HyperTeach
Training in Imaging Spectroscopy

Hands-on

— Airborne

— Spaceborne

— Water

— Geology

— Biodiversity

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Aim of Lesson

To learn how to do the atmospheric correction of airborne hyperspectral images. This lesson contains both field measurements and hands-on computer exercises.

Objectives

1. To learn how to do measurements with a spectroradiometer and a sun photometer
2. To perform atmospheric corrections with an Empirical Line method
3. To interpret the results of an atmospheric correction performed with a radiative transfer model approach

Background information

PRACTICAL ISSUES

Weather permitting, field measurements will be performed during the course. The measurements consist of determination of the aerosol optical depth and the water vapor with a sun photometer and spectral characterization of reference targets with a spectroradiometer. The required time for these measurements is estimated to be 45 minutes.

However all computer exercises can be carried out without these measurements.

This lesson relates to Section 8.1 of the HyperTeach Theory Syllabus. For further details about the techniques involved readers are recommended to read this section.

SOFTWARE

ENVI® is required to carry out the lesson.

Lesson outline

1. Field survey measurements

OBJECTIVE

Students will learn (1) how to operate a FieldSpecPro FR spectroradiometer and (2) how to perform measurements using a Microtops II sun photometer. A brief tutorial on how to use these instruments can be found in Section 14.2 and 14.4 of the ANNEX of the HyperTeach Theory Syllabus.

2. Hands-on computer exercises

IMAGE DATA

In the summer of 2004 airborne hyperspectral HyMAP data were acquired from several sites located in Belgium, The Netherlands, Luxembourg, Wales and Germany. The HyMAP sensor provides 126 spectral bands across the reflective solar wavelength region of 0.45 – 2.5 nm with contiguous spectral coverage and having bandwidths between 15 and 20 nm. The HyMAP provides a signal to noise ratio which exceeds 500:1.

In this lesson atmospheric correction will be carried out on a HyMAP image acquired from a rural area in Flanders near the village Idegem (Easting : 564832 m , Northing : 564832 m) on 8th June 2004. The image was acquired around 10:55 GMT. The average flight altitude was 2013 m above sea-level (asl), the mean ground level is 40 m. The field-of-view of the HyMAP sensor is 60 degrees with 512 across track pixels. This resulted in a pixel size of +/- 4,9 x 4,9 m (Figure 1.1). The acquisition of the HyMAP data was funded by the Belgian Science Policy Office.
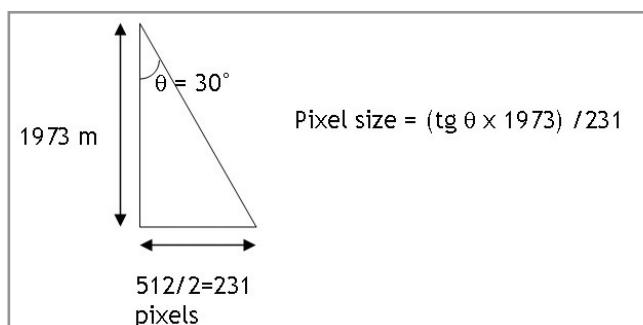
>> **Fig. 1. 1: Calculation of the across track pixel size**

$$\theta = 30°$$

$$1973 \text{ m}$$

$$\text{Pixel size} = (tg\,\theta \times 1973)\,/231$$

$$512/2 = 231 \text{ pixels}$$

OBJECTIVE

The objectives of this computer exercise are :

(a) To retrieve the surface reflectance (that characterises the surface properties) from remotely sensed imagery by removing the atmospheric effects using the Empirical Line method

(b) Interpretation of the radiative transfer atmospheric correction result

a. Empirical line approach

Field survey data :

During the airborne data acquisition a FieldSpec Pro FR spectroradiometer was used to measure the reflectance of three reference targets: a football pitch, a sandy beach and a parking lot (Figure 1.2 and 1.3). The location of the targets was measured with a GPS (Table 1). To perform an empirical line correction, the reference reflectance spectrum of at least one target is mandatory. If more than one spectrum is used, then the regression for each band will be calculated by fitting the regression line through all of the spectra. If only one spectrum is used, then the regression line will be assumed to pass through the origin (zero reflectance equals zero radiance).
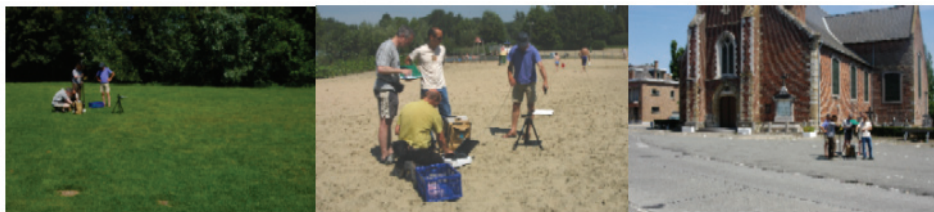
>> **Fig.1.2 : Pictures of the reference targets.**
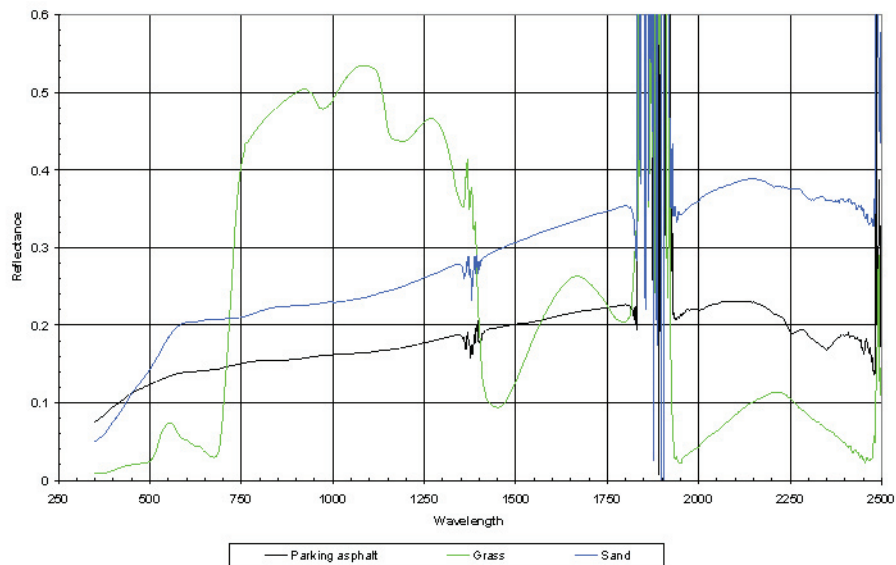
>> **Fig.1.3.: Reflectance spectra of the reference targets measured with the FieldSpec Pro FR spectroradiometer.**

Target	Easting (m)	Northing (m)
Football pitch	564895	5626871
Sandy beach	564798	5627022
Asphalt parking	565298	5628058

>> **Table 1 : GPS coordinates (projection: UTM zone 31, datum: WGS-84).**

Question 1.1 : In the HyperTeach Theory Syllabus some criteria are given which the reference targets should meet. Which target doesn't fulfil the 'featureless' criteria ?

Action : Open the HyMAP_image file and display a true colour image.

> **Hint** : In the ENVI <main menu> use the <Open Image File> to select HyMAP_image. Next, click with your right mouse button on 'HyMAP_image' in the <Available Band List dialog> and select <Load True Color>.

Question 1.2 : Display a Z-profile for the agricultural field located at pixel location (x: 401, y: 859). Why does this spectrum contain strong peaks ?

> **Hint** : a. In the main Image Display window select <Tools>, <Pixel locator>
> b. Display the Z-profile: <tools>, <profiles>, <Z-profile>

Action : Locate the reference targets in the image using their GPS coordinates and write down their pixel coordinates.

> **Hint** : In the main Image Display window select <Tools>, <Pixel locator>, <options>, <Map coordinates>.

Question 1.3 : Which target doesn't fulfil the 'size' criteria ?

To perform an empirical line correction HyMAP at-sensor radiance spectra of all reference targets are needed.

Action : Save a HyMAP at-sensor radiance spectrum of the football field to an ASCII file. Instead of saving the spectrum of only one pixel, it is better to save an average radiance spectrum of a larger area.

> **Hint** : a. Display the Z-profile of the football pitch : <tools>, <profiles>, <Z-profile>.
> b. Change the Z-profile average window size by selecting in the spectral profile <options>, <set Z-profile average window size >. Choose as window size 5 x5.
> c. Give a name to the spectrum : <edit>, <data parameters>, in the name field write football field, <apply>, <cancel>.
> d. Save this spectrum to an ASCII file with as filename football_HyMAP.txt (<file>, <save plot as>, <ASCII>). The numeric precision for the X and Y output ASCII variables can be set by clicking the arrow increment buttons. The data can be saved in Scientific (eg. 3.411640e+003) or Normal format (e.g. 3411.640000). For this exercise you can leave the data in the default formatting (X,Y precision : 6, Normal format).
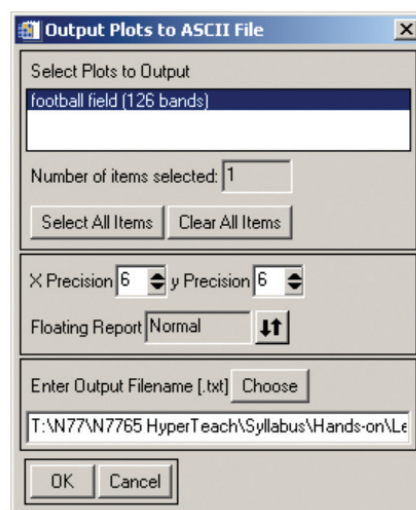
Action : Repeat previous steps for the asphalt parking and the sandy beach. Use a window size of 3 x 3 for the parking and 5 x 5 for the sandy beach and give the spectra an appropriate name. Save the spectra to ASCII files (parking_HyMAP.txt and beach_HyMAP.txt).

Action : You can start now with the empirical line correction. Select <Basic tools>, (<preprocessing>!), <calibration utilities>, <empirical line>, <compute factors and calibrate>. In the Empirical Line input File dialog double click the HyMAP_image file.

Action : Load the HyMAP radiance spectra of the reference targets.

> **Hint** : a. In the Empirical Line Spectra dialog, click the <Import Spectra> button in the <Data Spectra> section.
> b. In the data spectra collection dialog, click on <Import>, <from ASCII file>.
> c. Now you have to select the HyMAP radiance spectra of the different reference targets (football_HyMAP.txt, parking_HyMAP.txt and beach_HyMAP.txt, <open>.

d. In the input ASCII file dialog change the wavelength units into micrometer , click on <ok>.
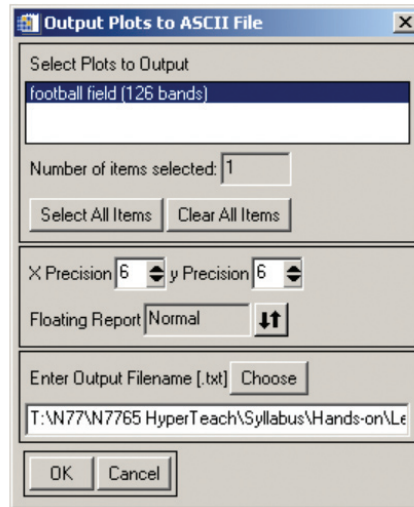
e. In the Data Spectra Collection dialog select all the spectra, click on <apply>, <cancel>.
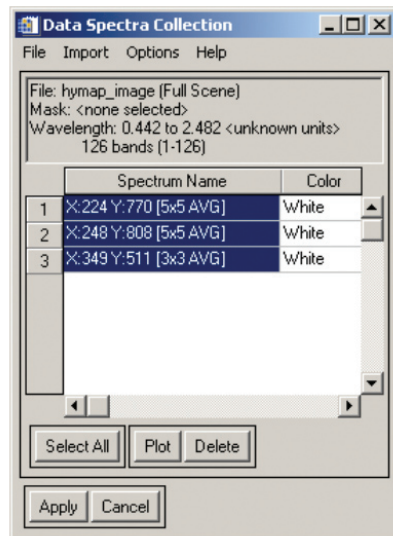
Action : Load the FieldSpec Pro FR spectra (Football_asd.txt, ….) of the reference targets in the same way you have loaded the HyMAP spectra.

  Hint :   click on the <Import Spectra> in the <Field spectra>section.

Action : After importing Data and FieldSpec Pro FR reference spectra into the Empirical Line Spectra dialog, pair the Data (HyMAP) and Field (FieldSpec Pro FR) spectra for use in the regression.

  Hint :   a. In the top list of the Empirical Line Spectra dialog, click on the 'sandy beach' data spectrum to select it.
  b. In the bottom list, click on the corresponding field spectrum name.
  c. Click <Enter Pair> to couple both spectra. The paired spectra are listed in the Selected Pairs text box.
  d. Repeat the selection process for the other 2 data and field spectra.
  e. Click OK.
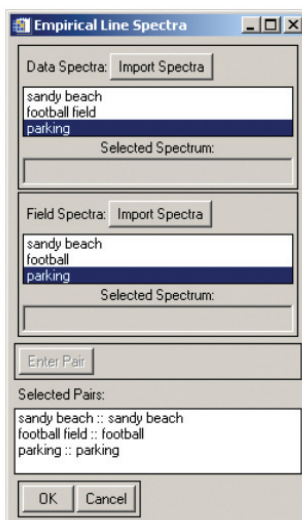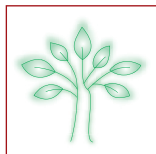
Action : Save the output of the empirical line to a file (eg. HyMAP_emp) and the calibration factors to HyMAP_cal.cff. Click <ok> to start the calibration.

The HyMAP_cal.cff file contains the gain and offset for each band which are used to predict the apparent reflectance spectrum for each pixel from its original image radiance spectrum. These gains and offsets are also given in the Calibration Factors window for each wavelength. The gain and offset values are then applied to the HyMAP_image data on a band by band basis, removing atmospheric attenuation. Note that the correction is applied band by band and not pixel by pixel.
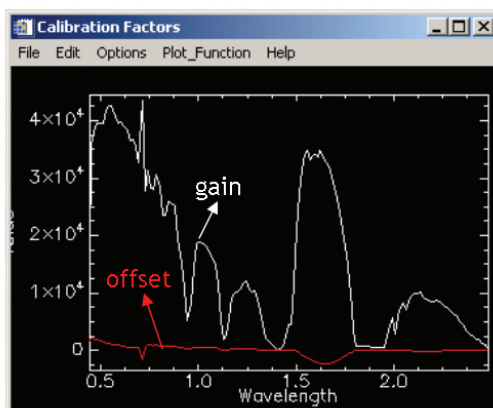
Action : Display a true color image of HyMAP_emp file in a new display window # 2 and and link both images.

> **Hint** : a. In the Main Image Display select <Tools>, <Link>, <Link displays>.
> b. In the Link Display window click <OK> to select it.
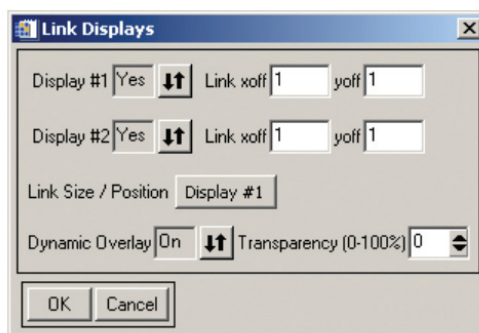
Action : Explore the difference between the radiance (# 1) and reflectance spectra (# 2) by displaying the Z-profiles of the following spectra :

- Agricultural field located at pixel coordinates (X: 414, Y: 855).
- Grass field located at pixel coordinates (X: 333, Y: 680)

Question 1.4 : Do you think the Empirical Line method corrected the atmospheric effect well? What errors might be included in the Empirical Line method?

Action : Close all windows

b. Radiative transfer approach

The same image has been corrected using the atmospheric correction software ATCOR. ATCOR is based on the radiative transfer code Modtran4. Inputs to ATCOR are summarized in table 2.

Date	8th June 2004
Flight altitude above sea level	2013 m
Terrain level	40 m
Flight heading	180°
Solar zenith	29.5°
Solar azimuth	157°
Visibility	50 km
Aerosol type	rural

>> **Table 2 : Input parameter values for atmospheric correction with ATCOR.**

The visibility (50 km) was estimated from the Microtops II sun photometer measurements performed simultaneously with the airborne campaign. The water vapour is automatically computed by ATCOR from the HyMAP image itself using the information content of the spectral bands located in the water vapour region (e.g. 920 – 960 nm). The alternative is using the water vapour content estimated from the sun photometer measurements.

In case no sun photometer measurements were performed the visibility can be estimated by iteratively changing the visibility until the retrieved reflectance of the reference targets fits well with the reflectance of these targets measured in the field.

If neither sun photometer data nor field reference spectra are available, dark targets (like dense coniferous forests in the blue and red) can help to set a lower bound for the visibility. To illustrate this we have corrected the same image with ATCOR using a visibility of respectively 10 and 20 km.

Action : Load a true colour image of HyMAP_atcor_10km.bsq, HyMAP_atcor_20km.bsq, HyMAP_atcor_50km. bsq in respectively display #1, # 2 and #3. Link all the displays. Turn off the dynamic overlay : In the 3 Main Image Display windows go to <Tools>, <Link> and click on < Dynamic Overlay Off>

Action : With pixel locator go to pixel (165, 493). Display the Z-profiles of this dark vegetation area for the 3 images.

Action : Compare the reflectance spectra by adding the profiles in one graph.

> Hint :   a. Click with the right mouse button in the spectral profile windows from display #1,#2 and #3 and select <plot keys> in the short cut menu
>
> b. Give the colour of Z-profiles in display #1, #2 and #3 in respectively red, green and blue. (<edit>, <data parameters, click on <color> with the right button and change the colour)
>
> c. In one of the spectral profile windows click on <options> <new window : blank> to create a new ENVI plot window.
>
> d. Drag all the Z-profiles in this new window : click and hold the left mouse button on the different plot labels and drag it into the new ENVI plot window and release the mouse button.

Question 1.5 : Why should (based on these Z-profiles) the visibility used in ATCOR to correct this image be higher than 20 km?

Answers to questions

Answer 1.1 : Which target doesn't fulfil the 'featureless' criteria ?

The ASD reflectance spectrum of the football field contains some absorption features due to plant pigments, leaf water content, ..

Answer 1.2 : Why does this spectrum contain strong peaks ?

The radiance, reflected by the target, is strongly absorbed at some wavelengths by atmospheric gases before it reaches the sensor. This absorption effect causes the peaks visible in this radiance spectrum. Major absorbers of solar radiation are (1) ozone, (2) oxygen, (3) water vapour and (4) carbon dioxide.
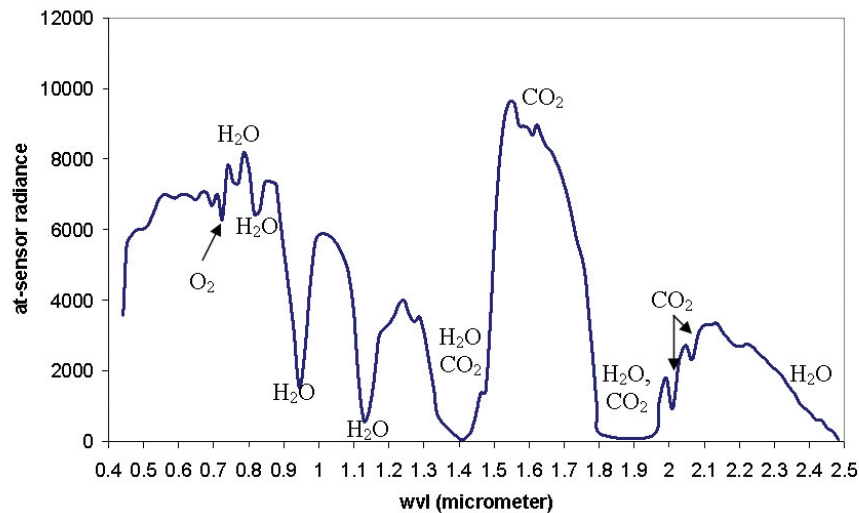
Answer 1.3 : Which target doesn't fulfil the 'size' criteria ?

The asphalt parking is quite small i.e. less than 5 x 5 pixels.
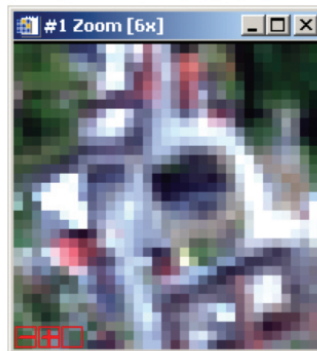
Answer 1.4 : Does the Empirical Line method corrects the atmospheric effect well?

Most of the atmospheric effects are removed quite well by applying the Empirical Line method except in the very strong H_2O absorption bands near 1.38 μm and 1.87 μm. (Left: at-sensor radiance, Right: apparent reflectance after Empirical Line correction).
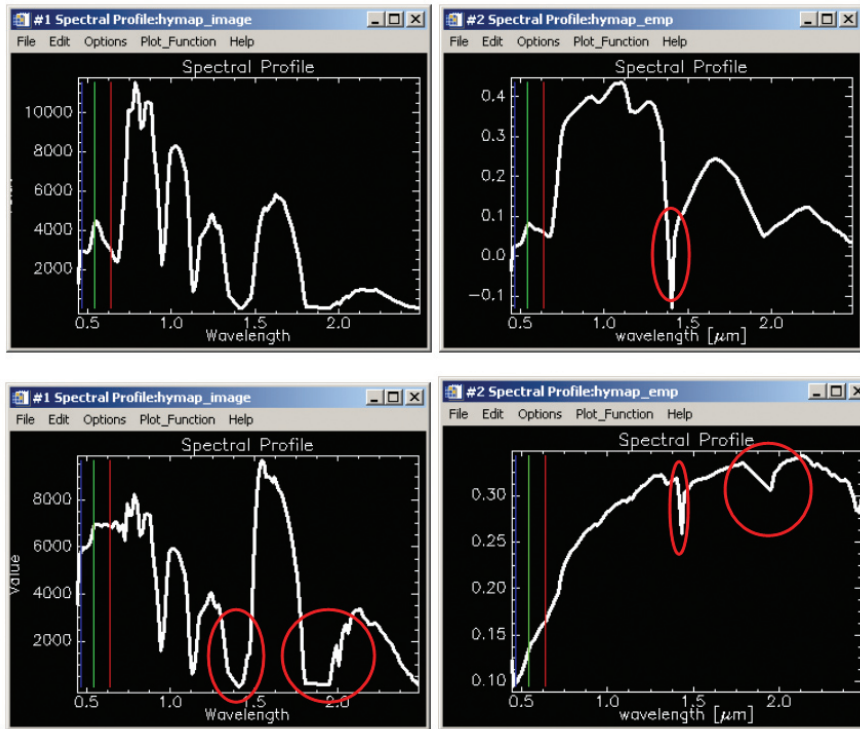
Answer 1.5 : Why should (based on these Z-profiles) the visibility used in ATCOR to correct this image be higher than 20 km?

When the assume visibility is too low the path radiance is overestimated this causes a negative (set to zero by ATCOR) or almost zero surface reflectance. Dark targets are most sensitive to this effect. The path radiance decreases with wavelength and the effect is mostly very small for wavelengths greater than 700 nm.
In this case the retrieved surface reflectance using a visibility of 10 km is (almost) zero in the wavelength range 400 – 700 nm. For a visibility of 20 km the spectrum looks already better in the green and red, but in the blue the reflectance is still almost zero.
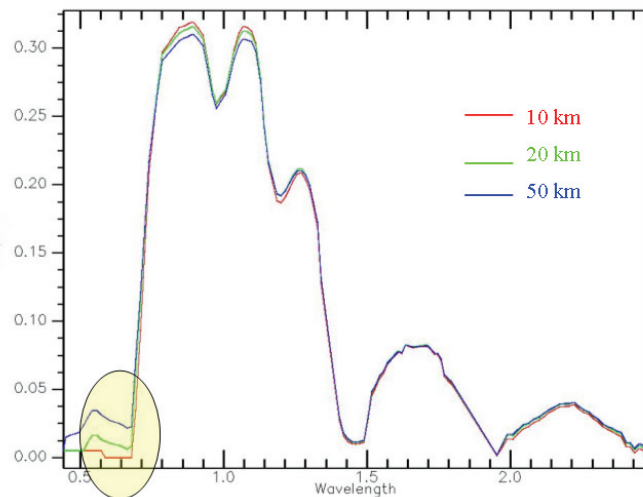
Objectives

1. To perform a geometric correction with Ground Control Points (GCPs)
2. To quickly compare the resulting geocorrected image with the results of a parametric approach

Lesson outline

Hands-on computer exercises

OBJECTIVE

In this exercise you will georeference a hyperspectral Compact Airborne Spectrographic Imager (CASI) image to a topographic map of the same area. The topographic map will be used as the basis to correct the CASI image.

IMAGE DATA

The CASI data were obtained in June 2003 in the framework of the BELCOLOUR project (http://www.mumm. ac.be/BELCOUR/). The topographic map dates from the period 1978- 1993 (Figure 1.4). The area covered in the data is Bredene-aan-Zee, Oostende, Belgium. The CASI sensor was installed in a Dornier 228 aircraft. The aircraft and CASI sensor were operated by NERC (Natural Environment Research Council), UK. The CASI was flown at an altitude of 2000 m, providing a spatial resolution of 4 m. The spectral configuration of the CASI was 96 channels from 405 to 947 nm with a FWHM of 6 nm.

>> **Fig.1.4 : (Left) uncorrected CASI image and (Right) topographic map.**

1. Open and display the CASI image and the topographic map

Action : In the ENVI < main menu> use the <Open Image File> option to open the uncorrected CASI image (Uncorrected) and display a true colour image (display #1).

Action : In the ENVI <main menu> use the <Open Image File> option to open the topographic map (TOPO. TIF) and load band 1 as a greyscale image into a new display window (# 2).

Action : Change the colours of the topographic map to have a nicer view (white background and black foreground)

> **Hint** : In the Main Image display select <tools> <color mapping> <ENVI color table>. Move the Stretch Bottom slider to the right and Stretch Top slider to the left.
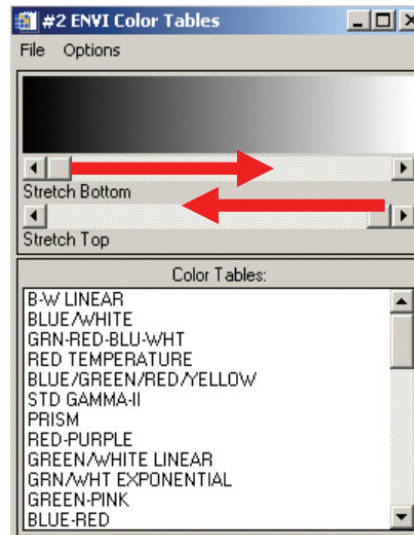
2. Beginning the georeferencing

Action : Select <Map> <Registration> , <Select GCPs : Image-to-Image>. When the <image to image registration> dialog appears, click on <Display # 2> (Topographic map) for the Base image (= image you use as reference, so already georeferenced) and on <Display # 1> (CASI image) for the Warp image (=uncorrected image)) .

Now you can start with collecting GCPs.

Question 1.6 : What is your definition of a set of ideal Ground Control Points? Can you fulfil in this case all the requirements? What is the problem?

Action : Add individual GCPs by positioning the cursor position in the two images on the same location : In the <Main Image> window of each image, position the <Zoom box> over the desired GCP area. In the zoom window, click the left mouse button on a specific pixel to position the cursor over that pixel. Once you think you have positioned your cursor as close as possible to the same point on each image click on <Add Point> in the <Ground Control Points Selection> dialog. The pixel information is loaded into the Ground Points Selection dialog. The GCP marker is placed showing the position in the zoom window. You should periodically save your results : In the <Ground Control Points Selection> dialog select <File> <Save GCPs to ASCII> and enter an output filename with the .pts extension.

> **Hint** : Zooming in as far as possible is not always the best strategy. Just zoom in far enough so that you can accurately position the cursor in each image.

Once you have at least 5 GCPs (this is sufficient to conduct a 1st degree polynomial warp), you will see that a total RMS (Root Mean Square) error is reported in the Ground Control Points Selection dialog. The RMS error for each point is also listed in the GCP List table. This error is calculated by applying a transformation across the image using the other points you have selected (hint : click on <show list>). The residual is the difference between the predicted location and the position of this point according to the reference map. The higher the RMS the further the point is away from where the transformation predicts it to be, based on the other points. The degree of polynomial used for calculating the error is displayed in the <Degree box> in the Selection dialog and can be changed when a sufficient number of GCPs has been selected.

Action : When you have a reasonable number (10 – 15) of ground control points you can start to produce a geocorrected version of the originally uncorrected image. Instead of georeferencing all 96 bands we will perform the georeferencing on only 1 band in order to reduce the computing time. In the <Ground Control Points Selection> dialog select <options>, <Warp Displayed Band (as image to map)>. Select as <Warp method> <polynomial> and as <degree> <1>. As <resampling> method we choose <nearest neighbour>. Click on <change output parameters> and change the <X, Y pixel size> into 4 meters.

Enter an output filename (corrected_pol_1) for your image.

Action : Repeat previous step but use as warping method a 2nd order polynomial. Save as <corrected_pol_2>.

Action : Repeat using this time <RST> which stands for (Rotation, Scaling, and Translation) as warping method.

Save as <corrected_RST>.

Action : First close the <Ground Control Points Selection> dialog and also the uncorrected CASI image.

The georeferenced bands (corrected_pol_1, .._pol_2, .._RST) should appear in the <Available Bands List>. Now you can start comparing your results with the topographic map.
Before you start, let's have a look at the results of a parametric approach. You can find this image with filename <geocorrected_parge> in your image directory. This image has been corrected with the geocoding software PARGE using attitude (roll, pitch, yaw) and position information (latitude, longitude, altitude) of the sensor measured during the flight.

Action : Open the <geocorrected_parge> file and display a true color image.

Action : Load the different georeferenced bands in new display windows. Now you can link all images on the basis of their geographic coordinates. In the Main Image Display of the topographic map select <Tools>, <Link>, <Geographic Link> and click on the arrow buttons [↕] to select <On> next to the display names. Now watch roads, shorelines, bridges,…. to check if they line up accurately.

Question 1.7 : Which image (corrected_pol_1 or .._pol_2 or .._RST geocorrected_parge) is positioned best? Why it is difficult to accurately georeference an airborne image using only GCPs data ?

——— Answers to questions ————————————————

Answer 1.6 : What is your definition of a set of ideal Ground Control points? Can you fulfil in this case all the requirements ? What is the problem?

GCPs are points that should be perfectly identifiable on both the reference map and the CASI image and that are unlikely to change over time (such as road intersections, land/water points, buildings,…). It is important to distribute the GCPs evenly across the image. Some points should be selected close to the edges, other more in the middle. In case you position your points all in one part of the image that area will be corrected quite good, but the remainder may be distorted.

The problem with this image is that we can't distribute the GCPs throughout the scene since in the sea part of the image no GCPs can be identified. Furthermore the reference topographic map is far older than the image and several roads were not yet present in the topographic map.

Answer 1.7 : Which image (corrected_pol_1 or .._pol_2 or .._RST geocorrected_parge) is positioned best ? Why it is difficult to accurately georeference an airborne image using only GCPs data ?

The image corrected with the parametric geocoding software (PARGE) has the best positional accuracy. In case the geocorrection is based on only GCPs no information is used about the sensor position and attitude (roll, pitch movement of aircraft) and it doesn't take into account distortions caused by the terrain relief. This can result in low-fitting accuracy because of the local character of the distortions. You can clearly see in the geocorrected_parge image that the aircraft has made some roll movements during the data acquisition. The Parametric approach uses this information during geometric correction.

Due to roll movement of the aircraft

Aim of Lesson

To visualize hyperspectral images, to explore image reflectance spectra and to prepare the images for later classification.

Objectives

1. To learn how to explore a hyperspectral image
2. To learn how image reflectance spectra can be explored
3. To investigate the impact of noise removal on hyperspectral images

Background Information

PRACTICAL ISSUES

Hyperspectral images, like most other remotely sensed digital images, often contain noise due to the limited accuracy of the sensor calibration, the inherent sensor design (electron noise, e.g. circuitry), the measurement itself (photon statistics) and the models used to perform the different data pre-processing steps. To compare the different image spectra and subsequently classify the images, noise has to be removed.

SOFTWARE

ENVI ® software is required to carry out the lesson.

Lesson outline

1. Exploring the hyperspectral image and its reflectance spectra

Before you start processing hyperspectral imagery you need to know how to explore the hyperspectral image and the reflectance spectra. You will first learn how to visualize 3 spectral bands in a colour image or show up individual bands in greyscale. Then you will learn to display and investigate the image reflectance spectra.

1. Open hyperspectral images and visualize 3 spectral bands in a colour image.

Action : In the 'ENVI' main menu use the 'Open Image File' option to open and display file \Lesson02\Data\ L1102rag10_Wh.

> **Hint:**   In the ENVI main menu [ENVI] use: <File> <Open Image File>

Action : Use the 'Available Bands List' to load band 1 in the blue (B) channel, band 14 in the green (G) channel and band 24 in the red (R) channel.

Info: The wavelength of band 1 is located in the blue region, the wavelength of band 14 is located in the green region and the wavelength of band 24 Is located in the red region of the electromagnetic spectrum. When assigning these bands to the corresponding Red, Green and Blue channel, an image is obtained, coloured identically as can be seen by the human eye.

> **Hint**:   Using the "Available Bands List", bands from the hyperspectral image can be allocated to the Blue, Green and Red channel as shown in Figure2.1.
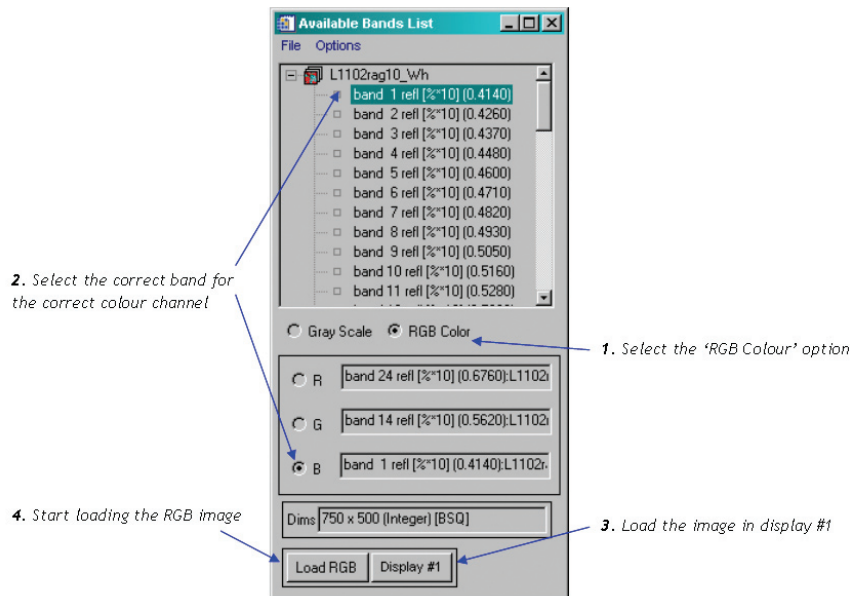
Figure 2.1: The image to be opened appears in the "Available Bands List" window, the bands to be displayed can now be chosen.

The image now pops up on the screen and you will notice three windows. The 'Scroll' window gives an overview of the complete scene. By shifting the red box around the scene (grab by left mouse button), a more detailed view is obtained in the 'Image' window. Again, the red box in this 'Image' window can be moved around to get an even more detailed view in the 'Zoom' window. You can zoom in and zoom out by clicking the + and – sign in the 'Zoom' window. A cross-hair can be placed in the 'Zoom' window (to indicate the actual pixel) by clicking the empty square, bottom left in the zoom window. This can be useful when you want to investigate individual image reflectance spectra (don't worry we'll explain this later!).

Because the hyperspectral image of 'De Westhoek' is rather small, it is sufficient and more convenient to display the image in only two windows. Therefore click the maximize button on the image window. As a result you will now see the complete hyperspectral image of the dunes, beach and even part of the sea as a whole in the 'Image' window. The 'Zoom' window is still present to explore the image in more detail.

Action: Explore the image by moving around the 'Zoom' window. Zoom in and out on the different parts of the scene to get an idea of the complexity of the hyperspectral image.

Info: You can enlarge the 'Zoom' window by grabbing one of the corners of the 'Zoom' window (left mouse button) and drag it to a larger size.

Question 2.1: You now have visualized three bands (1, 14 and 24) from the available 48 bands. What do you notice in the image? What can be the reason for this?

2. Investigate individual bands in a grey scale image.

Investigating the problem more in depth is possible by visualizing individual bands as grey scale images.

Action: Use the 'Available Bands List' to display band 1 as a 'Gray Scale' image. Load the image in display 2. Load consecutive bands for observation and notice the difference between them.

> **Hint**:   To create a new display, click the 'display' button in the 'Available Bands List' dialog and choose 'new display'.

Info: You can load other bands in the actual display by double clicking the required band in the 'Available Bands List'. Make sure that the active window selected, as indicated on the 'display' button, is 'Display #2'.

Action: After you investigated several bands you can now close display #2.

> **Hint**:   In the 'Image' window use: <File> <Cancel> or use the window close button at the top right of the image window.

3. Display and investigate image reflectance spectra.

When a large number of bands are to be investigated (which is mostly the case with hyperspectral imagery!),

displaying individual bands one by one is very time consuming. The Z profile or spectral profile can be used to get a clear overview of the different spectral band values at pixel level. This Z profile or spectral profile, also called the spectrum, is unique for each material on the Earth's surface and is the basis for hyperspectral image classification.

Action: Explore some pixel spectra. Compare the spectral profile of water pixels with the spectral profile of sand pixels and the spectral profile of vegetation pixels. Notice the difference in spectral profile in relation to the different materials at the Earth's surface.

> **Hint**:   In the 'Image' window use: <Tools> <Profiles> <Z Profile (Spectrum)…> move the 'Zoom' window around to investigate different pixels.

Question 2.2: How can you distinguish vegetation spectra from non-vegetation spectra? In other words, how does a typical vegetation spectrum looks like?

Often you need to compare different spectra against each other. Therefore an interesting option is to collect different spectra in the same 'Spectral Profile' window.

Action: Move the 'Zoom' window to the bottom right of the image where the blue stripes in the image are located (you still have band 1 on the blue (B) channel, band 14 on the green (G) channel and band 24 on the red (R) channel). Now collect some different spectra in this area by slightly moving the zoom box around.

> **Hint**:   In the 'Spectral Profile' window use: <Options> <Collect Spectra>. The 'Collect Spectra' option can be switched on/off. The option should be marked on.

Depending on the pixels selected, your 'Spectral Profile' window will look like Figure 2.2.
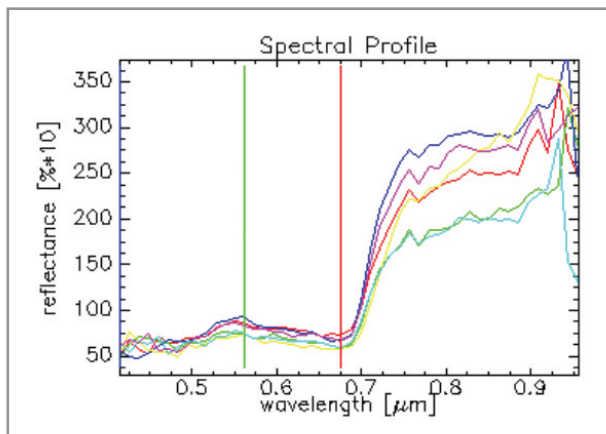
>> **Figure 2.2**: Spectral profile window showing different spectra collected from the hyperspectral image.

Question 2.3: Observe the collected spectral profiles carefully. What do you notice at wavelengths below 493 nm and above 885 nm? What could be the reason for this?

To view the spectral profile in more detail, the range of the X and Y axis can be changed.

Action: Zoom in on wavelength range 414-550 nm (blue) of the collected spectral profiles.

> **Hint**:   In the 'Spectral Profile' window use: <Edit> <Plot Parameters…>. Select 'X-Axis' and change 'Range 0.41400 To 0.55000', then select 'Y-Axis' and change 'Range 40.00000 To 100.00000'. Click <Apply> then <Cancel>.

After zooming in on the blue wavelength range, the 'Spectral Profile' window should look like Figure 2.3 below.
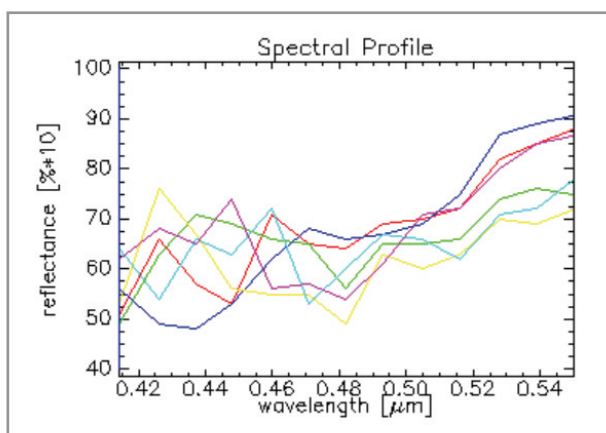
>> **Figure 2.3**: Spectral profile window showing the detailed part of the collected spectra between 414 nm and 550 nm.

Question 2.4: Now you have a detailed view of the low S/N ratio at the blue wavelength range. Can this problem be solved?

2. Noise removal

In this section you will learn how this noise can be removed from the image. It is not possible to correct the spectra for this noise in the blue region and at the NIR plateau, but we can remove the bands exhibiting noise.

Action: Remove bands 1 to 7 and bands 43 to 48 by creating a new file.

> **Hint**: In the ENVI main menu [ENVI] use: <Save File As> <ENVI Standard>.
> In the 'New File Builder' window use: <Import File…>.
> In the 'Create New File Input File' window: select the corresponding file (L1102rag10_Wh) and click <Spectral Subset>.
> In the 'File Spectral Subset' window: highlight the bands to be saved (select bands 8 till 42, in total 35 bands will be selected) and click <Ok> twice.
> Specify the path and filename were to store the new file by <Choose> in the 'New File Builder' window, i.e. use filename L1102rag10_Wh_c.

The newly created file contains less bands and therefore its size will be smaller than the original file (you can check this!). We will now continue using this newly created file which appeared automatically in the 'Available Bands List' after creation.

Action: Load the newly created file in 'Image #1'. Again load band 1 in the blue (B) channel, band 14 in the green (G) channel and band 24 in the red (R) channel.

Question 2.5: Your image will look a bit strange now. What happened? Use the 'Z profile' to explore the spectral profile.
You can reload the visual bands to obtain a naturally looking image. Load band 6 in the green channel and band 17 in the red channel, band 1 stays in the blue channel.

> **Hint**: You can easily load other channels to your image window by using the 'Spectral Profile' window. Grab the corresponding colour bar and drag it to the desired channel or wavelength (use the left mouse button). When all colour bars are on the correct channel, click with the right mouse button in the 'Spectral Profile' window and use <Load New RGB Combination>.

Now that you have reloaded a naturally looking image, you can again explore different spectra in the scene by moving the zoom box around and observing the spectra in the 'Spectral Profile' window.

Action: Observe the spectrum of the pixel located at pixel location: Sample=350, Line=250.

> **Hint**: In the 'Image' window use: <Tools> <Pixel Locator …>. In the 'Pixel Locator' window fill in 'Sample' 350, 'Line' 250 and click <Apply>. In the 'Spectral Profile' window use: <Option> <Plot Key>. You can also use the shorter option by right clicking in the 'Spectral Profile' window and left clicking on <Plot Key>.

Question 2.6: Your 'Spectral Profile' window should now look like Figure 2.4. Do you think this spectrum looks ok now? Especially look at the indicated areas. What might be the reason for this? How can this be solved?
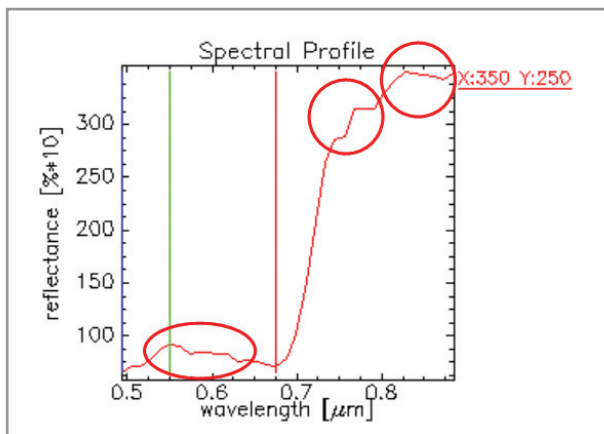
>> **Figure 2.4**: Spectral profile window showing a vegetation spectrum containing remarkable spectral features (circumvented in red).

ENVI also includes a spectral polishing algorithm, but we won't examine this option here. Instead the image \Lesson02\Data\L1102rag10_Wh_cp, which is polished by an external algorithm, is used.

Action: Load image L1102rag10_Wh_cp on display #2. Link this display with display #1 and display the Z profile. Overlay the spectrum of display #2 on the spectrum of display #1. Observe the effect of the external polishing algorithm.

> **Hint**: In the 'Available Bands List' use: <File> <Open Image File…> to open file \Lesson02\Data\L1102rag10_Wh_cp and load the image bands 1, 6 and 17 in display #2 as explained before.
> In the '#2 Image' window use: <Tools> <Link> <Link Displays…>.
> In the 'Link Displays' window set 'Link Size / Position' to 'Display #1' and click 'Ok'.
> Display the Z profile as explained before.
> In the 'Spectral Profile' window #2 use: <Edit> <Data Parameters…>.
> In the 'Data Parameters' window right click on the red square and change the colour to <Blue>.
> Use the 'Plot Key' as explained before, grab the spectrum (use left mouse button) and drag it to the '#1 Spectral Profile' window.

After these actions the 'Spectral Profile' window should look like Figure 2.5 where the polished spectrum (blue) is overlaid on the input spectrum (red). You can clearly see that the noisy input image spectrum has a smoother curvature after polishing. Now the image is ready for classification.
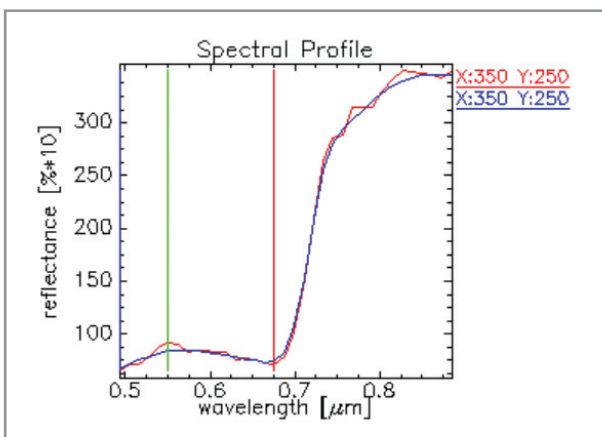
Figure 2.5: Spectral profile window showing a polished vegetation spectrum (blue) overlaid on the same non-polished vegetation spectrum.

Answers to questions

Answer 2.1: You now have visualized three bands (1, 14 and 24) from the available 48 bands. What do you notice in the image? What can be the reason for this?

As can be seen in the detailed view below (Figure 2.6) some striping is present in the scene. This striping is parallel to the scan direction of the hyperspectral sensor and is due to noise in some of the bands. This noise is the result of the limited calibration accuracy of the sensor, the low irradiance at the shorter wavelengths and the limited accuracy of the different models for radiometric and atmospheric correction.
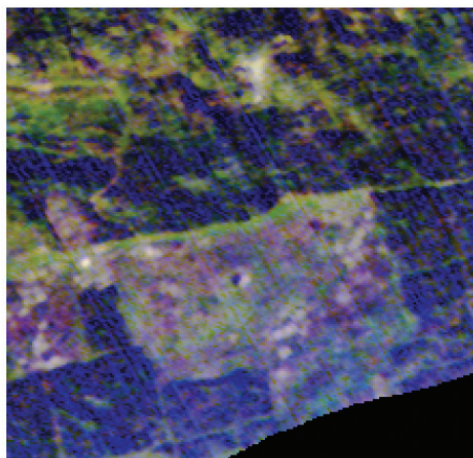
>> **Figure 2.6: Hyperspectral image showing band 1 in the 'Blue' channel, band 14 in the 'Green' channel and band 24 in the 'Red' channel.**

Answer 2.2: How can you distinguish vegetation spectra from non-vegetation spectra? In other words, how does a typical vegetation spectrum looks like?

Vegetation spectra can easily be distinguished from non-vegetation spectra by some characteristic features. Absorption by green plants is strongest in the blue and red part of the visible spectrum. The green part of the solar spectrum is less absorbed and this is the reason why plants look green to the human eye. This increased reflection in the green area around 550 nm is called the green peak and is one of the two characteristic spectral features for vegetation.

The energy contents of the non-visible short infrared is insufficient for photochemical reactions and therefore it is not absorbed by the chlorophyll and the other leaf pigments. This results in a strong increase of reflection around 690 nm called the 'Red-edge' this is typical for vegetation and is the second characteristic spectral features for vegetation. These typical features are illustrated in Figure 2.7.
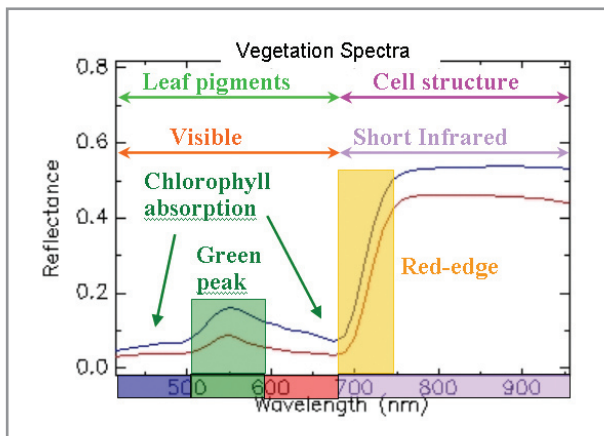
>> **Figure 2.7**: Vegetation reflectance spectrum showing some typical vegetation spectral features, i.e. the chlorophyll absorption features, the green peak and the red-edge.

Answer 2.3: Observe the collected spectral profiles carefully. What do you notice at wavelengths below 493 nm and above 885 nm? What do you think is the reason for this?

The two areas which look a bit suspicious are indicated by the two circles in Figure 2.8. The reason for this strange behaviour in the blue region (shortest wavelengths) was explained in answer 1. On the Near Infra Red (NIR) plateau there is an additional problem caused by water vapour absorption. Both phenomena result in a poor Signal to Noise ratio (S/N ratio) at these wavelengths.
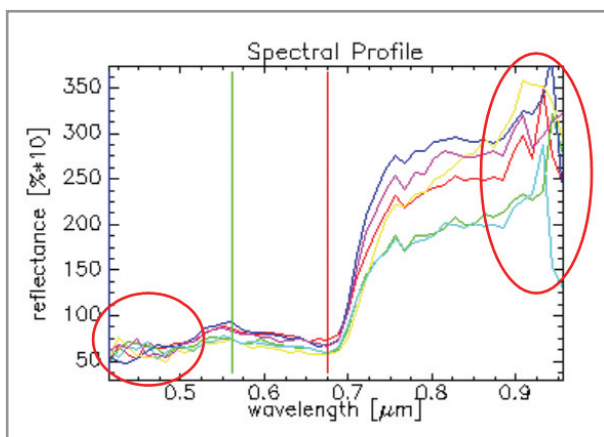
>> **Figure 2.8**: Spectral profile window showing noisy vegetation spectra.

Answer 2.4: Now you have a detailed view of the low S/N ratio at the blue wavelength range. Can this problem be solved?

Smoothing or polishing algorithms can't be used when the S/N ratio is too bad. So the only way you can solve this problem is by removing the bands with poor S/N ratios. This process is called "bad band removal".

Answer 2.5: Your image will look a bit strange now. What do you think happened? Use the 'Z profile' to explore the spectral profile.

Because the first 7 bands where removed you now loaded the same band numbers on the same colour channels but these band numbers now are allocated to higher wavelengths. In fact, by removing the first 7 bands, you're

displaying the original bands 8, 21 and 31, which are allocated to wavelengths 493 nm, 642 nm and 757 nm respectively. You can check the wavelength by clicking on the blue, green or red bar in the 'Spectral Profile' window (use left mouse button). The corresponding channel number, wavelength and pixel value will appear at the bottom of the window. See Figure 2.9 where channel 24, allocated to wavelength 757 nm and with pixel (reflectance) value 223 is shown.
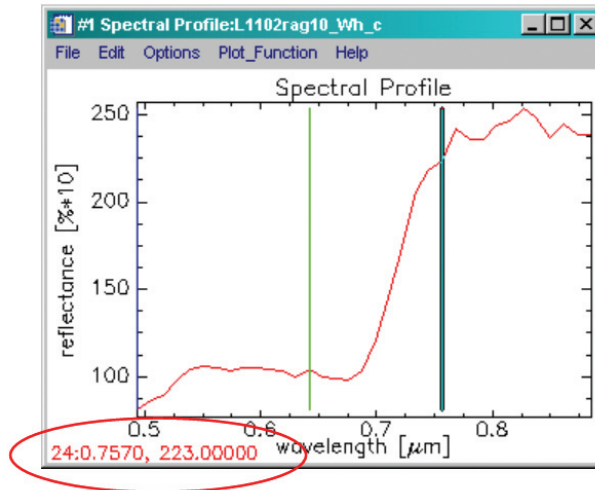
>> **Figure 2.9: The spectral profile window can be used to find out the reflectance value of a certain band at a particular wavelength. Here band 24 at 757 nm has a reflectance value of 0.223.**

Because you have assigned a NIR wavelength (channel 31 at 757 nm) to the red channel, the image displayed is in fact a false colour infrared. Because vegetation strongly reflects the NIR wavelengths (remember the red-edge!), it looks red now. Because the reflectance at the NIR plateau is determined by the water contents and the internal structure of the leaf, different plant types can be distinguished by the different shades of red. You can check this by carefully looking at the image, using the zoom window. We will explore this in more detail in lesson 9 (The colour of leaves).

Answer 2.6: Your 'Spectral Profile' window should now look like the one in Figure 2.4. Do you think this spectrum looks ok now? Especially look at the indicated areas. What might be the reason for this? How can this be solved?

These kinks aren't usual vegetation features. Again, as explained in answer 1, to solve this problem different smoothing and polishing algorithms exist but we're not going into depth in this lesson.

Aim of Lesson

To learn how the colour of water is affected by its constituents and hence how optical remote sensing can be used to estimate concentrations of chlorophyll-a (CHL) and total suspended particulate matter (TSM), water transparency and related parameters.

Objectives

1. To observe how the colour of water as seen by the human eye relates to radiance and reflectance parameters measurable by remote sensing.
2. To learn how the colour of water (reflectance) varies for high/low concentrations of CHL, TSM and dissolved organic matter.
3. To test algorithms for retrieving CHL and TSM on datasets acquired for different water bodies.

Background information

PRACTICAL ISSUES

Weather permitting, measurements will be made outdoors for nearby water bodies (canal, lake). In case of bad weather optical measurements will be made instead indoors with simple classroom equipment.

This lesson relates to Section 10.1 of the HyperTeach Theory Syllabus. For further details about the techniques involved readers are recommended to read this section.

SOFTWARE

Access to a PC with Excel is required to carry out the lesson.

Lesson outline

Part 1: Field Measurements (partially indoors if rain/snow)

Student will learn how the colour of water as seen by the human eye relates to radiance and reflectance parameters measurable by remote sensing by observing different water bodies using simple optical equipment (Secchi disk, Forel-Ule scale, coloured and polarised filters) and using a spectroradiometer system.

Aquatic optics and optical remote sensing

A spaceborne or airborne optical remote sensor detects sunlight that has been redirected towards the sensor by one of three processes: a) scattering by particles in water and water molecules, b) reflection at the air-water interface and c) scattering by particles in air (aerosols) and air molecules. Only the first of these processes will yield useful information about water composition, the other two processes must be avoided or corrected.

The study of aquatic optics is made easy by the possibility of observing many phenomena in everyday situations using our very own portable spectroradiometer, the human eye, and cheap and simple optical equipment. Students will observe themselves the following phenomena described in the Hyperteach Theory Syllabus: sunglint and sky reflection at the air-water interface and differences in water colour and transparency related to different water constituents.

Sunglint

A flat water surface acts partially as a mirror and will reflect directly the sun if viewed in the sunglint direction.
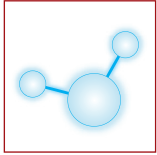
>> **Fig.3.1.1: Sunglint observed at sea.**

Action : Look at a water surface and, if sunny, identify the sunglint direction.

Question 3.1.1 : How is the water different from a mirror ? How "wide" is the sunglint direction and how does this width vary in different weather conditions?

Question 3.1.2 : Why does the SeaWiFS sensor tilt, pointing towards the North in the Northern hemisphere and towards the South in the Southern hemisphere?

Question 3.1.3 : The MERIS sensor does not tilt, but points downwards ("nadir viewing") in the centre column of an image. What is the consequence of this engineering choice on image quality ?

> **Hint** : Search for keywords "MERIS" and "sunglint" on the Internet.

Sky reflection

When we look at water we see both light from beneath the surface and light reflected at the surface (air-water interface), but in different proportions depending on the viewing angle.

>> **Fig.3.1.2 : Sky reflection seen in a photo of the sea taken from a boat.**

Action : Look at a water surface and see how the colour is different when viewing:
    a)   at oblique viewing angles
    b)   nearly vertically downwards.

Question 3.1.4 : For which viewing angles do you see better the water colour?

Question 3.1.5 : Why is satellite data flagged for large zenith viewing angles (i.e. far from vertical viewing) ?

Water colour

The colour of the water itself depends on the concentration and optical properties of particles in suspension and on dissolved matter, especially organic matter resulting from biodegradation of plants. By measuring the colour or "spectral reflectance" of water from a spaceborne or airborne optical remote sensor it is possible to deduce certain properties of the water such as the concentration of suspended particulate matter.
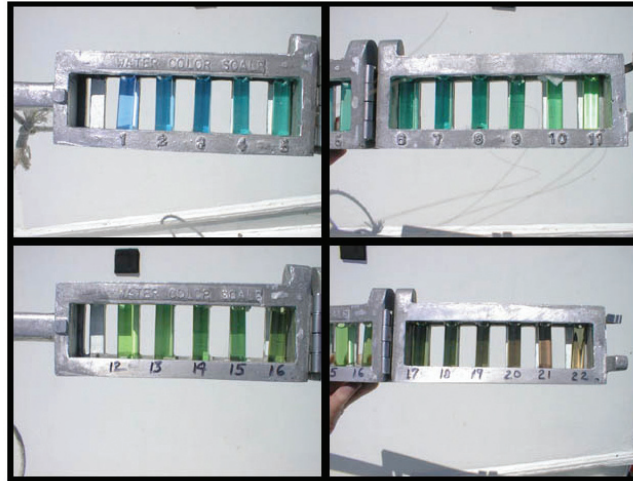
>> Fig.3.1.3 : Comparing water colour with the Forel-Ule scale.

Action : Look at different water surfaces using the Forel-Ule scale and take a bucket sample to see more clearly the suspended particles. The tutors will demonstrate use of a spectroradiometer system for measurement of spectral reflectance.

Question 3.1.6 : How are the water bodies different in colour ? Can this be related to the type/origin of water or to the suspended particles ? Where would you expect to see the very blue water, colour 1 of the Forel-Ule scale ?

>> Fig. 3.1.4 : Airborne photograph of Oostende harbour.

Question 3.1.7 : Look at the airborne photograph (Fig. 3.1.4). How do river and seawater differ in colour and why ?

Question 3.1.8 : How does the human eye differ from a hyperspectral airborne sensor such as CASI, APEX or HYMAP in terms of perception of colour ?

> **Hint**:   Search for keywords "human eye" and "spectral resolution" on the Internet.

Water transparency

The transparency of water also depends on the concentration and optical properties of particles in suspension and on dissolved organic matter. Water transparency affects the growth of microscopic aquatic plant life (phytoplankton), since photosynthesis can occur only in the near-surface layer where there is sufficient light ("euphotic zone").
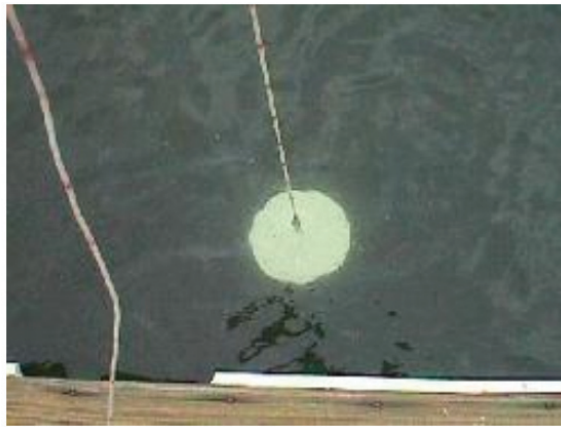
>>   **Fig.3.1.5 : Measuring water transparency with a Secchi disk.**

Action : Measure the water transparency for different water surfaces using the Secchi disk. The depth at which the disk can no longer be seen is called the "Secchi depth".

Question 3.1.9 : How are the water bodies different in transparency ? Can this be related to the type/origin of water or to the suspended particles ? Where in the world would you expect to find water with the greatest Secchi depth ?

Question 3.1.10 : Why is optical remote sensing of suspended particles more difficult when the Secchi depth exceeds the total water depth ?

> **Hint**:   What else do you see?

Question 3.1.11 : Apart from biologists interested in assessing phytoplankton growth (and associated issues such as the global carbon cycle) who else might be interested in water transparency?

> **Hint**:   Search for keywords "Naval Research" and "water transparency" on the Internet.

Part 2: Forward optical modelling: how spectral reflectance depends on total suspended (TSM), phytoplankton pigments such as chlorophyll-a (CHL) and coloured dissolved organic matter (CDOM)

The Theory Syllabus Section 10.2 describes a simple forward model which gives spectral reflectance as output for different input concentrations of non-algae particles (NAP), CHL and CDOM. In this model the total suspended particulate matter concentration (TSM) is obtained by adding the weight concentration of NAP and of algae particles, where the latter is estimated from CHL. Put simply, considering that reflectance is approximately proportional to backscatter divided by absorption:

- Increasing NAP will increase backscatter throughout the spectrum and hence tend to increase reflectance throughout the spectrum. However, since particles also absorb light, especially in the blue, the increased absorption may tend to reduce reflectance at least for certain parts of the spectrum.

- Increasing CHL will increase absorption for the blue spectral range 400-500nm, especially around 440nm and also for the narrow red spectral range 660-680nm and hence tend to reduce reflectance for these ranges. If TSM is composed mainly of non-algae particles, backscatter will change little for different CHL. However, if most suspended particles are algae particles then increasing CHL will increase also the total backscatter as well as absorption and, hence, possibly increase reflectance at least for spectral ranges where the increased backscatter is more important than the increased absorption.
- Increasing CDOM will increase absorption, especially for blue wavelengths, and hence reduce blue reflectance.

Action: Load the Excel workbook entitled "HYPERTEACH-OCMODEL-v0.1.xls". This contains 4 sheets as follows:

INPUT: This is the sheet where you enter input concentrations and see the resulting absorption and backscatter coefficients and water-leaving reflectance spectra.

README: This sheet gives some background documentation and a warning regarding use of the model with remote sensing data.

PARAMETERS: This sheet contains default parameters used by the model, which are set according to the optical theory and assumptions described in Section 10.2.1 of the Theory Syllabus.

These parameters should not be modified.

CALCULATIONS: This sheet contains all the calculations of absorption and backscatter coefficients and reflectance for wavelengths from 400nm to 800nm every 2nm. This sheet should not be modified, but is interesting for students wanting to see in more detail how the model works.

During this lesson the student will change inputs for Chlorophyll concentration (CHL), non-algae particle concentration (NAP) and coloured dissolved organic matter (CDOM) absorption at 443nm (the three cells marked in orange), called the "input triplet" in this lesson. These inputs are shown also in the left hand column plots of the screen (see Figure 3.2.1) entitled "Input water constituents" together with the resulting Total Suspended Matter (TSM). The values can be changed by using the spin buttons or by typing new values in the orange cells.

In the centre two plots the absorption and backscatter coefficients corresponding to this input choice are shown as components and as the total of all components.

In the right hand plots on the screen the water-leaving radiance reflectance is plotted against wavelength (using a logarithmic y-axis to show the large range of reflectances that can be encountered and using a linear scale to stress the variance in shape). The black curve corresponds to the input triplet. The other curves correspond to pre-generated combinations of input triplets.
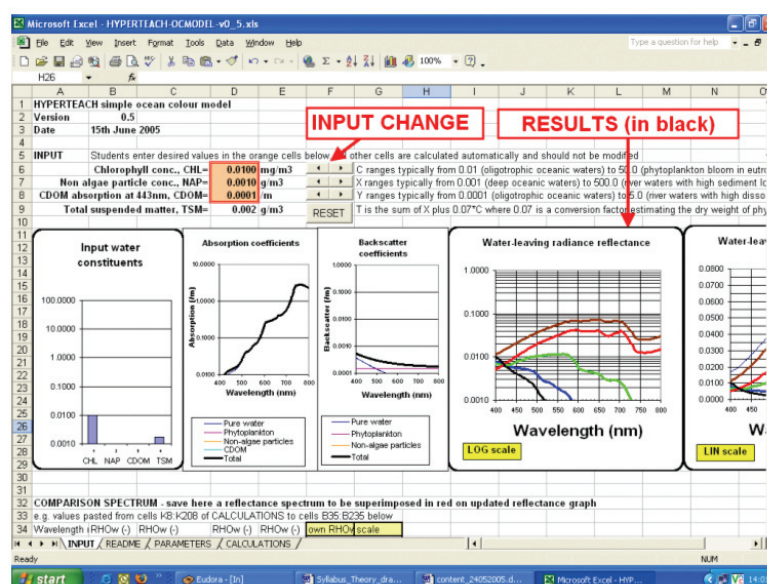
>> Figure 3.2.1. Screen shot of the Excel workbook "INPUT" worksheet where students change input and see results graphically.

Action: Set low values for all three input parameters: CHL=0.01 mg/m3, NAP=0.001 g/m3, CDOM=0.0001 /m (as in Figure 3.2.1). This can be done by pressing the "reset" button. See that the total absortion coefficient is almost identical to the pure water absorption coefficient (second plot from the left) and that the total backscatter coefficient is partly from phytoplankton and partly (in the blue) from pure water (third plot from the left). The reflectance (thick black line on the right hand plots) shows a peak in the blue (400nm) with rapid decrease to below 0.001 in the green (520nm). This is very clear blue water. Now vary the three input parameters and see how the reflectance changes and why (via the absorption and backscatter coefficients).

Question 3.2.1: How does increasing non-algae particle concentration (NAP),e.g. to 1.0 then to 10.0 then to 100.0 g/m3 affect: a) absorption, b) backscatter and c) reflectance?

Action: Reset all three components to low values and now investigate how reflectance changes as CHL is increased to 1.0 then to 30.0 mg/m^3.

Question 3.2.2: For low NAP and CDOM how does an increase in CHL affect the wavelength of maximum reflectance? How will this be seen in terms of the colour perceived by a human observer?

Action: Reset all three components to low values. Now try to find the input concentrations that correspond to the pregenerated reflectance spectra in the right hand plot by fitting the thick black curve in the reflectance plots to the other coloured curves.

Question 3.2.3: What CHL, NAP and CDOM combination gives a reflectance spectrum similar to that of the blue curve (low reflectance blue water)?

> **Hint 1**: The blue curve has very low red (600nm) reflectance and so has low NAP concentration.
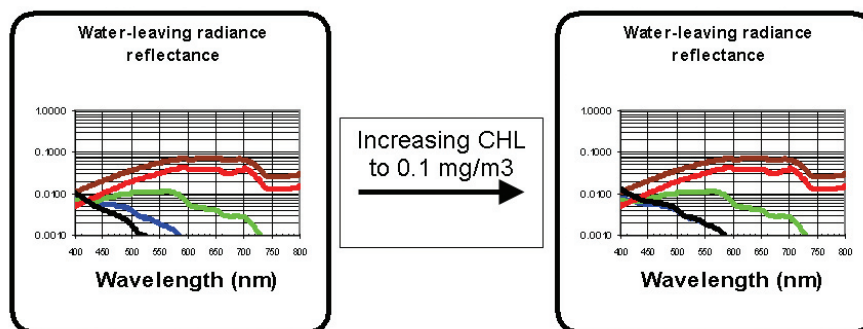
>> **Figure 3.2.2. The blue, green, red and brown curves are pregenerated and do not change. The black curve will change according to the inputs for CHL, NAP and CDOM. Here low values are given for all three inputs (CHL=0.01 mg/m3, NAP=0.001 g/m3, CDOM=0.0001 /m) in the left hand plot. Increasing CHL to 0.1 mg/m3 changes the black curve, increasing reflectance for 450-550nm as shown in the right hand plot, making it closer to the blue curve.**

> **Hint 2**: CDOM affects blue reflectance most but has less effect on green and red wavelengths. So set NAP and CDOM to low values and try to fit the spectrum at 500-550nm by varying CHL (see Figure 3.2.2). Then fit the spectrum at 400-450nm by varying CDOM absorption.

Question 3.2.4: What CHL, NAP and CDOM combination gives a reflectance spectrum similar to that of the green curve (medium reflectance green water)?

> **Hint 1**: Red (600nm) reflectance is now moderate. This can be achieved either by very high CHL or by moderate NAP concentrations. Try both to fit the spectrum for 550-720nm. Then vary CDOM to achieve a good fit in the region 400-450nm.

Question 3.2.5: What CHL, NAP and CDOM combination gives a reflectance spectrum similar to that of the brown curve (high reflectance, turbid red/brown water)?

> **Hint 1**: Red and even near infrared (700-800nm) is now significant suggesting a very high particle concentration. Reset all concentrations to low values then vary NAP to fit the near infrared spectrum.

> **Hint 2**: Next vary CDOM to fit the blue spectrum (400-450nm). Finally adjust CHL.

Question 3.2.6: In the previous exercise where do you see the biggest impact of a change in CHL? How is the red curve different from the brown curve ? Which CHL, NAP and CDOM combination gives a reflectance spectrum similar to that of the red curve (high reflectance, turbid red/brown water)?

> **Hint 1**: Vary NAP then CDOM then CHL as previously.

Part 3: Advanced optical modelling (extra-curricular or optional project work)

For students wishing to become experts in aquatic optics much, much more can be learnt from this simple model.

Action: Make a back-up of the original worksheet (save at a different name) and set challenge reflectance spectra for other students to match by pasting values from the CALCULATIONS sheet cells K8:K208 to the INPUT sheet cells B35:B235 (which is plotted as the blue curve).

Action: Play with the input concentrations until you are so familiar that you can a) estimate the concentrations just by looking at the reflectance spectrum and b) understand how the component absorption and backscatter coefficients are affecting the reflectance spectrum. In some cases the reflectance spectrum may not vary even if you multiply one of the inputs by ten. In reality this means that the colour of water is not sensitive to that parameter for that combination of the other parameters. As a consequence remote sensing of the insensitive parameter will not be feasible.

Action: Now modify the spreadsheet so that continuous (hyperspectral) spectrum are not seen, but only individual points corresponding to the discrete wavelengths of multispectral sensors such as SeaWiFs or MODIS.

Question 3.3.1: What information, if any, is lost?

Action: (for the truly adventurous) After making a backup of the original worksheet, now try modifying also some of the default parameters such as the logarithmic spectral slope of CDOM absorption (SCDOM) set in cell B13 of the PARAMETERS sheet. In reality this parameter is not known precisely but measurements show that it may take values between about 0.014 nm^{-1} and 0.022 nm^{-1}.

Question 3.3.2: If SCDOM were also considered unknown and set as a fourth variable input parameter, would it be possible to estimate it by fitting the reflectance spectrum as before? Would there be a unique solution for the four input parameters or is it possible that different combinations give equally acceptable solutions: a) in the hyperspectral case ? b) in the multispectral, e.g. SeaWiFS bands, case ?

_____ Answers to questions _____

Answer 3.1.1: A mirror would reflect the sun as a perfect disk of the same size as the actual sun. A water surface, even if rather flat, will always have some small waves which break up the image of the reflected sun. If waves are bigger the reflected sun will be spread over a larger area and be composed of glittering points of light corresponding to individual wave facets oriented at the perfect angle for reflection towards the viewer.

Answer 3.1.2: The SeaWiFS sensor tilts to avoid sunglint. SeaWiFS tilts (changes orientation) during each orbit so that it is always looking away from the sun and all of the image is thus usable.

Answer 3.1.3: The MERIS (and MODIS) sensor do not tilt but always point downwards (nadir-viewing). A part of each image (the Eastern part for Northern hemisphere images because of the morning overpass time) is thus contaminated by sunglint and cannot be used.

Answer 3.1.4: When viewing obliquely you see mainly sky reflection but not the colour of the water itself. When viewing vertically or near to vertical you see much les sky reflection and much better the water colour.

Answer 3.1.5: Satellite data of water bodies is usually flagged as suspect or poor quality for large zenith viewing angles (edges of image for wide swath sensors) because the sensor then sees mainly sky reflection instead of the water.

Answer 3.1.6: <Answered in practical demonstration (depends on conditions)>
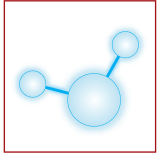
Answer 3.1.7: The river water is browner than the bluish seawater. This is because it contains a much higher concentration of suspended particles such as mud particles which scatter all colours but also absorb blue light.

Answer 3.1.8: The human eye contains many receptor cells of three different types. All human perceptions of colour can be decomposed into the intensity of these three colours. A television picture is for this reason generated using three basic colours. Hyperspectral sensors such as CASI, APEX or HyMAP have detectors specific for more than a hundred wavelengths. They can thus potentially detect differences in colour (e.g. because of atmospheric oxygen absorption near 762 nm) that a human cannot detect.

Answer 3.1.9: <first part is answered in practical demo> The greatest Secchi depths are found for the clearest waters, i.e. the waters with very few or no particles. Aquatic particles can come from rivers, from the bottom (by resuspension) or for the case of phytoplankton from microscopic plant growth. Thus, the greatest Secchi depths are found for deep waters, far from rivers and land and with low biological production. In general the deep oceans have large Secchi depths (e.g. tens of metres). The Sargasso Sea has very low biological production and is often considered as a typical very clear water region.

Answer 3.1.10: If the Secchi depth exceeds the total water depth this means you can still see your Secchi disk when it hits the bottom. This means also that an optical remote sensor will see not just the particles suspended in the water column but also the bottom sediments. A clever algorithm will be needed to separate the bottom sediments from the suspended particles.

Answer 3.1.11: The military are interested in water transparency for the detection of submarines and other underwater objects (mines, etc.). For example, the US Naval Research Laboratory has strong coastal optics activities.

Answer 3.2.1: Increasing non-algae particle concentration increases absorption for the blue spectral region, and for the green region if sufficiently high. Backscatter increases at all wavelengths, giving an increase in reflectance at all wavelengths at first, but when the increased blue absorption takes effect the blue reflectance increases no further while the green and red reflectances continue to increase rapidly at first, then more and more slowly at maximum reflectance is reached.
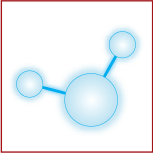
Answer 3.2.2: For low NAP and CDOM and CHL=1 mg/m^3, the reflectance spectrum has a maximum at 400nm and a local maximum at about 460nm. If CHL increases further to CHL=30 mg/m3 the reflectance at 400nm decreases, because phytoplankton absorb strongly in the blue, but the reflectance maxima around 490nm and 570nm increase because the total absorption is lower there. As CHL increases the water colour goes from blue to green.

Answer 3.2.3: Input of CHL=0.1 mg/m^3, NAP=0.001 g/m^3 and CDOM=0.004 /m were used to generate the "blue curve" reflectance spectrum.

Answer 3.2.4: Input of CHL=10.0 mg/m^3, NAP=0.001 g/m^3 and CDOM=0.04 /m was used to generate the "green curve" reflectance spectrum. NAP=1 g/m^3 and low CHL and CDOM gives a reasonable match for 550-720nm except for the local minimum seen near 670nm (especially in the log scale reflectance spectrum) which can only be achieved by high CHL.

Answer 3.2.5: Input of CHL=12.0 mg/m^3, NAP=55.0 g/m^3 and CDOM=1.50 /m was used to generate the "brown curve" reflectance spectrum.

Answer 3.2.6: When the brown curve in question 3.2.5 is well-fitted variation of CHL has little effect on the reflectance spectrum. It is only near 670nm that a difference can be seen when varying CHL. This implies that the blue and green spectral regions are not useful in algorithms for CHL retrieval in such high NAP and CDOM waters. The red curve is lower reflectance (so lower backscatter, so lower NAP) and has a clearer local minimum at 670nm (so has higher CHL). CHL=45.0 mg/m^3, NAP=23.0 g/m^3 and CDOM=2.50 /m was used to generate the red curve.

Answer 3.3.1: This is a broad question with no simple, unique answer. However, an example of what is lost with the SeaWiFs bands is that the local minimum near 670nm for high CHL can no longer be distinguished because neighbouring bands are spectrally too far away.

Answer 3.3.2: This question and other similar questions relating to uniqueness of solutions are being considered by various research groups internationally but no clear answer has been provided yet. It is suspected that if we have too many "unknown" variables to retrieve then there could be multiple solutions that are equally possible. i.e. optical remote sensing cannot give a single answer but gives potentially more than one answer which is completely coherent with the available data. In such cases extra data, e.g. from in situ measurements or from knowledge of parameters such as SCDOM (which can then be accepted as fixed), is needed to determine which solution corresponds to the reality. An interesting discussion of possible multiple solutions to athe optical remote sensing problem is given by [Sydor, Applied Optics, vol 43, no 10, 2004]. The problem of possible existence of multiple solutions is much more severe problematic when less spectral information is available (e.g. SeaWiFs bands instead of hyperspectral). In the extreme case of very limited spectral information (e.g. AVHRR bands 1 and 2) there is no way of distinguishing between non-algae and algae particles.

Lesson 4: Optical remote sensors for aquatic applications

_____ Aim of Lesson _____

To learn what satellite sensors exist for aquatic applications and how to choose the most appropriate sensor(s) for a specific application.

_____ Objectives _____

1. To understand the meaning of terms relevant to the technical performance of a sensor and platform (spatial and spectral resolutions, swath, orbit, revisit frequency, pointability, tilt, etc.).
2. To review the satellite data sources currently available, summarizing characteristics
3. To determine which characteristics are important for which applications and choose the best data source for some example applications.

_____ Background information _____

This lesson is related to Sections 2.2.2 and 4.1.1 of the Hyperteach Theory Syllabus.

SOFTWARE

Access to a PC with Excel, Internet and Acrobat Reader is necessary.

_____ Lesson outline _____

1. Technical terms and their importance were previously explained in the Hyperteach lecture on thematic applications for water. They will be revised here.
2. Students will be given an Excel spreadsheet cross-referencing satellite sensors with their characteristics (orbit, tilt, spatial resolution, spectral resolution, etc.). Students will search the Internet for information on the listed sensors and fill in the table.
3. Students will be presented with a few sample situations (e.g. a coastal manager needing near real-time warning of algae blooms, an environmental consultancy needing a first idea of suspended sediments in a small and remote region, a global change modeller needing data for interannual variability of chlorophyll-a in the North Atlantic). What is the best data source(s) for each application?

Part 1: Familiarising with the technical terms

While there are probably more than 30 current spaceborne sensors with spectral bands suitable in some way for aquatic applications, only a handful of these are sufficiently well-specified and supported to warrant detailed attention. Of these, SeaWiFS (also called Orbview-2), MODIS (TERRA and AQUA) and MERIS are the key "ocean colour" instruments with sufficient spectral resolution, sensitivity and calibration accuracy for mapping of chlorophyll a concentration. For mapping of suspended particulate matter (SPM) much less spectral information is needed and sensors such as AVHRR can be useful where ~1km resolution is sufficient and sensors such as SPOT-5 or ASTER can be useful if much finer spatial resolution is needed.

For this lesson nine sensors, potentially useful for aquatic applications, have been selected and Internet sites with technical information on them are provided. The Excel spreadsheet summarises the characteristics of some sensors. For others the entries are left blank and the student should supply the necessary information from searching the Internet (both suggested sites and others).

Action : Open the Excel workbook for Lesson 4 at the "TO DO" spreadsheet. This gives a table of 9 spaceborne sensors and the characteristics for 6 of them.
Figure 4.1 shows a screenshot when the Excel workbook is open. Before collecting the missing information familiarise yourself with the characteristics listed by answering the following questions.

Question 4.1.1 : Do you understand all the technical terms in column A of this spreadsheet ? If not, ask.

Most satellite sensors orbit the earth in a sun-synchronous near-polar orbit. This allows imaging of the whole earth with a regular overpass time every day or every few days. Such sensors typically have an orbital inclination of between 95° and 100°, a well-defined equator crossing time (in local solar time) and an altitude between 600km and 800km. Alternatives to such "polar orbiters" include geostationary satellites, at much higher altitude with permanent observation of a limited portion of the globe, or satellites with alternative orbital inclination giving preferential coverage of lower latitudes.

Question 4.1.2 : Do any of the six sensors whose characteristics are supplied in the Excel workbook have non-polar orbits ?

The orbit cycle defines the repetitivity of the satellite's orbit. This means that a satellite with an orbit cycle of 11 days the location of imagery will be identical for acquisitions exactly 11 days apart. However, the revisit time for any location defines the interval between successive imaging of the same location somewhere in the image. i.e. a revisit time of about 1 day means that a specified location will be visible on imagery approximately once per day, even though the images on successive days may cover different but overlapping areas. Large swath sensors generally have frequent imaging of the same location (low revisit interval in days/image) because of large overlap of imagery from different passes. Low swath sensors generally have less frequent imaging of any specified location as seen in the spreadsheet. However, the revisit interval is not just a function of swath.

Question 4.1.3 : What other sensor characteristic influences <u>potential </u>revisit time?

> **Hint**: KONOS-2 has a narrow swath which would generally give very infrequent imagery (long revisit time) as is the case for Landsat-7. However, it is possible to programme IKONOS-2 to change from the normal nadir imaging mode to satisfy user requests. A similar feature is available for the SPOT series of sensors.

The minimum spectral requirements for quantification of chlorophyll concentration from an optical remote sensor are given in the International Ocean Colour Coordinating Group (IOCCG) report 1 [http://www.ioccg.org/reports/report1.pdf] as at least three suitable located visible channels[1] and two suitably located near infrared channels.

Question 4.1.4 : Which of the six sensors meet this requirement? Check that they are listed in the IOCCG's list of "current ocean sensors" [http://www.ioccg.org/sensors/current.html].

Question 4.1.5 : Why are other sensors given in the workbook as suitable for "aquatic applications" ?

> **Hint**: See section 10.1.2 of the Hyperteach Theory Syllabus: Chlorophyll concentration is not the only relevant parameter for aquatic applications.

Part 2: Collection of information and sensor choice

Student will search the Internet for information on satellite-borne optical remote sensors, gathering sensor and platform characteristics for inter-sensor comparison on an Excel spreadsheet while finding key aquatic remote sensing web sites useful for future reference.

Action 4.2: Now search the Internet sites suggested and others you can find on the subject to fill in the missing information for SPOT-5, CHRIS-PROBA and MERIS.

Question 4.2.1.: Is any of the information you retrieved different from the values given in the "ANSWERS" spreadsheet? If so, don't worry, your information may be more accurate or more up to date! However, in the case of differences you should be able to justify your answer by referencing it back to a document or web site.

Question 4.2.2.: Suppose that you are supporting global change modellers looking at the ocean-atmosphere carbon exchange in the North Atlantic. They require monthly maps of chlorophyll a concentration over the last few years. Which of these three sensors would you recommend[2] for such an application?

> **Hint**: There is no problem of spatial resolution. Spatial coverage is important with preference for large swath instruments with frequent revisit all the time (not just when pointed on demand). Check whether the spectral resolution is sufficient. Then consider whether a standard CHL product exists.

Question 4.2.3.: Which of the other six sensors could you use for such an application?

Question 4.2.4.: Suppose that you have been asked by an engineering consultancy to provide a first estimate of areas of high suspended particulate matter prior to engineering works in an Asian port. The area under consideration has size of about 1km^2. Which of the three sensors would you recommend?

> **Hint**: Spatial resolution is crucial and should preferably be better than 100m so that different regions can be distinguished.

Question 4.2.5.: Which of the other six sensors could you use for such an application?

Question 4.2.6.: Suppose that you have been asked by a coastal manager to provide near real-time warning for the year 2006 of potentially harmful algae blooms for a 100km stretch of coastline covering up to 30km from the coast. These blooms are supposed to be sufficiently high biomass for optical detection. Which of the three sensors would you recommend?

> **Hint**: As in question 4.2.2. spectral resolution is crucial and the existence of a standard CHL product indicates the maturity of the sensor for algae-related applications.

Question 4.2.7.: Which of the other six sensors could you use for such an application?

Part 3: Self Study
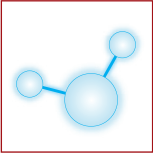
Action 4.3: If all exercises are completed (or after the course) the various Internet sites listed in the spreadsheet provided contain an enormous amount of information on sensor characteristics and many other aspects of optical remote sensing. The sites of the IOCCG and the SeaWiFS project in particular are well worth a few hours of surfing for students interested in more information on the subject.

⎯⎯ Answers to questions ⎯⎯

Answer 4.1.1: Answered orally in lesson.

Answer 4.1.2: NO: from the orbital inclination and altitude data it is clear that all six sensors given in the spreadsheet are sun-synchronous polar orbiters. This is the standard for ocean colour sensors because it gives regular global coverage. One exception (not included in our spreadsheet) is notable: the OCI sensor on ROCSAT-1 (Taiwanese Space agency) has a low inclination circular orbit (35°, 600km), which covers only the area between about 30°N and 30°S, including Taiwan [see http://www.oci.ntou.edu.tw/en/oci/cover.htm]. In future sensors in a much higher altitude geostationary orbit may become operational for aquatic applications.

Answer 4.1.3: Pointable sensors such as SPOT-5 and IKONOS are not limited to nadir-viewing but can be programmed to point across-track at targets not lying underneath the regular trajectory. Thus, <u>on-demand</u>, off-nadir revisit time can be much better than the nadir-viewing revisit time despite the narrow swath.

Answer 4.1.4: SeaWiFS, MODIS-AQUA and MODIS-TERRA meet the IOCCG spectral requirement for quantification of chlorophyll-a concentration and are included in the IOCCG list of "current ocean colour sensors".

Answer 4.1.5: NOAA-AVHRR, IKONOS-OSA and ASTER do not meet the IOCCG requirements for quantification of chlorophyll-a concentration because of insufficient spectral resolution. However, these sensors may still be used for quantification of suspended particulate matter concentration in turbid waters and so are included in this course.

Answer 4.2.1: Some of the information you find may be slightly different from those suggested in the "ANSWERS". In fact, it is surprisingly difficult to obtain a single answer for certain characteristics partly because of design or flight changes in the sensors.

Answer 4.2.2: MERIS is well-suited for this application. The spectral coverage of SPOT-5 is insufficient. The limited swath of SPOT-5 and CHRIS-PROBA and consequently limited revisit time (not pointed on demand) will give too few images of any given location. Neither SPOT-5 nor CHRIS-PROBA has a standard chlorophyll product.

Answer 4.2.3: SeaWiFS, MODIS-AQUA and MODIS-TERRA could all be useful for this application – they are all large swath instruments with good spectral resolution and a standard CHL product. In fact, if resources permit it might be interesting to combine data from all four sensors noted here for this application.

Answer 4.2.4: SPOT-5 is best-suited for this application. CHIRS-PROBA might also be usable. MERIS has insufficient spatial resolution to study the details of such a region. SPOT-5 has the best spatial resolution and will show any small scale features of relevance. CHRIS-PROBA has adequate spatial resolution. Whether it could be useful or not will depend on the availability of imagery for the region under consideration – CHRIS-PROBA is an experimental mission, less well-supported than SPOT-5, and acquisitions are severely constrained by data transfer limitations (only one or two locations of the world can be imaged on any single day). Moreover archived data may be available for earlier SPOT missions.

Answer 4.2.5: IKONOS-OSA and ASTER might also be useful since they have sufficient fine spatial resolution. NOAA-AVHRR, SeaWiFS, MODIS-TERRA and MODIS-AQUA must all be eliminated because of insufficient spatial resolution.

Answer 4.2.6: Of the three sensors MERIS is best-suited for this application. The spectral resolution of SPOT-5 is generally insufficient[3] and the spatial coverage (swath) of SPOT-5 and CHRIS-PROBA is severely limited. Existence of a CHL product for MERIS suggests maturity for algae-related applications.

Answer 4.2.7: SeaWiFS, MODIS-TERRA and MODIS-AQUA are in general all well-suited for such applications, though may be inferior to MERIS in some coastal waters because of less appropriate spectral resolution. AVHRR might be usable for certain very high biomass surface blooms visible as high reflectance patches. The spatial coverage of IKONOS-OSA and ASTER (not pointed on demand in general) is too limited for such an application.

Lesson 5: Satellite image processing for aquatic applications

Aim of Lesson

To learn the basic steps in satellite image processing for aquatic applications, including in particular how to identify unreliable data.

Objectives

1.   To load and perform simple visualisation tasks on imagery.

2.   To understand the principles of atmospheric correction, especially the   circumstances when large errors can be expected and identify bad data.

Background information

This lesson is related to Sections 8.2 (atmospheric correction) and 9.2 (data analysis and validation) of the Hyperteach Theory Syllabus.

Software

Access to a PC with Excel, ENVI ® and Internet is necessary. Prior experience with ENVI is an advantage and will enable students to progress much faster.

Lesson outline

1. The impact of atmospheric correction on imagery and the problems that can be encountered in imagery has been explained in the Hyperteach lectures and in Section 8.2 of the Theory Syllabus. The main points will be reviewed here before the exercises.
2. Students will be given MODIS imagery to be visualised and processed using ENVI.
3. Students will be asked to assess the quality of imagery. In cases of poor quality they will be asked to determine the cause of problems.

Part 1: Qualitative assessment of level 1 (top of atmosphere) imagery

In the Hyperteach Theory lecture on atmospheric correction for water bodies (see also Section 8.2 of the Theory Syllabus) we learnt that:

- An optical remote sensor often sees more light scattered by the atmosphere than light coming from the water, a dark target. The atmospheric correction of imagery for water bodies is therefore crucial and inaccuracies in atmospheric correction are probably the biggest cause of bad image data.
- Quality flags (0 or 1 values for each pixel) are usually supplied with spaceborne image data and contain valuable information about the reliability of the product.
- Even when using quality flags the user of optical remote sensing products for aquatic applications is advised to check qualitatively atmospheric conditions and products for signs of atmospheric correction problems, undetected clouds, etc.

We are going to look at MODIS imagery of 11th of April 2005 (Julian day 101) using ENVI. Different levels of data can be downloaded from NASA according to whether data is atmospherically corrected ("level 2" or Bottom Of Atmosphere, BOA products) or not ("level 1" or Top of Atmosphere, TOA products). In general for aquatic applications we want to use level 2 data which allows quantification of water quality parameters such as chlorophyll a concentration. Level 1 data might be used for classification purposes (rare for aquatic applications) but is more commonly used as a support for level 2 imagery. A RGB (red-green-blue) composite of level 1 imagery gives a quick impression of the atmospheric and aquatic conditions at the moment of acquisition, showing clearly regions of cloud, haze, contrails, land, water and very turbid water. Thus, level 1 imagery can be used to screen image archives and reject cloudy images, saving effort on atmospheric correction processing, and can be used to help determine whether the atmospheric correction applied to achieve level 2 imagery has performed badly in certain areas. So before looking at the more immediately useful level 2 image we first look at the level 1 image …

Action: Go to NASA's Ocean Colour web site [http://oceancolor.gsfc.nasa.gov/] and follow link to "level 1 and level 2 browser" to give the archive graphical user interface as shown in Figure 5.1. Select sensor "MODIS Aqua" at left, the day "11th April 2005" from the calendar and region between "51°N" and "52°N" and "2°E"

and "4°E" at right and click button "find swaths" to find which images are available corresponding to these search criteria.

One image is found denoted A2005101122000 with level "L1A" (TOA) and "L2" (atmospherically corrected) data. Quicklooks are shown for the "quasi true color" (level 1)[4], chlorophyll and Sea Surface Temperature (SST) – see Figure 5.2. From the quasi true color image clouds are seen over most of England and over much of Northern Germany with scattered clouds over Southern Belgium and North-East France. In the North Sea, even in this low resolution image some turbid water (brownish) can be seen near the Thames Estuary. A front, a "line in the sea" separating two different types of water (remember the airborne photo of Oostende harbour from Lesson 3?), can be seen running a few 100kms parallel to the Dutch coast – Figure 5.3. We will look closer into these features with the level 2 imagery.
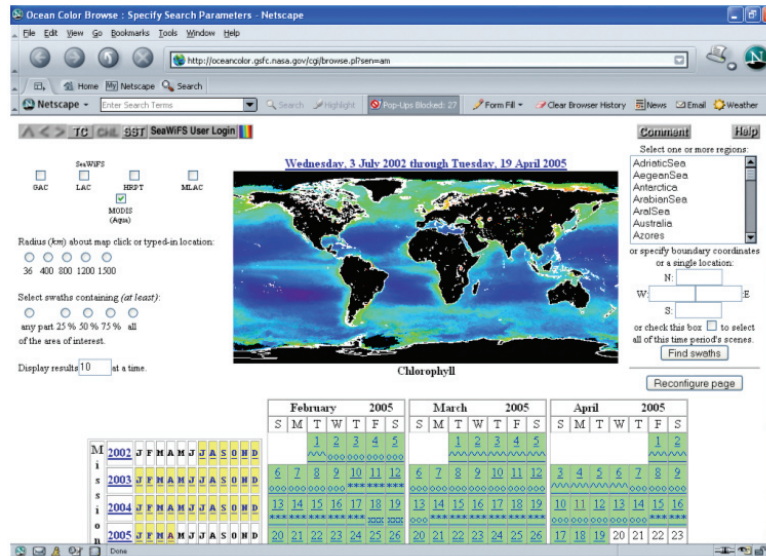
>> **Figure 5.1. Screenshot of NASA's ocean color data archive browser.**
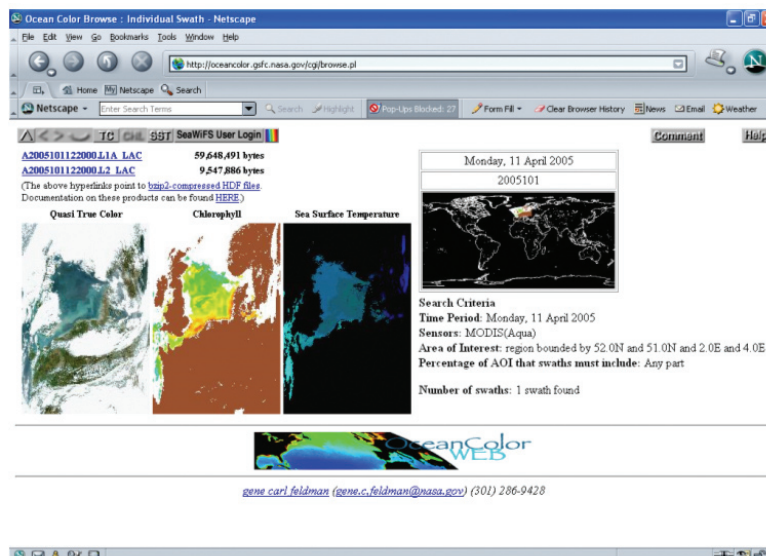
>> **Figure 5.2. Screenshot of quicklook MODIS imagery for 11th April 2005 for the Southern North Sea.**
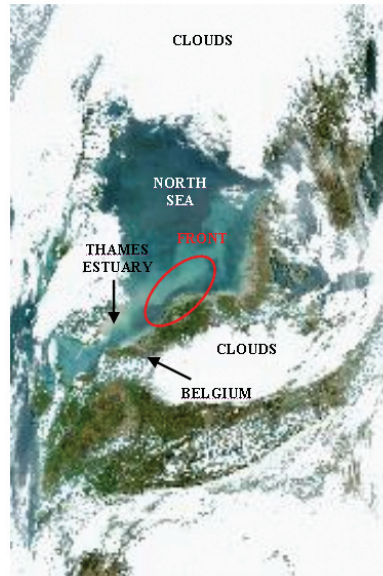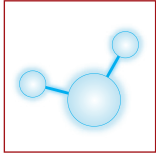
Figure 5.3. Low resolution quicklook RGB "quasi-true colour" MODIS image. The white areas are clouds. Water of different colours can be seen with the turbid water of the Thames Estuary appearing brownish and a front separating two different types of water running parallel to the Dutch coast.

Question 5.1.1 : What do the characters of the filename prefix "A2005101122000" mean?

Hint 1: Follow the "bzip2-compressed HDF files" link and look under "Data day and locator map".

Question 5.1.2 : Sea surface temperature (SST) is given as a MODIS product but this cannot be deduced from optical imagery. What spectral bands are used by MODIS to obtain SST?

Hint 1: Remember lesson 4? The MODIS web sites give all technical information explaining how products are derived.

For this region higher resolution geometrically corrected quasi true color imagery has been prepared from level 1 MODIS imagery. This can be found at http:/www.mumm.ac.be/OceanColour by following links "Products" then "Maps", and clicking the button "RGB" for MODIS AQUA and then selecting the relevant date – see Figure 5.4.
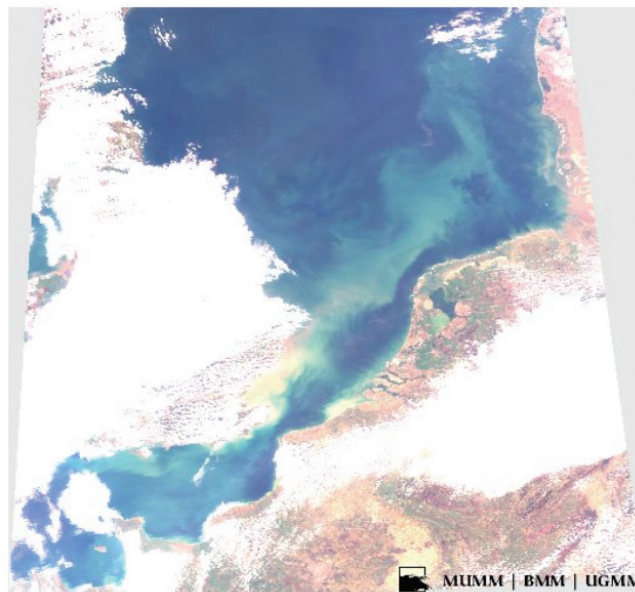
Figure 5.4. Higher resolution geocorrected quicklook RGB "quasi-true colour" MODIS image of 11th April 2005.

The higher resolution of Figure 5.4 shows more clearly regions of turbid water in Belgian waters and along the coast of East Anglia (South-East England). These regions seem to have a different colour (yellowish in Figure 5.4) compared to the water further to the North East North (greenish or bluish). Note that colours have been

enhanced here to give greater contrast and do not correspond exactly to what a human observer would see when looking at the water.

Part 2: Qualitative assessment of atmospherically-corrected imagery

A level 2 (atmospherically-corrected) MODIS image of 11th April 2005 has been downloaded and prepared for this lesson. This image consists of four files:

- A2005101122000_OC_NOS.tmp: the main image file with radiometric data
- A2005101122000_OC_NOS.hdr: the main header file with information on coordinates, band names, etc.
- A2005101122000_L2FL_OC_NOS.tmp: an image file with level 2 flags (described below)
- A2005101122000_L2FL_OC_NOS.hdr: a header file for the image of level 2 flags

Action: Start ENVI and load the file "A2005101122000_OC_NOS.tmp"

> **Hint**: Use the "File/Open Image file" menu option. ENVI should then show a "list of available bands" in this image.

In the imagery prepared for this lesson there are 10 bands: Chlorophyll-a concentration ("chlor a"); 6 bands of normalised water-leaving radiance ("nLw_") for wavelengths 412nm, 443nm, 488nm, 531nm, 551nm and 667nm; aerosol optical thickness at 869nm ("tau_869"); aerosol epsilon factor ("eps_78") and aerosol Angstrom coefficient ("angstrom_531"). The first 7 bands are related to properties of the water and are of prime interest for the aquatic applications. The last 3 bands are related to properties of the atmosphere and are useful here to assess the quality of the atmospheric correction.

Action: Make an RGB composite image from bands 443nm (blue), 551nm (green) and 667nm (red).

> **Hint**: Select "RGB color" in the "Available Bands list" window and enter these bands in the corresponding boxes below by clicking on them. Then hit the "Load RGB" button.

Three windows should appear entitled "Scroll", "Zoom" and "(R:nLw_667, G:nLw_551, B:nLw_443)". These show your image at different levels of zoom. The third, largest window will be called the "Image" window. The different colours in the image correspond to water of different colours, though they do not correspond to real water colours. Scroll around the image by dragging the square corresponding to the respective image and zoom area – there are many whirling patterns in the central North Sea which correspond to oceanic fronts separating water with different characteristics, including for the central North Sea different chlorophyll a concentration which causes different water-leaving radiance.

Action: Add coastline and border information to the image.

> **Hint**: Via the main menu option "Vector/Open Vector File/ENVI Vector File" choose the file "CoastlinesSNShc.evf". The menu "Available vectors list" appears. Click on the Coastlines vector layer, then "load selected" then "display #1" to add coastline information to your image.

Action: Open a new image showing chlorophyll-a concentration.

> Hint: In the "available bands list" click on "gray scale" option, then on the "chlor_a" band, then left mouse button on "display #1" choosing "new display" and then "load band".

Three new windows appear with a gray scale image of chlorophyll-a concentration. The variations can be seen more clearly if the colour table is changed to a false colour showing variation from blue (low concentration) to red (high concentration).

Action: First find the cursor location in the chlorophyll scroll window by clicking the right mouse button somewhere in this window and selecting "Cursor Location/value". A new window appears entitled "Cursor Location/value". This shows the location of the cursor (first line of information in pixel coordinates) as well as the data value at that location (last line).

Move your cursor to the pixel with coordinates (501, 826) and click the left mouse button to move the red square to this position. The Image area now corresponds to a chlorophyll map of the Southern North Sea.

Action: In the chlorophyll image window select menu "Tools/Color Mapping/ENVI color tables" and choose the "Rainbow" (Blue to Red) colour table. Then, in the Image window select "Enhance/[Image] Equalization" to contrast stretch the colours.

Now we see red areas (apparently high chlorophyll) along the Belgian and Dutch coasts and in the South-East coast of England as well as for the Dutch inland lakes (Ijsselmeer) and the Wadden Sea – see Figure 5.5.

Lesson 5: Satellite image processing for aquatic applications

Question 5.2.1.: At what concentration, approximately, do we have red values?

> **Hint:** Using the cursor location/value window you can see the values of points at the edge of the red patches. This is just one method, though, and there are many other possible ways of extracting the data values from this image.
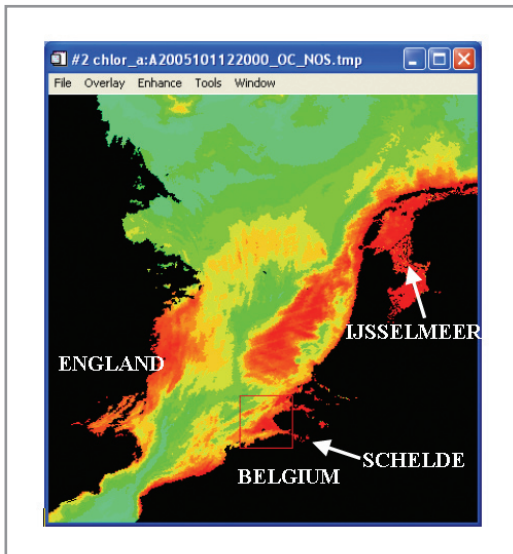
>> **Figure 5.5 Chlorophyll image.**

Now this is a pretty picture, but is this a realistic map of chlorophyll a concentration? One major difficulty of optical remote sensing for aquatic applications is that atmospheric correction is very difficult. Atmospheric correction errors are often significant and give totally erroneous chlorophyll maps. So we need to look also at the atmospheric parameters.

Action: Load into a new window as a grayscale image the band "eps_78" which is a measure of the spectral slope of scattering from aerosol particles. White aerosol particles have eps_78 approximately equal to one, while particles which scatter more blue light than red light will have higher values, typically between 1.05 and 1.2 for the atmosphere over this part of the North Sea. To see more clearly patterns in the water, stretch the histogram by using the "Enhance/Interactive Stretching" menu option on the "eps_78" image window. Stretch from 0.9 to 1.2 and click the "apply" button. So that the areas in the chlorophyll image and the eps_78 image can be compared more easily link the images by right-mouse clicking on one of the images and selecting "Link images" option. Add the coastline to the eps_78 image (see how this was done before or choose "Overlay/ Vectors" then "Options/Import Layers" and select "Coastlines" "OK"; to change the colour of the vector coastline right click on the white square next to "current layer" "items 1:20 /Red" and then "Apply").
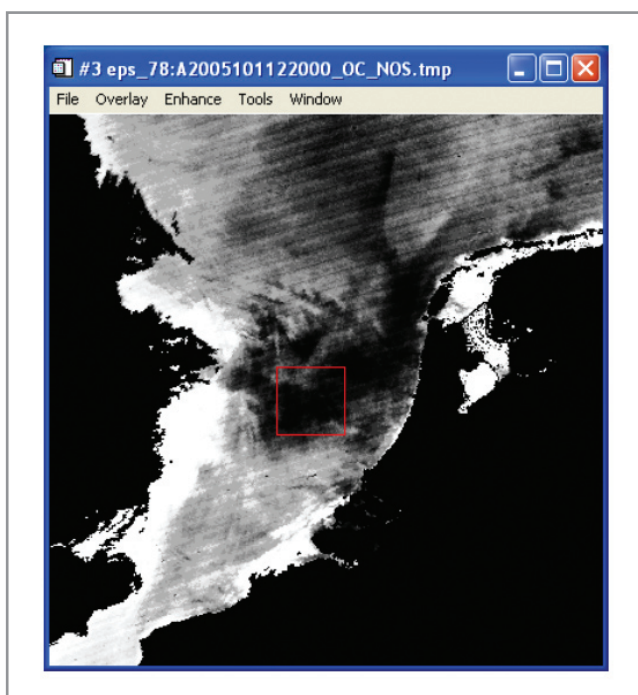
>> **Figure 5.6 Image of the eps78 aerosol product**

Lesson 5: Satellite image processing for aquatic applications

Question 5.2.2: Do you see any relationship between the white areas of the "eps_78" image and the red areas of the chlorophyll image?

For this region the concentration of aerosols is highly variable in time with wind patterns carrying aerosol particles over large distances. However, the optical type of aerosols does not vary greatly with most particles having eps_78 between 1.0 and 1.15. If the data shows eps_78>1.2 it is almost certain that the atmospheric correction has not functioned well and this occurs particularly in turbid waters. An incorrect eps_78 value will give incorrect water-leaving radiances, especially underestimating at blue wavelengths and consequently overestimating chlorophyll concentrations. Another, more severe sign of atmospheric correction errors can be found when this underestimation of water-leaving radiance gives negative water-leaving radiance, something that is clearly physically impossible in reality.

Question 5.2.3: For what areas of the image is the normalised water-leaving radiance at 412nm (band "nLW_412") negative?

> **Hint**: Load the "nLw_412" band and interactively stretch the histogram from a negative value (e.g. -0.08) to zero or a very small negative number (e.g. -0.017). In this way all positive radiances will appear white and negative radiances will appear grey or black.

Considering the aerosol "eps_78" map it seems that the high chlorophyll concentrations near the Belgian, Dutch and Danish coasts are unreliable.

Question 5.2.4: What about the high chlorophyll concentration East of England? Is this reliable?

——— Answers to questions ———

Answer 5.1.1: When decomposing the filename prefix "A2005101122000": "A" is the sensor MODIS-AQUA, "2005" is the year, "101" is the Julian day corresponding to 11th April (1st January is Julian day 1, 31st December is Julian day 365 except during leap years), "112200" denotes 11:22:00 UTC time in hours, minutes and seconds.

Answer 5.1.2: In addition to the visible wavelengths MODIS measures thermal infrared emission at wavelengths 3750, 3959, 4050, 11030 and 12020 nm. These are used to estimate the sea surface temperature.

Answer 5.2.1: In Figure 5.5, the red colour represents concentrations higher than approximately 8 μg/l.

Answer 5.2.2: The white areas along the Belgian and English coasts and for the Ijsselmeer correspond to red areas in the chlorophyll map. Because the eps_78 product is out of its usual range the corresponding red areas in the chlorophyll map cannot be trusted. This is an example of bad atmospheric correction giving pretty but unusable data.

Answer 5.2.3: There is a small area of negative 412nm water-leaving radiance at the mouth of the Schelde Estuary. In reality this is very turbid water with a particularly high water-leaving radiance. However, the atmospheric correction gives very erroneous values here.

Answer 5.2.4: Is it difficult to say whether the high chlorophyll a concentrations East of England are reliable or not! There is no obvious problem with the eps_78 parameter, nor with the water-leaving radiances so the atmospheric correction could be acceptable. However, even if the atmospheric correction is good there may be problems determining chlorophyll concentration because yellow substance can also absorb light (remember your experiments with the ocean colour spreadsheet in lesson 3?). So the answer is "maybe" though you probably need to have a water sample from that location on that day to be really sure.

Lesson 6: The spectral signatures of minerals and rocks

Aim of Lesson

To become familiar with the use of spectral libraries, to learn how to measure the reflectance of minerals and rocks in the laboratory and in the field, to interpret them in terms of interaction between matter and electromagnetic radiation, to build a spectral library and to identify the mineral composition of targets using the spectral analyst tool.

Objectives

1. Introduction: to observe and interpret spectral signature of minerals and rocks form ENVI built-in spectral libraries (USGS and JPL) and from RMCA collections.
2. To measure spectral signatures of minerals and rocks on hand specimen, on fresh cut surfaces or on natural surfaces with weathering, coating or varnish.
3. To measure spectral signatures in situ on natural targets.
4. To interpret the observed spectral features.
5. To learn how to build a spectral library in ENVI.
6. To compare and analyze the spectra with the spectral analyst tool.

Background Information

This lesson relates to the Sections 11.1 and 11.2.1 and 11.2.2 of the HyperTeach Theory Syllabus. For further details about the techniques involved, users are recommended to read these sections. The lesson intends to describe and exploit the techniques related to the measurement and interpretation of the spectral signatures of natural mineral targets, and to compare these to other objects such as vegetation, water and man made material.

The measurements are performed in the laboratory on samples coming from the collections of RMCA which represent a variety of minerals and rocks and in the field on vegetation, gravel, limestone and brick around the buildings and in the park of the RMCA.

A basic knowledge and understanding of the spectral properties of objects, and particularly minerals and rocks, is required in order to properly apply the hands on manipulations of the exercises of Lessons 7 and 8.

The field measurements are associated to the exploitation of hyperspectral image data in two domains:

- Calibration of the raw DN data to reflectance factors with dark and bright targets measured in the field and easy to locate on the imagery
- Identification of natural targets

SOFTWARE

A PC with ENVI ® software is required to carry out the lesson.

SPECTRAL DATA

A GER IRIS MARK VI and a FieldSpec Pro FR spectroradiometer (ASD) are used respectively in the laboratory and in the field. Their technical characteristics are compared in terms of IFOV, spectral range and resolution, precision, speed of measurement, facility of use, hardware and software. The way of averaging data is analyzed.

The data recorded by the spectroradiometer is first stored in its own format and then converted to ENVI spectral library format, with units of wavelengths and reflectances compatible to the built in ENVI databases (from USGS and JPL).

DATA PROCESSING

The collected individual spectra are grouped in spectral libraries and displayed for interpretation. They are processed with the spectral analyst tool in order to identify the mineral composition.

Lesson outline

1. Displaying and interpreting existing examples of spectral signatures

This first manipulation aims at making the user familiar with viewing and editing a spectral library of minerals and rocks, as well as at analysing simple relationships between the rocks composition and color and the corresponding spectral features.

A set of 20 rock hand specimen is presented. The spectral signatures have been measured with the GER IRIS MARK V.

Action: In the 'ENVI' main menu use the <spectral> button, then <spectral libraries> and <spectral library viewer> option to open and display the file \Lesson06\Data\spectra_hand_specimen\specimen_KMMA.sli
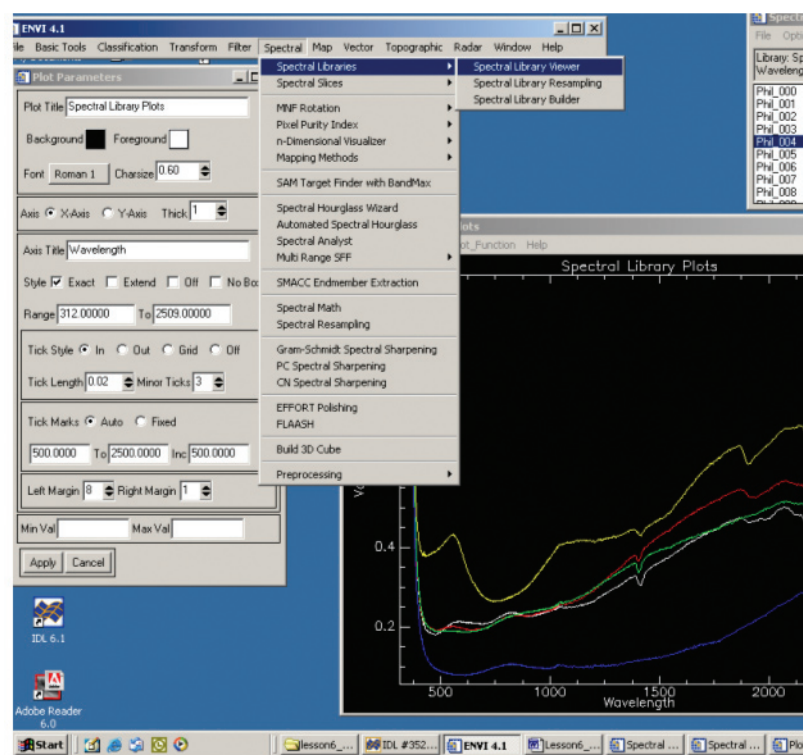
>> Fig.6.1: Spectral library viewer.

Action: Click on the samples names in the file list (phil_000 to phil_027) to display them in a graphic window.

> **Hints**: In the graphic display window, click on right mouse button and choose <plot key> to display the title of the curves.

To zoom on a spectral range in the graphic display, use the CTRL key and left mouse button to select the region to zoom.

Action: Explore a spectral curve and compare it to the lithology and to the colour of the hand specimen. Locate the absorption features in the NIR and SWIR ranges of the spectrum.

> **Hint**: the corresponding hand specimens are provided during the exercise; their jpg image can be found in the directory \Lesson06\Data\rock_photographs, and a lithological description in the file litho_description.xls in \Lesson06\Data\spectra_hand_specimen.
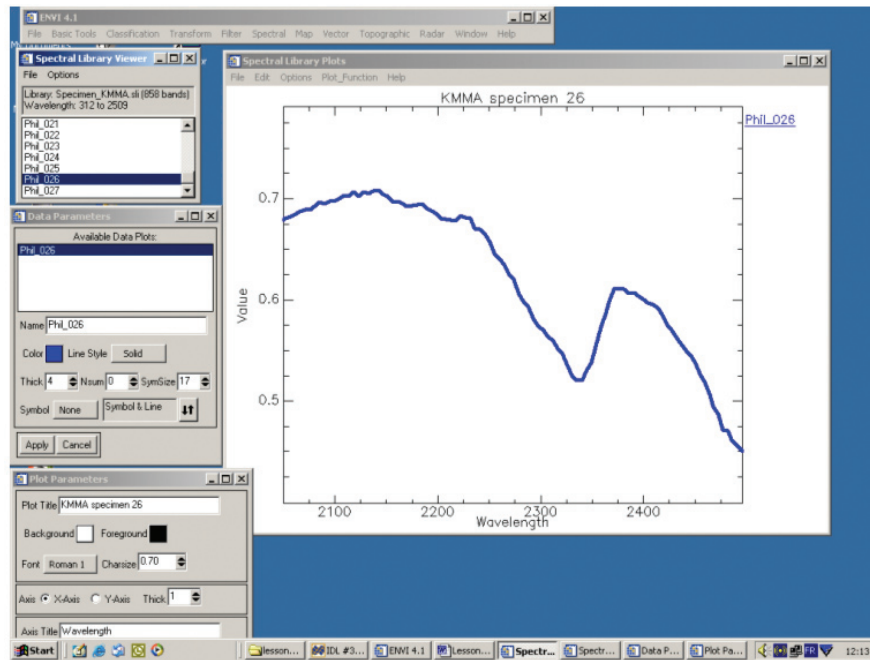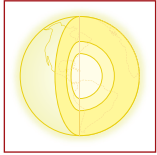
>> Fig. 6.2: Spectral library viewer: zoom on the SWIR range.

Repeat the operation until all the curves are displayed.

Action: Save these as a new spectral library called GER.sli in the directory \Lesson06\Data\spectra_hand_specimen\GER.SIG.

> **Hints**: In the spectral library viewer click < file> <save plot as> < spectral library> <Select all items> Keep default values and <choose> to save the file in directory \Lesson06\Data\spectra_hand_specimen\GER.SIG as new_spectra.sli

Action: Save the graph as an image file (jpeg)

> **Hints**: In the spectral library viewer click < file> <save plot as> < image file> Select output file type <jpg> to save the file in directory \Lesson6\Data\spectra_hand_specimen\GER.SIG as plot_spectra.jpg.

Action: In another window, use the spectral library viewer to open the USGS mineral spectral library \Lesson06\Data\USGS\usgs_min.sli.

Load the spectral curves of the following minerals: quartz2, calcite1, illite2, kaolinite1, goethite1, hematite1. Compare the spectral features with the specimens.

> **Hints**: While browsing the spectrum with the cursor, the exact values of the wavelength (X axis) and reflectance (Y axes) are indicated.
> Use <Edit> <plot parameters> and <Data parameters> to personalize the graphs.

Question 6.1: How can you recognize the presence of specific minerals in the rock samples?

2. Reflectance measurements of natural surfaces

The spectral signatures of natural surfaces can be measured in the laboratory, under optimal light conditions and no atmospheric interference.

They can also be measured in the field, in order to be directly used to calibrate and analyse hyperspectral imagery.

The laboratory exercise is realized using a double IFOV GER IRIS MARK VI spectroradiometer

Lesson 6: The spectral signatures of minerals and rocks
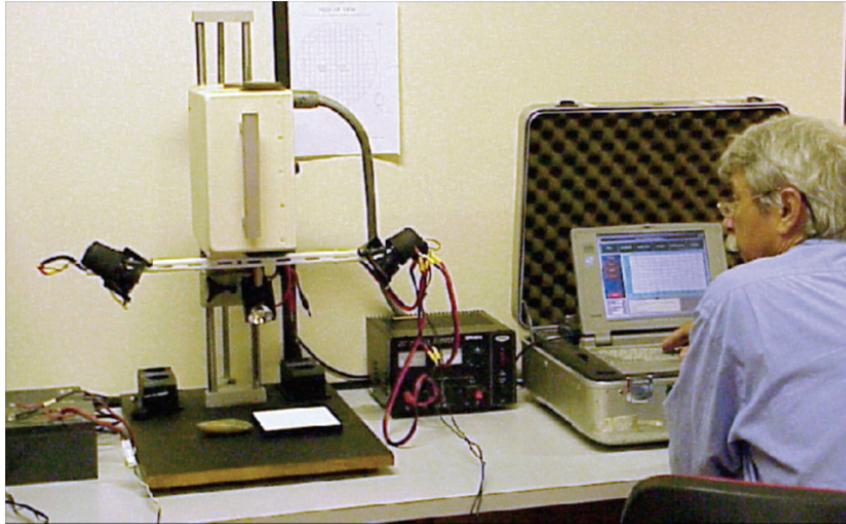
>> Fig.6.3. The laboratory exercise: GER IRIS spectroradiometer.

Action: For this measurements exercise, choose a set of samples from the presented collection of minerals and rocks.

Switch on the components of the spectroradiometer and the lamps and display the target and the Spectralon® reference in the correct fields of view. Check the position in the viewing grid.

In the 'GER' drive main menu, choose <take reflectance measurement> with double instantaneous field of view (IFOV).Check the measurements parameters (speed, diffraction grid and filters options, gain factors).

Close the switch of the measurement head and take the measurement.

Save the results with an explicit name and add a short description in the directory \Lesson06\Data\spectra_hand_specimen\GER.SIG.

> **Hint**:   spectra for all 28 specimens can already be found in the same directory (phil_000 – phil_027.sig).

Action: Choose the GER menu item <analyze> and display the spectral curve. Use the spectral range and zoom options to look at significant features.

The laboratory exercise is repeated on samples representing different lithologic compositions and surface conditions (fresh cut, weathered surface, coated surface).

 Action: In the GER menu item <analyze>, and display all the spectral curves you saved earlier and compare their properties. Save the entire set in an ascii file named GER.txt in the same directory \Lesson06\Data\spectra_hand_specimen\

> **Hint**:   There is an example called philippe.txt for the 28 spectra.

The in situ field exercise is realized using a single IFOV FieldSpec Pro FR spectroradiometer (see Theory Syllabus for technical description and measurement procedure).

If the weather conditions allow it, the exercise will be performed in the park of the RMCA. If not, the exercise will be simulated indoors with an artificial light source.

>> Fig.6.4.: The in situ exercise: FieldSpec Pro FR spectroradiometer

Actions: Choose a natural target, in the first case limestone. Choose the wider IFOV for the device (no lens on the optical fiber). Switch on the components of the spectroradiometer.
Check the different parameters.
With the option <reference>, take a measurement of the Spectralon panel. Take the measurement of the target.
Save the measurement with an explicit name and add a short description in the directory \Lesson06\Data\ spectra_hand_specimen\ASD.SIG.

> **Hint**: The spectroradiometer takes continuously repeated shots at a given rate and averages them. The displayed curve stabilises after a few second. You can then stop the process.

Actions: Repeat the measurement on different targets: grass, brick, gravel, water, …. Now measure the Spectralon® panel again.

Question 6.2: What are the advantages and inconveniences of the two spectroradiometer <concepts> when taking field measurements in support of an airborne hyperspectral campaign?

3. Building spectral libraries in ENVI and analyzing their mineral significance with the spectral analyst tool.

The spectral signatures (laboratory and field) can be imported in their respective ENVI spectral library. We will use the GER results as an example.

Action: In the <spectral>> main menu, use the <spectral library> <spectral library builder> <ASCII file> tool to import your own data saved in the GER.txt file.

> **Hint**: As a backup to GER.txt use the file \Lesson06\Data\spectra_hand_specimen\Philippe.txt. Copy this file as GER.txt if necessary.
> All the parameters of your own spectral libraries can be defined in this process. Check and adapt if necessary, the wavelength units (nanometers or microns, choose nanometers). Click <OK>. In the next screen <import> <from ascii file> re-select GER.txt, <OK> <Select all > <FILE> <Save spectra as> <Spectral library file>. Keep the default values (check the reflectance units (unit from 0 to 1 or percents from 0 to 100, choose 1.0) <OK> Choose <GER.sli> as name and save in the directory \Lesson06\Data\spectra_hand_specimen\GER.SIG
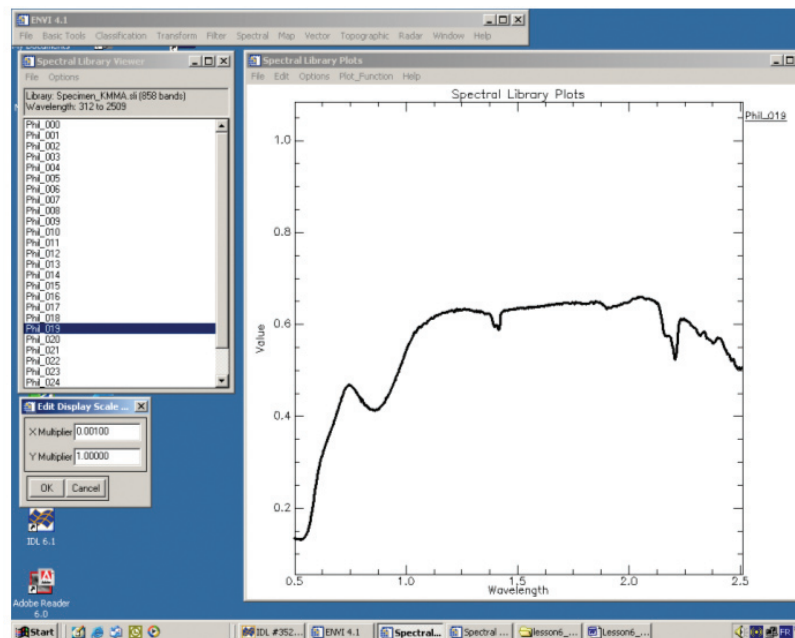
>> Fig. 6.5: Spectral library viewer. X and Y scaling.

The spectra can now be analysed in terms of mineral composition.

Actions: Open the spectral library \Lesson06\Data\spectra_hand_specimen\specimen_KMMA.sli with the spectral library viewer (see item 1 of this lesson)
Select the spectra phil_000, phil_002, phil_023, phil_026. Zoom into the wavelength region 1900-2500 nm.

Lesson 6: The spectral signatures of minerals and rocks

In the <spectral> main menu, open the <spectral analyst> tool.

Open the USGS mineral spectral library \Lesson06\Data\USGS\usgs_min.sli <OK> Two windows are shown. Use default values <OK> for "method weightings". In the "spectral analyst window" select <options> <edit X,Y scale factors> and adapt the units.

> **Hint**: The X and Y units of your own spectral library and the reference library must be compatible. The GER library is built with X units (wavelength) in nanometers, whereas the USGS reference library displays X units in micrometers. Use the <edit X,Y scale factors> option to make them compatible. With X scale=0.001, The GER wavelengths will be transformed to micrometers. Y scale may remain at 1.0.

Actions: Run the spectral analyst and interpret the results. <Apply> Select the spectrum to analyse (you will see a list with the names of the spectra displayed in the graph). Select phil_000 and <OK>. A list of best fitting minerals from the USGS library is displayed (the higher the score, the better the fit). Click twice on a name to display the spectrum in the graph. Use right mouse button <plot key> to display the names.

> **Hint**: the curves are displayed with continuum removed. To display in the usual form, select <plot function> <normal>.

Repeat the process for the other measurements.

>> **Fig. 6.6: Spectral analyst and wavelength subset.**

Answers to questions

Answer 6.1: How can you recognize the presence of specific minerals in the rock samples?

The spectral mixture of minerals composing a rock cannot be solved by linear unmixing. The optical path of electromagnetic radiation through the grains is complex and results in a non linear mixed signature, not directly related to the abundance of the components. For instance, a mixture of 80 % of feldpars and 20% of pyroxenes will display a spectral signature closer to the one of the pyroxenes than to the feldspar.
However, the <u>presence</u> of a mineral in a rock can be assessed by the presence of its specific spectral features (e.g. an absorption peak at 2.2 micrometers for clay minerals, and at 2.34 micrometers for carbonates).

Answer 6.2: What are the advantages and inconveniences of the two radiometer <concepts> when taking field measurements in support of an airborne hyperspectral campaign?

The advantage of the GER device is the double IFOV that guarantees the simultaneity of target and reference measurement. With a single IFOV device, the intensity of the illumination might change between the reference and target measurement.
The dimension of the GER IFOV, standard at 1m above ground, is fixed and very small (8 cm X 4 cm), whereas the FieldSpec Pro FR IFOV is variable and can reach a radius of 20 cm, allowing a much better averaging of spectral signatures, especially useful when used in relation with remote sensing imagery.
The speed of measurement of the GER is very slow (a few minutes for a single measurement), and does not allow the operator to take many measurements on a site, which is a problem when measuring sites for calibration purposes. On the opposite, the fast response of the FieldSpec Pro FR, in combination with its wide IFOV, provides ideal conditions for calibration purposes.

Question 6.3: Why does the spectral analyst tool work properly in some cases and not at all in others? How can this problem be partly solved? What are your conclusions concerning the interest of building a specific spectral library to support hyperspectral image processing?

Though the Spectral Angle procedure intends to minimize absolute value (albedo) effects, the spectral analyst tool is still quite sensitive to the absolute values of the spectra as well as to the non linear mixing of spectral features.
To minimize this problem, it is advisable to work on limited spectral ranges (e.g. SWIR only) to obtain better results.
There is quite a difference in nature between the spectral libraries measured on powders of very pure minerals and natural targets affected by many influences linked to granularity, surface conditions, micro shades, wetness, … Hence there is great interest of measuring in situ reflectances in association with a remote sensing campaign and of building specific site related spectral libraries.

Lesson 7: Pre-processing AVIRIS hyperspectral data

Aim of Lesson

To learn how to pre-process radiance data, to calibrate to reflectance factors, to interactively analyse spectral signatures, to mask vegetation and to apply basic image processing to extract mineral information.

Objectives

1. To describe the area studied in lessons 7 and 8: Cripple Creek gold fields, Colorado, USA, and the associated AVIRIS scene.
2. To add the wavelength values to the raw AVIRIS "radiance at the sensor" data.
3. To apply flat field calibration to obtain reflectance factors.
4. To eliminate bad spectral bands and to choose the spectral ranges to be studied in geological applications.
5. To split the image spectra to two significant spectral ranges for geological applications: VNIR and SWIR.
6. To mask out vegetation.
7. To apply basic image processing for the extraction of mineral information: colour composites with saturation stretch and classifications.

Background Information

Several pre-processing steps are needed in order to prepare raw hyperspectral data (sensor radiance) for spectral analysis. This lesson relates to the Sections 8.1.2.1 and 11 of the HyperTeach Theory Syllabus. For further details about the techniques involved, the readers are strongly recommended to read these sections. It intends to describe and exploit the techniques related to the pre-processing steps of hyperspectral data and to apply simple processing for the extraction of mineral information.

The exercises are performed on a sub scene of an AVIRIS image of Cripple Creek, Colorado. (courtesy of Prof. Carlos Roberto de Souza Filho, Brazil)

The geology of the area is described in the directory \Lesson07\Data\Geology of the CD coming with this Lesson.

The knowledge and understanding of the spectral properties of objects (Lesson 6) is required in order to properly apply the hands-on manipulations of the exercises of Lessons 7 and 8.

Software

A PC with ENVI® software is necessary to carry out the lesson.

Spectral data

An AVIRIS sub scene of Cripple Creek, Colorado, gold mining area is used. The interest of this area is the existence of epithermal and alteration minerals with marked spectral features in the VNIR and SWIR ranges. The original data is provided in raw format, so that the ancillary file containing the wavelength information must be used to prepare the images.

Data processing

The collected individual spectra are grouped in spectral libraries and displayed for interpretation, in order to identify the mineral composition.

Lesson outline

1. Displaying a raw image, adding the wavelength information.

In this section you will learn how to use an ancillary file to complete the parameters file.

Action: In the ENVI main menu use <file>, <open image file> to open the AVIRIS sub scene \Lesson07\Data\ AVIRIS_data\ AVIRIS _ Cripple Creek\f990930t01p02_r09_sc02.v1.img

Action: In ENVI main menu use the <file> <Edit ENVI header> option to look at the content of the image file <OK> and the different parameters. Add the wavelength information. <edit attributes> <wavelength>.

> Hint: You will notice there are no wavelengths, only channel numbers.
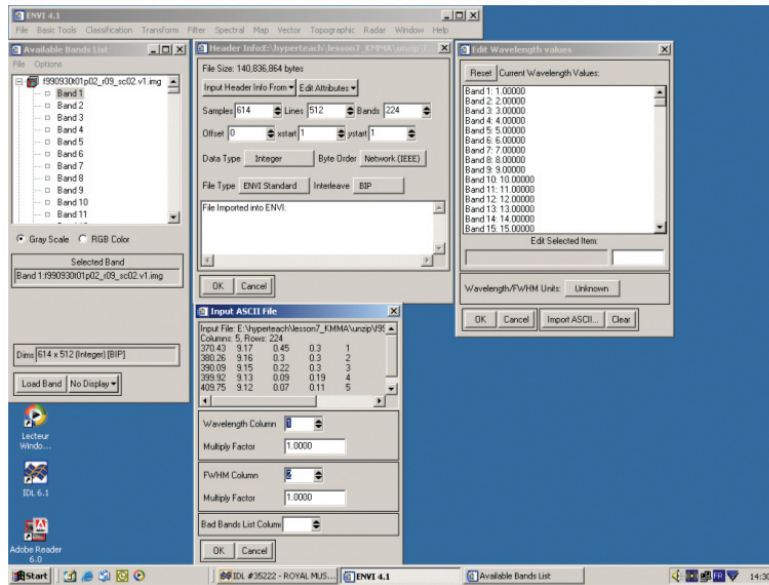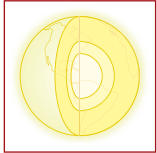
>>   **Fig. 7.1: The "Edit ENVI header" menu.**

Hint: The 224 wavelength parameters can be introduced one by one on the keyboard, but the AVIRIS dataset includes an ancillary file *.spc containing this information. Use this file to update the ENVI header.

Action: select <import ascii> and select the corresponding f990930t01p02_r09_sc02.v1.spc file in the \ Lesson07\Data\AVIRIS_data\ AVIRIS _ Cripple Creek directory. <open>

In the displayed table, wavelengths are in the first column. Set <wavelength column> to 1 <OK> <OK> <OK>

Hint: now the wavelengths are added in the "available band list".

2.   Displaying the sensor radiance image, running an animation and removing bad spectral bands.

In this section you will learn how to visualize the spectral bands images one by one in an animated sequence and detect the "bad" bands. You will see that some bands are so noisy that they should be removed before further processing.

Action: In the "available band list" select band 01 in a greyscale display window <load band>

Use the ANIMATION tool in the display menu to look at the 224 bands.

Action: in the display menu, use <tools> <animation> keep default values and <OK> Observe the animation.
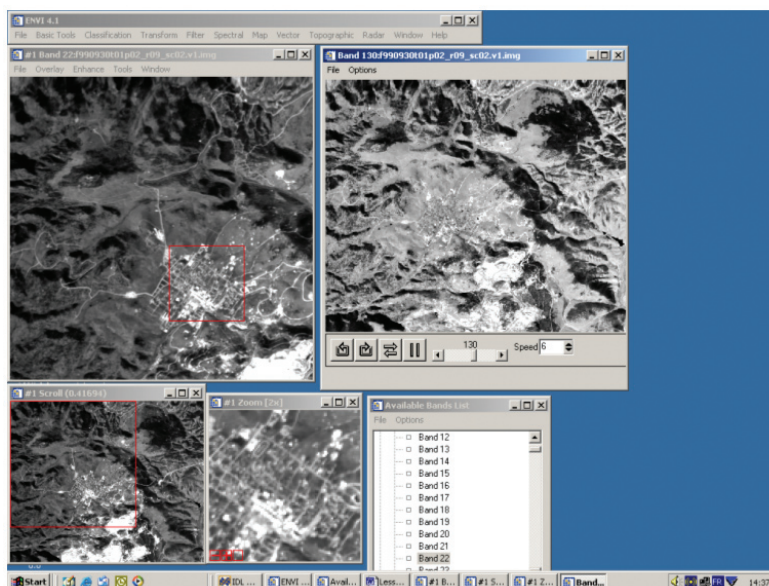
>>   **Fig. 7.2: Animation on 224 spectral bands.**

> **Hint**: In the animation window, you can choose the speed of animation as well as forward, reverse sequences and one step at a time.(experiment with arrows and options).

Action: Some spectral bands are quite noisy and should be removed for further processing. Through the fast visual examination of each of the 224 bands in the animated sequence, make a "bad bands" list. Write down this list.

Action: In the main menu, choose <basic tools> <resize data> and select the f990930t01p02_r09_sc02.v1.img file you are displaying. Choose <spectral subset>, <clear> the complete list of spectral bands, add the list of good bands that will be used, excluding the bad bands you identified.

> **Hint**: The easiest way to give the bands is by given ranges with the <add range> option in the <Basic tools>, <Resize data>, <spectral subset> menu.
> Good values are from 5 to 107, from 112 to 154 and from 165 to 224.

Action: Use <choose> to save the result as a new file in \Lesson07\Data\AVIRIS_data\ scene02_processing directory.

> **Hint**: Since the pre-processing steps can be numerous, always use file names as explicit as possible. There is a backup file \Lesson07\Data\AVIRIS_data\scene02_processing\bad_bands_removed_ f990930t01p02_r09_sc02.v1.img.

Action: Close all files with "available band list" <file> <close all files>

Question 7.1: How can you distinguish between acceptable and non acceptable spectral band data in this early stage of pre-processing?

3. Calibration to reflectance factors, best choice of spectral ranges in VNIR and SWIR.

Whatever approach is used, the hyperspectral images are usually not calibrated to real reflectance values, due to atmospheric and illuminations effects and non lambertian comportment of targets.

Several calibration techniques can be used, including model-based atmospheric correction or empirical regression on measured field targets.

We will use the simplest method called flat field calibration. It consists in finding a target (a few pixels large) in the image itself, with a spectral response as neutral as possible (the flat field) and using this response as a reference. All the radiance values will be divided by the mean value of this reference curve.

Find an area with a featureless (flat) spectral response.

Action: In the main menu, <file> <open image file> and select the "bad_bands_removed….img file you just saved (or the backup file if necessary).

In the main menu choose <Transforms>, <Principal component> <forward PC rotation> < compute new statistics and rotate>.

Select the bad_bands_removed file, keep default values and <OK>. Choose to compute the first 20 principal components in the option <Number of output PC bands>. Provide explicit names for the statistics file *.sta <output stats filemane> and the image file *.img both to be saved in \Lesson07\Data\AVIRIS_data\scene02_ processing

> **Hint**: There are backup files PNCP_bad_bands_removed.sta and PNCP_bad_bands_removed_sc02.v1.img.

Action: In "available band list" select the first PC image to display and use the animation tool to browse the 20 components. (see above item 2). It can be observed that PC1 corresponds to an "overall brightness" and that contrast between vegetation and non vegetation is concentrated in PC2.

Question 7.2: How can you conclude that PC1 is related to brightness and PC2 to a kind of vegetation index?

Action: With the first PC1 image displayed, use from the "display menu" the <enhance>, <interactive stretching> <histogram source> <scroll> option to evidence the highest values in the scene. Use the cursor in the left displayed screen to move the extreme values bar to select an interval with the highest values and click <apply> to stretch and look at the resulting stretched image.

> **Hint**: These figures can also be read from the "stretch" fields above the histogram.

Repeat until only a few white dots remain in the scene, corresponding to the brightest objects. Write down the used min. and max. stretch values.

> **Hint**: Good values are resp. 60.000 and 75.000.

Use <tools> <region of interest> <Band threshold to ROI> to select a bright area in the image.

Action: Select PC1 <OK> and give the min. and max. stretch values you just wrote down. <OK> <Yes> The ROI is displayed as a red overlay. To see where this ROI falls in the image, deactivate the stretch of PC1 using <enhance> <image linear 2%>

Save the defined ROI.

Action: In the "ROI tool" window, select <File> <save ROI> select the correct item <thresh(hold)> and give a explicit filename * roi. Save in the \Lesson07\Data\AVIRIS_data\scene02_processing.

> Hint: There is a backup file in \Lesson07\Data\AVIRIS_data\scene02_processing\white_flat_pncp1_sc02.v1.roi

Due to the nature of PC1, there is a good probability that the bright target ROI will be a featureless area. You can check it by displaying its radiance with the <Z profile> tool in the original bad_bands_removed image.

Action: Display 3 bands of the "bad_bands_removed" image as R,G,B. (f.ex. 29, 19, 9) for a true colour composite. In the image window, select <ROI tools> to activate the corresponding function. Select the <off> radio button.

> Hint: The ROI is displayed in red on the image. If necessary <file> <restore ROI> and load the corresponding *.roi file you saved previously.

Display the spectrum under the ROI, to check for flat field.

Action: <tools> <profiles> <Z profile>. In the Zoom display, zoom on the ROI area <+> until it covers 25% of the window and click on a single pixel. The corresponding spectrum is displayed.

> Hint: The spectra are in radiance. A flat field spectrum will not display absorption features except for atmospheric water related features. The whole curve resembles the solar irradiation curve.

To compare with other targets in the scene, choose <option> <collect spectra> and click in different places in the image. Pixels outside the ROI will show low radiance and pronounced absorption features.
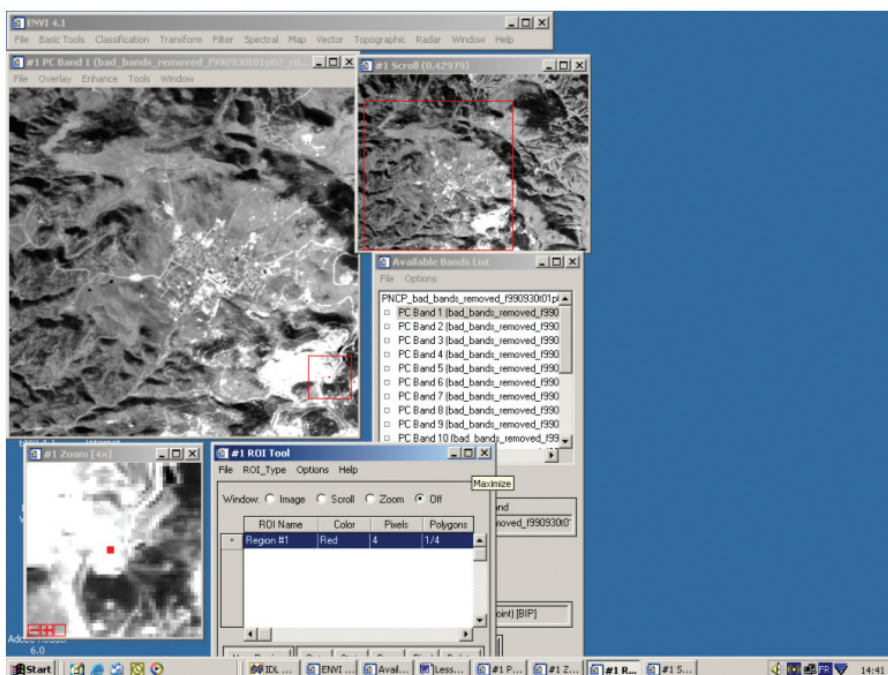
>> **Fig. 7.3.a: Image of PC1, ROI of the flat field target.**
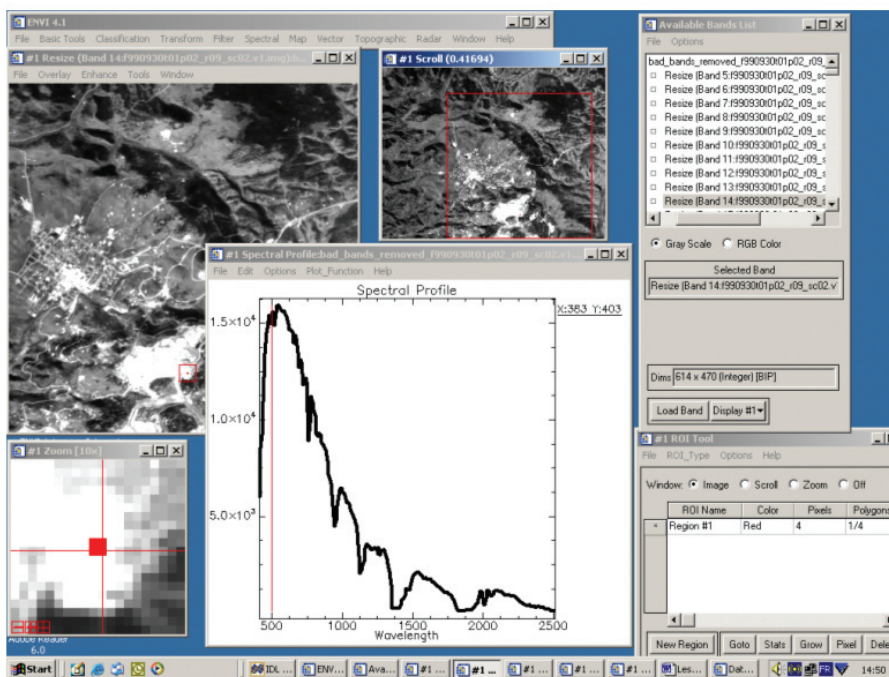
>> **Fig. 7.3.b: Corrected image, ROI of the flat field target and spectral profile.**

Apply the flat field calibration

Action: in the <basic tools> main ENVI menu, choose <preprocessing> <calibration utilities>, <flat field>. Select the displayed input file name (… bad_bands_removed …), keep default values, <OK>. In the "Select ROI for calibration" window, use the ROI of the flat field target you computed. Choose an explicit output filename and save it in \Lesson07\Data\AVIRIS_data\scene02_processing. <OK>

> **Hint**: There is a backup file named \Lesson07\Data\AVIRIS_data\scene02_processing\flat_field_from_PNCP1_calibrated_ f990930t01p02_r09_sc02.v1.img

4.   Masking out vegetation.

Because extracting mineral information from the image is our major concern, we do not want the vegetation reflectance to interfere with it. We will compute a vegetation index in order to mask out vegetation for the mineral extraction processes. The NDVI is calculated as where R_x is the reflectance value at a red (Red) or near-infrared (NIR) wavelength in the VNIR range.

Action: Open the calibrated file, load a false colour image in the display window (f.ex. bands 49, 132, 193). Vegetation will appear in reddish colours.

In the display menu, use <Tools> <profiles>, <Z profile> to display various vegetation spectra. Select the best spectral bands to represent the NIR plateau and the Red depression.

> **Hints**: Use the cursor in the "zoom" window to point appropriate pixels, in the bright and shaded sides of the hills.
> In the "spectral profile window" use <options> <collect spectra> and point different representative pixels in the "zoom" window. Each spectrum will be added to the "spectral profile" window.

Continue the procedure until you identified the pixel with the most typical vegetation signature.

> **Hints**: This is the spectrum with the lowest Red value and red edge NIR value.

Action: For this particular spectrum, find the wavelengths of this lowest red and highest NIR value.

> **Hints**: Point with the mouse in the "spectral profile" window, <left click>, a white ruler appears that slides over the spectrum. In the lower left corner of the window, the corresponding band number, wavelength and reflectance are displayed. A good candidate is band 32 (682.79 nm) for the Red depression and 43 (787.75nm) for the red edge NIR plateau.

Action: Compute the NDVI. In the main menu <basic tools> use the <band math> tool to define the math operation and assign the channels in the equation. Use <enter an expression> and type "float ((b1-b2)/ (b1+b2))" <OK> Select the b1 and b2 bands by pointing the bands you defined before (f.ex. 43 and 32). Choose an explicit filename and save the result in \Lesson07\Data\AVIRIS_data\scene02_processing.

A backup file exists in this directory: NDVI.img.

Load the NDVI image. You can check that the lowest values of the NDVI are the open pits in the lower-right part of the image, the roads and the street and building of Cripple Creek city in the center of the image.

> **Hint**:   When computing the NDVI, the result will be in the range of -1 to +1. If we us the formula b1-b2/b1+b2, the result may well have the format of a byte.
> Use the "float" option to be sure to obtain a value in "real" format.

Action: Create a non-vegetation region of interest (no vegetation = 1; vegetation = 0). Use the option <ROI tools>, <band threshold to ROI>. Try different upper (maximum) threshold values between 0.1 and 0.2, leaving the minimum value blank by default and observe the results. Select the best value (0.15 seems a good candidate) and save the ROI to a file.

> **Hint**:   Backup file: NDVI_max_threshold_015.roi

Action: Use the <Basic Tools> <Masking> <Build Mask> utility to create a non-vegetation mask (non vegetation = 1,vegetation = 0) on the basis of the ROI. Select Display 1 as background image, <options> <import roi> : your NDVI_threshold, and <options> <select areas "On">. Save the files with an explicit name.

> **Hint**:   Backup file is Mask_non_veg_passing.img.

Action: Create a vegetation ROI by the same procedure as above (vegetation = 1, non vegetation = 0), using the threshold value 0.20 for minimum and leave the maximum value blank. Save the ROI to a file.

> **Hint**:   Backup file: NDVI_minimum_threshold_020.roi
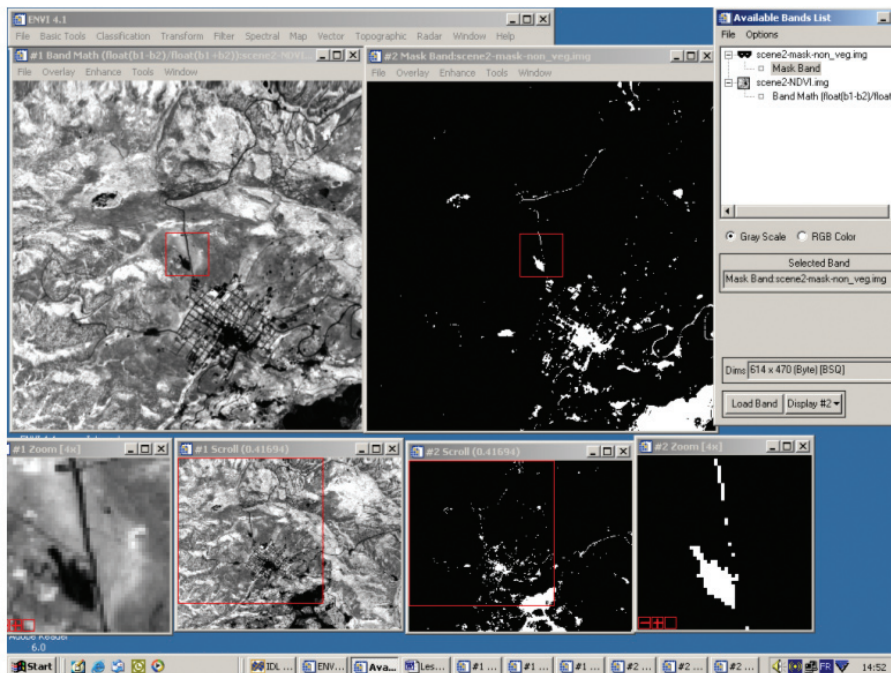
>> **Fig. 7.4: Image of NDVI, mask image.**

5.   *Simple image processing steps for mineral information extraction.*

The data is now ready for further processing. Before applying the full suite of hyperspectral image processing for mineral mapping (Lesson 8), we will apply simple processing steps to extract basic mineral information.

Colour composite

Action: Load a RGB false colour composite, with the wavelength 2341 nm in the red channel, 2201 nm in the green channel and 2001 nm in the blue channel.

The carbonates have a strong absorption peak around 2340 nm and will have a low red contribution; the clay minerals will have a low green contribution due to the absorption at 2200 nm. The channel displayed in blue is more neutral concerning those two mineral families. Because the three bands are fairly correlated, the resulting combination is pale and poorly contrasted. Best is to emphasize the contrast.

Hint: To emphasize the contrasts, use <transform>, <decorrelation stretch> in the main ENVI menu. Choose "display #1" and <OK>. Save the file.

A backup can be found with the name: decorrelation_RGB.img.
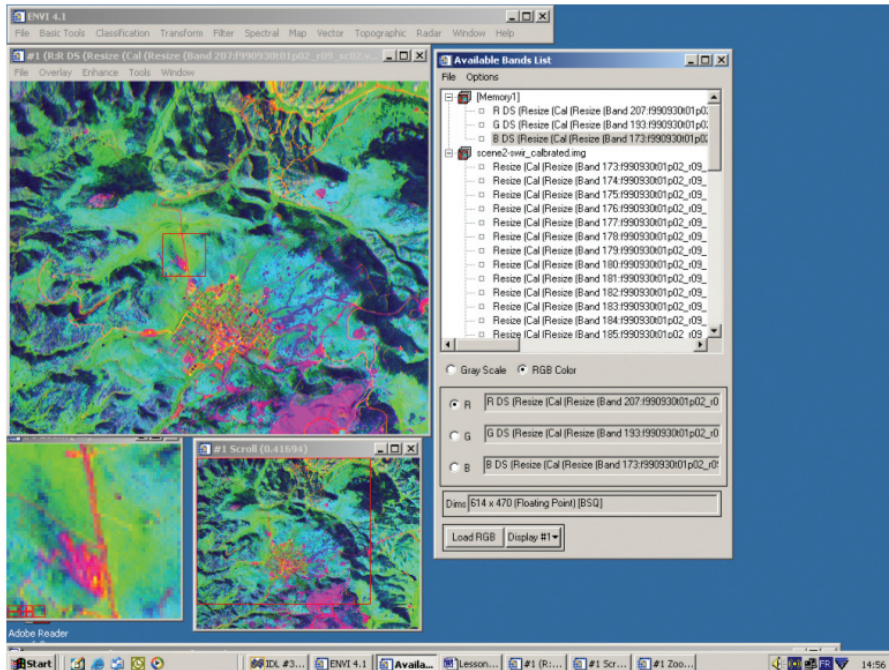
>> **Fig. 7.5: Decorrelated False colour image.**

In the decorrelated image, the impending effect of vegetation is also emphasized. Mask out the vegetation in black using the NDVI minimum threshold ROI calculated earlier.

Hint: Use in the "display window" <tools> <Region of interest> and select your ROI from the list. <right mouse click> on <color> <color 1-20> and choose "black".

Your image should now look like the one in Figure 7.6.
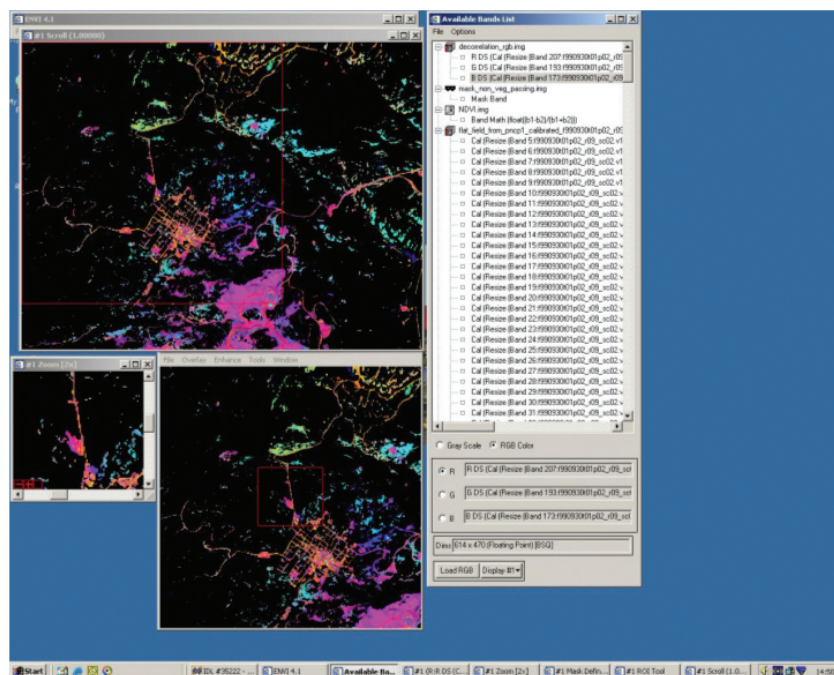
>> **Fig.7.6: Masked Decorrelated False colour image.**

The reddish–pink colour corresponds to an absorption in the green (attributed to 2200 nm) indicating the presence of different clay minerals.

The green-blue colour should correspond to carbonates, though a confusion may exist with shadows.

Unsupervised classification

In the ENVI main menu use <classification> <unsupervised> <isodata> select the "bad_bands_removed….. img" as input file, keep all default values, <select mask band> and give "mask_non_veg_passing.img <OK><OK>

For the classification parameters set these values: 5-10 classes, 10 max. iterations, min. pixel in class 400, and default all others. Save the file.

> **Hint**:   Backup file is isodata.img.

Display the result in a new window. Use <tools> <color mapping> <class color mapping> to adapt class names and colour as you like. (Figure 7.7)
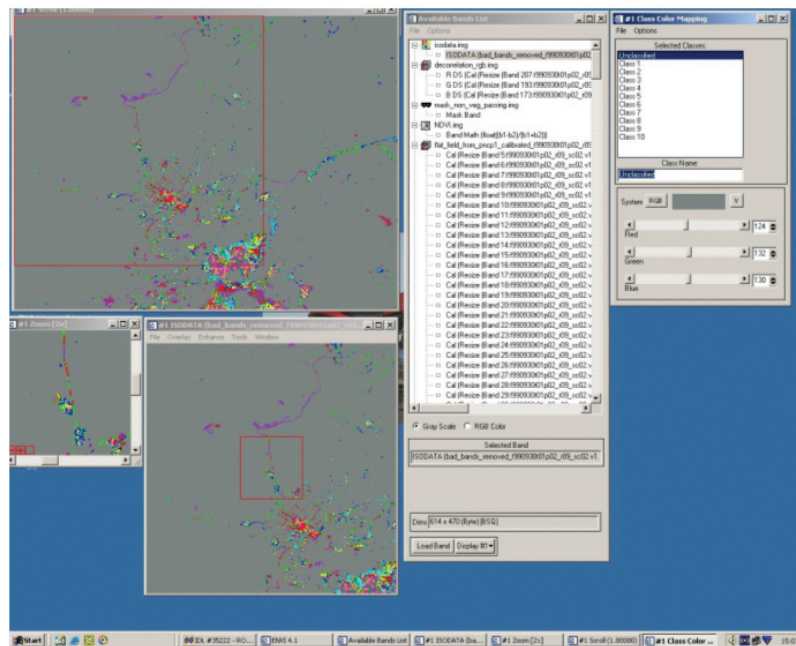
>> **Fig. 7.7: Result of unsupervised classification**

In Lesson 8, we will see that the different classes correspond to different types of clay minerals.

_____ Answers to questions _____

Question 7.1: How can you distinguish between acceptable and non acceptable spectral band data in this early stage of pre-processing ?

The B/W images of each spectral band "speak for themselves" and it is immediate to observe extremely noisy data compared to correct imagery.
The diagnostic can be confirmed using the Z profile tool (spectrum) on the whole set, on various locations.

Question 7.2: How can you conclude that PC1 is related to brightness and PC2 to a form of vegetation index?

In PC1, bright objects identified on the colour composites appear with a high value, whereas the shaded areas appear in dark.
In PC2, the streets of the city and the building roofs, as well as al the non minerals objects appear in dark (compare with the NDVI image). The vegetation has a bright response.

Aim of Lesson

To learn how to process reflectance data for a mineral application, to fulfil the complete ENVI "hourglass" procedure from noise removal, decorrelation and data dimensional reduction with MNF, pixel purity index research with PPI, n dimension interactive analysis and selection of spectral endmembers up to mineral mapping. To analyse the results of this processing and compare these with a deterministic approach to the problem.

Use mapping techniques based on both approaches.

Objectives

1. To remove the noise, decorrelate data and reduce significant data dimensionality through the minimum noise fraction method: compute MNF while masking out vegetation.
2. To analyze the statistics of MNF and to observe their content in terms of signal to noise ratio, with B/W image animation. To select the significant MNF bands for further processing.
3. To perform a pixel purity index analysis PPI with the standard ENVI procedure. To threshold the PPI image to a PPI ROI.
4. To compute the intersection of PPI ROI and "non vegetal" ROI to obtain a "mineral pixel purity index".
5. To built a deterministic mineral mask as an alternative to ENVI PPI.
6. To use the n-D Visualizer tool to interactively select spectral endmembers and build a spectral library.
7. To analyse the results and repeat point 4 and 5 using an interactive PPI on areas with known mineral composition.
8. To use the spectral angle mapper (SAM) method to determine mineral abundances.

Background Information

This lesson relates to the Sections 9.1.1, 9.1.4.1 and 11 of the HyperTeach Theory Syllabus. For further details about the techniques involved, users are recommended to read these sections. It intends to describe and exploit the techniques related to the full spectral processing of hyperspectral data for mineral identification/determination and mapping.

The exercises are performed on a sub scene of an AVIRIS image of Cripple Creek, Colorado.

Software

A PC with ENVI® software is necessary to carry out the lesson.

Spectral data

An AVIRIS sub scene of the Cripple Creek, Colorado, gold mining area is used. The goal is to show epithermal and alteration minerals with marked spectral features in the VNIR and SWIR ranges. For this lesson, the data has been calibrated to atmospherically corrected reflectance. The calibration has been performed with the ACORN software package.

Lesson outline

1. Pre-processing

Spatial and spectral subset extraction

In order to limit computation time a subset image from scene 3 of Cripple Creek, in reflectance factors and corrected for atmospheric effects is used.

The data is in the \Lesson08\Data\subset\ directory.

Action: Open the file:\Lesson08\Datat\subset\AVIRIS_scene2_atm_7-224subset.img

Action: Display a RGB image of bands 43, 35 and 19 (this will look like a Landsat 432). The vegetation appears in red and the outcropping mineral areas in bright blue to white.

Use the display menu <Tools> <Profiles> <Z profile> to collect spectra in the mineral areas (e.g. open pits in

the lower right part of the image). Use the <Options> <Collect Spectra> and <Stack Plots> in the Spectral Profile window to visualize several profiles. Point to different pixels of interest.

The outcropping minerals in Cripple Creek are mainly of epithermal or weathering origin. Lesson 6 has shown that the spectral features associated to these minerals are mainly present in the SWIR range.
However, the observation of the spectral features show that significant absorptions are present in the VNIR as well.
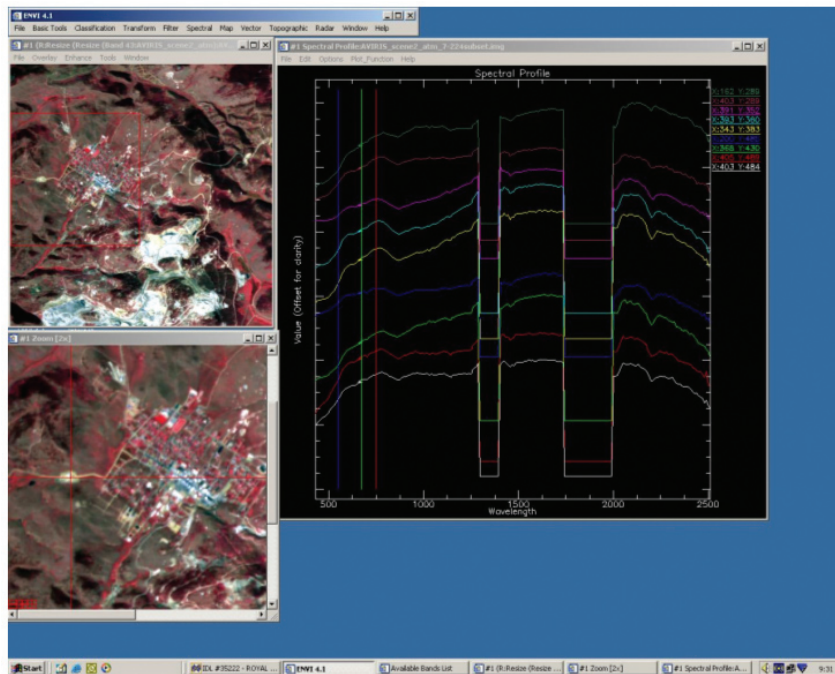
>> **Fig. 8.1: Z profile (spectrum) of mineral pixels.**

Hint: Looking at the "Available Band List" window, you can see that the first spectral band in the list is Band 7 from the AVIRIS original dataset. The first 6 bands were very noisy and have been removed (following the procedure applied in Lesson 7).

2. Build a MINERAL ROI with the standard ENVI iterative procedure

1. Masking vegetation

Following the same procedure as in Lesson 7, compute the NDVI from channels red = 675 nm (band 32) and NIR = 749.57 nm (band 43). Use the <band math> tool to define the math operation and assign the channels in the equation. Use <enter an expression> and type " float(b1-b2)/float(b1+b2)" <OK> Select the b1 and b2 bands by pointing the bands you defined before. Choose an explicit filename and save the result in \Lesson08\ Data\subset\.
A backup file exists in this directory: NDVI.img.

Hint: When computing the NDVI in Lesson 7, we used the formula float((b1-b2)/(b1+b2)) which was correct since b1 and b2 were already in" real" variable format (floating point). In this lesson, the calibrated data is in integer format, you can see this using the main ENVI menu <File> <Edit ENVI header>. To obtain a value in "real", we have to use the formula float(b1-b2)/float(b1+b2).

Action: Load the NDVI image. Look at the histogram with the Display menu <Enhance> <Interactive Stretching>, choose <Histogram Source>: Scroll. You observe a bimodal histogram, with a high frequency maximum for vegetation and a low maximum for non vegetation. Position the ruler (mouse, left button) on the diagram in the area separating the two populations. Read the NDVI value: 0.12.
Create a non-vegetation region of interest (no vegetation = 1; vegetation = 0). Use the option <ROI tools>, <band threshold to ROI>. Use the upper (maximum) threshold value of 0.12 and save the ROI to a file.

Hint: Backup file: NDVI_max_threshold_012.roi

Action: Use the <Basic Tools> <Masking> <Build Mask> utility to create a non-vegetation mask (non vegetation = 1,vegetation = 0) on the basis of the ROI. Select Display #1 as background image, <options>

<import roi> : your NDVI_threshold, and <options> <select areas "On">. Save the files with an explicit name.

> **Hint**: Backup file: file non_veg_passing.img

2. Minimum Noise Fraction

This first data transform has two main objectives: to decorrelate spectral relevant data from noise and to reduce data dimensionality for further processing. This is the first step in the search for "spectral endmembers".

> **Hint**: The bands with zero values in the original file will prevent the correct calculation of MNF. These bands position from 95 to 105 (AVIRIS channels 101 to 111) and from 140 to 166 (AVIRIS channels 146 to 172). We will remove them for further processing.

Action: In the 'ENVI' main menu, choose <Basic Tools> <Resize Data>. Choose the input file \Lesson08\Data\ subset\AVIRIS_scene2_atm_7-224subset.img.
In the <Spectral Subset> option, Clear all then add the ranges 1 to 94,106 to139 and save the file.
Backup file: \Lesson08\Data\subset\AVIRIS_scene2_atm_7-224subset_non_zero.img.

Action: In the 'ENVI' main menu use the <spectral> menu, then <MNF Rotation> < Foreward MNF> < Estimate noise statistics from data>. Select the image file (AVIRIS_scene2_atm_7-224subset_non_zero.img) and select the mask band (non_veg_passing.img) <OK> set <number of output MNF bands> to 30, give explicit filenames for the noise, statistics and output files. Keep other values default. <OK> runs the calculation.

> **Hint**: Backup files are MNFnoise.sta , MNFstat.sta and MNF30.img

Action: Look at the resulting eigenvalues curve in the graphic display window: the values come to a low contribution after a short ranking of MNF (less than 30).
Use the "animation" option (see Lesson 7) to compare the MNF images.
Load a colour composite of MNF 1 2 3 as RGB.
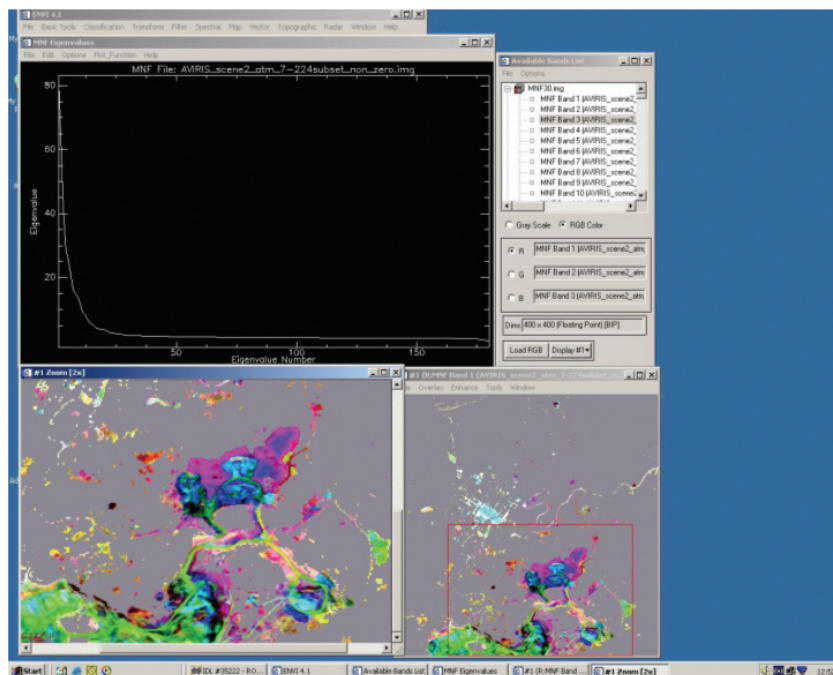
> >> **Fig. 8.2: Eigenvalues of the MNF set and colour composite MNF 123 as RGB.**

Question 8.1: What does this curve tending to zero mean in terms of MNF contribution to the whole signal and in terms of noise?

Question 8.2: How many MNF bands should be used for the following steps of processing?

3. Pixel Purity index

This second data transform aims at identifying spectral "endmembers", which represent pure pixels in the spectral domain at the extremes of the n-D 'cloud'.

Action: In the 'ENVI' main menu use the <spectral> option, then <pixel purity index>. Select the MNF as input, and choose the first 10. Run the program and save the result with an explicit file name. Choose a large number of iterations (25,000) and choose an output file name <OK>.

> **Hint**:   Backup file:PPI_10MNF_25M_iter.img

Action: Display the PPI image in a new display window and explore the value range. Use the ROI Tool to try several minimum threshold values to build ROI's: 3, 10, 20. Save the ROI's.

> **Hints**: The PPI image is free of "vegetal" endmembers thanks to the masking.

Question 8.3: What is the consequence of selecting a low minimum threshold value of PPI or a higher value? What is the meaning of the maximum threshold?

4. N dimensions visualizer

This tool allows the operator to identify groups (or classes) of endmembers.

Action: In the 'ENVI' main menu use <spectral>
<n Dimensional Visualizer> <Visualize with new data> . Select the file MNF30.img and select the first 10 MNF out of 30 as input, and use the ROI with threshold 20 saved earlier (PPI_threshold20.roi).

> **Hints**: In the "n-D control" window select <show axes> in order to visualise the 2D cross section of the n-D space displayed during the animation.

Action: Load MNF 1 to 4. Choose <start> to animate the n-D visualizer. The default speed being very fast, select a slower rotation (f.ex. 5).

> **Hints**: During the animation, groups of points move together and stay grouped in most of the 2D slices. Observe the movements of groups one at a time at slow speed. Stop the animation when the representation of a group seems the best.

Action: In the "n-D Visualizer window", interactively select classes by trial and errors. Click the right mouse button to create a new class <new class> and delineate the envelope for that class. Start the animation again and check that the selected points of each group stay together in all the 2D slices. If not, delete the class <right mouse> <clear> and select a more compact one.

> **Hints**: After the more obvious classes have been selected, use the <collapse classes by means> options in the n-D control window to group them and stretch the other values in the n-D space. Select new classes in this configuration and uncollapse the classes.
> You may also change the number of MNF bands to be visualized to determine the classes.

The identified classes spectra must be computed and saved.
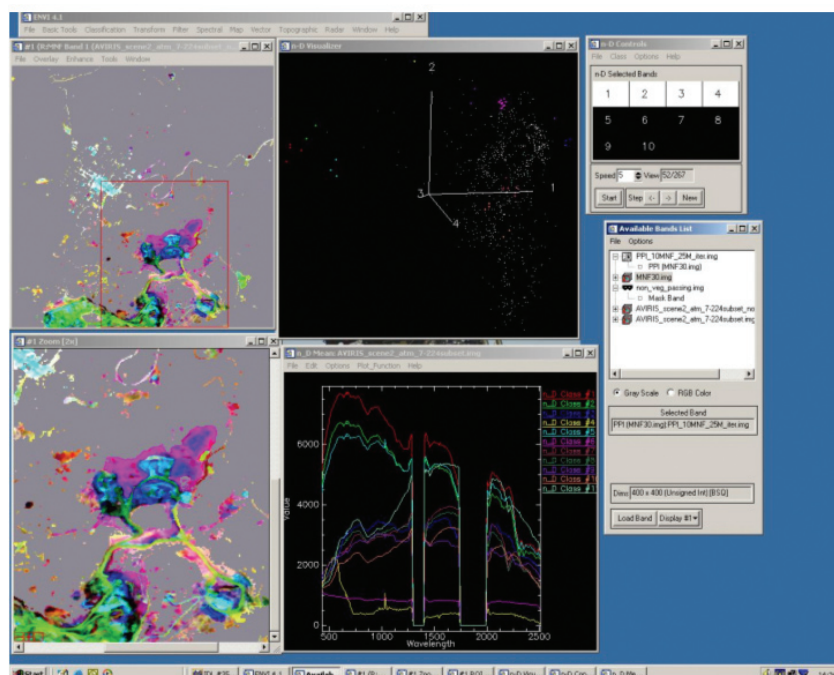
> >> **Fig. 8.3: The "n-D visualizer" session.**

Action: Use the <mean all> option in "n-D control" to compute class means, with the original image AVIRIS_ scene2_atm_7-224subset.img as input, <OK> computes the mean spectrum for each class and shows the spectra in a new window.

In this spectra window, choose <file> <save plot as> <spectral library> <select all items> <OK>. In the "output spectral library" menu, set X and Y scale factors to the requested values (X = 1; Y = 0.0001) and choose an explicit name for the library.

> **Hint**: Backup file is nD-Results.sli.

Check the physical location of the "objects" defined by the classes on the original image.

Action: Load channel 15 of the original image, in the nD-control menu click <export all> <select all> to display the locations of classes on the image.

> **Hint**: There will only be a few points on the entire scene.

Since the interactive session can often be improved and revisited, save the existing session scenario. In nD-control, select <file> <save a state> and choose a distinctive filename.

> **Hint**: Backup file is ND-session1.ndv

You can at any time during the session decide to delete particular endmember spectra. To do so, <file> <save plot as> < spectral library> and select to ones considered (f. ex. 1, 3, 6 to 10). Set scaling as previously and save again as a spectral library.

> **Hint**: Backup file is ND-results_7_endmembers.sli.

Only select the classes with typical spectral features like discriminant absorption bands at particular wavelengths (see Lesson 6).
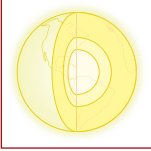
5. Deterministic mask of known minerals

An alternative approach to the PPI procedure from above is to directly build the ROI that will be used for further processing (step 6), based on known geology from the field.

Action: Display a true colour composite of the subset file AVIRIS_scene2_atm_7-224subset.img with bands 29,19 and 9 as red, green, blue, and use ROI tool to define areas of pure minerals based on the known geology of the area. Geological maps and other existing data are provided in the Lesson08\Data\geology directory on the CD. Display also the file: ground_truth.jpg as guide. Save your ROI's. (We have also done this exercise and the result is stored in mineral_outcrops_ground_thruth.roi).

Perform the same series of nD-vizualizer operations as in point 4 above, using the following files as input: the original image AVIRIS_scene2_atm_7-224subset.img, the MNF30.img and the mineral_outcrops_ground_ thruth.roi.

Save again the state of the visualizer session (Backup file ND_session2_empirical_PPI.ndv) and save the spectra of the identified classes as a spectral library (classes 1 to 4 and 7 in nD_results_empirical_PPI.sli)

Use the spectral analyst tools of Lesson 6 to compare the two spectral libraries that were created with each other and/or with the USGS library in \Lesson08\Data\USGS.

> **Hint**: Use your results from the spectral analyser to give a mineral name to the classes.

Question 8.4: What will be the expected differences between the results of the iterative automatic PPI procedure and the deterministic approach in terms of endmembers?

6. Mineral mapping

Different methods exist to map mineral occurrences included in a spectral library. We will use the Spectral Angle Mapper (SAM).

We will apply both to the two different libraries that we built in the previous steps 4 & 5.

Action: Close all files. <File> <open image file> "AVIRIS_scene2_atm_7-224subset.img" and the mask "non_ veg_passing.img".

Spectral Angle Mapper

This technique is in fact a pixel based classification, measuring the similarity of each pixel signature with spectra curves in the spectral library.

Action: <Spectral>, <mapping methods> choose <spectral angle mapper>. Use the original image as input file and the opened mask band in <select mask band>. Run the program <OK>

Action: <import> <from spectral library file> and <open> the first of your own spectral libraries saved in the previous step of this exercise ("nD_results_7_endmembers.sli"). <OK> Select all items and use Y data multiplier 0.0001. <select all> , set <output rule image> to "NO". Give an appropriate name to save.

> Hint: Backup: sam_classification_ENVI_hourglass.img

Action: Display the result and edit the class colour table with <tools> <color mapping> <class color mapping>.

>> **Fig. 8.4: Map and legend.**

Repeat now exactly this sequence with the sli file from the ground proofing.

> Hint: Backup: sam_classification_empirical_PPI.img

Action: Display the result and edit the class colour table with <tools> <color mapping> <class color mapping>. (Class 1 is illite, 2 is dickite, 3 is mixed signatures, 4 is kaolinite, 7 is alunite)

Use in the "display menu" <overlay> <annotation> < map key> to produce a "map with legend" of your study area. You can compare your results with the map provided in the \Lesson08\Data\geology directory (Cripple_Creek_AVIRIS_Prof. Carlos Roberto de Souza Filho.ppt)

Answers to questions

Question 8.1: What does this curve tending to zero mean in terms of MNF contribution to the whole signal, and in terms of noise?

The curve represents the percentage of contribution of each MNF image to the total variance of the original dataset. When this percentage of contribution decreases and tends to zero, it means that these MNF do not contribute much to the total variance and can be ignored without loosing information.

Question 8.2: How many MNF bands should be used for the following steps of processing?

The answer to question 1 indicates that the MNF of low contribution can be ignored: MNF 1 to 10 is a good choice to reduce computation time on the basis of the curve.
Another way to select the useful MNF bands is to display the MNF images one by one or with the "animation" tool and to observe at what rank the MNF images consist mainly of noise.
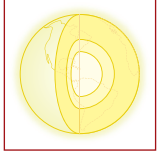
Question 8.3: What is the consequence of selecting a low minimum threshold value of PPI or a higher value? What is the meaning of the maximum threshold?

A low threshold value of PPI corresponds to a large number of pixels candidates for being a potential spectral endmember. The consequence will be more values in the n-D visualizer procedure. However, a very low threshold might keep too many candidates and make the n-D analysis confusing.

The higher the minimum threshold, the fewer pixels will be considered in the ROI. A high threshold is the "hard" option, excluding more candidates for spectral endmembers.

As a consequence, the choice has to be made by trial and error.

A maximum (upper) threshold can be used to exclude endmembers that would be "too obvious" in our research, like water, snow, very dark shade.

Question 8.4: What are the expected differences between the results of the iterative automatic PPI procedure and the deterministic approach in terms of endmembers?

The PPI procedure looks for intrinsic spectral endmembers. This is a specific property of targets strictly restricted to their spectral properties, which may not have a clear "physical" meaning.

The interest of the method is to be able to detect "unexpected" spectral endmembers that would be ignored in a deterministic approach.

The deterministic method requires an a priori knowledge of local occurrences of minerals to be mapped. Its advantage is to establish a direct link between mineral composition and spectral properties in the image.

To distinguish different vegetation species by their leaf reflectance spectra and to use different indices to characterize these differences.

Objectives

1. To learn how to use the FieldSpec Pro FR (ASD) field spectroradiometer, combined with the contact probe, to measure leaf reflectance.
2. To learn how different leaf reflectance spectra vary according vegetation species.
3. To calculate different vegetation indices for observing species specific parameters and leaf chemical properties.

Background Information

PRACTICAL ISSUES

First you will learn how to carry out leaf reflectance measurements. Therefore, from three different plant species, three randomly chosen healthy leaves are selected for in-vivo reflectance measurements with the FieldSpec Pro FR (ASD) field spectroradiometer combined with the contact probe. Next, you will observe the differences in reflectance spectra between different plant species and the difference in reflectance spectra between leaves of the same species. Finally, you will learn how the differences in reflectance spectra can be measured by different vegetation indices.

This lesson relates to the Sections 5.2, 12.1 and 12.2.4 of the HyperTeach Theory Syllabus. For further details about the instruments or techniques involved readers are recommended to read these sections. The measurement procedure for the FieldSpec Pro FR (ASD) and contact probe is described in the ANNEX of the HyperTeach Theory Syllabus.

SOFTWARE

A PC with ENVI® software and Microsoft Excel is required to carry out the lesson.

Lesson outline

Leaf reflectance measurement

In this section you will learn why healthy leaves appear green to the human eye and how the green colour is related to the measured reflectance spectrum. The FieldSpec Pro FR (ASD) field spectroradiometer, combined with the contact probe, is used to measure reflectance spectra from three different plant species. To simplify the interpretation of the measured reflectance spectra, you should choose plant species which look different in colour to the human eye. If possible choose also a red-coloured species.

Measurement protocol

Because extensive field spectroradiometer measurements can lead to confusion, it is important to write down the measurements which are performed in chronological order. In the annex at the end of this lesson, a measurement protocol sheet is included as an example.

Choose three different plant species to carry out the measurements. From each species you randomly select three healthy leaves. Repeat the measurement sequence below three times for each leaf:

- Perform the first measurement on the reference panel
- Perform the next four measurements on different leaf locations

Make sure the measurements are performed in 'RAW digital number' mode (RAW DN), this means that the leaf reflectance has to be calculated afterwards. This can be done by dividing the measured leaf radiance value by the measured reference panel radiance:

$$Leaf\ reflectance = \frac{Leaf\ reflected\ radiance}{Reference\ panel\ reflected\ radiance}$$ (9.1)

An example of leaf measurements can be found in the data directory: \Lesson09\Data\ASD_raw/*.*. We will use this dataset to show how the "raw" data can be used to create a spectral library containing the reflectance spectra of three common indoor plant species. The three species used are: Ficus Sp., Hedera Sp. and Yucca Sp.

Raw data handling

When all spectroradiometer measurements are done, we will use ENVI to build a spectral library from the raw data.

Action: In the 'ENVI' main menu use the 'Spectral Library Builder' option to open the ASD raw data files. Use this data to build a spectral library containing the reflectance spectra.

> Hint: In the ENVI main menu [ENVI] use: <Spectral> <Spectral Libraries> < Spectral Library Builder>; in the' Spectral Library Builder' window switch-on the 'First Input Spectrum' radio button as shown in Figure 9.1 and click 'Ok'.
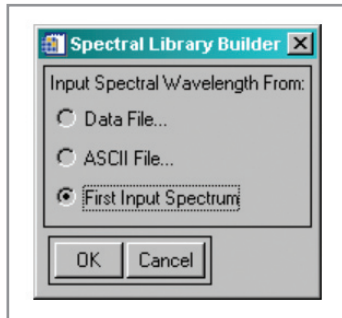
>> Figure 9.1: In the 'Spectral Library Builder' window, the 'First Input Spectrum' radio button has to be set when importing the raw ASD spectra.

Now you get the 'Spectral Library Builder' window. In this window use <Import> <from ASD binary file…> to import the ASD raw data from disk. Select all ASD files for import. After that your 'Spectral Library Builder' window will show a list of the ASD files.

Action: Visualize the ASD raw data and explore the measured spectra.

> Hint: In the 'Spectral Library Builder' window, highlight the first five spectra, as shown in Figure 9.2 and click the 'Plot' button. In the 'Endmember Collection Spectra' window, right click the mouse and choose 'Plot Key' to show the names of the different spectra. Your 'Endmember Collection Spectra' window will now look as shown in Figure 9.2 (right).
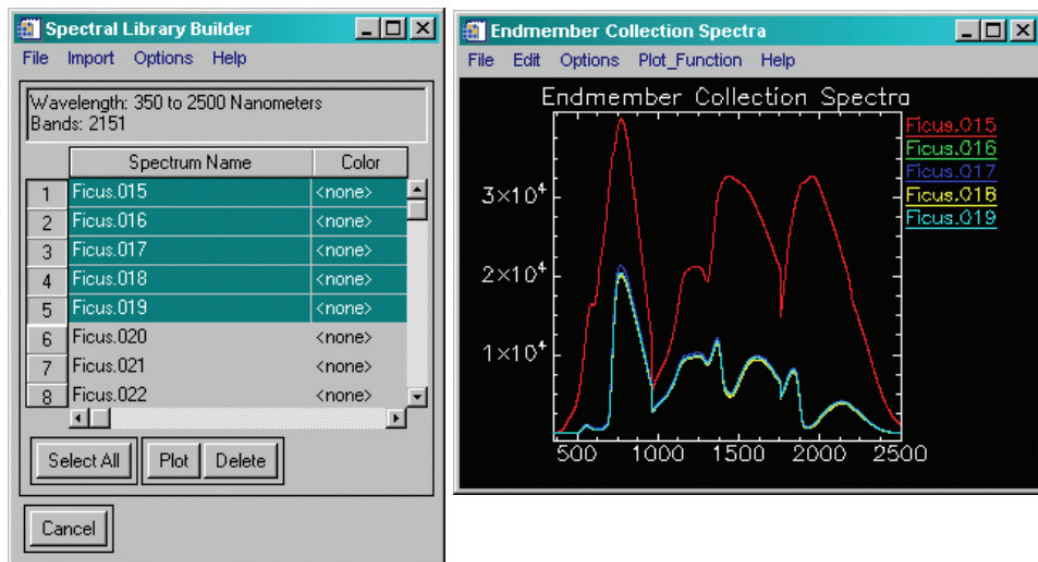
>> Figure 9.2. Via the 'Spectral Library Builder' window, the raw ASD data can be imported into ENVI. Highlight the spectra and use the 'Plot' button to display the corresponding spectra.

Action: Calculate the reflectance spectrum for every measured leaf by using the 'Spectral Math' function.

> Hint: For each leaf, you first measured the reference panel and subsequently four different locations on the leaf. When calculating the reflectance spectrum, the four leaf measurements have to be averaged. The leaf reflectance is defined according to formula (1) and can be calculated using the 'Spectral Math' option in the ENVI main menu. In the ENVI main menu [ENVI] use: <Basic Tools> <Spectral Math> and enter the expression: "((S1+S2+S3+S4)/4) / S0" and click 'Ok'. You will now see a window, 'Variables to Spectra Pairings', as shown in Figure 9.3:

Make sure you map the correct spectrum from the 'Available Spectra list' (just highlight) to the correct 'Variables used in expression' (again highlight). In Figure 9.3 this can be seen for the 'Ficus.017' spectrum, which is matched with S2 variable of the formula. Also make sure that the measured reference panel spectrum is mapped to S0. Once all spectra are assigned to the formula variables the average reference spectrum can be calculated by clicking 'Ok'. Make sure you select 'New Window' to output the calculated reflectance spectrum.

! Remark: In the 'Available Spectra list' of the 'Variables to Spectra Pairings' window, you will only find the spectra which have been displayed via the 'Spectral Library Builder' as explained earlier. You can list all spectra in the 'Available Spectra list' by clicking 'Select All' followed by 'Plot' in the 'Spectral Library Builder' window.

Action: Calculate the reflectance spectrum for the remaining leaves of the same plant species by using the 'Spectral Math' module.

> **Hint**: Use <Spectral Math> with the same formula as before to calculate the average reflectance spectra of the two remaining leaves of the same species. You can move the newly calculated average spectrum to the same plot window as the first calculated average spectrum. Grab the spectrum by its spectrum name using the right mouse button and drag it to the correct window. The plot window will now look as shown in Figure 9.4:
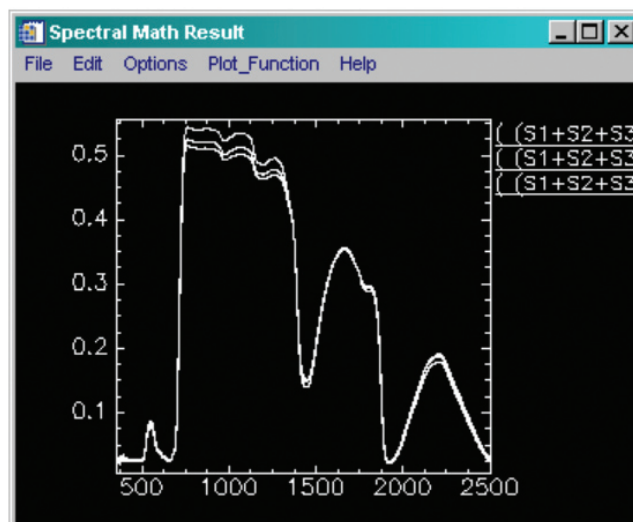
>> **Figure 9.4 :** The 'Spectral Math Window' was used to collect the average spectrum of three different leaves.

Action: Calculate the average reflectance spectrum of the three leaves of the same plant species by using 'Spectral Math'.

> **Hint**: Use <Spectral Math> and enter the formula: (S1+S2+S3)/3. Use this formula to calculate the average reflectance spectrum.

! Remark: In the 'Spectral Math Result' window you can change name and colour of the spectrum via <Edit> <Data Parameters…>. Change the name to 'Ficus' and give the spectrum a 'Red' colour.

Action: Repeat this sequence to obtain the reflectance spectra of the two other plant species. Give them the corresponding names 'Hedera' and 'Yucca', with colours green and blue respectively.

> **Hint**: When you arrived at this stage without to many problems, you are considered as an experienced 'hyperspectral image processing' operator! Try to build the plot shown in Figure 9.5.
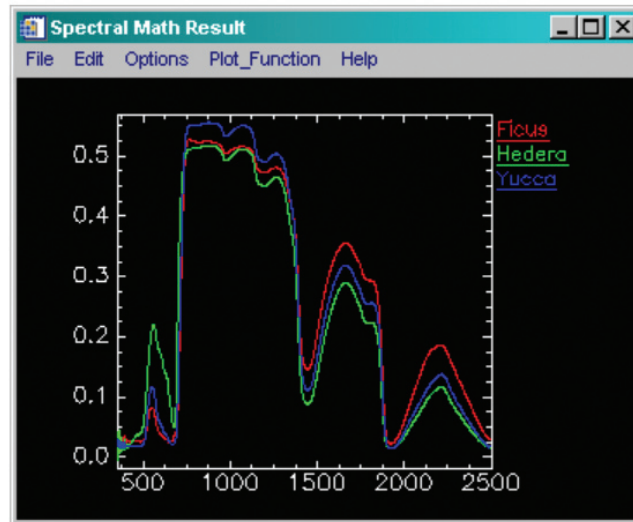
> >> **Figure 9.5: The 'Spectral Math Result' window was used to collect the average spectrum of the three different plant species, Ficus Sp., Hedera Sp. And Yucca Sp., which were measured in the lab.**

These spectra can also be found in the data directory where it is saved as a spectral library named: \Lesson09\ Data\ASD_spec\Plant_Species_Lib.

Question 9.1: You now have visualized the reflectance spectra of three different plant species. Can you deduce from the measured spectra the colour of the leaves as seen by the human eye?

Calculating different vegetation indices

Once the measured reflectance spectra are stored in a spectral library, they can be used to calculate different vegetation indices. The best and easiest way to do this is by saving the spectra to a text file and importing these into Microsoft Excel.

Action: Save the spectra to a text file and import it in Microsoft Excel.

> **Hint**: Spectra can be saved to a text file via the "Spectral Math Results" or "Spectral Library Plots" window. Use: <File> <Save Plot As> <ASCII…> to save the spectra to a text file. This text file can be imported in Excel, using the import utility: <file> <open>. Once loaded, the data can easily be used to calculate different vegetation indices. Figure 9.6 shows how the spectra are saved in a text file.
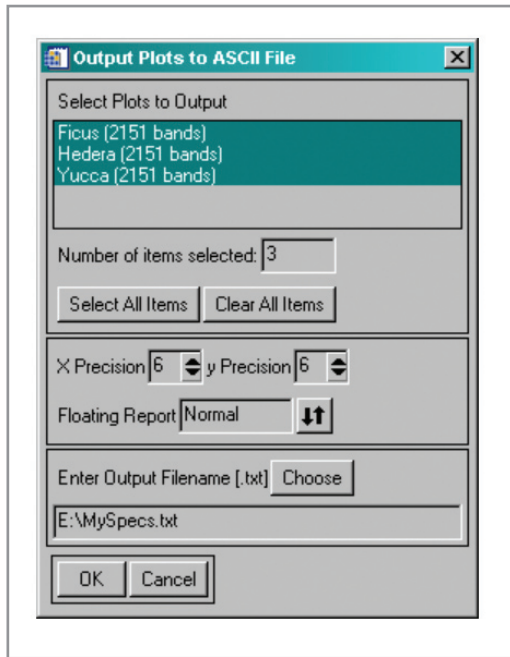
Numerous vegetation indices retrieved from the reflectance spectrum are studied for all kinds of applications. This lesson will focus on only five of them:

- 'Normalized Difference Vegetation Index' (NDVI)
- The reflection value at the inflection point ($R_{red\ edge}$)
- The wavelength at the inflection point ($R_{red\ edge}$)
- Chlorophyll content 1
- Chlorophyll content 2

More info on vegetation indices can be found in the HyperTeach Theory Section 12.2.4.

The 'Normalized Difference Vegetation Index' (NDVI) is a widely used canopy greenness indicator which is calculated as:

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad (9.2)$$

Use the reflectance value at wavelength 676 nm for RED and 776 nm for NIR.

Generally the red-edge is convexo-concave. The wavelength at which the concave shape changes into the convex shape is called the red-edge inflection point. Each vegetation species has its own specific red-edge inflection point and can change (i.e. a blue shift) when vegetation is stressed (e.g. by drought or heavy metals). The exact location of the inflection point can be calculated by an inverted Gaussian model which is rather complex. For this lesson we will use a more simplified method (Guyot G. et al., 1988):

First the reflection at the inflection point is calculated as:

$$R_{red\ edge} = \frac{(R_{670} + R_{780})}{2} \qquad (9.3)$$

Where R_i stands for the reflectance value at wavelength i.

Subsequently a linear interpolation is used to estimate the wavelength corresponding to the reflectance at the inflection point:

$$\lambda_{red\ egde} = 700 + 40 * \left(\frac{R_{red\ edge} - R_{700}}{R_{740} - R_{700}} \right) \qquad (9.4)$$

The typical vegetation spectral reflectance curve is caused by absorption at specific wavelengths, caused by different leaf pigments, mainly chlorophyll. Different ratios of reflectance values at specific wavelengths correlate with the chlorophyll content (Gitelson A.A. et al., 2003)

$$Chlorophyl\ content\ 1 \approx \frac{R_{750}}{R_{700}} - 1 \qquad (9.5)$$

$$Chlorophyl\ content\ 2 \approx \frac{R_{750}}{R_{550}} - 1 \qquad (9.6)$$

Action: Import the measured reflectance spectra into Excel and calculate the different vegetation indices NDVI, $R_{red\ edge}$, $\lambda_{red\ edge}$ and the chlorophyll content indices.

Question 9.2: Can you interpret the calculated values obtained by the different indices?

____ Answers to questions ____

Answer 9.1.: Can you deduce from the measured spectra the colour of the leaves as seen by the human eye?

Absorption by higher plants is strongest in the blue (400 – 500 nm) and red part (600 – 700 nm) of the visible spectrum. The green part (500 – 600 nm) of the spectrum is less absorbed by healthy leaves and this is the reason why they look green to the human eye. Some species, like red beech (Fagus Sp.), have dark red-brownish coloured leaves due to a decreased absorption in the red part (600 – 700 nm) of the spectrum, they possess a different leaf pigment composition. These phenomena can be observed in Figure 9.7.
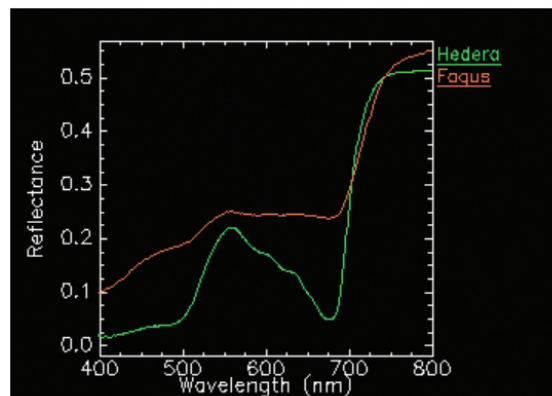
>> **Figure 9.7: Spectral plot showing a spectrum of a green leaved vegetation species (Hedera Sp.) versus a red leaved vegetation species (Fagus Sp.).**

Answer 2: Can you interpret the calculated values obtained by the different indices?

Table 9.1 shows five different vegetation indices calculated for the example spectra in \Lesson09\Data\ASD_spec\Plant_Species_Lib.

		Ficus	Hedera	Yucca
NDVI		0.880	0.826	0.923
Red-Edge reflectance		0.277	0.283	0.286
λ Red-Edge		718.2	703.4	717.0
Chlorophyll content	R750/R700 – 1	4.4	0.9	3.6
	R750/R550 – 1	5.3	1.4	3.6

>> **Table 9.1. Five different vegetation indices were calculated for the three vegetation species.**

The canopy greenness indicator, which is represented by the NDVI value, clearly differs for the different plant species. This value reflects the red-edge leap which is typical for vegetation, i.e. a large NDVI value indicates a large red-edge leap. In the example spectra, Yucca has the largest NDVI value (0.92), while Ficus has the smallest NDVI value (0.88). These values correspond with the size of the red-edge leap as can be seen in the spectral plot in Figure 9.8 (red arrow).

Different vegetation species have their own specific reflectance (Red-Edge reflection) and wavelength (Red-Edge) value at the red-edge inflection point. These values also depend on external stress factors (e.g. drought, heavy metal uptake) and can therefore be used for vegetation stress detection.

The absorptions in the blue and red part op the spectrum are mainly determined by the chlorophyll content of the leaves. Both 'chlorophyll content indices' show high chlorophyll concentrations in Ficus, less in Yucca and the lowest concentration in Hedera.
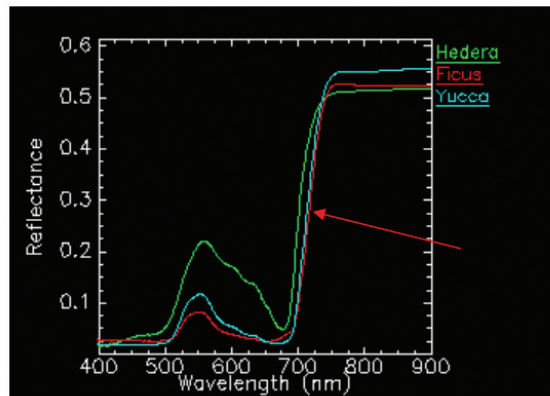
>> **Figure 9.8: Plot window showing part of the vegetation reflectance spectra between 400 nm and 900 nm.**

Related papers

Gitelson A.A., Gritz Y., Merzlyak M.N., 2003, Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. Journal of plant physiology. 160 : 271-282.

Guyot G. and Baret F., 1988, Utilisation de la haute résolution spectrale pour suivre l'état des couverts végétaux. Proceedings of the 4th International Colloquium on Spectrale Signatures of Objects in Remote Sensing. ESA SP-287, Aussois, France : 279-286.

PC : Toshiba Libretto + IBM Thinkpad
Software = RS^2 - Version 2.11 + RS^2 - Version 2.3

ASD No.	6165 (=1)
Sheet No.	1

Site	Labo	Reference Panel	Spectralon 100%					
Date	24/02/2005	Fore Optic	~~1°~~	5°	5°	~~18°~~	~~COS~~	~~None~~
Operator	MR & JM	Illumination						
Instrument On	13:30	Mode	Raw DN		Radiance		Recflectance	
Directory	C:\ASD\PlantSpecies	Configuration	Spectrum: 10		DC: 25		WR: 10	

Time	Opt	DC	WR	Filename Root	Filename Ext	Description	Sky	Processed Filename
Meting met PC: Toshiba Libretto - RS^2 Version 2.11								
	x		x	Hedera	000	Spectralon panel		
				"	002	Leaf 1		
				"	003	Leaf 1		
				"	004	Leaf 1		
			x	"	005	Spectralon panel		
				"	006-009	Leaf 2		
			x	"	010	Spectralon panel		
				"	011-014	Leaf 3		
			x	Ficus	015	Spectralon panel		
				"	016-019	Leaf 1		
			x	"	020	Spectralon panel		
				"	021-024	Leaf 2		
			x	"	025	Spectralon panel		
				"	026-029	Leaf 3		
			x	Yucca	030	Spectralon panel		
				"	031-034	Leaf 1		
			x	"	035	Spectralon panel		
				"	036-039	Leaf 2		
			x	"	040	Spectralon panel		
				"	041-044	Leaf 3		

[0] Clear Sky; [1] Haze; [2] Thin cirrus - sun not obscured; [3] Thin cirrus - sun obscured; [4] Scattered cumulus - sun not obscured; [5] Cumulus over most of the sky - sun not obscured; [6] Cumulus - sun obscured; [7] complete cumulus cover; [8] Stratus - sun obscured; [9] Drizzle

Aim of Lesson

To learn how to classify vegetation species using Compact Airborne Spectrographic Imager (CASI) imagery.

Objectives

1. To calculate a vegetation mask based on a Normalized Vegetation Difference Index NDVI.
2. To learn how to define a region of interest based on the field survey data and imagery.
3. To learn how to classify an image using Spectral Angle Mapper SAM.
4. To learn how to assess the accuracy of the classification.

Background Information

This lesson relates to the Sections 9.1.4.1, 9.1.5 and 12 of the HyperTeach Theory Syllabus. For further details about the techniques involved readers are recommended to read these sections. This lessons describes a method to classify vegetation species in the nature reserve 'De Westhoek' using CASI imagery. 'De Westhoek is located at the West coast of Belgium near the French border.

Different government institutions require actual, frequently updated vegetation maps of the active dunes, mud flats and salt marshes along the Belgian coast. The Flemish governmental institution 'Administratie Waterwegen en Zeewezen' (AWZ), uses this information for coastal protection to prevent the coast from flooding caused by storms. The 'Instituut voor Natuurbehoud' (IN), has a need for vegetation maps to monitor biodiversity and ecological recovery. In addition, these maps are suitable for scientific research on the variety and evolution of vegetation in the different nature reserves.

Software

An ENVI® student license is required to carry out the lesson.

Image data

The CASI sensor was mounted in a Dornier 228. A Global Positioning System (GPS) and an Inertial Navigation System (INS) was installed in the aircraft to measure respectively the position (lat, long, height) and attitude (pitch, yaw, roll) of the aircraft. A GPS base station was used to obtain more accurate differential GPS measurements of the aircraft's position. The CASI data was recorded at a spatial resolution of 1 m x 1 m. The reflected solar radiance was measured in 48 spectral bands within the wavelength range from 415 nm to 956 nm. Hyperspectral data was collected along the complete Belgian coast (approx. 66 km) in October 2002.

The raw data (i.e. the digital numbers generated by the CASI sensor) was radiometrically, geometrically and atmospherically corrected to obtain geocoded reflectance images. The collected data is registered in 12 bits (0:4096) and stored in band sequential (bsq) format, which means that the different bands are stored sequentially.

To distinguish between the different data files collected along the Belgian coast, the filenames are coded. In this exercise we will use part of the flight line flown above 'De Westhoek'. The file is named L1102rag10_Wh_cp and is coded as follows: L11 indicates the flight line; 02 indicates that the data was collected in 2002; rag stands for radiometric, atmospheric and geo-corrected data; 10 indicates a ground or pixel resolution of 1 m x 1 m; _Wh indicates that the data is a cutout (Wh stands for Westhoek) of a larger data file. Cp indicates that some noisy bands are cut and noise is removed from the remaining bands. How noise removal was performed can be found in Hands-on Lesson 2: Data preparation.

Field survey data

GPS locations of three different reference vegetation types (grass, shrub and dune vegetation) were measured during a field survey. The reference plots have at least a diameter of 5 m of homogeneous vegetation cover. Table 10.1 lists the geographical location (Belgian Lambert 72) of the central points of the measured vegetation plots.

#	Type	Eastern (m)	Northern (m)
1	Shrub	23151.0	199293.0
2	Shrub	23076.0	199201.0
3	Shrub	22686.0	199205.0
4	Grass	22494.0	199136.0
5	Grass	23097.0	199270.0
6	DuneVeg	23066.0	199478.0
7	DuneVeg	22789.0	199411.0
8	Shrub	23020.0	199189.0
9	Grass	23142.0	199229.0
10	Shrub	22950.0	199186.0
11	Grass	22507.0	199188.0

>> Table 10.1: Belgian Lambert 72 coordinates (m) of different vegetation plots.

Lesson outline

Creating a vegetation mask

Whenever a large number of spectral bands have to be investigated (which is mostly the case with hyperspectral imagery!) displaying individual bands one by one is very time consuming. The Z profile or spectral profile of an individual pixel gives a clear overview of the different spectral band values of the corresponding pixel. This spectral profile or reflectance spectrum is characteristic for each material on the Earth's surface and is the basic for hyperspectral image classification.

Action: In the 'ENVI' main menu use the 'Open Image File' option to open and display file L1102rag10_Wh_cp.

>   **Hint**:   In the ENVI main menu [ENVI] use: <File> <Open Image File>

Action: Use the 'Available Bands List' to load band 1 in the blue (B) channel, band 14 in the green (G) channel and band 24 in the red I channel.

>   **Hint**:   You have learned in "Lesson 2: Data preparation" why these channels are used. Trace back if you don't remember.

Action: Explore some pixel spectra. Compare the spectral profile of water pixels with the spectral profile of sand pixels and the spectral profile of vegetation pixels. Notice the difference in spectral profile in relation to the different materials at the Earth's surface.

>   **Hint**:   In the 'Image' window use: <Tools> <Profiles> <Z Profile (Spectrum)…>
>   Move the 'Zoom' window around to investigate different pixels.

Question 10.1: How can you distinguish vegetation spectra from non-vegetation spectra? In other words, how does a typical vegetation spectrum looks like?

Hyperspectral images contain a large amount of data. All redundant information needs to be removed in order to decrease computation time. In this lesson the aim is to identify or classify different vegetation types, therefore all non-vegetation pixels can be regarded as redundant information and can be masked out. The vegetation mask is created using the 'Normalized Difference Vegetation Index' (NDVI).

NDVI = (near IR band – red band) / (near IR band + red band)

Action: Calculate an NDVI image using bands 17 and 28, with wavelengths 676 nm and 803 nm respectively. In this case band 17 is located in the red area of the electromagnetic spectrum at 676 nm, band 28 is located at the NIR plateau at 803 nm. Both wavelengths are ideally suited for calculating the NDVI value.

>   **Hint**:   In the 'ENVI' main menu [ENVI] use: <Basic Tools> <Band Math>.
>   In the 'Band Math' window under 'Enter an expression;' type: (float(b1) – b2)/(b1+b2) and click 'Ok'.
>   In the 'Variables to Bands Pairings' window highlight 'B1' and select Band 28 (803 nm) in the 'Available Bands List'.
>   In the 'Variables to Bands Pairings' window highlight 'B2' and select Band 17 (676 nm) in the 'Available Bands List'.
>   Specify the output path and filename (e.g. L1102rag10_Wh_cp_ndvi) and click 'Ok'.

Before the redundant pixels can be removed a NDVI threshold has to be defined. Pixels with a NDVI value below this threshold will be considered non-vegetation pixels and will be removed, i.e. masked out, in the hyperspectral image.

Action: Find out which threshold level should be used to mask out the non-vegetation pixels.

> **Hint**: Load the newly created NDVI image in 'Display #2' and maximize as explained before.
> In the 'Image' window use: <Tools> <Color Mapping> <Density Slice…>.
> In the 'Density Slice Band Choice' select the newly created mask band and click 'OK'.
> In the '#2 Density Slice' window click 'Clear Ranges'.
> In the '#2 Density Slice' window use: <Options> <Add New Ranges…>
> In the 'Add Density Slice Range> window set 'Range Start' to -1 and 'Range End' to 0.12 and click 'OK' & 'Apply'.

Question 10.2: You will now see a coloured region in the NDVI image. What do you think this coloured region represents in the real world? Change the ranges in the 'Density Slice' window by using <Edit Range>. Is the given range (-1 to 0.12) suitable to select the non-vegetation pixels? Check this by displaying the spectral profile for different pixels.

> **Hint**: Make sure you have the coloured NDVI image on display #2 and the hyperspectral image on display #1. Link both images as follows: in the '#2 band Math' window use <Tools> <Link> <Link Displays …> and click 'OK'.
> Now display the Z profile of the hyperspectral image in display #1. Notice that once the images are linked you have to move around the red zoom box to get the different pixel spectral profiles.

Once the NDVI range for non-vegetation pixels is defined, a mask can be generated. This mask is applied to the hyperspectral image by which the non-vegetation pixels can be removed.

Action: Create a non-vegetation mask and save this mask file temporary to memory.

> **Hint**: In the 'ENVI' main menu [ENVI] use: <Basic Tools> <Masking> <Build Mask>.
> In the 'Mask Definition Input Display' window click 'Display #2 (the hyperspectral image)'.
> In the '#2 Mask Definition' window use: <Options> <Import Band Data Range…>.
> In the 'Import Band Data Range' window set: 'Band Min Value' to -1 and 'Band Max Value' to 0.12. Make sure to set the 'selected band' to the band math image (it is not necessarily the default!).
> In the '#2 Mask Definition' window use: <Options> <Selected Areas "Off">.
> In the '#2 Mask Definition' window set the 'Memory' radio button and click 'OK'.

You have now created a mask file to select all vegetation pixels. This mask file is not saved to any file but temporary stored in memory. It will also appear in the 'Available Bands List' and you can visualize the mask. To try this, use Display #3 to load the mask you created.

Once the mask file is created it has to be applied to the hyperspectral image to remove all non-vegetation pixels.

Action: Use the generated mask to remove all non-vegetation pixels from the hyperspectral image (L1102rag10_Wh_cp). Save the result in a new file named L1102rag10_Wh_cp_mkd.

> **Hint**: In the 'ENVI' main menu [ENVI] use: <Basic Tools> <Masking> <Apply Mask>.
> In the 'Apply Mask Input File' dialog highlight the file 'L1102rag10_Wh_cp'.
> Click <Select Mask Band> to open the 'Select Mask Input Band' window and highlight the 'Mask Band' created in 'memory1'. Click 'OK'.
> In the 'Apply Mask Parameters' window use 'Choose' to specify the path and name for the masked result. Use filename L1102rag10_Wh_cp_mkd. Click 'OK'.

Selecting reference spectra

In this paragraph we will perform a supervised classification using the Spectral Angle Mapper classification tool which will use ground truth data collected during a field survey. Table 10.1 shows the geographical location in the Belgian Lambert 72 projection system of the different vegetation plots. The measured coordinates will be used to define Regions Of Interest (ROIs). ROIs are image pixels used to extract pixel spectra. To obtain a representative spectrum for each reference location we will define ROIs of 3 by 3 pixels. Because the pixel size is 1 m x1 m the defined ROIs of 3 by 3 pixels are within the observed field plot (5 m diameter).

Action: Close all windows and load the masked hyperspectral image L1102rag10_Wh_cp_mkd in Display #1 as explained before. Use the geographical locations listed in table 10.1 to define the different ROIs.

> **Hint**: Load image 'L1102rag10_Wh_cp_mkd' in Display #1 by using the 'Available Bands List'. By right clicking the file name in the 'Available Band List' you can load true colour spectral bands by selecting <Load True Color>.
> In the '#1 Image' window use: <Overlay> <Region of Interest…> to start up the Region Of Interest Tool.
> In the '#1 Image' window use: <Tools> <Pixel Locator…>.
> In the '#1 Pixel Locator' window use: <Options> <Map Coordinates>.
> Enter the Eastern and Northern coordinates of the first location and click <Apply>.
> In the '#1 Zoom' window enlarge the pixels, this can be done by clicking the + sign at the bottom left in the zoom window.

In the '#1 ROI Tool' window use: <ROI_Type> and click <Point>. You will select pixels in the zoom window so highlight the radio button 'window: zoom'.
In the '#1 Zoom' window first click the crosshair at the bottom left to select the central pixel and his eight neighbours.

You have now created your first ROI of 'Shrub', it measures 3 by 3 pixels and is coloured red. You can now add the other plots via the 'New Region' button in the 'ROI Tool'. Via the 'ROI Tool' you can edit each entry and change the name and colour of the corresponding vegetation type. You also can change the colour such that each vegetation type looks the same. Try this, colour all 'grass' types green, the 'dune vegetation' yellow and the 'shrubs' blue.

Defining all the ROIs for the locations in Table 10.1 is a time-consuming job. In file 'L1102rag10_Wh_Field' all the ROIs from the Table 10.1 are saved.

Action: Load the predefined ROIs from file'L1102rag10_Wh_Field' by using the ROI Tool.

> **Hint**:   n the '#1 ROI Tool' window use: <Options> <Delete All Regions>
> In the '#1 ROI Tool' window use: <File> <Restore ROIs…> and select the file 'L1102rag10_Wh_Field'.

Question 10.3: Eleven ROIs are loaded for three different vegetation types. Each ROI contains 9 pixels. Why do you think three ROIs, one for each vegetation type, with each ROI containing only one pixel is insufficient?

You now have loaded eleven ROIs for three different vegetation types. Check the spectral variability by displaying the mean spectra for each ROI.

Action: Display the mean spectra for the different ROIs.

> **Hint**:   In the '#1 ROI Tool' window use: <Options> <Mean for All Regions>.
> Right click in the 'ROI Means' window and click <Plot Key>.

Spectral Angle Mapper classification

Now you are ready to perform the Spectral Angle Mapper (SAM) classification. You don't have to tremble, it's not that difficult ☺.

You will use the mean spectra of the ROIs defined in the previous section to perform the classification. The Spectral Angle Mapper calculates a Rule image for each reference spectrum. The value of a Rule pixel represents the angle between the reference spectrum and the spectrum of the corresponding image pixel. A small Rule value means a small spectral angle between reference and input spectrum, indicating a similar shape of the spectra. Therefore the final class for a pixel is assigned to the smallest Rule value found.

Action: Perform a SAM classification by using the overlaid ROIs.

> **Hint**:   In the 'ENVI' main menu [ENVI] use: <Spectral> <Mapping Methods> <Spectral Angle Mapper>.
> In the 'Classification input File' select the file 'L1102rag10_Wh_cp_mkd', click 'OK'.
> In the 'Endmember Collection:SAM' window use: <Import> <from ROI from Input File…>.
> In the 'Input Regions of Interest' window use: <Select All Items> & <OK>.
> In the 'Endmember Collection:SAM' window use: <Apply>.
> In the 'Spectral Angle Mapper Parameters' window: set the <None> radio button, specify the 'Output Class Filename' (i.e. L1102rag10_Wh_cp_mkd_Cl) and the 'Output Rule Filename' (i.e. L1102rag10_Wh_cp_mkd_R) & <OK>.

The Spectral Angle Mapper Classifier will take some time. Depending on the speed of your computer, 5 sec to 1 min. The results, the classified image and the Rule image, are available in the 'Available Bands List' for loading.

You can load the classified image in 'Display #2' and the Rule image in 'Display #3' and link both with the image in Display #1 (use Display #1 as reference).

Question 10.4: Use the 'Pixel Locator' to locate the pixel at Sample:558 and Line: 311. To which class is this pixel assigned. Try to find out what the minimum Rule value is. To which class should this pixel belong. Compare with the classified image. Is the pixel classified correctly in L1102rag10_Wh_cp_mkd_Cl?

Accuracy assessment

Checking the accuracy of the SAM classification can easily be done using ENVI.

Action: Check the accuracy of the SAM classification.

> **Hint**:   In the 'ENVI' main menu [ENVI] use: <Classification> <Post Classification> <Confusion Matrix> <Using Ground Truth ROIs>.
> In the 'Classification Input File' select the classified result 'L1102rag10_Wh_cp_mkd_CL' & <OK>.
> In the 'Match Classes Parameters' use: <OK>.
> In the 'Confusion Matrix Parameters' use: <OK>.

It can easily be seen in the 'Class Confusion Matrix' that the overall accuracy equals 80% with Kappa Coefficient equal 0.78.

Question 10.5: How many pixels in the 1st grass ROI (Ground Truth) are correctly classified? The confusion matrix is saved as 'conf_matrix.txt'.

—— Answers to questions ——————

Answer 10.1.: How can you distinguish vegetation spectra from non-vegetation spectra? In other words, how does a typical vegetation spectrum looks like?

Vegetation spectra can easily be distinguished from non-vegetation spectra by some characteristic features. Absorption by green plants is strongest in the blue and red part of the visible spectrum. The green part of the spectrum is less absorbed and this is the reason why plants look green to the human eye. This increased reflection in the green area around 550 nm is called the green peak and is one of the two characteristic spectral features for vegetation.

The energy contents of the non-visible short infrared is insufficient for photochemical reactions and therefore it is not absorbed by the chlorophyll and the other leaf pigments. This results in a strong increase of reflection around 690 nm called the 'Red-edge' which is typical for vegetation and is the second characteristic spectral feature for vegetation. These typical features are illustrated in Figure 10.1.
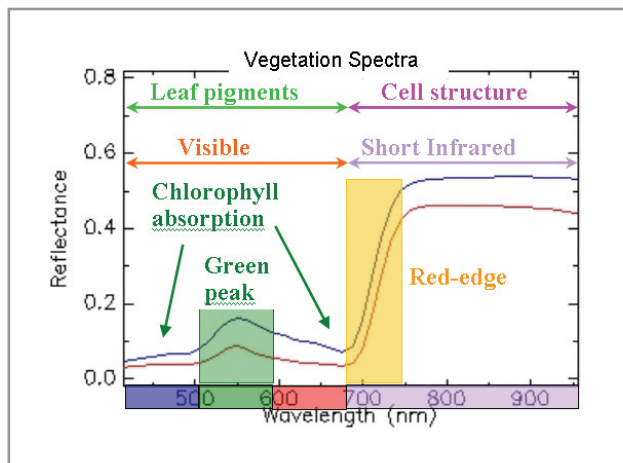
>> **Figure 10.1: Vegetation spectra are characterized by two typical spectral features; the green peak and the red-edge.**

Answer 10.2.: You will now see a coloured region in the NDVI image. What do you think this coloured region represents in the real world?

It looks like all non-vegetation pixels (water and sand) are coloured red. Using the 'Density Slice' option it is possible to colour a certain NDVI range. By checking the corresponding spectral profiles in the linked hyperspectral image, it is possible to decide on the optimal threshold level for vegetation/non-vegetation selection. As was already mentioned, the non-vegetation range is situated in the NDVI range between -1 and 0.12. This method for vegetation/non-vegetation selection is empirical, but is suitable for this purpose.

Answer 10.3.: Why do you think three ROIs, one for each vegetation type, with each ROI containing only one pixel is insufficient?

There is a lot of variability in the hyperspectral imagery. Pixels are not always pure, most of the time pixels are a mixture of reflectance from green leaves, soil, etc. Identical spectral signatures in the same hyperspectral image are not realistic and therefore choosing only one pixel spectrum as a reference is not advisable. The geographical positions measured during the field survey are located in a homogenous area with a diameter of at least 5 m. Choosing a ROI of 3 by 3 pixels (when the pixel resolution is 1 m x 1 m), will result in a ROI within the homogenous region. The final ROI spectrum for this particular ROI will be the average of these nine pixels, resulting in a spectrum which is more representative for this particular vegetation type. By defining several ROIs for each vegetation type, the variability between individuals within the same vegetation type will be covered.

Answer 10.4.: To which class should this pixel belong. Compare with the classified image. Is the pixel correctly classified in L1102rag10_Wh_cp_mkd_Cl?

When locating the pixel at Sample: 558 and Line: 311, the zoom window will look like the one in Figure 10.2. You can see that the requested pixel is coloured blue, which means that it is assigned to the 'shrubs' class. You can use <Tools> <Cursor Location/Value…> to check this.
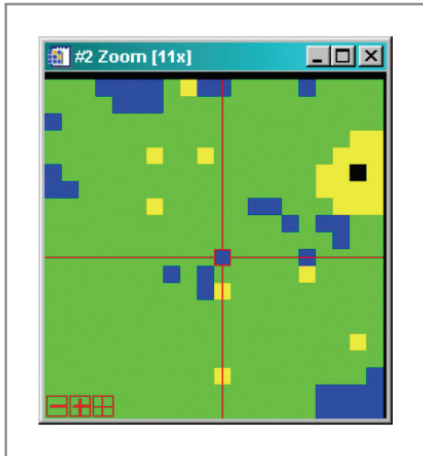
>> **Figure 10.2:The zoom window showing the pixel at location Sample:558 and Line:311.**

To find out the values of the Rule image you can load the Rule image as a RGB image, link it with the other images and display the Z profile. By left mouse click in the 'Spectral Profile' window you can find out that the lowest Rule value, i.e. 0.01457, is found in band 2 as indicated by the Figure 10.3. This means that the corresponding pixel is spectrally resembling the reference spectrum of the second ROI (band 2) and therefore is assigned to the shrub class in the classification result.
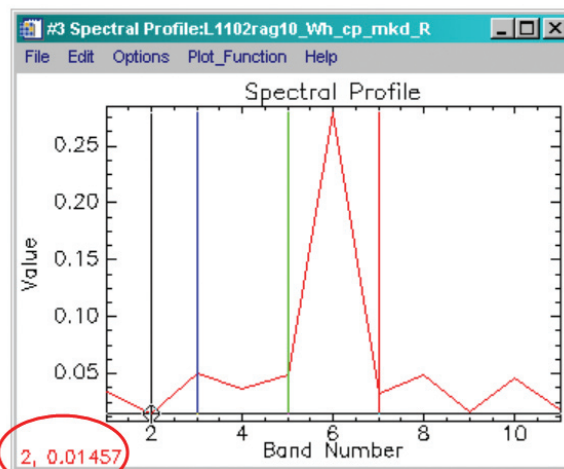
>> **Figure 10.3: The spectral profile of the calculated "Rule values" show the lowest value, 0.014, in band 2. This means the corresponding pixel will be assigned to class of band 2 which is in this case the scrub class.**

Answer 5: How many pixels in the 1st grass ROI (Ground Truth) are correctly classified?

Each ROI contains 9 pixels. In the 1st grass class, 8 pixels are classified as grass, one pixel is classified as shrub.

ACKNOWLEDGEMENTS

Aim of Lesson

Using statistical techniques to classify vegetation species with hyperspectral imagery

Objectives

1. Introduction to statistical techniques for classifying hyperspectral imagery
2. Using binary classifiers for multi-class problems
3. Reducing salt and pepper by smoothing classified images
4. Introduction to the Discrete Wavelet Transform

Background Information

This lesson relates to the Sections 9.1.2 and 9.1.4.2 of the HyperTeach Theory Syllabus. For further details about the techniques involved readers are recommended to read these sections. This lessons describes a method to classify vegetation species in the nature reserve 'De Westhoek' using AISA imagery. 'De Westhoek is located at the West coast of Belgium near the French border.

SOFTWARE

A PC with ENVI® software is required to carry out the lesson.

IMAGE DATA

The AISA image with 32 bands is used (AISA_bands.img).

A pixel based classification image is also provided (AISA_class.img) and the output of a Discrete Wavelet Transform Transformation (AISA_dwt.img). Please refer to lesson 10 for more information of the data.

Lesson outline

1. Introduction to statistical techniques for classifying hyperspectral imagery

1.1 Fundamentals

Supervised classification, as opposed to unsupervised classification focuses on pre-defined classes. The classifier can be built with a training set and later be used for classifying new objects. Supervised classification requires ground truth data, for labelling the classes, needed for training. Unsupervised classification clusters the data without prior definition of the groups. This lesson will only focus on supervised classification.

There are many methods for supervised classification. Among them, linear discriminant analysis (LDA) is very popular. Although relying on strong assumptions that are often not met in practice, this method has proven to be very useful.

- Discriminant analysis is based on an assumption of normality.
- In addition, linear discriminant analysis assumes that all the classes have the same variance.

Question 11.1: The following distributions are all normal. Where would you define a classifier and how do the distributions differ? Are the assumptions for LDA met in all figures? What can you tell about the distribution in Figure11.3 ?
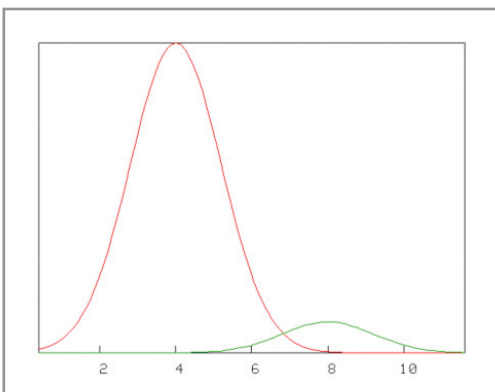How should we deal with prior knowledge about the class probabilities?
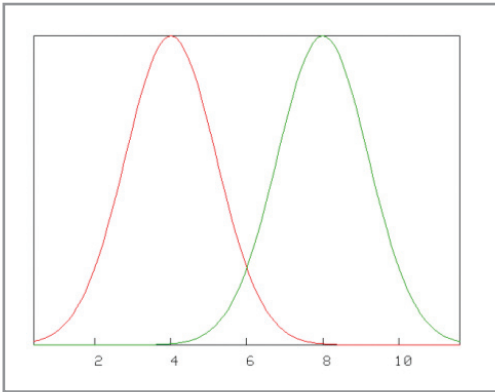
>> Figure 11.1:Class probability distribution 1 for a given output variable x.
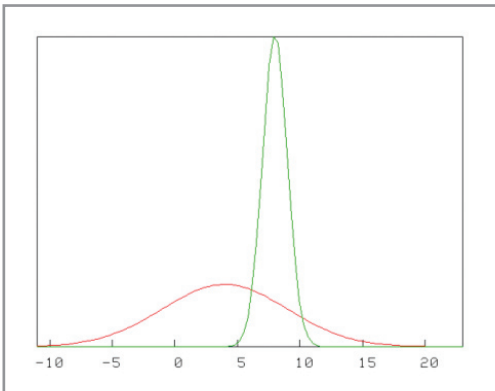
>> Figure 11.2:Class probability distribution 2 for a given output variable x

>> Figure 11.3:Class probability distribution 3 for a given output variable x

Question 11.2: The training and test set used for validation must be two different sets. Why?

Question 11.3: What is meant by over-training? Is there a relationship between the dimensionality of the variables and the number of training samples required? What does this mean for classification of hyperspectral data?

Question 11.4: Often, the available ground truth is split. Half of the data is used for training and half for validation. In case few ground truth is available, what are the options you can think of?

Linear Discriminant Analysis (LDA) uses the notion of scatter matrices[5]. Similar to covariance matrices[5], they indicate the extend to which two random variables co-vary. By definition, the covariance matrix is symmetric. Also, the covariance of any component of the random variable with itself, is that component's variance. The magnitude of a covariance between component X_j and a component X_k depends on the standard deviations of both X_j and X_k. To obtain a more direct indication on how two components co-vary, we scale covariance to obtain correlation:

$$\rho_{jk} = \frac{\text{cov}(X_j, X_k)}{\sigma_j \sigma_k},$$

where σ_j and σ_k are the standard deviations of X_j and X_k, respectively. By construction, the correlation is always between -1 and +1.

2. Using binary classifiers for multi-class problems

Fisher LDA provides a solution for both binary and multi-class problems. From the Theory Syllabus, it is clear that the projection vector is easier to compute for binary classes than for the multi-class problem. However, the multi-class problem can be solved by combining binary classifiers. Often, this method even turns out to outperform the direct multi-class solution.

Question 11.5: Suggest two methodologies to combine binary classifiers to solve the multi-class problem.

3. Reducing salt and pepper by smoothing classified images

Pixel based classification results are cursed with a noise referred to as salt and pepper. Individual pixels with label A are in contrast to homogeneous patches with label B from which they are surrounded. Not only, the effect is less "pleasing" to the end user, small isolated areas are less likely to occur in nature and tend to be misclassifications.

These artefacts can be reduced using post-classification methods. A quick and dirty method is based on a majority analysis, using a specific kernel (moving window). This method is included in the ENVI package.

Action 1: Open the classification image AISA_class.img in ENVI.
Perform a smoothing operation using the post classification method in ENVI

> **Hint**: Menu: Classification->Post Classification->Majority/Minority Analysis, with a kernel size of 3x3. Select all classes, and specify an output filename. Compare the two classification images using Tools->Link->Link Display. Click on the image and check if single pixels are reduced. The same exercise can be performed using a kernel of size 5x5.

4. Introduction to the Discrete Wavelet Transform

Action 3: Open the multi band images AISA_bands.img and AISA_dwt.img in ENVI. This image corresponds to the 32 coefficients obtained from a Discrete Wavelet Transform performed on the AISA image. The filter used is the HAAR filter. Compare the spectra of the two images, using the Z-profile build-in function.

Question 11.6: Where are the low scale coefficients located, where are the high scale coefficients located?

Question 11.7: How many bands are used for each scale?

Tip: Think about the Heisenberg uncertainty and the downscaling after each filtering operation.

Related papers

Duda, R.O., Hart P. E., and Stork D.G., Pattern Classification, 2nd, Edition. Wiley, 2001.

_____ Answers to questions _____

Answer 11.1: The following distributions are all normal. Where would you define a classifier and how do the distributions differ? Are the assumptions for LDA met in all figures? What can you tell about the distribution in Figure11.3 ?
How should we deal with prior knowledge about the class probabilities?
A classifier can be defined with its threshold for decision located at the cross section of both distributions. In the second plot, two thresholds must be defined. This distribution does not meet the assumption of equal standard deviations. All three plots have identical means. The last plot shows an example of different prior probabilities[6]
. Notice how the ideal thresholds differ in plot 11.1 and plot 11.3, though means and standard deviations are identical. Prior probabilities should be multiplied to the conditional distributions to obtain the posterior probabilities needed for classification (Bayes).

Answer 11.2: The training and test set used for validation must be two different sets. Why?

Training and test set used for validation must be two different sets, because of positive bias. No knowledge of validation data can be used during training, or the estimation of accuracy is too optimistic.

Answer 11.3: What is meant by over-training? Is there a relationship between the dimensionality of the variables and the number of training samples required? What does this mean for classification of hyperspectral data?

Overtraining occurs if a classifier lacks generalization. The classifier "knows" the training samples too well and is not able to classify an unknown sample. Complex classifiers tend to over-train. The higher the dimensionality of the variables, the more training samples are needed for a good classifier. A rule of thumb is about ten times the dimensionality, four times is a minimum. Hyperspectral data have a high dimensionality and thus require a lot of training samples if a lot of bands are retained for classification.

Answer 11.4: Often, the available ground truth is split. Half of the data is used for training and half for validation. In case few ground truth is available, what are the options you can think of?

Cross validation is a way to optimize the available training samples. A classifier is trained with a selection of the samples and validated with the remaining set (left out). In particular, "leave-one-out" is often used, where all but one samples are used for training. The validation is repeated until all samples are left out. The accuracy of the classifier is estimated as the mean of all validation results.

If not enough training samples are available, the dimensionality can be reduced via feature selection. The best performing features are retained for classification.

Some classifiers can better generalize than others. In general, a simple (linear) classifier is more capable of generalizing than a more complex (quadratic, K-nearest neighbour) classifier. Support vector machines are becoming very popular as well and are known to generalize very well.

Sometimes, the problem is just too complex and the number of classes must be reduced.

Answer 11.5: Suggest two methodologies to combine binary classifiers to solve the multi-class problem

Two common methodologies are:" one to one" and "one to all".

Answer 11.6: Where are the low scale coefficients located, where are the high scale coefficients located?

The low scales (high frequencies) are located at the high band numbers. The highest scale (DC component) is located at the first band.

Answer 11.7: How many bands are used for each scale?

1 band for DC component, 1 band for scale 5, 2 bands for scale 4, 4 bands for scale 3, 8 bands for scale 2 and 16 bands for scale 1 (highest frequency). After each filtering operation, the signal is down sampled with a factor of two.

Acknowledgements

Footnotes

[1]   For the purposes of this lesson we consider channels between 400nm and 700nm as "visible" and between 700nm and 1200nm as "near infrared". (Lesson 4, page 32)

[2]   When providing recommendations in this lesson you do not need to consider budgetary constraints either for the purchase of data or for the processing of imagery. However, in the real world such issues and related questions of software, personnel and data policy for research and for commercial usage are, of course, important. (Lesson 4, page 33)

[3]   One exception regarding the need for good spectral resolution is the case of massive surface algae blooms such as Nodularia spumigena in the Baltic, which could be seen by sensors with even a crude spectral resolution such as SPOT-5 (also AVHRR, Landsat, etc.). (Lesson 4, page 34)

[4]   True color images are generated by adding together red, green and blue colors in the image where the intensity of each is determined by the value of reflectance measured for sensor bands with red, green and blue wavelengths respectively. A true color image is therefore close to human perception of color. Quasi true color images are similar except that the sensor bands or color component intensities may be varied to give better contrast or to conform to available sensor bands. (Lesson 5, page 36)

[5]   They only differ in a scaling factor (number of samples -1) (Lesson 11, page 78)

[6]   A prior probability is knowledge about the occurrence of a the classes irrespective of the observation (such as pixel reflectance value). As an example, a prior probability can be based on the knowledge that a specific class is very rare in some region. (Lesson 11, page 79)