS includes two sets of libraries of laboratory spectra. Digital spectra for approximately 135 minerals are provided courtesy of Jet Propulsion Laboratory (Grove et al., 1992). The second set consists of digital spectra of 25 well characterized minerals, each measured on five different spectrometers as part of International Geologic Correlation Project 264 (IGCP-264, Remote Sensing Spectral Properties, Kruse, unpublished data).

The JPL spectra are hemispherical reflectance measurements from 0.4  $\mu\text{m}$  to 2.5  $\mu\text{m}$  made on a Beckman UV5240 spectrophotometer. The sampling interval is every 0.001  $\mu\text{m}$  (1 nm) between 0.4  $\mu\text{m}$  and 0.8  $\mu\text{m}$  and 0.004  $\mu\text{m}$  (4 nm) from 0.8  $\mu\text{m}$  to 2.5  $\mu\text{m}$ . Spectral resolution is approximately 1% of the wavelength measured. Two sets of three (six total) spectral libraries are provided corresponding to three grain sizes (125–500  $\mu\text{m}$ , 45–125  $\mu\text{m}$ , and < 45  $\mu\text{m}$ ) measured at JPL. One set of the three libraries is provided at full resolution to allow use of this resolution or resampling to specific AVIRIS wavelengths. The second set of the three libraries is provided resampled to 1989 AVIRIS wavelengths (data prior to 20 September 1989).

The IGCP-264 spectral libraries included in SIPS represent the prototype database of approximately 25 well-characterized minerals identified

as critical for geologic mapping by a 1987 international survey (Kruse, unpublished data). Five spectral libraries measured on five different spectrometers for the 25 minerals are provided. The same samples were measured on a Beckman UV5270 spectrophotometer at CSES, a Beckman UV5240 spectrophotometer at the U.S. Geological Survey in Denver (Clark et al., 1990), on the "RELAB" spectrometer at Brown University (Pieters, 1990), on the "SIRIS" field spectrometer in the laboratory at CSES (Geophysical and Environmental Research, 1988), and with the prototype of a new high resolution field spectrometer, the "PIMA II" (manufactured by Integrated Spectronics Pty. Ltd.), in the laboratory at CSES. The CSES Beckman lab spectrometer measures at constant 3.8 nm resolution (sampled at 1 nm) throughout the 0.7–2.5  $\mu\text{m}$  range. The USGS spectra are provided at the standard "1  $\times$ " resolution ranging from 2 nm to 10 nm in the 0.4–2.4  $\mu\text{m}$  range and falling off to nearly 30 nm in the 2.4–2.5  $\mu\text{m}$  range. The RELAB spectra are provided at 2–13 nm resolution (sampled at 5 nm) in the 0.4–2.5  $\mu\text{m}$  range. The SIRIS spectra are sampled from 2 nm to 5 nm in the 0.4–2.5  $\mu\text{m}$  range; however, spectral resolution information for this specific instrument has not been determined. The PIMA spectra are sampled at 2 nm in the 1.3–2.5  $\mu\text{m}$  range. While the spectral resolution function is not yet available for this instrument, comparison to measurements from the other spectrometers indicates that resolution is better than 4 nm throughout the measured spectral range. All spectra were measured with halon as the reference and reduced to absolute reflectance using a NBS halon spectrum. A sixth IGCP-264 spectral library consists of the library spectra measured on the USGS spectrometer re-sampled to 1989 AVIRIS wavelengths (data prior to 20 September 1989).

#### *Spectral Slices (Stacked, Color-Coded Spectra)*

Extraction of spectral slices from the images allows display of spectral data as color-coded stacked spectra (Marsh and McKeon, 1983; Kruse et al., 1985; Huntington et al., 1986) (Fig. 3). The color slice uses a standard 18-level density slice where white and red correspond to high intensity values and black and blue correspond to low intensity values. SIPS\_View is able to extract three different types of slices: horizontal, vertical,

and arbitrary. A horizontal slice extracts spectra along a horizontal line in the image. A vertical slice extracts spectra along a vertical line in the image (Fig. 3). An arbitrary slice extracts spectra along an arbitrary, user defined path. Each extracted slice occupies its own window. Up to five slice windows may be open at any one time.

There are two general stages to using the slice option. First, SIPS\_View extracts the desired slices the user has defined and places them into their own windows. Once these windows have been created, the user can move the mouse cursor around in the slice windows and see a specific spectrum plotted in the Current Spectrum Window. The line and sample position for the pixel associated with that spectrum are listed in the Slice Window, as well as the band and reflectance value under the cursor. The Zoom Window also follows along and updates the current pixel location.

#### *The Spectral Angle Mapper (SAM)*

The Spectral Angle Mapper (SAM) is a tool that permits rapid mapping of the spectral similarity of image spectra to reference spectra (Boardman, 1993a). The reference spectra can be either laboratory or field spectra or extracted from the image. This method assumes that the data have been reduced to "apparent reflectance," with all dark current and path radiance biases removed. The algorithm determines the spectral similarity between two spectra by calculating the "angle" between the two spectra, treating them as vectors in a space with dimensionality equal to the number of bands (nb). A simplified explanation of this can be given by considering a reference spectrum and a test spectrum from two-band data represented on a two-dimensional plot as two points (Fig. 6). The lines connecting each spectrum-point and the origin contain all possible positions for that material, corresponding to the range of possible illuminations. Poorly illuminated pixels will fall closer to the origin (the dark point) than pixels with the same spectral signature but greater illumination. Notice, however, that the angle between the vectors is the same regardless of their length. The SAM algorithm (Boardman, 1993a) generalizes this geometric interpretation to nb-dimensional space. The calculation consists of taking the arccosine of the dot product of the spectra. SAM determines the similarity of a test

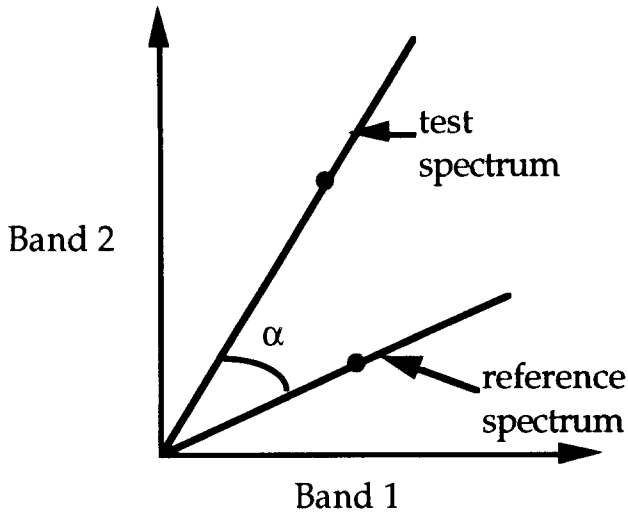


Figure 6. Plot of a reference spectrum and test spectrum for a two-band image. The same materials with varying illumination are represented by the vectors connecting the origin (no illumination) and projected through the points representing the actual spectra.

spectrum  $t$  to a reference spectrum  $r$  by applying the following equation:

$$\cos^{-1}\left(\frac{\vec{t} \cdot \vec{r}}{\|\vec{t}\| \cdot \|\vec{r}\|}\right),$$

which can also be written as

$$\cos^{-1}\left(\frac{\sum_{i=1}^{nb} t_i r_i}{\left(\sum_{i=1}^{nb} t_i^2\right)^{1/2} \left(\sum_{i=1}^{nb} r_i^2\right)^{1/2}}\right),$$

where  $nb$  = number of bands.

This measure of similarity is insensitive to gain factors because the angle between two vectors is invariant with respect to the lengths of the vectors. As a result, laboratory spectra can be directly compared to remotely sensed apparent reflectance spectra, which inherently have an unknown gain factor related to topographic illumination effects.

SIPS\_View allows up to 10 reference spectra to be processed simultaneously using SAM. Spectra can be selected from SIPS spectral libraries, ASCII spectra files, or any spectra contained in the Saved Spectra Window. Reference spectra must have the same wavelength set as the image to which they will be compared. If a bad-bands file is associated with the image cube, then SAM will use the reference spectra with the bad-bands

masked, ignoring the bad bands in the calculations. Optionally, all bands can be included, and SAM will perform its calculations on all the bands over the defined range.

For each reference spectrum chosen, the spectral angle  $\alpha$  is determined for every image spectrum, and this value, in radians, is assigned to that pixel in the output SAM image. A unique spectral range may be chosen for each reference spectrum. This allows the algorithm to focus on spectral regions that are significant for a particular reference spectrum. The derived spectral angle maps form a new data cube with the number of bands equal to the number of reference spectra used in the mapping. Results can be viewed immediately using the interactive SAM Viewer (Fig. 7). The dynamic nature of the viewing interface helps the user to analyze the spatial patterns of spectral variability in the image and to rapidly map areas that are spectrally similar. The SAM Viewer Window displays the results for each reference spectrum separately as gray-scale images. Small spectral angles correspond to high similarity and these pixels are shown in the brighter gray levels. Larger angles, corresponding to less similar spectral shapes, are shown in the darker gray levels. Two interactive sliders, titled "Low Threshold" and "High Threshold," can be used to fine-tune the contrast stretch of the image. Values between the two slider settings are stretched linearly between black and white. Values outside this range are set to black if they have a spectral angle greater than the High Threshold setting (less similar to the reference) and white if they have a spectral angle less than the Low Threshold setting (more similar to the reference). In addition, the two sliders can be "locked" one radian apart. In the locked setting, the image displayed is a binary map of all pixels more similar than the High Threshold.

## SIPS ANALYSIS PROGRAMS

The analysis module provides tools that perform complex calculations on an entire image and are too time-consuming for interactive use. Currently, only the *unmix* analysis tool which performs linear spectral unmixing is available in this module. A knowledge-based, expert system analysis utility is presently undergoing testing and revision (Kruse

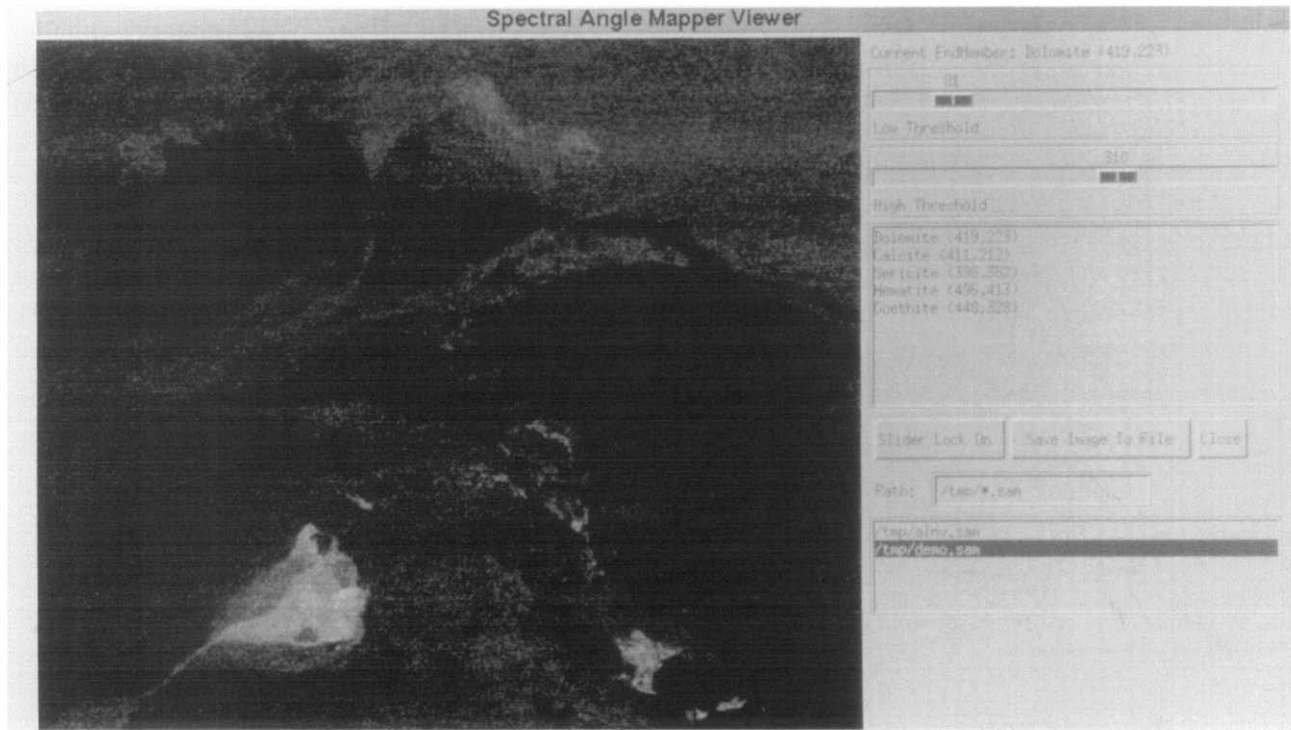


Figure 7. SAM Viewer Window showing gray-scale results for comparison of image spectra to a reference spectrum corresponding to dolomite. Brighter areas represent better matches.

et al., 1993) and will be released in the next version of SIPS. Other analysis modules are being developed and will be added at a later date.

Spectral mixing is a consequence of the mixing of materials having different spectral properties within the GFOV of a single pixel (Singer, 1981; Smith and Adams, 1985; Boardman, 1991). The SIPS unmixing program, written in IDL, uses a simple linear mixing model. This model assumes that observed spectra can be modeled as linear combinations of endmembers contained in a spectral mixing library (Boardman, 1993b). The unmixing approach seeks to determine the fractional abundance of each endmember within each pixel. Given more bands than mixing endmembers, the problem can be cast in terms of an overdetermined linear least-squares inversion for each image spectrum (Fig. 8) (Boardman, 1989; 1990; 1991).

The SIPS unmixing program provides three types of unmixing algorithms: unconstrained, partially constrained, and fully constrained (Boardman, 1990). The unconstrained version provides a classic least-squares solution to the unmixing

problem and the derived abundances are free to take on any value including negative ones. In the constrained versions the derived abundances are required to be nonnegative. When fully constrained, their sum must be unity or less (Fig. 9).

Several steps are involved in using the unmixing program. Any user should become familiar with the concept of unmixing and its inherent assumptions and limitations before trying to unmix their data (Singer, 1981; Smith and Adams, 1985; Boardman, 1991 and references therein). The first and most important step is the selection of the spectral mixing library endmembers. In the SIPS unmixing procedure, the mixing library is formed by interactively choosing members from the imaging spectrometer cube or from any number of spectral libraries using SIPS\_View. The unmixing library should contain all the materials believed to be mixing in the scene. Conversely, it should not contain members that are not present. Once the mixing library is formed, the endmember spectral are displayed, and a subset of the full spectral range can be chosen to ignore noisy bands and any spectral variability in wavelength

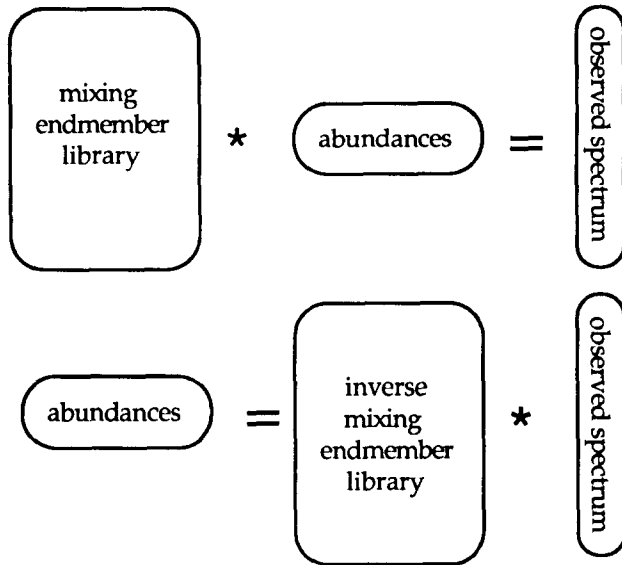


Figure 8. Linear spectral mixing forward and inverse models. If the number of endmembers in the library is less than the number of bands in the data, then the problem is an overdetermined linear least squares inversion.

regions that are not of interest. Bad bands can also be excluded using the bad-bands file. Once the type of unmixing constraints are chosen, the program inverts the spectral library using singular value decomposition (Golub and Van Loan, 1983; Press et al., 1986; Boardman, 1991; 1993b), and optionally displays the singular values of this library matrix. The library's degeneracy is determined by examining the products of the decomposition. If the library of endmembers consists of completely spectrally separable, orthogonal endmembers, the normalized singular values will all be equal. For a wholly degenerate library, all but one singular value will be zero, indicating that all of the endmembers are linearly scaled versions of each other. At this stage, the user can choose to start again and revise the library. Finally, once the user is satisfied with the library selected, the program processes the full image data cube one line at a time. The unconstrained Unmix program runs in about 1 h for a standard AVIRIS scene while the fully constrained Unmix program takes about 5 h (times for five endmembers on a DEC-Station 5000/200).

The output of the unmixing process is another image data cube. It has the same spatial dimensions as the input data. The number of output bands is equal to the number of endmembers plus two. This cube contains one image for each

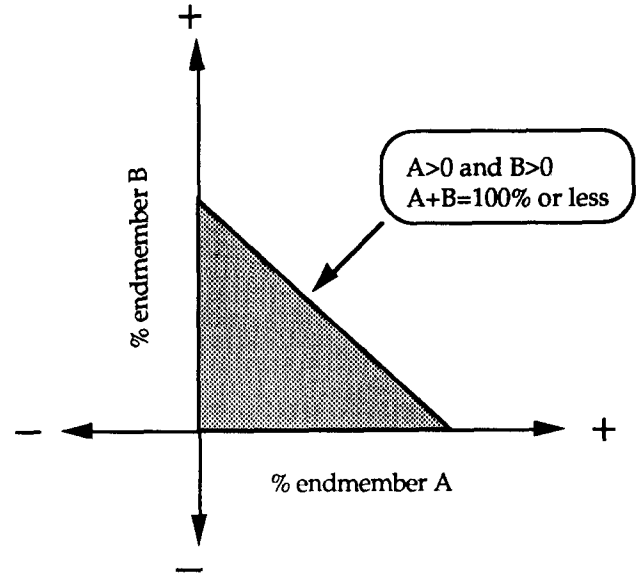


Figure 9. Sketch of the constrained inversion solution space for two endmembers. Best-fitting abundances must be positive and sum to unity or less. The reconstruction fit error must be greater than or equal to that for the unconstrained solution.

endmember showing the derived spatial patterns of abundance for that endmember. The additional two images are useful in assessing the uncertainty in the unmixing results. They are 1) an image of the sum of the abundances at each pixel and 2) the root-mean-square (RMS) error at each pixel. The error image displays how well the mixing library can be used to model each observed spectrum, and can be used to assess the validity of the mixing library. If contiguous regions of high error exist, a required mixing endmember was probably omitted. Refinement of the results involves iterative unmixing with revised libraries until the RMS errors are low. The resulting abundance images comprise estimates of the spatial distribution of the mixing endmember materials.

## TYPICAL USER SCENARIO

The following is a typical SIPS user scenario for AVIRIS data acquired for geologic investigations. Many of the steps are common to analysis of any type of imaging spectrometer data and illustrate some of the relations between the different parts of SIPS. The scenario is presented sequentially (in the normal order executed) in outline format

to clearly show the logical progression of the steps involved in the analysis.

### Data Preparation

- receive and read AVIRIS tape using *rd\_avimage*, *rd\_avwave* getting BSQ image and wavelength files
- view radiance images using SIPS\_View to verify data location and quality; locate and extract polygons for calibration areas
- build spectral library containing ground spectra for the calibration areas using *make\_slb*
- use empirical line method to calculate gains and offsets for calibration to reflectance with *make\_gainoff*
- calibrate to reflectance using *dn2ref* to apply gains and offsets
- calculate histogram parameters using *make\_hist*
- view spectra from the calibrated cube using *make\_bbl* and interactively select bad bands
- rotate image 180° to north using *rotate\_cube*
- make BIP cube using *convert* to allow efficient spectral viewing and analysis

### Interactive Viewing and Analysis in SIPS\_View

- display gray-scale image
- use Spectra Browse function to evaluate spectral character of images
- select polygons containing calibrated light and dark targets, load into View Spectra and compare to ground spectra used for calibration; validate calibration
- browse through several gray-scale images using the slider-bar to look for spectral differences
- produce a variety of color images based on absorption bands of known materials to locate areas with absorption features
- extract spectral slices to evaluate spectral changes along specific traverses
- use histograms and linear stretches to produce enhanced images and save to color PostScript files
- produce color printer quicklook copies for reference

- use Spectra Browse function to examine individual spectra and the Spectra Average function to extract average spectra for areas showing color differences and save to spectra library
- examine spectra using View Spectra option, load spectral libraries and compare to determine minerals and other materials
- use image endmembers in saved image spectral library to perform SAM analysis within SIPS\_View
  - select endmembers from library
  - edit spectral ranges
  - view results using SAM viewer
  - use sliders to highlight areas of high match
  - save to SAM results cube
- exit SIPS\_View and reload SAM results cube as color image to show mixtures
- save results to files for filmwriter
- display single endmembers as density-sliced images and save to files for filmwriter

### Analysis

- Reexamine endmembers based on results of SAM analysis using BSQ and BIP cubes in SIPS\_View
- Unmix image using unconstrained unmixing
  - select endmembers
  - evaluate degeneracy of the library and adjust if required
  - unmix
  - evaluate abundance images, error images and sum
  - revise endmembers if required
- Unmix image using constrained unmixing
  - reselect endmembers if required
  - evaluate degeneracy of the library and adjust if required
  - unmix
  - evaluate abundance images, error images and sum
  - revise endmember images if required
  - rerun unmixing if required

### Output

- import gray-scale images, color composites, SAM analysis results images, unmix-



ing results images into standard image processing software, or IDL for further image analysis, classification, statistics, etc.

- produce hardcopy output using filmwriter

### Integrated Analyses

- Register images to map base
- transfer results to GIS system for further analysis with results from other images, field mapping, field spectra, and laboratory analytical work

### CONCLUSIONS

SIPS is an integrated software system for analysis of imaging spectrometer data. SIPS is designed to take advantage of the inherent strength of imaging spectrometer data, simultaneous high resolution spectral measurements and spatial display. It provides the basic capabilities to proceed from raw radiance data, through calibration, to interactive viewing and analysis, to quantitative results and hardcopy output. It provides utilities for input of data, data formatting, data calibration, and other common image processing procedures. Data visualization tools are provided for rapid, exploratory analysis and numerical tools are provided for quantitative modeling.

SIPS makes possible routine display and analysis of a volume and complexity of information that up until now have detailed analyses difficult. It has been used for analysis of imaging spectrometer data from AVIRIS, GERIS, and GEOSCAN, and to look at other multispectral data sets from Landsat MSS, Landsat TM, and SPOT. The prototype interactive software system using IDL on UNIX-based workstations simplifies analysis of imaging spectrometer data by allowing scientists to rapidly interact with entire datasets. It is our hope that these tools will be useful across multiple disciplines and allow quantitative analysis that will lead to new scientific discoveries using imaging spectrometer data.

CSES is continuing to develop SIPS as a general tool for analysis of imaging spectrometer data. One of the main goals of this effort is to modularize the program to allow users to add customized functions.

### SOFTWARE RELEASE

SIPS is being released to organizations outside CSES for analysis of imaging spectrometer data such as that produced by AVIRIS. To promote scientific use of these data, SIPS will be provided free of charge or royalties to any organization interested in use of imaging spectrometer data. CSES plans to continue development of these programs and retains the title and copyright to the software, documentation, and supporting materials. Recipients of this software are required to execute a memorandum of understanding (MOU) provided by CSES that specifies in detail all of the associated conditions. To get a copy of the software agreement contact Kathy Heidebrecht or Fred Kruse by electronic mail (sips@cses.colorado.edu), phone (303-492-1866), or FAX (303-492-5070).

### HARDWARE / SOFTWARE REQUIREMENTS

SIPS runs on Unix-based workstations under either Motif or Openlook window managers in 8-bit color mode. The platforms and the software versions on which SIPS has been tested are shown in Table 1. IDL version 2.4 or higher is required. While SIPS should work on any platform that supports IDL (with widgets), these are the only platforms that have been tested to date. For more information concerning IDL, contact Research Systems, Inc., 777 29th St., Boulder, CO 80303.

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*SIPS was originally developed as a means for viewing and analyzing AVIRIS data. Many of the ideas and techniques incorporated into SIPS are the result of nearly 10 years experience with imaging spectrometer analysis by principals at CSES. The SPAM and ISIS software provided some impetus towards the types of analyses we wanted to perform, and we would like to acknowledge this influence. SIPS, however, was developed from scratch using the IDL programming language to satisfy specific analysis requirements not available in any existing software package. The basic interactive package (SIPS\_View) was developed under funding from NASA as part of the Innovative Research Program funded research proposal "Artificial Intelligence for Geologic Mapping," NASA Grant NAGW-1601 (Dr. F. A. Kruse, Principal Investigator). Additional support for documentation of SIPS and development of unmixing routines included as part of SIPS were supported respectively by NASA Grant NAS5-30552 (Dr. A. F. H. Goetz, Principal Investigator) and by a NASA Graduate Research Fellowship (Dr. J. W. Boardman). The interactive SIPS\_View program, version 1.0, was written by A. B. Lefkoff with version 1.1 additions by A. T. Shapiro, P. J. Barloon, and K. B. Heidebrecht. J. W. Boardman wrote the SIPS spectral unmixing*

routine and the Spectral Angle Mapper algorithm. Continuing development and support of SIPS as a HIRIS-team resource is funded by NASA Grant NAS5-30552 (Dr. Alexander F. H. Goetz, Principal Investigator).

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