Atmospheric Correction in Polar and Subpolar regions

Evaluation and improvements of the 6S program

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Abstract

This masters thesis is a part of the nordic collaboration project NorSEN, whose goal is to improve the environmental surveillance in the regions north of the Arctic circle. This implies the build-up of a data-acquisition network that can be used for tracing environmental changes over the years. The data from these sites can also be used as a reference for satellite image validation and to improve the atmospheric correction procedures of satellite imagery. Atmospheric correction is the process where an image taken at satellite level is recreated as it would have looked like on the ground. The signal is distorted along its way through the atmosphere by the means of absorption and scattering. Sweden's contribution to this project is a raft with on board spectrometers placed on the lake Torneträsk near Abisko in the summer of 2005. Its geographical position is N 68° 21' 39", E 18° 50' 4". The lake is surrounded by mountains which are often covered with clouds that changes the light conditions. This poses a problem for the atmospheric correction since these types of situations are more difficult to model. The lake is also often exposed to rough weather with strong winds, leading to high waves. When this occurs, it is much harder to calculate the reflectance from the data. Severe rainfalls can also lead to sediments in the lake which changes the lakes reflectance. One part of the project is therefore to evaluate if Torneträsk is a good reference surface. This part will however not be covered by the report.

The masters thesis has been devoted to the evaluation and changing of the satellite signal simulation program 6S, which is also able to apply atmospheric correction to known satellite signals. Pictures from the instrument MERIS on board ESAs Earth observation satellite ENVISAT has been available within the project. Some assumptions in 6S that has proved to be a problem is that of horizontal homogeneity and the plane-parallel assumption. Since the clouds and mountains need to be modeled, an inhomogeneous model must be implemented. This can be done by introducing a horizontal x-scale which adds a parameter to all the equations governing the radiative transfer in the atmosphere. Since the x-scale can't go on forever, there must however be a combination of the homogeneous and the inhomogeneous model where the homogeneous assumption is used at the boundary layer of the inhomogeneous model. Tests have been made with a horizontal scale of 300 kilometers. The grid has to be about this wide since the atmosphere is modeled with an altitude of 150 kilometers and it is desired that as many beams as possible, they are traveling with different inclinations, reaches the top of the atmosphere. This however slows down the program significantly. The computation is therefore made with less accuracy the further you get from the lake, while an area of 10 kilometers where the raft is situated is modeled with high accuracy.

Up to date it is hard to draw any substantial conclusions about whether the changes made to 6S will lead to any significant improvement. This is because the evaluation of the program has taken so long time, leaving very little time to test the new program. However, it looks like we have made some progress.
Sammanfattning


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Chapter 1

Introduction

The recent years studies on climate change predict significant changes in the polar regions during the coming decades. The study of these environmental effects has therefore become a very important topic, since the effects will influence the climate globally. In the meantime, the means for environmental studies has been taking quantum leaps with the development of new imaging instruments for satellites. An increasing number of parameters that earlier only could be measured in situ in harsh conditions, can now be monitored with remote sensing technique from space and airborne measurements.

However both satellite and airborne instrumental data needs to be validated and calibrated to assure the correctness of the data produced. One reason is that the gases in the atmosphere absorb light in certain wavelengths. An individual photon may also be scattered several times before reaching the top of the atmosphere. This means that the image being taken from the satellite is not exactly what is being sent out from the Earths surface. This has been known for a long time and solutions to the problems has also been found. These are however almost always optimized for dense population areas, i.e. mid latitudes. They therefore need to be adapted for usage in the high north and low south where the conditions are different. Examples of parameters that could influence the measurements are sun and viewing angles and atmospheric conditions.

NorSEN is a nordic collaboration project which aims to improve the environmental surveillance north of the Arctic circle. This masters thesis has been a small part of that goal, namely to modify and improve the atmospheric correction procedure for satellite images, according to the problem description above. The project has been provided with satellite images from MERIS for comparison with spectra from the ground. Both the code and the underlying equations of an atmospheric correction program called 6S has been extensively studied and possible flaws and improvements have been examined. The project has therefore had the characteristics of an evaluation work with little time to actually implement any changes to the program.

This report will describe the NorSEN project, the satellite MERIS, the equations used in 6S to describe the radiative transfer through the Earths atmosphere and modifications made to the 6S program. Future improvements that can be made will also be discussed.
Chapter 2

NorSEN

The Nordkalotten Satellite Evaluation co-operation Network (NorSEN) is a collaboration between Sweden, Norway and Finland. The project started in April 2005 and is planned to go on until December 2007. The main objective is to improve the environmental surveillance to the north of the Arctic circle. This includes the extraction of data to make climate predictions in the Nordkalotten area more feasible.

To meet this objective, a series of satellite validation stations has been built within already existing infrastructure, so that they can be easily accessed. They are positioned in characteristic Arctic and sub-Arctic conditions. Data from different sites will be compared, so a uniform set of validation tools are used.

The project is also focused on phenological observations, which means that the annual recurrence of animal and plant life is studied. These are considered as important indicators of climate effects, this is even more obvious with plants that grow near the limit of their northern distribution. The mountain ridge between Sweden and Norway along with the influence of the Gulf stream makes the climate gradient from east to west very large, which means that the climatic patterns does not follow any national borders. This calls for international collaboration and the sharing of relevant data between the involved countries are also a big part of the project.

The Swedish contribution is focused on ground based reflectance measurements and atmospheric correction of satellite images. These activities are correlated in the manner that reflectance measurements can be used as an errata sheet for atmospheric correction, so called satellite image validation. The reflectance measurements must be made on a well chosen reference surface. It should not be able to have seasonal variations, as is the case with leaves and plants that changes color, sometimes vary rapidly. The lake Torneträsk in the north of Sweden was chosen for this purpose, since it is a clear alpine lake with few organisms and not so much suspended or dissolved particles. It is therefore likely to yield homogeneous spectral response across the lake, with exception from areas closest to the shore. The location was also well chosen since Abisko scientific research station (ANS) is situated on the lakes shoreline.
Chapter 3

The Lake Torneträsk raft

The purpose of the raft is to be a platform for the ground based measurements for satellite image validation. It is situated near the island Abiskosuolo where the weather influence is expected to have least impact, see Figure 3.1. The geographical position of the raft is N 68° 21’ 39”, E 18° 50’ 4”. It is then protected against the waves coming from the west, which is the prevailing wind for stormy weather in the area. It is desired that the raft should be in as much a stationary state as possible so it is anchored with three anchors positioned in a triangle.

The raft is equipped with at least two spectrometers, sometimes three. One is measuring the downwelling irradiance ($\frac{W}{m^2}$), denoted $E_d$. The other one is measuring the upwelling radiance ($\frac{W}{m^2sr}$), denoted $L_u$, from the water corresponding to light from an approximately 12 meter deep water column.

The radiance is measured with an angle of 30° from the ground so that the risk of sun glint is minimized. The field of view for the radiance sensor is 7°. The raft has sometimes also been equipped with a third radiance sensor looking upwards in 30° angle from the sky (denoted $L_d$). The configuration of the sensors can also be seen in Figure 3.1. The third sensor can be used for correcting the sensor looking down with respect to any sun glint that entering the sensor. The reflectance can be estimated with the formula

$$\rho(\lambda) = \frac{\pi \cdot L_u(\lambda)}{E_d(\lambda)}.$$  (3.1)

For all spectrometers, and therefore also for the reflection, $\lambda \in [350, 950]$ nm. The equipment is driven by a car battery, ranging from 12V to 24V. The spectrometers are turned on 6 hours between 7:00-13:00 UTC and yields data continuously in that period with the chosen integration time.

The upward-looking sensor also has an inclinometer used for determining the influence of waves on the spectra.

The spectrometers used are manufactured by TriOS Optical Sensors and they belong to the RAMSES-family. The measuring frequency can be set individually for each spectrometer. The raw data from the spectrometers are calibrated to physical quantities using a program from TriOS called MSDA_XE.

There is also a pressure indicator on the instruments, mainly for the usage when they are submerged under water. This will not be used in this experiment.
Figure 3.1: The Lake Torneträsk raft with the island Abiskosoulo in the background.
3.1 Conditions

The upward-looking irradiance sensor is built so that it receives light from the entire hemisphere, and the calculations for retrieving different spectra relies on that fact. However, since the raft is situated on a lake near a relative high island, this is not the case. And since the lake is situated in the north of Sweden, it has a lot of big mountains surrounding it. These factors combined together shields the light so that it doesn’t come from half a hemisphere anymore. This has to be encountered for.

The weather is also a factor to be considered. The ideal case would be a cloudless sky with no wind. This however, occurs very seldom in these parts. The lake is often surrounded with clouds giving an even more shielding effect. This should be visible in the data since less intensity reaches the ground than in a cloudless day, giving the opportunity of removing these data from the dataset. The wind itself is not a problem but the waves that follow the wind are, since the spectra is taken from different angles than wanted. These data should too be removed from the dataset. The waves also makes it difficult to download the data and charging the battery.

Another limiting fact in this experiment is the sediment and organic material in the lake. Preferably, the water should be absolutely clear, which it of course isn’t. The lake is however most of the time very clear, with exception from the beginning of the summer with wild spring rivers and in rainy days which brings lots of sediments down in the lake. To couple the amount of sediments and organic material in the lake with the reflectance measurements, sight depths are made from time to time. This is done with a so called Secchi disc. This is a tool that basically is put down in the lake until it is no longer visible, the depth is then measured. This is of course a very subjective tool and by no means perfect, but it is good enough for this purpose.
Figure 3.2: The Secchi disc used in the experiment.
Chapter 4

6S

A large part of this master thesis has been devoted to the understanding and evaluation of the atmospheric correction program called 6S (The Second Simulation of the Satellite Signal in the Solar Spectrum). The main goal of the project was to implement changes to this program so that it is better equipped to deal with the conditions of the lake Torneträsk. In order to accomplish this, all equations and written code must be fully understood.

The 6S is written by E. F. Vermote, D. Tanré, J.L. Deuze, M. Herman and J.J. Morcrette and it is an improved version of the 5S developed by the Laboratoire d’Optique Atmosphérique in 1987. The programming language is Fortran77.

The program predicts a satellite signal between 0.25 and 0.4 $\mu$m, assuming cloudless atmosphere. The code can also be used in at atmospheric correction mode, that reproduces the reflectance on the ground, given the reflectance at the satellite level. All important atmospheric parameters are calculated at ten discrete wavelengths, namely 0.40, 0.488, 0.515, 0.550, 0.633, 0.694, 0.860, 1.536, 2.25 and 3.75 $\mu$m. These wavelengths are chosen because they correspond to the atmospheric windows used in remote sensing [4]. The parameters are then interpolated to fit the wavelength of interest.

The input parameters required by the user in atmospheric correction mode are geometrical conditions, atmospheric model for gaseous components, aerosol model (type and concentration), spectral conditions and the ground reflectance. At each of these steps, the user can either select a standard model or define his own conditions. An example of an input card is showed in appendix A.1.1. The result is given in text files showing numerous calculated quantities. The result from the input card in A.1.1 is showed in appendix A.1.2. The most important parameter for this project is the “atmospherically corrected reflectance” at the end of the file.
Chapter 5

Radiative transfer in the atmosphere

Meteorological and Earth remote sensing satellites measure the radiance reflected by the Earth. In the ideal case, the received radiance is a direct result of the surface reflectance. A fraction of the incoming photons is then absorbed by the surface, whilst the rest is reflected back to space. This then carries all information necessary for categorizing the surface properties.

In the actual case, the signal received by the satellite is perturbed by the Earths atmosphere. Of the photons leaving the target, only about 80% at 0.85 \( \mu m \) and 50% at 0.45 \( \mu m \) reaches the satellites sensor [4], with the result that the target seems less reflecting. The missing photons have been lost mainly through two atmospheric processes, namely absorption and scattering.

5.1 Absorption

Photons are being absorbed in the atmosphere by aerosols and atmospheric gases, the largest absorbers are \( O_3 \), \( H_2O \), \( O_2 \), \( CO_2 \), \( CH_4 \) and \( N_2O \) [4]. The absorption by aerosols is generally small and since the molecular absorption bands are well known, satellite sensor channels can avoid them. Therefore, the atmospheric absorption does not pose a big problem for satellite imagery, except for the fact that some wavelengths in the reflectance spectra cannot be fully examined.

5.2 Scattering

Scattering is the process when an incoming photon hits an atom or molecule and is re-emitted at the same wavelength but in another direction than the incoming one. The photon can be scattered several times before it leaves the atmosphere. From the satellite view it seems that all photons originate from the target in question, when in fact some of them have been scattered along the way creating a disturbance in the measurements since they don’t carry any information about the target.
Rayleigh scattering

When light is scattered against particles smaller than the wavelength of the incoming light, it is called Rayleigh scattering. The theory therefore applies to atoms and molecules as well as small aerosols. In 1871, Lord Rayleigh showed that the scattered lights irradiance is inversely proportional to the fourth power of the incoming lights wavelength [2]. The irradiance is therefore about five times higher for blue light than for red light, explaining why the sky is blue.

Mie scattering

When the scattering particles becomes larger than a wavelength, the Mie theory applies instead of Rayleigh. It is not as wavelength dependent as Rayleigh scattering and therefore produces white light, containing about the same amount of irradiance for all wavelengths.

Aerosol scattering

Aerosol scattering can not be explained either by only Rayleigh or Mie scattering, it is rather a combination of the both. This is due to the fact that aerosols can have all different kind of shapes, sizes and structures and can not be modeled by a unified theory. They are however becoming increasingly important in the radiative transfer discussion because of the human activity that increases the amount of some kind of aerosols (due to industrial processes and traffic) in the atmosphere.

Scattering paths

There are several ways in which scattering can influence the satellite measurements. As a first step, lets consider the photons coming from the Sun and scattered by the atmosphere on their way to the surface [4]:

- Some photons are scattered directly back to space without interacting with the surface. The signal received by the satellite is a pure interference term and does not carry any information about the target.

- The remaining photons finds their way to the surface along scattered paths and compensate to the attenuation of the direct solar paths. These photons carry information about the target and must therefore be considered in the useful signal.

Photons can also be scattered when they have been reflected by the surface and are on their way toward the satellites sensor [4]:

- Photons outside the target can be scattered so that they seem to originate from the target. These signals can be useful if the target has a uniform surface. However, if the surface has a patchy structure, the term will introduce another perturbation effect.

- In the final case, a fraction of the photons reflected by the surface outside the target will be scattered back against the target creating a third component of illumination. This phenomenon is called the trapped radiation. Generally, the convergence is fast and the process can be neglected after one or two interactions.
5.3  The equation of transfer

6S uses the successive orders of scattering (SOS) method to calculate the atmospheric transmission and reflectance. The method can be described as based on the equation of transfer and this section will deal with this equation and with SOS. The equation of transfer governs the radiation field in a medium which absorbs, emits and scatters radiation. The equation contains several important atmospheric properties described below.

**Absorption coefficient**

Radiation that travels through a medium will be weakened by the interaction with the matter. If the specific intensity \( I_\nu \) \([\text{W m}^{-2} \text{sr}^{-1} \text{nm}]\), where the \( \nu \) indicates the frequency of the light, becomes \( I_\nu + dI_\nu \) after traveling through a medium of thickness \( ds \) in the direction of propagation, the change in intensity can be written as [1]:

\[
dI_\nu = -\kappa_\nu \rho I_\nu ds \tag{5.1}
\]

where \( \rho \) is the density of the absorbing material. The quantity \( \kappa_\nu \) defines the mass absorption coefficient for the radiation of frequency \( \nu \). The reduction in radiation is however not necessarily lost, it may appear in other directions as scattered radiation as will be described further on in the text.

**Phase function**

If only scattering and no absorption is present in the material, it can be characterized by a mass scattering coefficient \( \kappa_\nu \). The energy is then scattered from an element of cross section \( d\sigma \) and height \( ds \) at the rate [1]

\[
\kappa_\nu \rho ds \times I_\nu \cos \theta d\sigma d\omega \tag{5.2}
\]

in all directions. The mass of the element is [1]

\[
dm = \rho \cos \theta ds \tag{5.3}
\]

so (5.2) can also be written as

\[
\kappa_\nu I_\nu dmd\nu d\omega. \tag{5.4}
\]

It is however not a fact that the scattering is distributed equally in every direction. Therefore the angular distribution of the scattered radiation is specified with the phase function \( p(\cos \Theta) \) so that [1]

\[
\kappa_\nu I_\nu p(\cos \Theta) \frac{d\omega'}{4\pi} dmd\nu d\omega \tag{5.5}
\]

gives the rate at which energy is scattered into an element of mass \( dm \) of solid angle \( d\omega' \) and at an angle \( \Theta \) to the direction of incidence. The rate of loss of energy in all directions becomes

\[
\kappa_\nu I_\nu dm d\nu d\omega \int p(\cos \Theta) \frac{d\omega'}{4\pi}. \tag{5.6}
\]

It is clear that this agrees with (5.4) if the phase function is normalized to unity, that is if

\[
\int p(\cos \Theta) \frac{d\omega'}{4\pi} = 1. \tag{5.7}
\]
**CHAPTER 5. RADIATIVE TRANSFER IN THE ATMOSPHERE**

### Single scattering albedo

The above discussion about the phase function requires that the absorption coefficient is 0. However, eq. (5.5) still holds for the more general case of both absorption and scattering, but with the addition that \[ \int p(\cos \Theta) \frac{d\omega'}{4\pi} = \varpi_0 \leq 1. \] (5.8)

The general case therefore differs from the case of pure scattering only by the fact that the phase function is not normalized to unity. As eq. (5.8) shows, \( \varpi_0 \) represents the fraction of light lost from the incident radiation due to scattering. This term is called the single scattering albedo.

### Emission coefficient

The radiation that an element of mass \( dm \) emits in the direction confined to an element of solid angle \( d\omega \) in the frequency interval \( (\nu, \nu + d\nu) \) and in time \( dt \) is given by [1]

\[ j_{\nu}(dmd\omega d\nu dt), \] (5.9)

where \( j_{\nu} \) is called the emission coefficient. In a medium that scatters radiation, there will be a contribution to the emission coefficient from these scatterings. If there is scattering of radiation from a direction of \((\vartheta', \varphi')\), then this scattering contributes, in accordance with eq. (5.5), to radiation in the direction of \((\vartheta, \varphi)\) at the rate [1]

\[ \kappa_{\nu} d\omega d\nu d\omega p(\vartheta, \varphi; \vartheta', \varphi') I_{\nu}(\vartheta', \varphi') \frac{\sin \vartheta' d\vartheta' d\varphi'}{4\pi}, \] (5.10)

where the \( p(\vartheta, \varphi; \vartheta', \varphi') \) indicates the phase function for the angle between the directions of \((\vartheta, \varphi)\) and \((\vartheta', \varphi')\). Hence the total contribution to the emission coefficient by scattering alone is

\[ j^{(s)}_{\nu} = \kappa_{\nu} \frac{1}{4\pi} \int_0^\pi \int_0^{2\pi} p(\vartheta, \varphi; \vartheta', \varphi') I_{\nu}(\vartheta', \varphi') \frac{\sin \vartheta' d\vartheta' d\varphi'}{4\pi}. \] (5.11)

For a scattering atmosphere, that is when there is no contribution to the emission coefficient others than scattering,

\[ j_{\nu} \equiv j^{(s)}_{\nu}. \] (5.12)

### The source function

The ratio between the emission and the absorption coefficient is called the source function, \( \xi_{\nu} \). Following eq. (5.11) and (5.12), the source function for a scattering atmosphere is described by

\[ \xi_{\nu} = \frac{j_{\nu}}{\kappa_{\nu}} = \frac{1}{4\pi} \int_0^\pi \int_0^{2\pi} p(\vartheta, \varphi; \vartheta', \varphi') I_{\nu}(\vartheta', \varphi') \sin \vartheta' d\vartheta' d\varphi'. \] (5.13)
5.3. **THE EQUATION OF TRANSFER**

The equation of transfer

Consider a small cylindrical element of cross-section \(d\sigma\) and height \(ds\) in the absorbing and scattering medium. The difference in radiant energy in the frequency interval \((\nu, \nu + d\nu)\) crossing the two faces normally in time \(dt\) and confined to an element of solid angle \(d\omega\) is given by [1]

\[
\frac{dI_\nu}{ds} \, d\sigma \, d\omega \, dt. \tag{5.14}
\]

This difference in energy must the excess of emission over absorption in the frequency interval and element of solid angle be accounted for. The amount of radiation being absorbed is [1]

\[
\kappa_\nu \rho ds \times I_\nu d\nu d\sigma d\omega dt, \tag{5.15}
\]

while the radiation being emitted is [1]

\[
j_\nu \rho d\sigma ds d\nu d\omega dt. \tag{5.16}
\]

If the gains and losses are counted up while the radiation travels through the cylinder, the change in energy is

\[
\frac{dI_\nu}{ds} = -\kappa_\nu \rho I_\nu + j_\nu \rho \tag{5.17}
\]

This can be rewritten with the source function, eq. (5.13), as

\[
-\frac{dI_\nu}{\kappa_\nu \rho ds} = I_\nu - \xi_\nu. \tag{5.18}
\]

This is what is known as the equation of transfer.

**Optical thickness**

Another parameter needed for solving the equation of transfer is the optical thickness, also known as optical depth, denoted \(\tau\). It is a factor that says how much radiation is lost for a given depth of the atmosphere. \(\tau\) can be calculated between the points \(s\) and \(s'\) as [1]

\[
\tau_\nu(s, s') = \int_{s'}^{s} \kappa_\nu \rho ds. \tag{5.19}
\]

To calculate the loss of radiation, the incident radiation is multiplied with \(e^{-\tau}\). That is, the larger \(\tau\), the more radiation is lost by absorption.

In 6S, there are two different optical thicknesses and they are calculated in different ways. The molecules optical thickness is calculated using empirical data and the amount of water vapor and ozone given by the user as input. The aerosols optical thickness is also based on empirical data but it is required that the user chooses some aerosol model or define his own, based on four aerosol types; dust, soot, oceanic and water soluble. The amount of each is given in percentage. Is is also required that the user gives the total aerosol optical thickness at 500 nm, or the visibility which is a meteorological parameter that
can be used for calculating the optical thickness, as input. The importance of
the different aerosol types can be seen in Figure 5.1, which has been created
with output from 6S. The Figure shows the rescaling factor for the four types
of optical thickness as a function of the ten discrete wavelengths used in 6S
(see chapter 4 on page 9). The rescaling factor means that at the current
wavelength, the optical thickness at 550 nm given as input should be rescaled
with the current factor.

What can be seen from Figure 5.1 is that the soot and water soluble aerosols
are more important than the other two in low wavelengths, whilst the dust
and oceanic are the most important in greater wavelengths. This should be
considered an important factor when giving the aerosol concentration as input; a
wrong concentration can lead to errors in the atmospheric correction procedure.

Solution to the equation of transfer

The differential equation of (5.18) is fairly easy so solve. The solution is

\[
I_\nu(s) = I_\nu(0)e^{-\tau(s,o)} + \int_0^s \xi_\nu(s')e^{-\tau(s',o)}\kappa_\nu\rho ds',
\]

(5.20)

where \(I_\nu(s)\) is the intensity at point \(s\) and \(I_\nu(0)\) is the intensity at the starting
level, i.e. the ground or the top of the atmosphere. The physical interpretation
of eq. (5.20) is that the intensity at any point and in a given direction is a
result of the emission from all the anterior points, but reduced with the factor $e^{-\tau_{(s,s')}}$ to account for the radiation lost by absorption.

The equation of transfer for plane-parallel problems

6S deals with the commonly used assumption of plane-parallel atmospheres. It is assumed that the physical properties are invariant over a plane. This is a harmless assumption when looking at small horizontal scales. In this case it is convenient to measure the linear distances normal to the plane of stratification, the horizontal plane. If the vertical distance is denoted $z$, then the equation of transfer becomes

$$-\cos \theta \frac{dI_{\nu}(z, \theta, \varphi)}{\kappa_{\rho} dz} = I_{\nu}(z, \theta, \varphi) - \xi_{\nu}(z, \theta, \varphi),$$

(5.21)

where $\theta$ denotes the zenith angle measured from the $z$-axis ($\theta=0$ means that the radiation is coming from straight above) and $\varphi$ denotes the azimuth angle measured from a suitably chosen $x$-axis. A commonly used notation which will be used from now on is that $\cos \theta = \mu$.

The optical thickness measured from infinity down to a point $z$ (called the normal optical thickness) may be written as

$$\tau_{\nu} = \int_{z}^{\infty} \kappa_{\rho} dz.$$  \hspace{1cm} (5.22)

The equation of transfer for radiation traveling upwards ($-1 \leq \mu < 0$) can then be written as

$$\mu \frac{dI_{\nu}(\tau, \mu, \varphi)}{d\tau} = I_{\nu}(\tau, \mu, \varphi) - \xi_{\nu}(\tau, \mu, \varphi).$$  \hspace{1cm} (5.23)

This is known as the standard form of the equation of transfer for plane-parallel atmospheres. For a finite atmosphere that is bounded at two sides at $\tau = 0$ (top of atmosphere) and at $\tau = b$ ($b$ is then the optical thickness at the ground), eq. (5.20) reduces to

$$I_{\nu}(\tau, +\mu, \varphi) = I_{\nu}(b, \mu, \varphi)e^{-(b-\tau)/\mu} + \int_{\tau}^{b} \xi_{\nu}(\tau', \mu, \varphi)e^{-(\tau'-\tau)/\mu} \frac{d\tau'}{\mu}.$$  \hspace{1cm} (5.24)

and

$$I_{\nu}(\tau, -\mu, \varphi) = I_{\nu}(0, -\mu, \varphi)e^{-\tau/\mu} + \int_{0}^{\tau} \xi_{\nu}(\tau', -\mu, \varphi)e^{-(\tau-\tau')/\mu} \frac{d\tau'}{\mu},$$  \hspace{1cm} (5.25)

where ($1 \geq \mu > 0$). These equations gives respectively the upwards and the downwards transmission of radiation. The prefix ‘ in eq. (5.24) and (5.25) indicates the former scattering event.

5.3.1 Successive orders of scattering

In the following discussion, the suffix $\nu$ will be omitted, since it should by now be obvious that the intensity depends on the frequency.

The basic idea of successive orders of scattering is that the intensity is computed individually for photons scattered once, twice, three times and so forth.
The total intensity is the sum over all orders, i.e. all scattering events. Therefore, the total upwards and downwards intensities may be written as [2]

$$I(\tau, \mu, \varphi) = \sum_{n=1}^{\infty} I_n(\tau, \mu, \varphi)$$

(5.26)

and

$$I(\tau, -\mu, \varphi) = \sum_{n=1}^{\infty} I_n(\tau, -\mu, \varphi),$$

(5.27)

where $n$ denotes the order of scattering. To solve this problem, the atmosphere is stratified into a finite number of layers and the radiation is computed at these levels for the primary radiation (no scattering event), radiation scattered once, twice, three times and so on. The primary radiation is computed with the first part of equations (5.24) and (5.25), that is

$$I_0 = I(b, \mu, \varphi)e^{-(b-\tau)/\mu}$$

(5.28)

for the upward transmission and

$$I_0 = (0, -\mu, \varphi)e^{\tau/\mu}$$

(5.29)

for the downward transmission. By integrating the expressions above $\mu$ and $\varphi$, the incoming radiation to a scattering event, called $J$, can be calculated [6]:

$$J_n(\tau, \mu, \varphi) = \frac{1}{4\pi} \int_{-1}^{1} du' \int_0^{2\pi} d\varphi' \cdot p(\tau, \cos \alpha) \cdot I_{n-1}(\tau, \mu', \varphi'),$$

(5.30)

where $\cos \alpha$ describes the angle between the incoming and the outgoing radiation, such as

$$\cos \alpha = uu' + \sqrt{1-u^2}\sqrt{1-u'^2} \cos (\varphi - \varphi').$$

(5.31)

The outgoing radiation for the scattering event is computed by integrating (5.30) over $\tau$ [6]:

$$I_n(\tau, \mu, \varphi) = \int_{\tau}^{b} J_n(\tau', \mu, \varphi)e^{-(\tau'-\tau)/\mu} d\tau'$$

(5.32)

for the upwelling radiation and [6]

$$I_n(\tau, -\mu, \varphi) = \int_{0}^{\tau} J_n(\tau', -\mu, \varphi)e^{-(\tau-\tau')/\mu} d\tau'$$

(5.33)

for the downwelling radiation. These expressions then goes into equation (5.30) to calculate $J_{n+1}$ and so the radiation for the next scattering event can be calculated. This goes on until equations (5.26) and (5.27) has been fulfilled. However, since the radiation decreases for each scattering event, the serie converge and does not have to be computed for an infinity number of scattering events. It depends on atmospheric conditions and viewing geometry, but usually it only takes about 6-10 scattering events for the series to converge.
SOS in 6S

6S uses a maximum of 21 iterations for the SOS computation, together with convergence tests for breaking the loop earlier if possible to save time. Another trick being used in 6S is for the solution of the source function (eq. (5.13)). A numerical integration is performed using the decomposition in Fourier series (for $\varphi$), the Legendre polynomials and Gaussian quadrature (for $\mu$). Legendre polynomials and Gaussian quadrature is just a clever way of replacing an integral with a summation which is easier to implement in the code.

6S stratifies the atmosphere into 26 layers, this is arbitrary chosen by the authors of the program. They are chosen so that the optical thickness has a linear dependence with the layer number. The first layer is between 150 km and 13.9 km. The rest of the layers together with the optical thickness is shown in Figure 5.2. When creating this Figure, the optical thickness for aerosols at a wavelength of 550 nm was given as input in 6S as 0.5. This was just for testing the atmospheric stratification, so the scale on the x-axis doesn’t say too much about the optical thickness. The slope of the curve is however important as it shows how the optical thickness of the atmosphere decreases with altitude.

The SOS calculation is done for 25 discretized zenith angles in 6S. The final result is the summation over these angles.

To summarize: 6S has a loop over incident angles with a nestled loop over the atmospheric layers, so equations (5.32) and (5.33) is calculated for each 26 optical thickness layers at each 25 zenith angles. This is done for each scattering event until the series converge, or a maximum of 21 times.

5.4 Atmospheric correction

As mentioned, a signal recorded by a remote sensing sensor will include additional radiance derived from atmospheric scattering. This radiance has not interacted with the target and will therefore create a disturbance in the received signal. The extra radiance is of great importance to water observations, as the signal from the water is usually small compared to terrestrial objects [8]. In addition to the scattering, the atmospheric particles and gases will also influence the signal by the means of absorption. Disregarding the interaction between the ground and atmosphere, a simplified atmospheric correction formula can be written as [3]

$$T_g \cdot (\rho_t T_\downarrow T_\uparrow + \rho_a) = \rho^*, \quad (5.34)$$

where $T_g$ is the gaseous absorbance, $T_\downarrow$ and $T_\uparrow$ is the transmittance downwards and upwards, $\rho_a$ is the intrinsic reflectance of the atmosphere, $\rho_t$ is the targets reflectance and $\rho^*$ is the apparent reflectance seen by the satellite. All the scattering effects can be modeled by a radiative transfer model, such as the successive orders of scattering method, to yield $T_\downarrow$, $T_\uparrow$ and $\rho_a$. The gaseous absorbance must be known or calculated from some standard model knowing the concentration of some important atmospheric absorbers (see chapter 5.1).

Atmospheric correction is then the, at least in a mathematical sense, simple solving for $\rho_t$ in (5.34) for each wavelength. The result is that

$$\rho_t = \frac{\rho^* - T_g \rho_a}{T_g T_\downarrow T_\uparrow}, \quad (5.35)$$
All satellite imagery suppliers implement this or a similar code on the satellite products. However, they use some standard atmospheric model and other assumptions that may or may not be applicable for the area of interest. One part of this project, and the main focus of this report, was to implement changes in the 6S-program for usage on non-atmospheric corrected satellite data and see if the final result was any better than the satellite's own atmospheric correction model.

5.5 Radiative transfer modeling in 6S

Rayleigh scattering has been extensively studied throughout the years and the values of the three atmospheric functions reflectance ($\rho$), transmission ($T$) and spherical albedo ($S$) has been tabulated by Chandrasekhar among others [5]. However, these tables are not so convenient to implement in the program, instead analytical expressions giving a sufficient accuracy have been used.

The aerosols atmospheric functions are calculated with the SOS approximation which gives a very accurate result. The accuracy of the aerosol+Rayleigh system in 6S is better than a few $1 \cdot 10^{-4}$ reflectance units, according to Vermote et al. 1997.
Chapter 6

MERIS

The spectra from the raft and from 6S will be compared to satellite images from MERIS (MEdium Resolution Imaging Spectrometer). Pictures from the 29th of August and the 17th and 23rd of September 2005 are available. Of these, only the one from August has the right conditions. There are too many clouds in the other pictures.

The instrument is positioned on ESA's observation satellite ENVISAT. The satellite is equipped with ten instruments and the focus of the mission is on global surveillance of the Earth's environment. It was launched on the 1st of March 2002 in an orbit of 800 km [7].

MERIS is a programmable, medium-spatial resolution, imaging spectrometer that operates in 16 wavelength bands in the solar reflective spectral range. 15 of the bands are selected for transmission to the ground.

The MERIS data is available at three different levels of processing, level 0, level 1 and level 2 and at three different spatial resolutions, full (FR) with a resolution at about 300 meters per pixel, reduced (RR) with 1200 meters per pixel and low (LR) with about 4300 meters per pixel. Level 0 is raw data, level 1 is calibrated radiance at the satellite level and level 2 is calibrated and atmospherically corrected reflectance at ground level. The level 2 data has also been processed with some spectral recognition technique that enhances borders on the picture, i.e. cloud and shore borders etc. Both level 1 and level 2 is of interest to this project. We want to atmospherically correct the level 1 data so that it corresponds to the data from the raft in a better way than the level 2 data does. So the atmospherically corrected level 1 data should be compared to the level 2 data and the reflectance given by our spectrometers.

The difference between the two levels of processing can be seen in Figure 6.1 on page 22. As seen in the pictures, the coastal line of Norway and the borders of the clouds is more obvious in the level 2 data than in the level 1 data. One problem is that you lose some data where the processing procedure can’t decide exactly what the satellite is looking at. This can be seen on the shorelines of lake Torneträsk and where there only is a thin cloud coverage. In these areas, some pixels has been turned black, i.e. a pixel value of 0. Figure 6.2 shows a zoom in of the lake in the level 2 data, where the clouds surrounding it can be clearly seen.
Figure 6.1: The Figure shows the MERIS pictures used in the project, taken on the 29th of August 2005. Plot 1 (to the left) shows 1st level data and plot 2 (to the right) shows 2nd level data. The lake Torneträsk is shown with a red circle around it. South is to the left in the pictures.
6.1 Comparison between MERIS and 6S data

For the purpose of comparing the spectra from MERIS with spectra from 6S and from the raft, the reduced resolution (RR) should be accurate enough. The lake Tornetrask is about 10 kilometers wide at the place where the raft is situated. However, since the raft is close to the shore and to an island, this pixel can not be chosen for comparison with MERIS. It is then a risk that the MERIS pixel contains some information about the land and not only the water reflectance. Therefore, a pixel in the middle of the lake is chosen, and the assumption that the reflectance is the same all over the lake has to be made. Figure 6.3 shows a first comparison between the atmospheric correction of MERIS and 6S. The difference between the two can clearly be seen and is probably due to the fact that 6S is not built for the conditions concerning lake Tornetrask, described in chapter 3.1. This will be further discussed in chapter 7. The two spectra is also shown with the original level 1 data of MERIS, which is about a factor 10 smaller than the atmospherically corrected due to the different atmospheric absorption and scattering processes.

What can also be seen from Figure 6.3 is that the atmospheric correction procedures of both MERIS and 6S has made the reflectance stronger in shorter wavelengths, under about 650 nm, and less obvious in the longer wavelengths. This is due to the different absorbing and scattering mechanisms in the atmosphere that influence the radiation differently in various wavelength regions.

The data used when creating Figure 6.3 is shown in appendix B.1 and B.2, where the radiance and the reflectance is given. The reflectance in the level 2 data is however seemingly small, in fact it is to small to be a realistic value. An educated guess is therefore that the reflectance has not yet been corrected for the bandwidth. This means that all the reflectance measurements in the data should be multiplied with the bandwidth, which is also given in the MERIS output.

In the level 2 data, you can also get useful information about the aerosols
optical thickness and the amount of water vapor and ozone in the atmosphere. This information is used as input to 6S, as showed in the input card in appendix A.1.1. The level 1 data is only given as radiance, and must therefore be converted into reflectance. This is done with the general formula [4]

\[ \rho = \frac{\pi \cdot L}{E_s \cdot \cos(\theta_s)} \]  

(6.1)

where \( \rho \) is the dimensionless reflectance, \( L \) is the measured radiance, \( E_s \) is the solar flux at the top of the atmosphere and \( \cos(\theta_s) \) is the angle towards the sun. The solar flux used when calculating the reflectance is given by 6S as shown in appendix A.2.2.
Chapter 7

Limitations in 6S

6S has a number of limitations or flaws that may be harmless in some conditions, but severe in others. This chapter will deal with some of these that has been discovered during this project.

7.1 Homogeneous assumption

6S assumes that the atmosphere looks the same in all horizontal directions, meaning that the phase function is constant when varying $\varphi \in [0, 2\pi]$. Therefore, only the zenith angle $\theta$ is modeled. It is also assumed that the phase function is constant over optical thickness. The equation for $J_n$, see (5.30), is in these cases reduced to

$$J_n(\mu, \tau) = \frac{1}{4\pi} \int_{-1}^{1} p(\cos \alpha) I_{n-1}(\mu', \tau) d\mu'$$

(7.1)

and the equations for $I_n$, (5.32) and (5.33), are reduced to

$$I_n(\tau, \mu) = \int_{\tau}^{b} J_n(\tau', \mu) e^{-((\tau'-\tau)/\mu)} d\tau'$$

(7.2)

for the upwelling and

$$I_n(\tau, -\mu) = \int_{0}^{\tau} J_n(\tau', -\mu) e^{-((\tau-\tau')/\mu)} d\tau'$$

(7.3)

for the downwelling radiation.

These assumptions are quite harmless and not far from the reality. But in addition, the $\mu$ angle is only calculated from 0 to 90 degrees, which means that only half the sky is being covered and that there is no way of separating two halves from each other. This is later on adjusted as the result is multiplied by 2. The homogeneous assumption would be harmless if the target were in the middle of the ocean and in a cloudless atmosphere, since the sky would then look the same in all directions. This assumption can however not be made if you want to model clouds and mountains.
7.2 Low target reflectance

By looking at eq. (5.35) it is clear that the apparent reflectance must be greater than the inner reflectance of the atmosphere times the gaseous absorption for the result to be positive. A negative result has no physical meaning and therefore is of no interest. Clear water has a very low reflectance, only about 0.045 of the blue light is reflected, therefore the apparent reflectance seen by the satellite is also low. In these cases it is important that both the gaseous absorption and the atmospheric reflectance is calculated correctly or else a negative result may appear. This has indeed happened when MERIS bands 1 and 2 from a pixel in the Lake Torneträsk has been atmospherically corrected in 6S with an aerosol optical thickness of 0.5. This is a possible flaw in 6S, the importance of the error however decreases as the wavelength and the received radiance increases.

A recommendation is that atmospheric correction should not be considered when $\rho_a < 10\rho_t$, where $\rho_a$ is the atmospheric inner reflectance and $\rho_t$ is the target reflectance. This is unless $\rho_a$ is very exactly modeled, which is not the case in 6S.

7.3 Plane parallel assumption

6S uses a plane parallel assumption, which in practice means that all lines are straight. The curvature of the Earth and the curved paths of light are disregarded. However, the further up north (or south) you go, the lower the sun angles are and the light paths from the Sun becomes more and more curved. Lake Torneträsk is situated north of the Polar circle, and in this case it is not obvious that the plane parallel assumption can be used.
Chapter 8

Modifications to 6S

Besides the pure evaluation work about 6S, time has also been spent trying to modify 6S so that it is better equipped to deal with the conditions surrounding the Lake Torneträsk. This chapter will describe how the modifications have been implemented in the code.

8.1 Inhomogeneous model

As mentioned, the Lake Torneträsk is surrounded by mountains that changes the light conditions. In addition, the lake is almost always surrounded by clouds that contributes to the atmospheric inner reflectance, see Figure 8.1. These can not be considered in the original version of the 6S and an inhomogeneous model must therefore be implemented.

Figure 8.1: The lake Torneträsk is surrounded by mountains which almost always are covered with clouds. This calls for the implementation of an inhomogeneous model. 't' stands for target.
8.1.1 Introducing the horizontal parameter $x$

Equations (7.1)-(7.3) must be modified in 6S in order to model contributions from part of the scene, such as the mountains and clouds surrounding the lake Torneträsk. If $x$ denotes the horizontal distance and we want to model a cloud with a disturbance $D$ between $x_1$ and $x_2$ at some level $\tau$, we should at that level implement the perturbation

$$I_0(\mu, \tau) + D(x), \quad x_1 < x < x_2$$

and leave $I_0(\mu, \tau)$ as it is otherwise. This should just slightly change the performed calculations in 6S. However, $J_n(\mu, \tau, x)$ instead of $J_n(\mu, \tau)$ needs to be saved from each iteration and we have to loop and summarize over all $x$-levels, this of course also goes for $I_n$. The final result should then be divided with the total number of $x$-levels so that we get a mean value of the radiation.

The horizontal scale can’t go on for ever so at some point the boundary conditions must be considered. A solution to this problem is to use the inhomogeneous model within the area of interest, and use the homogeneous model at the boundary conditions. This is done in practice by saving the $J$-value from the homogeneous for each $\tau$-level for all beam inclinations and for all orders of scattering. This can then be used to initiate beams with the current inclination from the boundary at the discretized $\tau$-levels for the current order of scattering. This is shown in Figure 8.2 for a zenith angle of approximately $40^\circ$. In reality, there are 26 layers instead of the 6 used in picture, there will also be far more $x$ levels and beams traveling at 25 different zenith angles (chosen by the authors of 6S) both from the right and from the left and both upwards and downwards.

The anomaly that occurs when the beams of Figure 8.2 reaches the boundary must also been taken into account. In reality, these beams would of course continue upwards causing more scattering events. We have however chosen to disregard the beams that travel outside the grid, since they should not make a noticeable contribution for the satellite.

8.1.2 Grid

The fact that the beams traveling outside the grid is being disregarded requires that the grid is wide enough to handle all the beams traveling through it. The height of the atmosphere in 6S is 150 km so the grid should be at least wider than this for as much beams as possible to reach the top. Another question is how densely the $x$-levels should be positioned. As seen in Figure 5.2 the atmospheric layers close to the ground lies close together, the first is at an altitude of only about 100 meters. The $x$-levels should be of about the same scale for an accurate approximation. The closer they are, the more accurate the model is. However, since each new $x$-level requires additional calculation time for the program, a compromise between the calculation time and the accuracy of the approximation has to be made. One solution is that the calculation is accurately estimated calculated over the interesting area, i.e. over the raft, and less accurate otherwise. This has shown to be a satisfying way of solving the problem. The distance (in km) between the $x$-levels is then calculated with the
equations:

\[ \exp \left( \frac{8(x_1 - x)}{x_{nr}} \right) \cdot \frac{1}{10}, \quad 0 < x < x_1 \]  \hspace{1cm} (8.2)

\[ \frac{1}{10}, \quad x_1 < x < x_2 \]  \hspace{1cm} (8.3)

and

\[ \exp \left( \frac{8(x - x_2)}{x_{nr}} \right) \cdot \frac{1}{10}, \quad x_2 < x < x_{nr} \]  \hspace{1cm} (8.4)

where \( x_1 \) and \( x_2 \) are limits at where the calculation should be more accurate and \( x_{nr} \) is the number of x-levels chosen. \( x_1 \) and \( x_2 \) has been chosen so that the interesting area covers 10 kilometers in the middle of the grid where the raft is positioned. 10 kilometers is about the width of the lake. When going away from this area, the distance between the x-levels increases with the exponential function above, where the number 8 is arbitrary chosen. This procedure, with \( x_{nr} = 500 \), results in a grid like the one in Figure 8.3.
Figure 8.3: The grid produced when using equations (8.2)-(8.4), $x_1 = 200$, $x_2 = 300$ and $x_{nr} = 500$. 
8.2 Modeling clouds in 6S

Now that 6S is equipped with an inhomogeneous model, we can try to model clouds. As a first step, the clouds will just be modeled as an additional radiation at the ground level. When looking from a satellite’s viewpoint that fact should be true, since the water in the lake looks dark and the clouds surrounding it looks bright. This is as much as the time frame for this masters thesis work allows, the more realistic modeling of the clouds and mountains will be done later on.

The additional radiation of the clouds has been accomplished by multiplying the outgoing radiation with 5 around the lake. This means that all the beams in the grid (see Figure 8.3) traveling from an area where \( x < 140 \) km and \( x > 160 \) km will be multiplied. This is of course a very rough estimate, but it should give some pointers if we are heading in the right direction. The result can be seen in Figure 8.4 along with the MERIS level 2 data and the result from the original version of 6S. As can be seen from the figure, the spectrum from the new version at least looks more like the one from MERIS level 2, which should mean that we have done something right. However, it can’t be said that MERIS level 2 data holds the correct answer, since the satellite too uses some atmospheric correction procedure. In fact, it is this procedure that we want to improve. But since we haven’t done so much progress yet, the atmospheric correction procedure of MERIS is probably better than ours. The real errata sheet should however come from the spectrometers on the raft, since they are

![Graph](image)

Figure 8.4: Spectra from MERIS level 2 along with spectra from MERIS level 1 atmospherically corrected with the old and the new version of 6S.
the only ones that sees the spectra as it really is, without any distortion. This should be further discussed in the next chapter.
Chapter 9

Reflectance from the raft

Taking spectra from the raft has not been proven to be problem free. As mentioned in the beginning of the report, the conditions on the lake Torneträsk has caused some difficulties in extracting the reflection of the lake. Waves, sunglint, particle flows in the water and shades from clouds and mountains are examples of parameters that must be considered when looking at the data. This is something that my co-worker in this project, Frida Holmberg, has been working on [9]. These parameters makes it quite difficult to extract a general spectrum from a general day, since pretty much all spectras look different from each other. There were sediment flows near the rafts position the day where we’ve got the best MERIS pictures, so these data doesn’t give a representative picture of the common situation. The sediment flows were most visible near the shorelines, which means that they shouldn’t pose any problem for the MERIS pictures that were taken in the middle of the lake. However, no depth sights measurements are available from this date, so we can’t be sure of this fact. Figure 9.1 shows the reflectance spectra from the raft on that day, while Figure 9.2 shows the spectra from a day with similar conditions, but without the sediments. The spectra from MERIS and from 6S (see Figure 8.4) seems to be a combination of these two. This can also be expected since it is possible that there were some sediments even in the middle of the lake, but not as much as by the shorelines.
Figure 9.1: Reflectance from the spectrometers on the raft, taken on 20050829. Each curve represents separate measurements. Measurements are taken with one minute intervals.
Figure 9.2: Reflectance from the spectrometers on the raft, taken on 20050915. Each curve represents separate measurement. Measurements are taken with one minute intervals.
Chapter 10

Conclusions and outlook

This master thesis work lays the foundation for all work to come regarding atmospheric correction in this project. However, the time frame has not allowed all the improvements to the 6S necessary to be made. The clouds should of course be on a higher level than the ground, but then the interaction between the clouds and the ground has to be taken into account. This is the reason why it has not already been made, it is not a trivial implementation. Regarding the clouds, we have also made a very rough estimate about the additional radiation. This has to be studied further for a more correct model. In addition, the clouds are not perfectly white, so the spectral dependence has to be taken into account. When the clouds are in the right altitude, we should also model the mountains underneath them. This requires good knowledge about the topography of the area.

The plane parallel assumption has also been mentioned in the report, but there was no time to adjust this in 6S. The curvature of the Earth however poses another problem. When the grid is as wide as it is with 500 x-levels, it can not be taken for granted that the Earth’s surface can be modeled as flat. In fact, at the end of the x-scale, there is a difference of 7 kilometers in altitude between the curved Earth and the flat model. The optical thickness has a very steep slope in the first kilometers of the atmosphere so this is something that has to be studied further. Regarding the optical thickness, it is to this date assumed that it is constant over the grid, but this is not the case in the reality. Inside the clouds, there are more aerosols than outside, so we should also have a higher optical thickness inside. That also goes for the composition of the different types of aerosols. During this project, there has not been any available data regarding the composition. This is a necessary input to 6S, and we have therefore been forced to make a educational guess about the composition. It is desired that these kinds of data should be available in the future.

The low resolution of the satellite pictures also poses a problem. As it is now, we must assume that the reflectance is the same at the position of the raft as it is in the middle of the lake where the satellite image is taken. A more highly resolved image would solve this problem. Then we could also make some more accurate comparisons between the reflectance given by 6S and by the spectrometers on the raft. To do these comparisons, we should also have
more satellite images. The only useful satellite image we have now is from day when the conditions in the lake made the measurements unreliable.

The fact that the project is not finished yet makes it difficult to draw any substantial conclusions. What can be said is that the 6S uses a lot of assumptions which limits its usage. This is something that this masters thesis work has begun taking care of, but more needs to be done in the future. Figure 8.4 at least shows that we are heading in the right direction.
Appendix A

6S files

A.1 Original program

A.1.1 Input card

0 (USER'S CONDITIONS, FOLLOWS ON NEXT LINE(S))
59.52 168.68 5.71 113.31 8 29
8 (USER DEFINED IDATM)
1.26 0.2943 (\(uH2O, uO3\))
4 (AEROSOLS MODEL)
0.1 0.5 0.35 0.05 (% of DUST-LIKE, WATER-SOL., OCEANIC, SOOT)
0 (NEXT VALUE IS THE AER. OPT. THICK \(\Phi550\))
0.05 (AEROSOL OPTICAL THICKNESS \(\Phi550\))
-0.341 (TARGET AT 341 m)
-1000 (MEASUREMENT FROM SATELLITE)
0 (USER DEFINED WAVELENGTH)
0.4075 0.4175 (WAVELENGTH BAND)
1 (GROUND TYPE, I.E. NON UNIFORME SURFACE)
2 1 0.50 (TARGET, ENV., RADIUS (KM))
-0.1623 (APPARENT REFLECTANCE ON MERIS BAND 1)
A.1.2 Result

******************************************************************************

geometrical conditions identity
-------------------------------
user defined conditions
-------------------
month: 8 day: 29
solar zenith angle: 59.52 deg solar azimuthal angle: 168.68 deg
view zenith angle: 5.71 deg view azimuthal angle: 113.31 deg
scattering angle: 123.60 deg azimuthal angle difference: 55.37 deg

atmospheric model description
-----------------------------
atmospheric model identity:
user defined water content: uh2o = 1.260 g/cm2
user defined ozone content: uo3 = 0.294 cm-atm

aerosols type identity:
user defined aerosols model
  0.100 % of dust-like
  0.500 % of water-soluble
  0.350 % of oceanic
  0.050 % of soot

optical condition identity:
visibility: 151.58 km opt. thick. 550nm: 0.0500

spectral condition
------------------
constant
value of filter function:
wl inf = 0.407 mic  wl sup = 0.417 mic

target type
-----------
inhomogeneous ground, radius of target: 0.500 km

environmental reflectance:
spectral clear water reflectance: 0.041
spectral vegetation ground reflectance: 0.063

target elevation description
-------------------------------
ground pressure [mb]: 972.44
ground altitude [km]: 0.341
gaseous content at target level:
  uh2o = 1.260 g/cm2  uo3 = 0.294 cm-atm

atmospheric correction activated
--------------------------------
input apparent reflectance: 0.162

******************************************************************************

integrated values of:
apparent reflectance 0.1758  appar. rad. (w/m2/sr/mic) 48.334
total gaseous transmittance 1.000

 coupling aerosol -wv :
 wv above aerosol : 0.176  wv mixed with aerosol : 0.176
 wv under aerosol : 0.176

 int. normalized values of :
 % of irradiance at ground level
 % of direct irr.  % of diffuse irr.  % of enviro. irr
 0.647 0.341 0.012
 reflectance at satellite level
 atm. intrin. ref.  environment ref.  target reflectance
 0.148 0.007 0.021

 int. absolute values of
 irr. at ground level (w/m2/mic)
 direct solar irr.  atm. diffuse irr.  environment irr
 413.647 217.878 7.985
 rad at satel. level (w/m2/sr/mic)
 atm. intrin. rad.  environment rad.  target radiance
 40.696 1.904 5.734

 int. funct filter (in mic)  int. sol. spect (in w/m2)
 0.0100000 17.031

 integrated values of :
 downward  upward  total
 global gas. trans. : 1.00000 1.00000 1.00000
 water "  " : 1.00000 1.00000 1.00000
 ozone "  " : 1.00000 1.00000 1.00000
 co2  "  " : 1.00000 1.00000 1.00000
 oxyg  "  " : 1.00000 1.00000 1.00000
 no2  "  " : 1.00000 1.00000 1.00000
 ch4  "  " : 1.00000 1.00000 1.00000
 co  "  " : 1.00000 1.00000 1.00000
 rayl. sca. trans. : 0.76449 0.86273 0.65955
 aeros. sca. "  " : 0.95601 0.98304 0.93980
 total sca. "  " : 0.73104 0.84542 0.61804

 rayleigh  aerosols  total
### APPENDIX A. 6S FILES

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<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
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<td>Spherical albedo</td>
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<td>0.02330</td>
<td>0.21148</td>
</tr>
<tr>
<td>Optical depth total</td>
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<td>0.06821</td>
<td>0.37363</td>
</tr>
<tr>
<td>Optical depth plane</td>
<td>0.30542</td>
<td>0.06821</td>
<td>0.37363</td>
</tr>
<tr>
<td>Reflectance</td>
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<td>0.00557</td>
<td>0.14800</td>
</tr>
<tr>
<td>Phase function</td>
<td>0.98056</td>
<td>0.17846</td>
<td>0.83413</td>
</tr>
<tr>
<td>Single scattering albedo</td>
<td>1.00000</td>
<td>0.84902</td>
<td>0.97244</td>
</tr>
</tbody>
</table>

**Atmospheric correction result**

- Input apparent reflectance: 0.162
- Measured radiance [W/m²/sr/mic]: 44.629
- Atmospherically corrected reflectance: 0.023
- Coefficients xa xb xc: 0.0088 0.23946 0.21148
- \[ y = xa(\text{measured radiance}) - xb; \quad \text{acr} = y / (1. + xc*y) \]
A.2. ALTERED PROGRAM

A.2 Altered program

A.2.1 Input card

500 (NUMBER OF X-LEVELS)
15 (LOOP 15 TIME(S))
0 (USER'S CONDITIONS, FOLLOWS ON NEXT LINE)
59.52 168.68 5.71 113.31 8 29
8 (USER DEFINED IDATM)
1.26 0.2943 (uH2O, uO3)
4 (AEROSOLS MODEL)
0.1 0.5 0.35 0.05 (% of DUST-LIKE, WATER-SOL., OCEANIC, SOOT)
0 (NEXT VALUE IS THE AERO. OPT. THICK @ 550)
0.05 (AEROSOL OPTICAL THICKNESS @550)
-0.341 (TARGET AT 341 m)
-1000 (MEASUREMENT FROM SATELLITE)
61 (MERIS BAND 1)
1 (GROUND TYPE, I.E. NON UNIFORME SURFACE)
2 1 0.50 (TARGET, ENV., RADIUS (KM))
-0.1623 (APPARENT REFLECTANCE ON MERIS BAND 1)
1 (BOTH AEROSOL AND RAYLEIGH REFLECTANCE)
62 (MERIS BAND 2)
-0.1303 (APPARENT REFLECTANCE ON MERIS BAND 2)
63 (MERIS BAND 3)
-0.0909 (APPARENT REFLECTANCE ON MERIS BAND 3)
64 (MERIS BAND 4)
-0.0788 (APPARENT REFLECTANCE ON MERIS BAND 4)
65 (MERIS BAND 5)
-0.0526 (APPARENT REFLECTANCE ON MERIS BAND 5)
66 (MERIS BAND 6)
-0.0346 (APPARENT REFLECTANCE ON MERIS BAND 6)
67 (MERIS BAND 7)
-0.0286 (APPARENT REFLECTANCE ON MERIS BAND 7)
68 (MERIS BAND 8)
-0.0266 (APPARENT REFLECTANCE ON MERIS BAND 8)
69 (MERIS BAND 9)
-0.0241 (APPARENT REFLECTANCE ON MERIS BAND 9)
70 (MERIS BAND 10)
-0.0204 (APPARENT REFLECTANCE ON MERIS BAND 10)
72 (MERIS BAND 11)
-0.0183 (APPARENT REFLECTANCE ON MERIS BAND 11)
73 (MERIS BAND 12)
-0.0130 (APPARENT REFLECTANCE ON MERIS BAND 12)
74 (MERIS BAND 13)
-0.0117 (APPARENT REFLECTANCE ON MERIS BAND 13)
74 (MERIS BAND 14)
-0.0117 (APPARENT REFLECTANCE ON MERIS BAND 14)
75 (MERIS BAND 15)
-0.0093 (APPARENT REFLECTANCE ON MERIS BAND 15)
A.2.2 Result

- project NorSEN result
  
  Band: meris 1 (407.500–417.500 nm)
  
  | aerosol optical thickness     | 0.06821 |
  | rayleigh optical thickness    | 0.30542 |
  | aerosol+rayleigh optical thickness | 0.37363 |
  | aerosol reflectance           | 0.00557 |
  | rayleigh reflectance          | 0.13934 |
  | aerosol+rayleigh reflectance  | 0.14800 |
  | input apparent reflectance    | 0.16230 |
  | atmospherically corrected reflectance | 0.03439 |
  | Solar flux [W/m^2/mic]        | 1698.507 |

- Band: meris 2 (437.500–447.500 nm)
  
  | aerosol optical thickness     | 0.06333 |
  | rayleigh optical thickness    | 0.22860 |
  | aerosol+rayleigh optical thickness | 0.29183 |
  | aerosol reflectance           | 0.00520 |
  | rayleigh reflectance          | 0.10684 |
  | aerosol+rayleigh reflectance  | 0.11433 |
  | input apparent reflectance    | 0.13030 |
  | atmospherically corrected reflectance | 0.03587 |
  | Solar flux [W/m^2/mic]        | 1833.111 |

- Band: meris 3 (485.000–495.000 nm)
  
  | aerosol optical thickness     | 0.05688 |
  | rayleigh optical thickness    | 0.15018 |
  | aerosol+rayleigh optical thickness | 0.20706 |
  | aerosol reflectance           | 0.00470 |
  | rayleigh reflectance          | 0.07267 |
  | aerosol+rayleigh reflectance  | 0.07866 |
  | input apparent reflectance    | 0.09090 |
  | atmospherically corrected reflectance | 0.02688 |
  | Solar flux [W/m^2/mic]        | 1891.299 |

- Band: meris 4 (505.000–515.000 nm)
  
  | aerosol optical thickness     | 0.05452 |
  | rayleigh optical thickness    | 0.12759 |
  | aerosol+rayleigh optical thickness | 0.18211 |
  | aerosol reflectance           | 0.00451 |
  | rayleigh reflectance          | 0.06207 |
  | aerosol+rayleigh reflectance  | 0.06772 |
  | input apparent reflectance    | 0.07880 |
  | atmospherically corrected reflectance | 0.02597 |
  | Solar flux [W/m^2/mic]        | 1866.333 |

- Band: meris 5 (555.000–565.000 nm)
  
  | aerosol optical thickness     | 0.04896 |
  | rayleigh optical thickness    | 0.08707 |
  | aerosol+rayleigh optical thickness | 0.13603 |
  | aerosol reflectance           | 0.00404 |
  | rayleigh reflectance          | 0.04263 |
  | aerosol+rayleigh reflectance  | 0.04755 |
  | input apparent reflectance    | 0.05260 |
  | atmospherically corrected reflectance | 0.01788 |
A.2. ALTERED PROGRAM

* Solar flux [W/m²/mic] 1810.914 *
* *
* Band: meris 6  (615.000-625.000 nm) *
* --------------------------------------------------- *
* aerosol optical thickness : 0.04348 *
* rayleigh optical thickness : 0.06755 *
* aerosol+rayleigh optical thickness : 0.10103 *
* aerosol reflectance : 0.00361 *
* rayleigh reflectance : 0.02824 *
* aerosol+rayleigh reflectance : 0.03247 *
* input apparent reflectance : 0.03460 *
* atmospherically corrected reflectance : 0.00950 *
* Solar flux [W/m²/mic] 1662.788 *
* *
* Band: meris 7  (660.000-670.000 nm) *
* --------------------------------------------------- *
* aerosol optical thickness : 0.04006 *
* rayleigh optical thickness : 0.04331 *
* aerosol+rayleigh optical thickness : 0.08337 *
* aerosol reflectance : 0.00332 *
* rayleigh reflectance : 0.02125 *
* aerosol+rayleigh reflectance : 0.02504 *
* input apparent reflectance : 0.02860 *
* atmospherically corrected reflectance : 0.00824 *
* Solar flux [W/m²/mic] 1514.714 *
* *
* Band: meris 8  (677.500-685.000 nm) *
* --------------------------------------------------- *
* aerosol optical thickness : 0.03894 *
* rayleigh optical thickness : 0.03927 *
* aerosol+rayleigh optical thickness : 0.07822 *
* aerosol reflectance : 0.00322 *
* rayleigh reflectance : 0.01927 *
* aerosol+rayleigh reflectance : 0.02291 *
* input apparent reflectance : 0.02660 *
* atmospherically corrected reflectance : 0.00765 *
* Solar flux [W/m²/mic] 1460.875 *
* *
* Band: meris 9  (703.750-713.750 nm) *
* --------------------------------------------------- *
* aerosol optical thickness : 0.03704 *
* rayleigh optical thickness : 0.03323 *
* aerosol+rayleigh optical thickness : 0.07027 *
* aerosol reflectance : 0.00304 *
* rayleigh reflectance : 0.01630 *
* aerosol+rayleigh reflectance : 0.01972 *
* input apparent reflectance : 0.02410 *
* atmospherically corrected reflectance : 0.00832 *
* Solar flux [W/m²/mic] 1360.872 *
* *
* Band: meris 10  (750.000-757.500 nm) *
* --------------------------------------------------- *
* aerosol optical thickness : 0.03439 *
* rayleigh optical thickness : 0.02609 *
* aerosol+rayleigh optical thickness : 0.06048 *
* aerosol reflectance : 0.00278 *
* rayleigh reflectance : 0.01279 *
* aerosol+rayleigh reflectance : 0.01690 *
* input apparent reflectance : 0.02040 *
* atmospherically corrected reflectance : 0.00775 *
* Solar flux [W/m²/mic] 1235.551 *
APPENDIX A. 6S FILES

Band: meris 12 (771.250-786.250 nm)

- aerosol optical thickness : 0.03295
- rayleigh optical thickness : 0.02273
- aerosol+rayleigh optical thickness : 0.05569
- aerosol reflectance : 0.00264
- rayleigh reflectance : 0.01113
- aerosol+rayleigh reflectance : 0.01407
- input apparent reflectance : 0.01830
- atmospherically corrected reflectance : 0.00703
- Solar flux [W/m^2/mic] : 1166.230

Band: meris 13 (855.000-875.000 nm)

- aerosol optical thickness : 0.02898
- rayleigh optical thickness : 0.01497
- aerosol+rayleigh optical thickness : 0.04395
- aerosol reflectance : 0.00226
- rayleigh reflectance : 0.00732
- aerosol+rayleigh reflectance : 0.00974
- input apparent reflectance : 0.01300
- atmospherically corrected reflectance : 0.00525
- Solar flux [W/m^2/mic] : 954.659

Band: meris 14 (880.000-890.000 nm)

- aerosol optical thickness : 0.02821
- rayleigh optical thickness : 0.01365
- aerosol+rayleigh optical thickness : 0.04186
- aerosol reflectance : 0.00219
- rayleigh reflectance : 0.00667
- aerosol+rayleigh reflectance : 0.00909
- input apparent reflectance : 0.01170
- atmospherically corrected reflectance : 0.00422
- Solar flux [W/m^2/mic] : 954.849
Appendix B

MERIS files

Data from 20050829 taken from the middle of Lake Torneträsk. See Figure 6.1.

B.1 L1b

Product: subset_3_MER_RR__1PNDX20050829_100408_000023432040_00194_18284_4298

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latitude: 68.391846 deg
longitude: 18.867363 deg
dem_alt: 431.7422 m
dem_rough: 259.83594 m
lat_corr: -1.5220702E-4 deg lon_corr: -9.6276955E-4 deg
sun_zenith: 59.50258 deg sun_azimuth: 168.69151 deg
view_zenith: 5.629351 deg view_azimuth: 113.32548 deg
zonal_wind: -0.13125001 m/s merid_wind: 3.0875003 m/s
atm_press: 995.5301 hPa
APPENDIX B. MERIS FILES

ozone: 294.32443 DU
rel_hum: 63.908592 %

ll_flags.COSMETIC: false
ll_flags.DUPLICATED: false
ll_flags.GLINT_RISK: false
ll_flags.SUSPECT: false
ll_flags.LAND_OCEAN: false
ll_flags.BRIGHT: false
ll_flags.COASTLINE: false
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B.2. L2

Product: subset_11_MER_RR__2PNPD20050829_100408_000023432040_00194_18284_4343

Image-X: 493 pixel
Image-Y: 97 pixel
Longitude: 18°52'03" E degree
Latitude: 68°23'31" N degree

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l2_flags.PCD_19: false
l2_flags.COASTLINE: false
l2_flags.COSMETIC: false
l2_flags.SUSPECT: false
l2_flags.ABSOA_CONT: false
l2_flags.ABSOA_DUST: true
l2_flags.CASE2_S: true
l2_flags.CASE2_ANOM: false
l2_flags.TOAVI_BRIGHT: false
l2_flags.CASE2_Y: false
l2_flags.TOAVI_BAD: false
l2_flags.ICE_HAZE: false
l2_flags.TOAVI_CSI: false
l2_flags.MEDIUM_GLINT: false
l2_flags.TOAVI_WS: false
l2_flags.DDV: false
l2_flags.HIGH_GLINT: false
l2_flags.TOAVI_INVAL_REC: false
l2_flags.P_CONFIDENCE: false
l2_flags.LOW_PRESSURE: true
Bibliography


