Objectives

1. To understand what happens with light at the air-water interface
2. To familiarize students with the WATCOR functionalities
3. To learn how to retrieve the required atmospheric input parameters for WATCOR
4. To interpret WATCOR output images

Software

Access to a PC with Excel, ENVI®/IDL and internet connection.

Data

Students will work with CASI data which were obtained on 16 June 2003 in the framework of the BELCOLOUR project (http://www.mumm.ac.be/BELCOLOUR/). The area covered in the data is Bredene-aan-Zee, Oostende, Belgium. The CASI sensor was mount in a Dornier 228 airplane. The CASI was flown at an altitude of +/- 2000m, providing a spatial resolution of 4 m. The spectral configuration of the CASI sensor was 96 spectral bands from 405 to 947 nm with a FWHM of 6 nm.

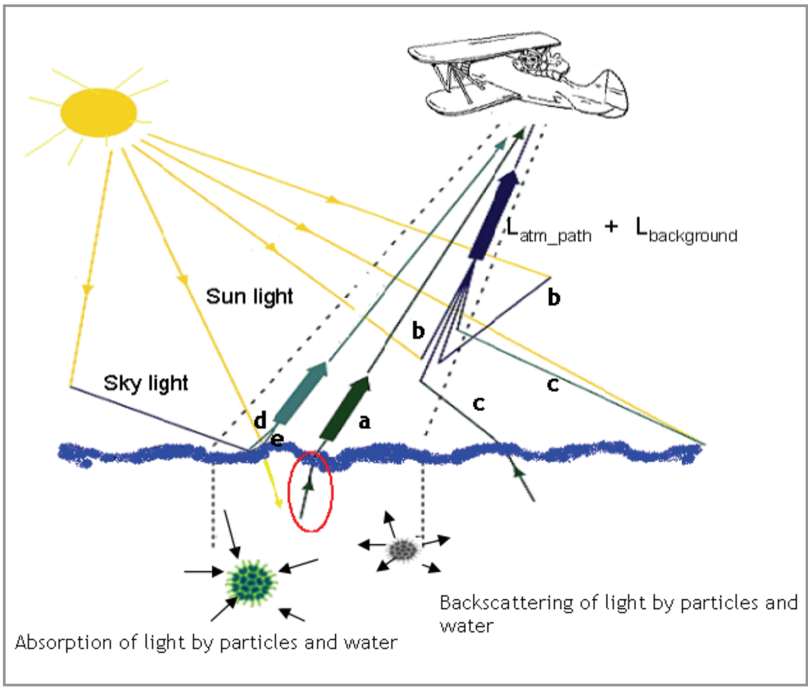
Lesson outline

Theoretical background information

To better understand the exercises, we will first review some theoretical background.

The radiance received by an airborne sensor (L_{rs}) can be composed of the following components (see also figure 12.1):

a. **Water-leaving radiance** (L_w): the light has entered the water body and scattered back up trough the water surface
b. **Atmospheric path radiance** (L_{atm_path}): radiance scattered by the atmosphere into the field-of-view of the sensor without interaction with the surface
c. **Background radiance** (L_{backgr}): radiance reflected from neighbouring pixels and scattered into the field-of-view of the sensor
d. **Surface reflected sky radiance** (L_{sky}): specular reflected sky light at the surface (i.e. sky glint). Light from the sky comes from a large area and is more or less diffuse, meaning scattered and arriving from all directions.
e. **Surface reflected sun light** (L_{sun}): specular reflected sun light at the surface (i.e. sun glint)
f. **White caps radiance** (L_{caps}): radiance diffusely reflected by white caps (not shown in figure)



>> Figure 13.1: Components contributing to the at-sensor radiance.

Only the water-leaving radiance contains useful information about the water quality since this part of the radiance has interacted with the water constituents. Therefore atmospheric correction algorithms for water bodies should not only correct for the atmospheric scattering and absorption but also for the air-water interface effects. This can be accomplished by VITO's in house software WATCOR with the exception of correction for white caps and sun glint, for which additional correction steps are required.

Refraction and **reflection** at the air-water interface must be taken into account when calculating the radiance entering or leaving the water body. Light entering or exciting a water surface is bent by refraction. Refraction of light occurs when light passes from one medium to another with a different index of refraction. The speed of the light is different in the second medium and therefore the light is bent. The index of refraction for water (n_w) is 4/3 (~1.34), implying that light travels 3/4 as fast in water as it does in vacuum. The index of refraction for air (na) can be approximated by 1.

Snell's Law or the Law of Refraction provides the relationship between angles and indices of refraction if a lightwave crosses the plane interface between, two media (e.g. air and water) :

$$n_a \sin\theta_a = n_w \sin\theta_w \qquad \textbf{(13.1)}$$

where θ_a and θ_w are respectively the incident zenith angles in air and water (see also Figure 2).

>>Figure 13.2: Refraction of incident light at the air-water interface.

At the air-water interface part of the light is reflected. Fresnel's equation determines the amount of this reflected light as a function of the angle of incidence and refractive index .

For the air-incident case the Fresnel's formula is :

$$r(\theta_a) = \frac{1}{2}\left\{\left[\frac{\sin^2(\theta_a - \theta_w)}{\sin^2(\theta_a + \theta_w)}\right] + \left[\frac{\tan^2(\theta_a - \theta_w)}{\tan^2(\theta_a + \theta_w)}\right]\right\} \qquad \textbf{(13.2)}$$

For the water-incident case the Fresnel's formula is :

$$r(\theta_w) = \frac{1}{2}\left\{\left[\frac{\sin^2(\theta_w - \theta_a)}{\sin^2(\theta_w + \theta_a)}\right] + \left[\frac{\tan^2(\theta_w - \theta a)}{\tan^2(\theta_w + \theta_a)}\right]\right\} \qquad \textbf{(13.3)}$$

r is the Fresnel reflectance and gives the fraction of the incident irradiance of a collimated beam that is reflected by the water surface.

Action: Use Excel to calculate the Fresnel reflectance function for several incident angles between 1 and 90°. Do this for both the air-incident and water incident case and display the results in a graph.

Hint: For the air-incident case:

1. Make a column with different θ_a angle in degrees
2. Make a second column with the θ_a in radian units (function radians in Excel)
3. Make a third column with the θ_w in radian units. These values can be calculated by applying Snell's Law (formula 13.1) with na =1 and nw =1.34. This gives (function as in Excel)

$$\mathrm{Arcsin}\left(\frac{\sin\theta_a}{1.34}\right) = \theta_w$$

4. Make a fourth column with θ_w in degrees (function degrees in Excel)
5. Make a fifth column with the Fresnel reflectance function r calculated according to formula 13.2.
6. Display column 1 (θ_a degrees) versus column 5 (fresnel reflectance r)

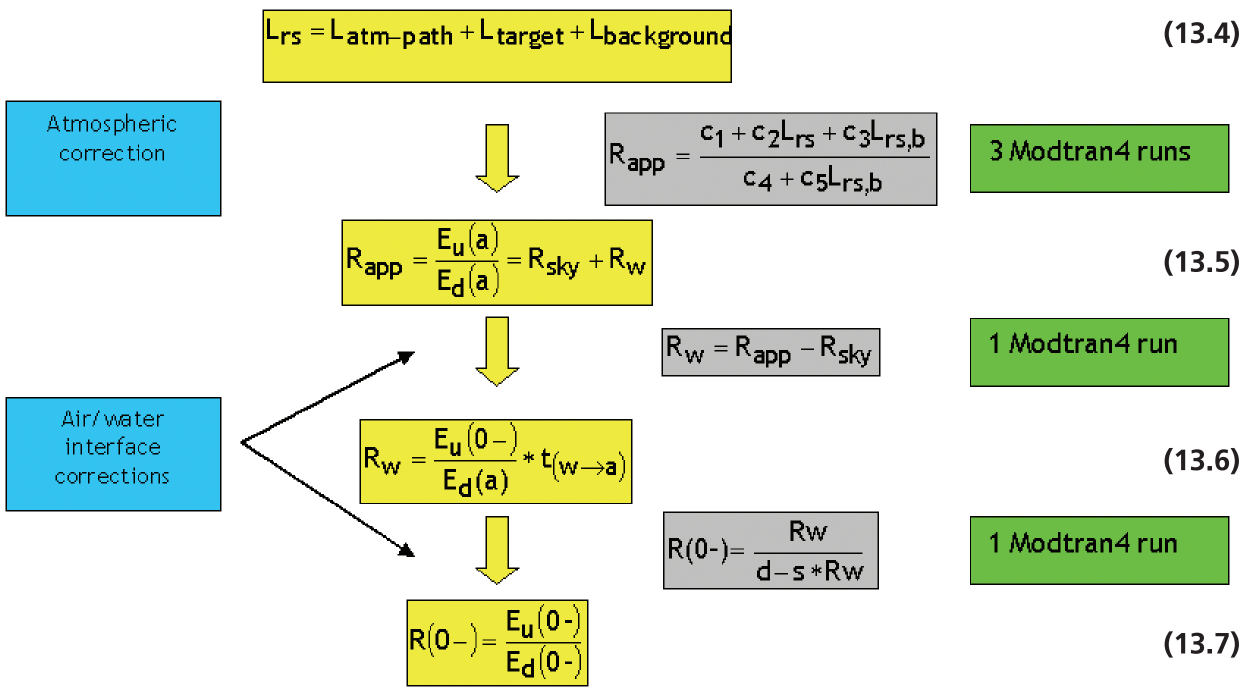
For the water-incident case:

1. Make a column with different θ_w angle in degrees
2. Make a second column with the θ_w in radians units (function radians in Excel)
3. Make a third column with the θ_a in radians units. These values can be calculated by applying Snell's Law (formula 13.1) with na =1 and nw =1.34. This gives
4. Make a fourth column with θ_a in degrees (function degrees in Excel)
5. Make a fifth column with the Fresnel reflectance function r calculated according to formula 13.3.
6. Display column 1 (θ_w degrees) versus column 5 (Fresnel reflectance r)

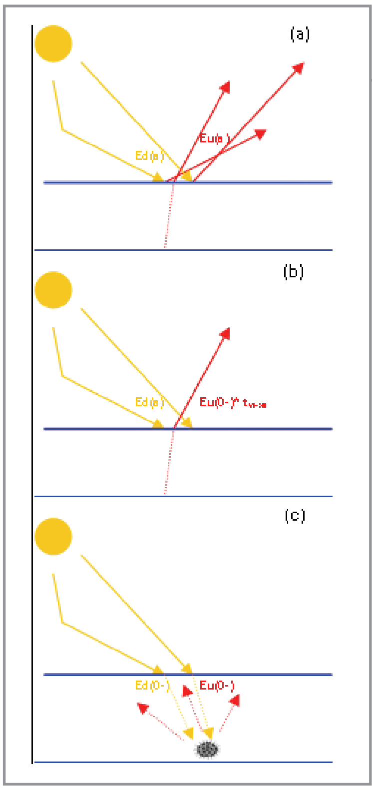
Question 13.1: What happens if the angle of incidence exceeds 48° for both the air-incident and water-incident case?

WATCOR formulas

1. WATCOR uses the radiative transfer code Modtran4 (Berk et al., 2003) and corrects in different steps (Figure 13.3). The first step is a standard atmospheric correction. The at-sensor radiance Lrs is converted to **Apparent Reflectance** (R_{app}) which is the ratio of upward $E_u(a)$ to downward $E_d(a)$ irradiance directly above the water surface (Figure 13.4a). To perform this correction three Modtran runs are required to calculate the atmospheric correction parameters (c1, c2, c3, c4, c5). R_{app} is composed of the surface reflection of sky light (R_{sky}) and the **water-leaving reflectance** (R_w).
2. The two following steps are air-water interface corrections. First R_{app} is converted to $R_{w.}$ This requires one Modtran run to calculate R_{sky}. Rw is the ratio of 'upward irradiance from beneath the water surface that has been transmitted back to the air ($E_u(0\text{-})*t_{w\text{->}a}$)' to 'downward irradiance above the surface $E_{d(}a)$' (Figure 13.4b).
3. In the last step R_w is converted to the **subsurface irradiance reflectance** R(0-) which is the ratio of upward $E_u(0\text{-})$ to downward $E_d(0\text{-})$ irradiance directly below the water surface (Figure 13.4c).



>> Figure 13.3: WATCOR processing steps.



>> Figure 13.4: Schematic representation of R_{app}, Rw and R(0-). (a)

WATCOR interface

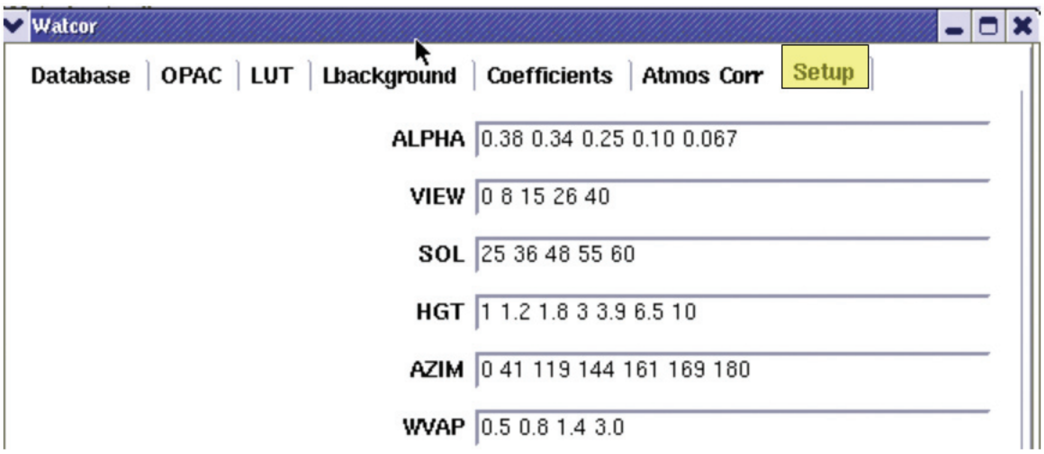
The WATCOR interface consists of several different modules (Figure 13.5):

>> Figure 13.5: The modular set-up of the WATCOR Interface.

WATCOR allows to :

Option 1. creates a large look-up table of Modtran outputs. This LUT is valid for different sensors, water vapour concentrations and sensor-sun geometries. Modtran simulations are performed for different sets of combination of the extinction coefficient (ALPHA), viewing nadir angle (VIEW), solar zenith angle (SOL), flight altitude (HGT), azimuth angle between sun and view direction (AZIM) and water vapour (WVAP). These parameters can be specified in the Setup module (Figure 13.6). Using special interpolation algorithms the correction parameters (c and d coefficients) can be calculated for one specific situation.

Option 2. creates a very small look-up table valid for only one sensor, specific sensor-sun geometries and limited amount of atmospheric conditions

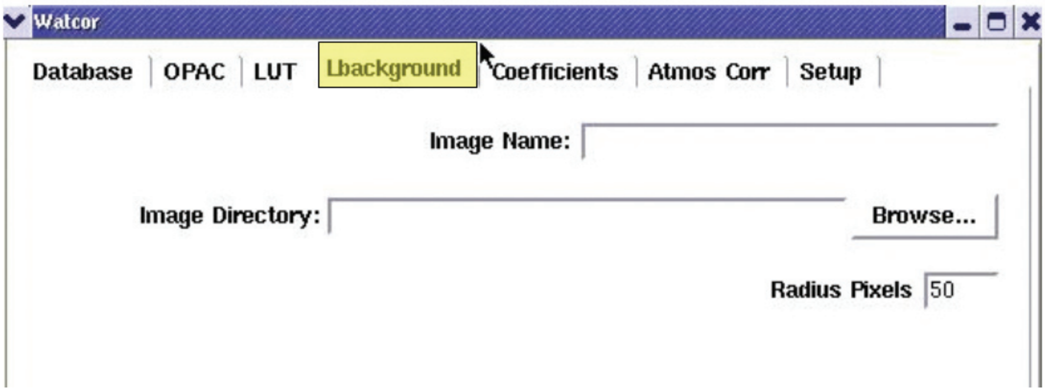


>> Figure 13.6: Setup module containing the interpolation points for all the Modtran simulations. ALPHA: extinction coefficient at 550 nm (visibility (km) = 3.912/(alpha+0.0119)); VIEW: viewing nadir angle (°); SOL: solar zenith angle (°) ; HGT: flight altitude (km) ; AZIM: azimuth angle between sun and view direction (°); WVAP: water vapour (cm).

Question 13.2: Under which circumstances would you prefer "option 1"?

Question 13.3: Can you intuitively give some disadvantages of using "option 1" compared to "option 2"?

The **Lbackground** module (Figure 13.7) calculates the average at-sensor radiance of surrounding pixels within a specified radius. The background radiance is required in the atmospheric correction to account for adjacency effects (for more information see HyperTeach Theory Syllabus Section 8.1.1).

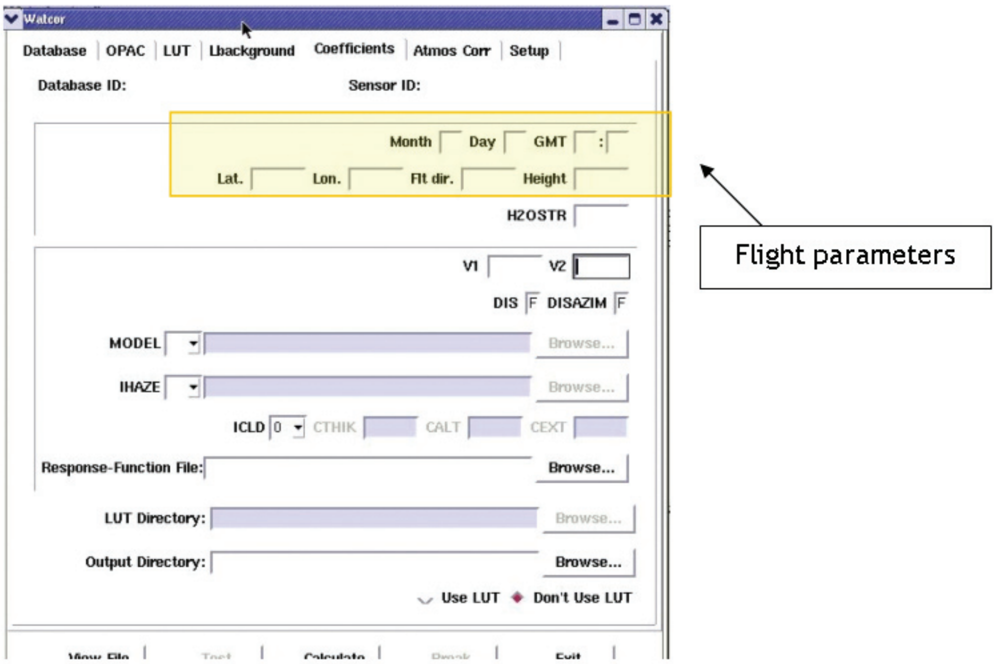


>> Figure 13.7: Lbackground module.

Question 13.4: Under which circumstances will the incorporation of the background radiance in the atmospheric correction algorithm strongly contribute to the accuracy of the final reflectance image?

Hint: For oceanic studies background radiance is often ignored.

The **Coefficients** module (Figure 13.8) calculates the c and d correction coefficients for one specific situation. There are 2 possibilities: (1) interpolation of the coefficients (option: use LUT) and (2) the coefficients are calculated directly for one specific image with defined altitude, time, location and atmospheric conditions (option: don't Use LUT).



>> Figure 13.8: Coefficients module.

Action: Explore the navigation file (navigation_CASI.nav) and specify the flight parameters (indicated in the yellow rectangle in Fig. 13.8) required in WATCOR.

Hints :
- Open the navigation file with Excel and make column averages.
- If you don't have a clue what each column represents consult the hands-outs of the presentation on Geometric correction.
- Information about the zone and datum of the coordinates can be found in the header line.
- With <ENVI> <MAP> <Map Coordinator Converter> the coordinates can be converted to Latitude, Longitude with as datum WGS84.

Retrieval of visibility for the atmospheric correction

Visibility is an important input parameter in the atmospheric correction. Different approaches exist to retrieve the visibility:

- **Airports/meteorological services**: Several airports and meteorological services report visibility and other meteorological conditions several times a day. These data can be achieved from the following websites (http://www.wunderground.com/; http://www.weeronline.nl/asiestdf.htm; http://meteo.infospace.ru/wcarch/html/index.sht)
- **Sun photometer data**: Sun photometers measure the aerosol optical depth (AOD) at different wavelengths. AOD can be converted to aerosol transmittance (T_{aer}) and compared to Modtran simulations of T_{aer} for different visibilities. At 550 nm the aerosol optical depth is independent of the aerosol type and atmospheric model and only varies with the visibility.
- **Dark target approach**: The dark target approach assumes that there is a pixel in the deeper water regions for which the water-leaving radiance is negligible in the near-infrared. Given equation 13.5 this implies that the apparent reflectance R_{app} equals R_{sky}. The visibility can be set by running WATCOR with a variety of reasonable visibility values until R_{app} equals R_{sky} in the near-infrared for the darkest pixel.

Action: Consult the http://meteo.infospace.ru/wcarch/html/index.sht website and search for the visibility reported by the nearest airport at the same day as the airborne hyperspectral campaign in Oostende.

Question 13.5: What is the visibility reported by the Oostende airport?

Students can now try to specify the visibility based on this dark target approach.

Action: In the ENVI < main menu> use the <Open Image File> option to open the at-sensor radiance image (CASI_Lsensor) and display a grey scale image of the near-infrared band 81 (860.7 nm).

Action: Locate the darkest water pixels in this band and write down the image coordinates of one dark water pixel preferably located around nadir.

> **Hint**: In the Main Image display select <tools> <color mapping> <density slice>. Select band 81 in the <Input Density Slice Band> box. The lowest radiance value in this band is 406. We will locate the Pixels with this value by giving them a special colour. Click on <clear ranges>. Under <Options> select <Add New Ranges> and specify <Range Start> and <Range End> as 406 and click on <OK>. Click on <Apply> in the <Density Slice> toolbox. Maximize the scroll image and zoom in on the lower part of the image. Try to find a red coloured pixel. In the Main Image display select <Tools> <Cursor Location Value> and move the cursor to a red pixel around nadir. Write down the pixel coordinates.

With WATCOR the following images have been prepared:

- Band81_Rapp (*.hdr): this image contains the **apparent reflectance** values at 860.7 nm for a visibility of respectively 15, 20 and 25 km
- Band81_Rsky (*.hdr): this image contains the **surface reflectance of sky light** values at 860.7 nm for a visibility of respectively 15, 20 and 25 km

Action: In the ENVI <main menu> use the <Open Image File> option to open these 2 images. Display a grey scale image of Band81_Rapp and of Band81_Rsky at 15 km in respectively window # 2 and #3.

Action: Link the windows

> **Hint** : In the Main Image display select <Tools> <Link> <Link Displays> <Ok>.

Action :Plot the Rapp and Rsky values for the 3 different visibilities for the above located darkest water pixel.

> **Hint**: In one of the Main Image displays select <Tools> <Pixel Locator>. Specify the samples and lines and click <Apply>. Next, in the Main Image displays of Band81_Rapp (#2) and of Band81_Rsky (#3) select <Tools> <Profiles> <Z-profile>.

Question 13.6: The apparent reflectance Rapp and the surface reflectance Rsky vary differently in function of the visibility. Can you try to intuitively explain this?

Question 13.7: Which is the optimal visibility based on the dark target approach?

> **Hint**: Plot the keys by selecting in the Profile Windows <Options>,<Plot Key>. Click with the left mouse button on the key in Profile window #3 and drag the key to profile window #2. Based on the dark target method using the 860 nm band the optimal visibility is where the apparent reflectance is equal to the surface reflectance.

Exploring the WATCOR results

At-sensor radiance image (CASI_Lsensor) has been corrected for atmospheric and air-water interface effects with WATCOR. Spatial/Spectral subsets of the resulting images at different levels of corrections will be explored by the students.

Action: Close all open windows. In the ENVI < main menu> use the <Open Image File> option to open and display RGB images of the following files: CASI_sub_Rapp, CASI_sub_Rsky, CASI_sub_Rw, CASI_sub_R0 in respectively window # 1 #2, #3 and #4.

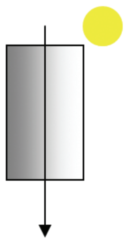
Action: Link all the windows and compare the spectra of the different correction levels by plotting the spectra in one plot window.

Hint: In the Main Image display select <Tools> <Link> <Link Displays> <Ok>. In the Main Image displays of #1,#2,#3 and #4 select <Tools> <Profiles> <Z-profile>. Plot the keys by selecting in the Profile Windows <Plot Key>.Give the spectra different colors and change the key names in 'Rapp', 'Rsky', 'Rw' and 'R0' by selecting in the Profile Windows <Edit>, <Data parameters> and change the Name. The color can be changed by clicking with the left mouse button on the square next to 'color'. Make one new plot window by selecting in one of the Profile Windows <Options>, <New Window: Blank>. Drag all the plot keys to this new plot window.

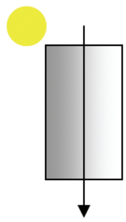
Question 13.8: Can you explain on the basis of the formulas (13.6) and (13.7) why R(0-) is normally higher than Rw?

Question 13.9: Can you, based on the CASI_sub_Rsky image, make assumptions on the flight direction in function of the sun azimuth angle. Which of the following two options is most plausible?

Option 1:



Option 2:



Hint: Take into account that sky light is specularly reflected and that the pattern of skylight polarization depends among others on the solar position.

Sun glint

Sun glint is caused by specular reflection of direct sun light off the water surface into the field-of-view of the sensor.

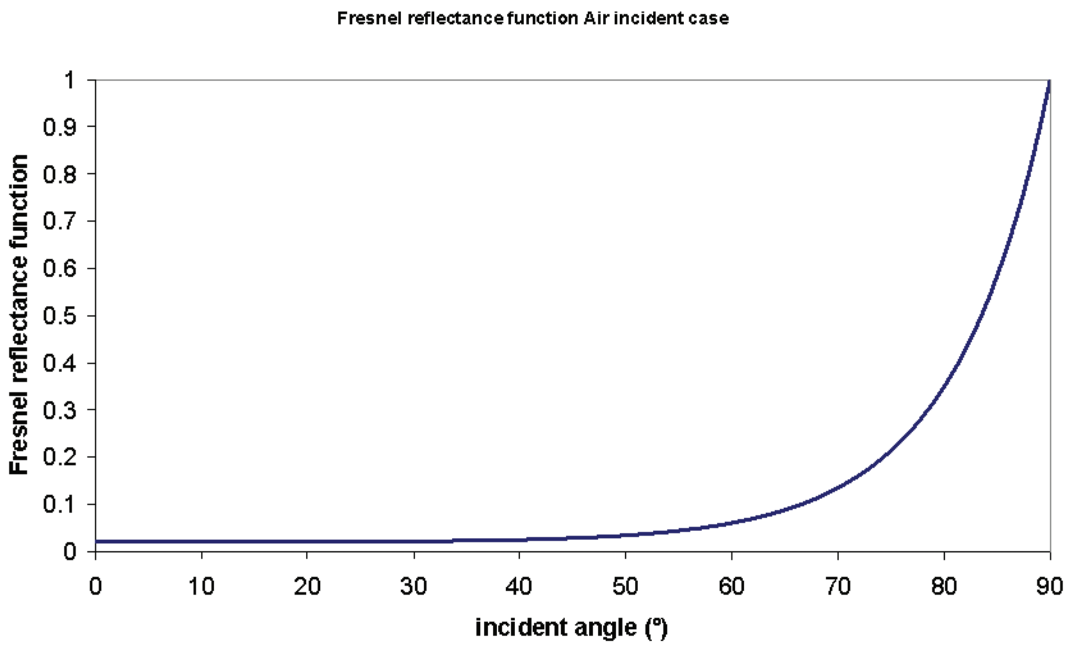
Question 13.10: Suppose you have to organize a hyperspectral airborne campaign with a sensor which has a FOV of 60° over a flat water area. How will you plan your flight lines in function of the solar zenith and azimuth angles to minimize the probability of contamination of the image by sun glint ?

Since the sea surface is rarely flat, the problem of sun glint can not always be avoided. The probability of sun glint depends not only on the solar/sensor zenith and azimuth angles but also on the wind speed and wind direction. As mentioned before WATCOR doesn't correct for sun glint effects. Additional corrections are required. These correction will be explained in detail during lesson 12.

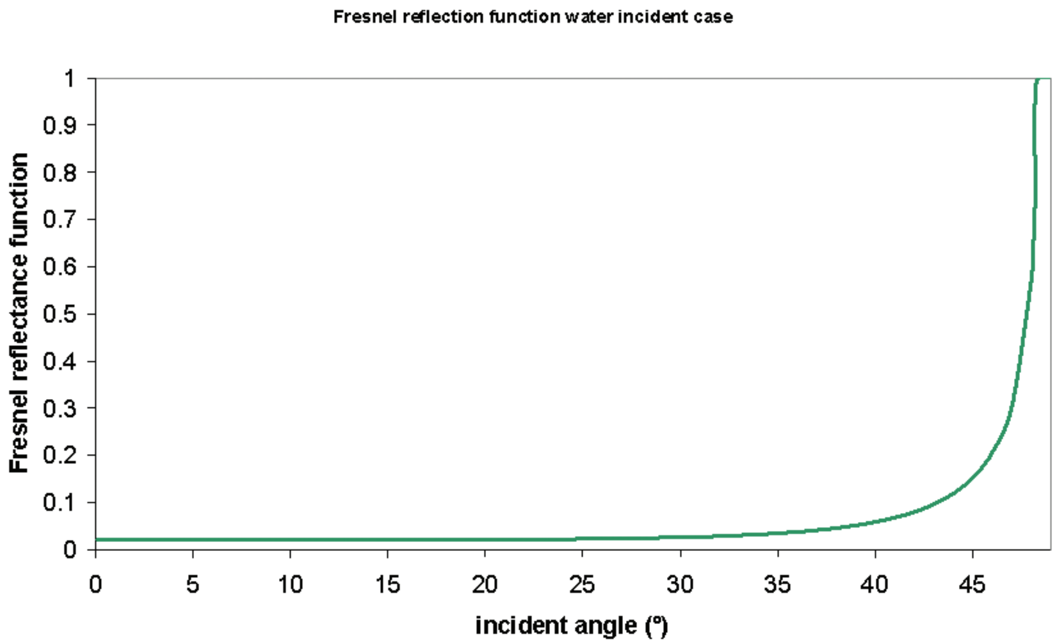
Answers to questions

Answer 13.1: What happens if the angle of incidence exceeds 48° for both the air-incident and water-incident case?

<u>Air-incident case</u>: From the graph it can be shown, that the Fresnel reflectance remains low about 2-6% for solar zenith angles ranging from 0-60 degrees and rising rapidly after it. So for most of the day, there is very little light lost due to reflectance at the air-water interface if the sea is relatively flat.



Water-incident case : As the incident angle arrives at the critical angle of 48.3 degrees from vertical, the incident rays from the subsurface illumination are completely reflected back into the water at the air-water interface and do not pass out from the water into the air.



It is therefore much easier for light to get “into the water” than it is for light to get “out of the water”.

Answer 13.2: Under which circumstances would you prefer “option 1”?

Option 1 “creation of large look-up table” is preferred when a large set of hyperspectral airborne data, acquired with different sensors and from large range of study areas, have to be corrected.

Answer 13.3: Can you intuitively give some disadvantages of using “option 1” compared to “option 2”?

Option 1 is very computationally intensive. Furthermore, the final reflectance images can contain some minor inaccuracies due to the interpolation of the correction parameters if for instance the final acquisition geometry deviates strongly from the interpolation points (e.g. flight altitude is 1.5 km, while the nearest interpolation points are 1.2 and 1.8 km.).

Answer 13.4: Under which circumstances will the incorporation of the background radiance in the atmospheric correction algorithm strongly contribute to the accuracy of the final reflectance image?

It is important to include adjacency effects (in terms of the average background radiance) for pixels near the coast or for inland waters since for those kind of water pixels the reflectance differs strongly from the surrounding non-water pixels.

Anwer 13.5: What is the visibility reported by the Oostende airport?

At GMT 12:00 the reported visibility was 20 km (see table)

16.06.2003 - Hourly observations (atmosphere)

Time local / GMT	Air temp.	Pressure @ sea level mm (hPa)	Pressure @ 5 m mm (hPa)	Rel. humid.	Dew point	Wind, m/s direction - speed (gust)	Visibility	Cloudiness	Cloud base altitude (form)	Conditions (SYNOP code)
01:00 / 00:00	+11.3°C	765 (1020)	765 (1019)	86%	+9.1°C	E (90°) - 1 (4)	15.0 km	80%	3000 m (Ci)	
07:00 / 06:00	+14.3°C	764 (1019)	764 (1018)	79%	+10.7°C	0 (2)	12.0 km	40%	1750 m (Ci)	
13:00 / 12:00	+20.1°C	763 (1018)	763 (1017)	61%	+12.3°C	N (9°) - 5 (5)	20.0 km	30%	3000 m (Ci)	
19:00 / 18:00	+20.7°C	761 (1015)	760 (1014)	53%	+10.9°C	NE (50°) - 6 (6)	20.0 km	80%	3000 m (...)	
Mean	**+16.6°C**	**763 (1018)**	**763 (1017)**	**70%**	...	**3 m/s**	...	**60%**	...	

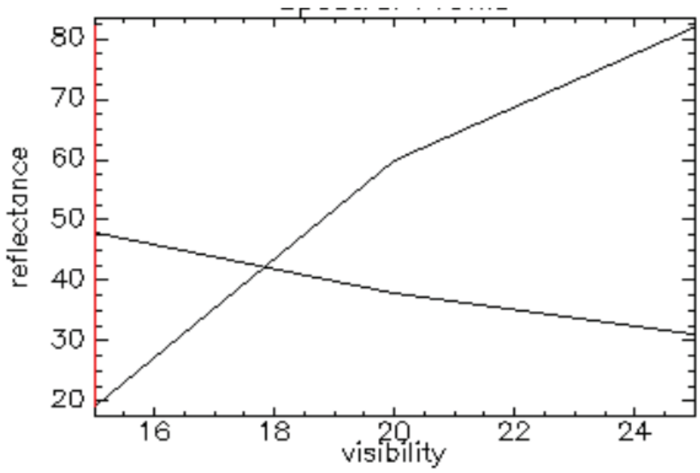
Answer 13.6: The apparent reflectance Rapp and the surface reflectance Rsky vary differently in function of the visibility. Can you try to intuitively explain this?

Rapp: In case of low reflectance targets such as water the total at-sensor radiance is mostly influenced by the path scattered radiance. When visibility increases, scattering decreases and thus Lrs decreases. Therefore in the atmospheric correction process when input visibility increases path radiance subtracted from Lrs decreases, leaving more radiance coming from the target and therefore apparent reflectance increases.

Rsky: The lower the visibility, the higher the surface reflection of the sky light. This is caused by the higher amount of diffuse light and resulting larger average zenith angles which lead, according to Fresnel's formula (13.2) to a higher Fresnel reflectance function.

Answer 13.7: Which is the optimal visibility based on the dark target approach?

Approximately 18 km (see figure)



Answer 13.8: Can you explain on the basis of the formulas (13.6) and (13.7) why R(0-) is normally higher than Rw? Normally:

$$R(0-) = \frac{E_u(0-)}{E_d(0-)} > R_W = \frac{E_u(0-) * t_{(w \to a)}}{E_d(a)}$$

since

(1) $t_{(w \to a)} \leq 1$ => the numerator of R(0-) ≥ numerator of Rw,

and

(2) normally : $E_d(a) \geq E_d(0-)$: the transmitted irradiance just below the water surface is less than the irradiance above the water surface since some of the incident irradiance is reflected by the surface* => the denominator of R(0-) ≤ denominator of Rw.

*In this statement we are considering only the contribution of made by irradiance transmitted through the surface. However, the value of contains also a contribution of the upwelling light that has been reflected back downward by the water surface ( ). In special circumstances the total can exceed .

Answer 13.9: Can you, based on the CASI_sub_Rsky image, make assumptions on the flight direction in function of the sun azimuth angle. Which of the two options is most plausible?

Option 1 is most plausible. The distribution of skylight from clear blue skies is non-uniform. In general the minimum sky light radiance appears on the anti-solar half of the hemisphere.

Answer 13.10: Suppose you have to organize a hyperspectral airborne campaign with a sensor which has a FOV of 60° over a flat water area. How will you plan your flight lines in function of the solar zenith and azimuth angles to minimize the probability of contamination of the image by sun glint?

1. flight azimuth relative to solar azimuth should be +/- 0° or 180° i.e. flying directly into or out of the solar azimuth
2. solar zenith angle should be < 30°. High solar elevation angles (e.g. at solar noon at low latitudes) can result in sun glint in the centre of the image.

References

Berk, A., Anderson, G. P., Acharya, P. K., Hoke, M. L., Chetwynd, J. H., Bernstein, L. S., Shettle, E. P., Matthew, M. W. and S.M. Adler-Golden, 2003. MODTRAN4 Version 3 Revision 1 User's Manual. Air Force Research Laboratory, Space Vehicles Directoriate, Air Force Materiel Command, Hanscom AFB, MA 01731-3010, Hanscom.