Examensarbete

Atmospheric Transmission Models for Infrared Wavelengths

Björn Hässler

Reg nr: LiTH-ISY-EX-1909

December 18th 1998

Atmospheric Transmission Models for Infrared Wavelengths

Master Thesis

Division of Automatic Control

Department of Electrical Engineering

Linköping University

Björn Hässler

Reg nr: LiTH-ISY-EX-1909

Supervisor:	Hans Pettersson	SAAB
	Johan Rättvall	SAAB
	Fredrik Gunnarsson	LiTH
Examiner:	Inger Klein	LiTH

Linköping, December 18th 1998

Abstract

In the demanding environment in which modern combat aircraft perform, it is vital for the pilot to uphold situation awareness of his surroundings; are there other objects in the vicinity of the aircraft and if so is there any risk that they are hostile? Of equally vital importance is the extent of the somewhat vague term ”surroundings”. Different types of sensors have different range capabilities under different conditions, weather and time for instance. This means that the size of the volume in which it is possible to uphold situation awareness will depend on the type of sensors included in the aircraft sensor suite.

This thesis investigates the atmosphere with the purpose of finding factors which influence the range of sensors that detect infrared radiation. The result is expected to form a basis for models concerning ranges of infrared sensors and atmospheric transmission.

A range equation considering atmospheric transmission is suggested for infrared sensors. The single most important parameter in an atmospheric transmission model is the water vapour content, since water vapour effects the transmission both directly and indirectly. Another crucial parameter is the amount of particles dissolved in the atmosphere. This amount changes constantly and this makes modelling difficult. Clouds have a dramatic attenuation effect upon infrared radiation, and the random nature of clouds also adds to the complexity of this matter.

Acknowledgements

I would like to start by thanking my supervisors at Saab AB, Hans Pettersson and Johan Rättvall for their help and support during the long and winding path leading to this thesis. I also want to send a thankful thought to my supervisor at the Division of Automatic Control, Linköping University, Fredrik Gunnarsson who contributed with valuable comments and ideas.

I would like to thank Inger Klein for that she on such short notice shouldered the examiners burden.

Then I want to thank Per Hedberg, who provided me with constructive comments both on the technical details of this thesis and the overall layout.

I am glad that I have had the privilege to meet with Arne Hågård and Rolf Persson at the Defence Research Establishment, Department 3, Linköping, Sweden, who have contributed with interesting discussions, information and help; both in articles and in person.

I would like to thank my guinea pigs Henrik Schinzel and Niklas Ferm who have been exposed to not only my presence but also parts of the manuscript and some advanced human factor studies.

A huge thank combined with a hug to my dear and beloved Grandmother who has, with superior knowledge of the English language, enhanced the quality of this thesis considerably (however she hasn't seen these acknowledgements...).

Finally I would like to thank my family and friends, in particular my girlfriend who has put up with me during this sometimes quite intense and demanding time in the name of science.

Linköping, December 1998
Björn Hässler

Notation

”Humpty Dumpty: When I use a word it means just what I want it to mean, neither more nor less.”
(Lewis Carroll, *Alice in Wonderland*)

Acronyms

Acronym	*Explanation*
AFGL	Air Force Geophysical Laboratory (now Phillips Laboratory)
CIA	Collision Induced Absorption
FASCODE	Fast Atmospheric Signature CODE
FIR	Far InfraRed
FOV	Field Of View
FOA	Defence Research Establishment
HITRAN	HIgh-resolution TRANsmission, a database.
IR	InfraRed
IRST	InfraRed Search and Track
LASER	Light Amplification by Stimulated Emission of Radiation
LOWTRAN	LOW-resolution TRANsmission code
LWIR	Long-Wave InfraRed, λ 6-16 μm
MODTRAN	MODerate-resolution TRANsmission code
MWIR	Mid-Wave InfraRed, λ 3-6 μm
PPMV	Parts Per Million by Volume
PPMW	Parts Per Million by Weight
RADAR	RAdio Detection And Ranging
RH	Relative Humidity
RMS	Root Mean Square
SA	Situation Awareness
SAS	Sub-Arctic Summer
SAW	Sub-Arctic Winter
SNR	Signal to Noise Ratio
SPIE	the Society of Photo-optical Instrumentation Engineers
SWIR	Short-Wave InfraRed λ 0.8-3 μm
UV	Ultra Violet

Symbols

Symbol	*Explanation*	*Unit*
L	Radiance	[W/m^2]
λ	Wavelength	[m]
C_1	First constant in Planck's law	[W m^2]
C_2	Second constant in Planck's law	[m K]
T	Temperature	[K, °C]
c	Speed of light	[m/s]
h	Planck's constant	[Ws^2]
k	Boltzmann's constant	[Ws/K]
σ	The constant in Stefan-Boltzmann's law	[W/m^{2}K^4]
W	Energy	[J]
ν	Frequency (also wavenumber $0.01/\lambda$)	[Hz] ([cm^{-1}])
σ_{ext}	Extinction coefficient ($=\sigma_{sca} + \sigma_{abs}$)	[km^{-1}]
σ_{sca}	Scattering coefficient	[km^{-1}]
σ_{abs}	Absorption coefficient	[km^{-1}]
a	Absolute humidity	[kg/m^3]
φ	Relative Humidity, RH	[%]
r	Mixing ratio	[PPMV, g/m^3]
N	Number of molecules	[-]
M_{air}	Molecular weight of air	[u]
M_{H2O}	Molecular weight of water vapour	[u]
τ	Atmospheric transmission	[-]
P	Power	[W]
P_0	Initial power	[W]
R	Range	[km]
I	Intensity	[W]
NEI	Noise Equivalent Irradiance	[W/m^2]
E	Irradiance	[W/m^2]
p	pressure	[atm]
Z	Pathlength in MODTRAN	[km]
β	Back scatter coefficient	[m^{-1}]
A	Area	[m^2]
SNR_{min}	Smallest amplitude of a signal required for the detection of an object in a noisy image	[-]

Table of Contents

1 INTRODUCTION 1

1.1 BACKGROUND 1
1.2 OBJECTIVES 3
1.3 LIMITATIONS 3
1.4 THESIS OUTLINE 3

2 THEORY 5

2.1 INFRARED RADIATION 5
2.1.1 The Electromagnetic spectrum 5
2.1.2 Radiation laws 6
2.2 ATMOSPHERE 9
2.3 UNITS AND QUANTITIES 10
2.3.1 Concepts 10
2.3.2 Water vapour content 10
2.4 CLOUDS 12
2.4.1 Cloud formation 12
2.4.2 Causes for cloud formation 13
2.4.3 Cloud types 14
2.5 ATMOSPHERIC ATTENUATION MECHANISMS 15
2.5.1 Absorption 15
2.5.2 Continuum Absorption 17
2.5.3 Scattering 18
2.5.4 Refraction 19
2.6 GAS ATTENUATION 19
2.6.1 Gas absorption 20
2.6.2 Molecular scatter 22
2.7 AEROSOL ATTENUATION 23
2.7.1 Aerosol scatter 23
2.8 ATTENUATION COEFFICIENT 24
2.9 ATMOSPHERIC TRANSMISSION 25
2.10 RANGE EQUATION 26

3 PROBLEM DESCRIPTION 27

3.1 INFORMATION SOURCES 27
3.2 BASIC CONSIDERATIONS 28

4 MODTRAN 29

4.1 WHAT IS MODTRAN 29
4.2 MODTRAN METHOD 29
4.3 MODTRAN ACCOMMODATION 31

5 ATMOSPHERIC INVESTIGATIONS 33

5.1 MODTRAN TEST PLATFORM 33
5.2 GASES 35
5.2.1 Water vapour 36
5.2.2 Carbon dioxide 37
5.2.3 Ozone 37
5.2.4 Gas summary 38
5.3 AEROSOLS 38
5.3.1 Wavelength independence 39
5.3.2 Effects of Humidity Variations on Aerosol Properties 41
5.3.3 Backscatter coefficient 41
5.3.4 Aerosol summary 43
5.4 CLOUDS 43
5.4.1 Clouds summary 45
5.5 RANGE 45
5.5.1 Effective transmission 46
5.5.2 Range Summary 50

6 DISCUSSION 51

6.1 IMPORTANT PARAMETERS 51
6.2 ATMOSPHERIC MODEL APPROACHES 52
6.2.1 Available code accommodation 52
6.2.2 Model from scratch 53
6.2.3 Combined further development 53
6.3 A WAY TOWARDS A MODEL IMPLEMENTATION 53
6.4 RANGE EQUATION APPLICATION 54
6.5 FUTURE WORK 54
6.5.1 Model implementation 55
6.5.2 Sensor model 55
6.5.3 Target model 55
6.5.4 Sensor measurements 55

6.5.5 Model improvements *55*
6.5.6 Integration with other models *56*

7 CONCLUSIONS **57**

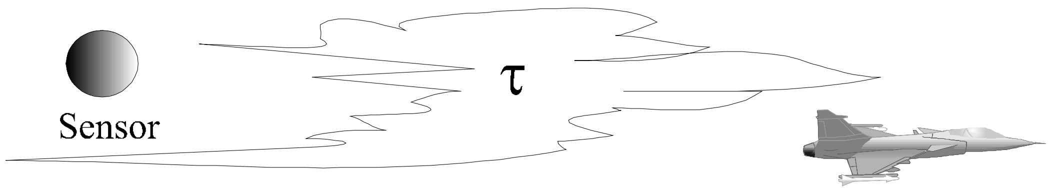
REFERENCES **59**

APPENDIX **61**

MODTRAN USERS GUIDE 61
Overview *61*
Create and save an input file *62*
How to run an input file *62*
Create and save output plots *62*
How to view and save an output file *63*
Restore a saved input file *64*
Restore a saved plot *64*
Some advanced applications *64*
Help *64*

1 Introduction

This Chapter is intended to describe the purpose of this master thesis and to motivate further reading. The concluding paragraph includes a thesis outline that is meant to serve as a readers guide.



1.1 Background

All objects, man-made or not, emit radiation of some kind. Sir William Herschel showed as early as in the year 1800 that there is a relation between heat (radiation) and wavelength. This means that you can detect and even obtain information about an object just by investigating the radiation emitted by the object in question.

This ability to get information about radiant objects has many applications, for instance finding lost people in difficult terrain. Of course there are also several military applications, and of our special interest are those that are airborne. Nowadays most modern combat aircraft have means of investigating radiation.

It is of vital importance that the pilot upholds situation awareness, SA, of his surroundings. SA is a popular and widely used term and it can be defined as the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future, (Endsly 1988). In order to apply this practically it can be translated into; Are there other objects in the vicinity of the aircraft and if so is there any risk that they are hostile? This kind of SA is to be achieved by using the aircraft's own sensor suite.

The precise extent of the somewhat vague term ”surroundings” is also of vital importance. Different types of sensors have different range capabilities. This means that the size of the volume in which it is possible to have SA will depend on the type of sensors included in the aircraft sensor suite.

The kind of optical sensors that detect infrared, IR, radiation are passive. This means that the sensor merely detects emitted energy. It does not need to emit any energy to provide the pilot with awareness of his environment. In a military aircraft this feature could prove to be very useful as the pilot can become aware of his surroundings, even beyond visual range, without revealing his position by using for instance the energy emitting radar[1].

The range performance of all sensors is to some extent dependant on the present weather situation. Microwave sensors, like radar, are normally less sensitive to weather concerning range performance than are optical sensors. In practice, optical sensors are found at ultra violet, visual, near-infrared and infrared wavelengths. For optical sensors, range performance can be expected to depend heavily on atmospheric transmission.

The atmosphere is - as most things where nature is concerned - an extremely complex phenomenon and an intriguing matter for further investigations.

”Some Are Weatherwise;
Some Are Otherwise”
(Benjamin Franklin, *Poor Richard's Almanac*, 1735)

[1] RADAR, RAdio Detection And Ranging is a active sensor that emits radiation and measure the reflected radiation and thereby achieves information about objects within its active range. This information consists of range, bearing, elevation and often velocity.

1.2 Objectives

The overall goal is to develop an operational model for sensor ranges in the atmosphere. The objective for this master thesis is to evaluate the possibilities to develop such a model. A way to accomplish this is by identifying problems, the need for new models and the usability of these. This should be done with focus on the atmospheric transmission or rather the factors which influence atmospheric transmission, both qualitatively and quantitatively. The result is expected to form a basis for models of sensor ranges for the determination of the size of the SA volume.

1.3 Limitations

- The study contains only atmospheric parameters. Information about the sensor, object and background are considered to be known and static.
- Primarily, we study conditions at high altitudes, at about 8-12 kilometres of altitude.
- This study is done in the IR area at wavelengths between 3-12 micrometers.

1.4 Thesis outline

The first thing to notice when reading this thesis is the *Notation,* in front of the table of contents, which includes both the acronyms and the symbols used. The table of references is found at page 59 after the conclusions

Chapter two is intended to provide a reader with little or no previous knowledge of atmospheric attenuation and infrared radiation with relevant information, in order to enable him/her to understand the following chapters. First a brief introduction to infrared radiation in general, then some basics considering our atmosphere and the attenuation of Infrared radiation within it. This chapter could be disregarded by readers who have prior knowledge in this area.

Chapter three, this chapter is an analysis and discussion of the problems to be studied in order to fulfil the purposes of this thesis.

Chapter four introduces the reader to MODTRAN, an atmospheric radiance and transmittance code, that is used extensively during this study. In the Appendix an users guide have been included in order to simplify future use of MODTRAN.

Chapter five is in fact the kernel of this thesis. In this chapter the basic investigations from Chapter two are deepened in the identified interesting areas and the ground is prepared for the discussion in chapter six.

Chapter six. In this chapter we discuss the results that have been derived during this thesis and presented in the previous chapter. We also discuss how to continue the work started in this thesis by suggesting some improvements and further work in adjacent areas.

Chapter seven concludes with a summary of the conclusions drawn within this thesis.

2 Theory

This chapter starts with a brief introduction to infrared radiation. To get a more thorough orientation of this subject see (Zissis 1993). We then discuss our atmosphere, clouds and the mechanisms of attenuation in these. Finally a way to calculate the theoretical range of optical sensors sensitive in the infrared wavelength band is covered.

2.1 Infrared radiation

Sir William Herschel was one of the pioneers in the infrared area and he came into contact with infrared radiation accidentally. In the year 1800 he was performing an experiment with a prism placed in a window where it intercepted the sunlight. The prism spread the light into a spectrum from violet to red. Herschel measured the temperature at each colour and he noticed that the temperature increased progressively.

This experiment shows that there is a relationship between wavelength and temperature. When he moved the thermometer past the visible red, he found that the temperature still was separated from the ambient temperature. This energy was called infrared because it was found beyond red. (Lovell 1981)

2.1.1 The Electromagnetic spectrum

Now we know that Herschel only found a small part of the wider electromagnetic spectrum, see Figure 2-1, which includes radiation from gamma rays to radio waves. This kind of radiation propagates through space as transverse waves and their frequency is equal to the speed of light in vacuum divided by their wavelength.

These wavebands of wavelengths are named, somewhat arbitrarily, but are however standardised throughout the physics and electrical communities. There is no exact division of the IR wavebands but the region from 1 to 3 μm is called the near infrared or the short-wave infrared, SWIR. The next octave, double the frequency, up to 6 μm is called the middle infrared or mid-wave infrared, MWIR. The next region up to 16 μm is called long-wave infrared, LWIR.

Finally, the region from 16 μm to 1 mm carries the name far infrared, FIR, or extreme infrared. Accordingly, this research will proceed in the MWIR and LWIR bands. (Spiro 1989)

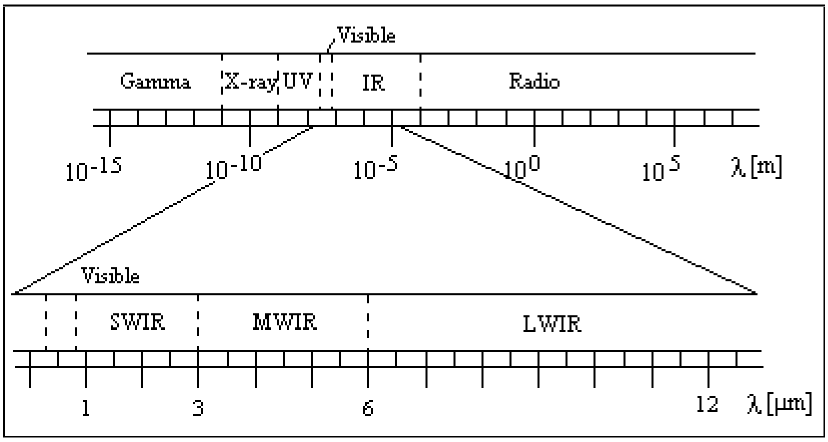


Figure 2-1 *The electromagnetic spectrum, magnified at the wavelengths of primary interest for optical sensors.*

2.1.2 Radiation laws

In order to express radiation, there are a couple of fundamental laws the reader must be familiar with. These radiation laws are more completely covered in (Zissis 1993, Wolfe 1993).

- Planck's law
- Stefan-Boltzmann's law
- Wien's law

Planck's law states that the spectral radiance, L(λ), from a blackbody[2] is

$$L(\lambda) = \frac{C_1}{\lambda^5} \cdot \frac{1}{e^{(C_2/\lambda T)} - 1} \; [\mathrm{W/m^2\ m}] \qquad \textbf{\textit{(2-1)}}$$

where:

$\lambda =$ wavelength, [m]

$C_1 = 2h\pi c^2 = 3.74691 \times 10^{-16}$ W m^2

$C_2 = ch/k = 1.4397 \times 10^{-2}$ m K

$T =$ absolute temperature, [K]

$c =$ velocity of light = 3×10^8 m/s

$h =$ Planck's constant = 6.626×10^{-34} Ws^2

$k =$ Boltzmann's constant = 1.3807×10^{-23} Ws/K

[2] A blackbody is a perfect absorber and emitter at all angles and wavelengths. This kind of body has no radiation reflected from its surface and absorbs all radiation crossing its path. The fact that such a body would appear black to the human eye has given it its name, blackbody (Spiro 1989).

Figure 2-2 shows calculated blackbody curves at three different temperatures.

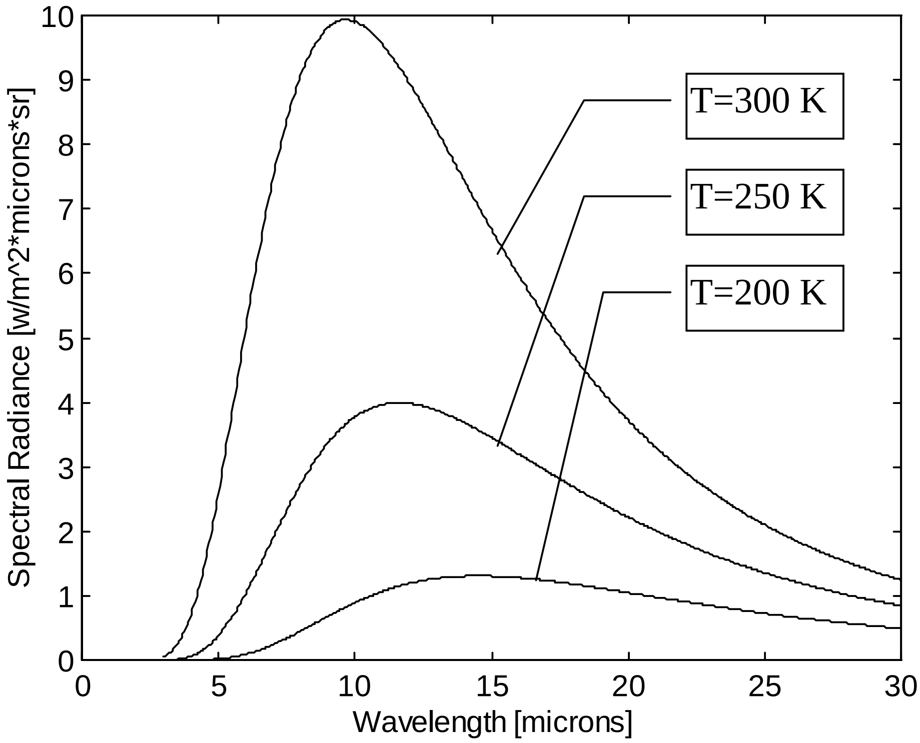


Figure 2-2 *Blackbody curves for temperatures 300, 250 and 200 K.*

Planck assumes that the energy can only increase in complete steps, which differ by hν (2hν, 3hν, etc.) called quantum, in order to get the radiation law correct for all wavelengths. A quantum is also called a photon. Planck also states that all photons of the same wavelength carry the same energy, W.

$$W = h\nu = \frac{hc}{\lambda} \text{ [J]} \qquad \textbf{\textit{(2-2)}}$$

where:

$h =$ Planck's constant = 6.626×10^{-34} Ws^2
$\nu =$ frequency, [Hz]
$c =$ speed of light = 3×10^8 m/s
$\lambda =$ wavelength, [m]

Stefan-Boltzmann's law states that the total amount of radiation emitted is a function of temperature as

$$L_{tot} = \sigma T^4 \ [\mathrm{W/\ m^2}] \tag{2-3}$$

where:

$L_{tot} =$ total power radiated by a blackbody per square metre, [W/ m^2]
$\sigma = 5.670\times10^{-8}$ W/ m^2 K^4
$T =$ temperature [K]

Stefan-Boltzmann's law can be derived from Planck's law by integrating over all wavelengths from zero to infinity.

Wien's displacement law

$$\lambda_{\max} T = \text{constant} = 2.897\times10^{-3}\ \mathrm{m\ K} \tag{2-4}$$

where:

$T =$ temperature, [K]
$\lambda_{\max} =$ wavelength for maximum spectral radiance, [m]

The displacement effect is illustrated in Figure 2-2. This law can also be obtained from Planck's law. In this case, by differentiating Planck's law, with respect to λ, and finding the maximum. (Spiro 1989, Zissis 1993, Wolfe 1993)

2.2 Atmosphere

> ”Sometimes gentle, sometimes capricious, sometimes awful, never the same for two moments together; almost human in its passions, almost spiritual in its tenderness, almost divine in its infinity.”
>
> (John Ruskin, *The Sky)*

The Earth is surrounded by the atmosphere, a circumstance that is in fact essential for almost all life on this planet. The atmosphere consists of gases and particles and reaches out 500 km from the surface of the earth.

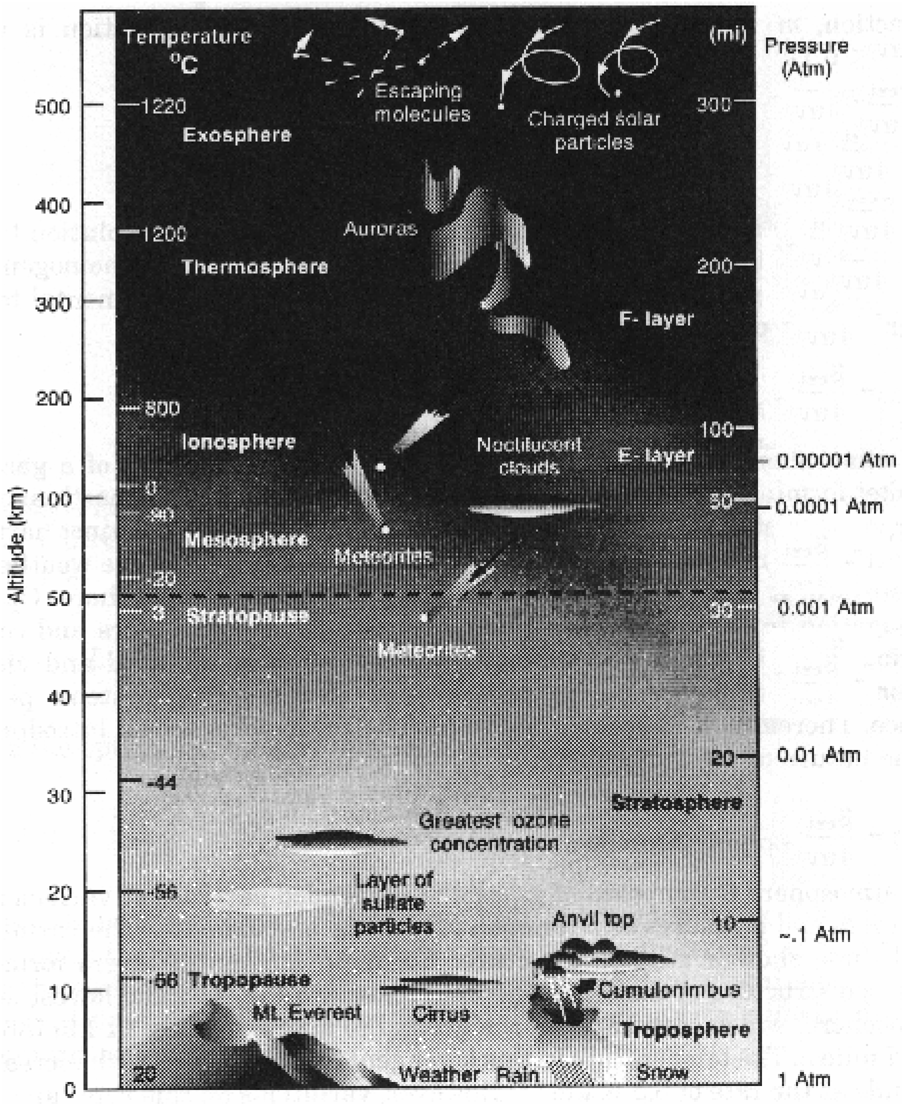


Figure 2-3 *The structure of the atmosphere with altitude, (Smith 1993).*

The word, atmosphere, originates from the Latin word, *atmosphae'ra* which in turn consists of the two Greek words *atmo's*, vapour, and *sphai'ra*, sphere. Usually the atmosphere is divided into six layers, see Figure 2-3, each with different properties concerning gas mixing ratios, particles etc. The first layer, located between 0-11 km is called the *troposphere* and the following are called, *stratosphere* 11-50 km, *mesosphere* 50-90 km, *ionosphere* 90-300 km, *thermosphere* 300-400 km and finally the layer 400-500 km is called the *exosphere*.

In the troposphere, where aircraft normally tend to fly, most of the significant atmospheric attenuates exist. These attenuates are water vapour, carbon dioxide, clouds, fog and of course all kinds of particles dissolved in the air called aerosols, more about this in sections 2.4 to 2.7. (Anthes 1975, Smith 1993)

2.3 Units and quantities

There are several possibilities when describing the gas contents of the atmosphere. Some units and quantities are only used when describing atmospheric properties and therefore we have related these to more commonly used equivalents. As water vapour is one of the most important absorbers, we have chosen to derive some equations for water vapour, however equations that applies for other atmospheric constituents are quite similar to these.

2.3.1 Concepts

The *dew point* is the temperature to which a parcel of air, with constant pressure and water vapour content, must be cooled if saturation is to occur. Further cooling produces condensation to liquid water, see section 2.4.1. The *absolute humidity* is the mass of water vapour in a unit volume of air; this means that it actually is the water vapour density within the air. The *relative humidity*, φ, is the ratio of the actual water vapour pressure of the air to the saturation water vapour pressure at the ambient air temperature. Relative humidity is, as the name indicates, a relative measure and is expressed in percent. (Smith 1993)

2.3.2 Water vapour content

Water vapour content or mixing ratio can be expressed as the number of water molecules in a certain volume divided by the total number of molecules in the same volume.

$$r = \frac{\left(N_{H_2O}\right)}{\left(N_{molecules}\right)} \qquad (2\text{-}5)$$

where:

N_{H_2O} The number of water molecules in the volume

$N_{molecules}$ The total number of molecules in the volume

The mixing ratio is rather small and therefore enhanced to the more commonly used Parts Per Million by Volume, PPMV[3]. PPMV is a mixing ratio expressed for a certain volume of air as

$$PPMV = 10^6 \cdot \frac{\left(N_{H_2O}\right)}{\left(N_{molecules}\right)} \left(= 10^6 \cdot r\right) \tag{2-6}$$

Table 2-1 *The air density varies with the altitude. In the two right columns we have included a typical sub-arctic water content profile for both summer and winter to stress the seasonal variations as well as the altitude variations, (Abreu 1996).*

Alt [km]	*Air density, ρ_{air}, [kg/m^3]*	*Water vapour content [PPMV] Sub-Arctic summer*	*winter*
0	1.23	11900	1410
1	1.11	8700	1620
2	1.01	6750	1430
3	0.91	4820	1170
4	0.82	3380	790
5	0.73	2220	431
6	0.66	1330	237
7	0.59	797	147
8	0.53	400	33.8
9	0.47	130	29.8
10	0.41	42.4	20

This unit is somewhat abstract and difficult to visualise and therefore we have related it to a ”normal” unit, gram per cubic meter, [g/m^3].

$$r_{H_2O} = \frac{r_{PPMV}}{10^6} \cdot \rho_{air} \cdot \frac{M_{H_2O}}{M_{air}} \tag{2-7}$$

[3] The mixing ratio can also be expressed by weight instead of volume PPMW, Parts Per Million by Weight, which is quite similar to PPMV and derived in the same way.

where:

r_{H_2O} = Water content [g/m^3]

r_{PPMV} = Water content [PPMV]

$M_{air} = 28.9645$, molecular weight of air

$M_{H_2O} = 18.02$, molecular weight of water vapour

ρ_{air} = air density, see Table 2-1

For example 1 g/m^3 is equal to 1312125 PPMV, at sea level. It is important to remember that the density varies with altitude, see Table 2-1.

2.4 Clouds

In our atmosphere the phenomena we call clouds are quite common. As an example weather statistics from Ljungbyhed, in Sweden, show that clouds are present 20.5 % of the time at an altitude of 1000 meters, (Nilsson 1990). The cloud influence on optical radiation is quite dramatic and the random nature of clouds makes them difficult to model. More about this in section 5.4.

2.4.1 Cloud formation

The amount of water vapour that a parcel of air can hold depends on the air temperature and air pressure, and the limit is indicated by the dew point, see section 2.3.1. Warmer air can carry more water. For example, water often condense around the surface of a cold soft-drink bottle or can. The air in contact with the container is cooled and soon the saturation level is reached, and the excess water vapour in the cooled air condenses into liquid water droplets on the container.

Clouds appear when an air mass is cooled and therefore becomes saturated with water vapour which starts to condense. The water vapour condenses around small particles, with a radius about 0.1 µm, e.g. dust and salt particles, that are always present in the atmosphere. Then the cloud droplets continue to grow due to further condensation, collisions and fusion with other droplets. The dew-point depends also on the size and the composition of these cloud droplets. Larger particles can bind more water.

Consequently there are two criteria that must be fulfilled if clouds are to appear. First we must have an air mass that for some reason has an excess of water vapour. The second and equally important criteria is that some kind of particles, condensation nuclei, must be present around which the cloud droplet can develop.

When the cloud becomes cold enough, for instance during transportation upward in the atmosphere, the cloud droplets freeze to ice-crystals. This phenomenon starts on particles dissolved in the droplets, so called ice-kernels. Depending on the composition of these ice-kernels the freezing initiation temperature varies. If the air was completely free from such particles the forming of ice would not start until the temperature dropped below minus 40 °C. However some particles are always present, and this normally means that forming of ice starts at about minus 10-15 °C.

Clouds appearing at higher altitudes, where the temperature falls below these values, will consequently normally consist of ice crystals. See ”high clouds” in section 2.4.3. The ice crystals grow faster than ordinary cloud droplets. Therefore they reach the point where the cloud no longer can carry the ice and the ice falls down through the cloud as precipitation. The temperature below the cloud base determines whether the ice will reach the ground as snow or rain. (deBlij 1996)

2.4.2 Causes for cloud formation

Warm air rises because it has lower density than cold air. When it rises it expands in the lower air pressure. Therefore a parcel of air is cooled down when it is moved upward in the atmosphere. There are three causes for these air movements.

- Convection
- Frontal movements
- Orographic movements

Convection is when warmer bubbles or cells of air, due to their lesser density, rise through the atmosphere. These movements can reach quite high speeds. In the tropics such high speeds as 40 m/s are common. Clouds formed under these conditions are called convection clouds. This kind of cloud may produce showers of precipitation that sometimes can be quite intensive. On the other hand, the clouds dissolve rather quickly.

As we know converging warm and cold air masses possess different densities; they do not mix. Air masses are bounded by surfaces along which contact occurs with neighbouring air masses possessing different characteristics. Therefore, such narrow boundary zones mark sharp transitions in density, humidity and temperature, this boundary is called a *front*.

If cold air is moved toward warmer air, the denser cold air will squeeze itself beneath and push the lighter warm air upward. And on the contrary, if a warmer air mass approaches a stationary colder air mass it will ride up over the cooler air. In both situations we have the lifting of warm, often moist, air that will be cooled and this leads to condensation, precipitation and clouds. Clouds formed during this process are called stratiform clouds. When the air rises along these sometimes long fronts, the clouds and the following rain can cover very large areas during quite long periods of time.

The air can also be forced upward *orographically*[4], by an obstacle in the terrain. The clouds that form, orographic clouds, appear on the windward side of the obstacle. Thus, clouds and precipitation are most common on the windward side of mountain ranges. (deBlij 1996, Scorer 1972)

2.4.3 Cloud types

The clouds in our atmosphere are often divided into ten main groups depending on whether they are convection or stratiform clouds as well as on the altitude of their appearance, see Table 2-2. Within these groups there are several species and special types of clouds. The altitude limits vary with latitude, and the figures mentioned further on refer to the temperate climate zone.

Table 2-2 *A classification of clouds, by how they are formed and at which altitude they are present, (deBlij 1996).*

Altitude Type	*Cause Type*	*Name*	*Comment*
Low 0-2 km	Convection	Cumulus	nice weather
		Cumulonimbus	precipitation
		Stratocumulus	
	Fog	Stratus	separated from ground
Medium2-7 km	Stratiform	Altostratus	precipitation
		Nimbostratus	precipitation
	Convection	Altocumulus	
High 5-13 km		Cirrus	
		Cirrostratus	halo
		Cirrocumulus	

Among low clouds, at 0-2 km altitude, we find the convection clouds *cumulus*, a nice weather cloud, and *cumulonimbus*, i.e. large precipitation cloud. *Stratocumulus* is a cloud formed when the convection broadens horizontally. Another low cloud is *stratus*, fog cloud, which forms a grey curtain that differ

[4] Oro is the Greek word for mountain.

from fog in that it is separated from the ground. All these types of clouds consist mainly of water droplets.

In the group medium high clouds, at 2-7 km altitude, the upper parts of the clouds start to freeze which leads to a stratification of the cloud. Here we find the stratiform clouds *altostratus* and *nimbostratus*, where the latter one is a pure rain cloud. Among the medium high clouds there is also a convection cloud Altocumulus, that originates from convection in the higher air layers.

Finally we consider the high clouds, at 5-13 km altitude. At these altitudes the clouds consist of almost nothing but ice crystals. Here we find Cirrus, Cirrostratus and Cirrocumulus. Cirrus has the shape of threads, stripes or diffuse formations, while Cirrostratus forms a uniform layer of ice crystals that scatter radiation and sometimes leads to beautiful halo[5] phenomena. (deBlij 1996)

2.5 Atmospheric attenuation mechanisms

The range of an optical sensor in search of a distant object depends upon, among other things, the amount of radiation able to penetrate the atmosphere between the object and the sensor. The atmosphere attenuates optical radiation by the following major causes

- Absorption
- Scattering
- Refraction

2.5.1 Absorption

The photons that transfer energy can be devoured by gas molecules and aerosols. During this absorption the radiation transforms into kinetic energy, heat. The gases are normally the most important absorbers and this kind of absorption is coupled to the bonding in the gas molecules, see section 2.6. When the photons are absorbed, absorption lines occur. If there are several lines present, side by side, they will form an absorption band. Bands with low absorption are often called *transmission windows*. In Figure 2-8, page 21, the atmospheric windows, 3-5 µm and especially 8-12 µm can be seen clearly.

These lines are not limited to one wavelength but to a small interval with an absorption maximum at a certain centre wavelength. For a particular

[5] Halo is a light phenomenon appearing in the sky. It occurs when sunlight is scattered and/or refracted, in certain angles, by ice particles present in the atmosphere. The most common is the small Halo, which forms a ring around the sun with an angle distance of 22 degrees, and the large Halo, 46 degrees. These phenomena are common in the polar and Alpine regions but more unusual in the lowlands.

absorption line we get a line width that mainly consists of the following three line-width types:

- Natural (Lorentz) line-width
- Doppler line-width
- Mixed (Voigt) line-width

A line shape only based on the time it takes for a photon transition to occur is called a *natural* line, and consequently this line-width is called the natural line width. This line-width is widen by temperature and pressure.

Another broadening contribution is the Doppler effect. Since photons from the source move in more than one direction they achieve slightly different Doppler shifts. This *Doppler* line-width usually exist when the half-width due to pressure and temperature broadening is much smaller than the half-width caused by the natural line-width.

When the Doppler effect and the natural line-width both have approximately the same effect on the line-width they produce a mixed line result called *mixed* line-width.

The emission from gases and particles is strongly coupled to the absorption in these atmospheric constitutes. This emission increases the background radiance and thereby reduces the contrast between the object and the background. (Zissis 1993, Wolfe 1993)

2.5.2 Continuum Absorption

This kind of absorption have small variations with wavelength, without any absorption peaks, in difference with the line absorption. These effects still lack a satisfactory explanation, but scientists believe that they may be caused by a summation of the ”tails” of the absorption lines in the absorption bands, (Nilsson 1994).

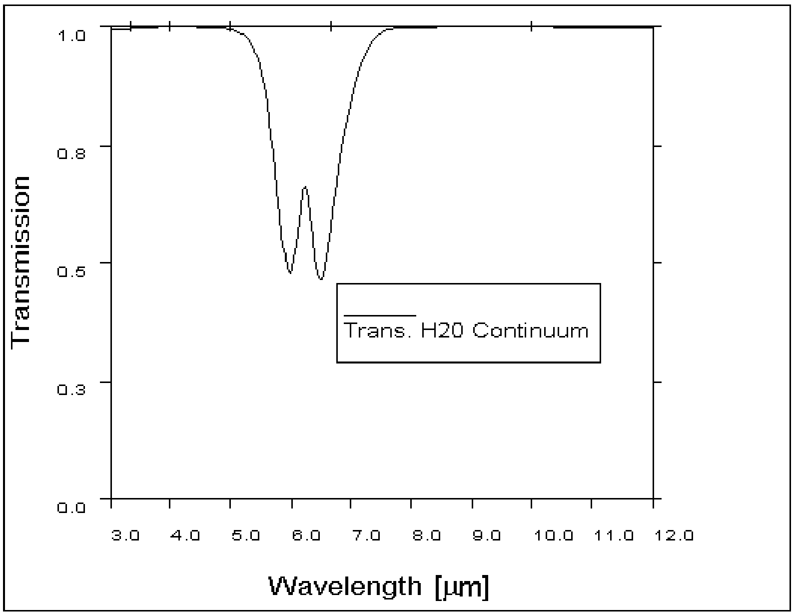


Figure 2-4 *Continuum absorption induced by water vapour, from MODTRAN.*

Some causes have been isolated though, for instance, strong collisions between neighbouring molecules in O_2 and N_2 induces a dipole moment that exists only during the duration of the collision[6]. Since these collisions are very brief is the line width very broad and the single transitions merge into broad band structures, (Smith 1993).

Water vapour, for instance, has got rather strong continuum absorption, see Figure 2-4.

[6] This is called Collision Induced Absorption, CIA

2.5.3 Scattering

Scattering has the effect of redirecting photons. This means that both desired photons from our object of interest can disappear from the sensor Field Of View, FOV, see Figure 2-5, and that undesired photons from, for instance, the background are directed into the sensor, thereby reducing the contrast between object and background. The scattering is caused by the molecules and the aerosols in the air.

Aerosols and molecules have different impact on the atmospheric transmission because they have different sizes. Aerosols are about 10^{-6} up to 10^{-4} meters in diameter and the molecules are somewhat (100-10000 times !) smaller, i.e. about 10^{-8} meters in diameter. Normally, attenuation caused by the aerosols is the most important scattering contribution in the Infrared wavelength band because of their size.

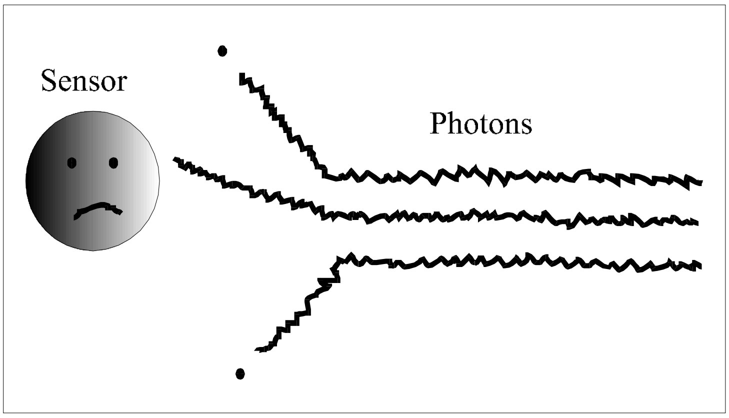


Figure 2-5 *Some desired photons do not reach the sensor though , they get obstructed on their way from the object,. they get scattered.*

The characteristics of the scatter will depend primarily on the ratio between the wavelength and the size of the particles obstructing the path of the photons, see Figure 2-6. When calculating scatter from aerosols, the particles have approximately the same diameter as the wavelength and can often be considered to be spherical. A method of analysing this kind of scatter is the Mie theory see section 2.7.

When considering scatter caused by molecules, with a diameter considerably smaller than the wavelength, another theory is applicable, the Rayleigh approach see section 2.6.

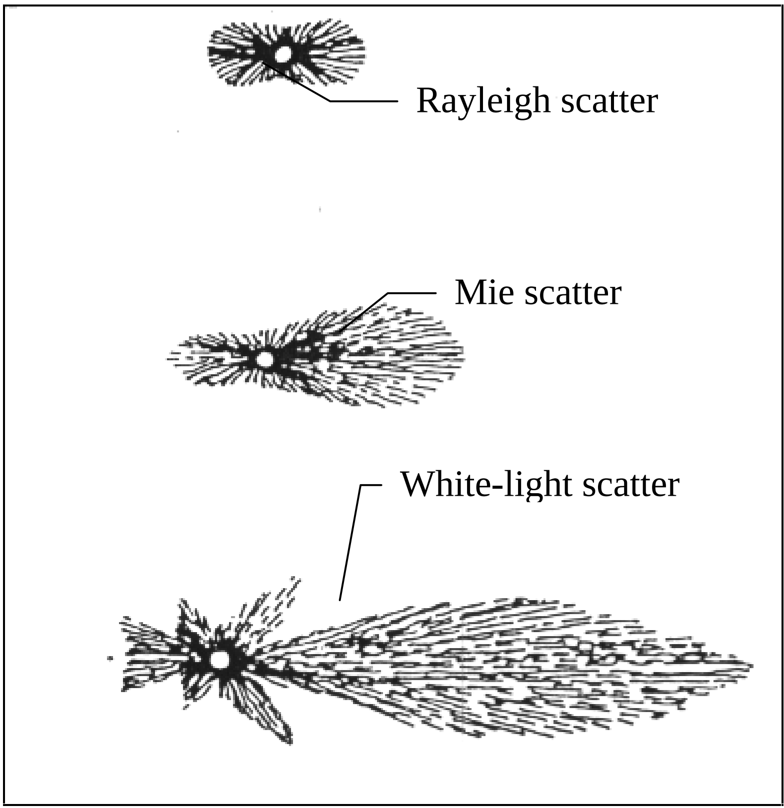


Figure 2-6 *The asymmetry of the three different types of scattering. Rayleigh, Mie and finally white-light scatter. The differences between these types of scatter is related to the size of the particles. The light comes from the left in the figure, Nilsson (1994).*

2.5.4 Refraction

Radiation is refracted, in the same way as light through a lens, due to the refractive index of the atmosphere. This refractive index is dependent upon the current temperature. The refraction induces directional errors and these effects are pronounced at long ranges and low altitudes over land or sea.

2.6 Gas attenuation

As mentioned in section 2.2, the atmosphere consists of particles and gases. However, only a few of these gases are active in the IR area and thereby attenuate by the above mentioned mechanisms.

2.6.1 Gas absorption

When considering gases, or rather the molecules forming the gases, absorption is the most wavelength-selective attenuation effect in the optical spectrum. Absorption by molecules defines the transmission windows available in the atmosphere. For example, the Greenhouse effect is caused by absorption of blackbody radiation with a maximum in the 10 μm region from the earth's surface. The energy that the atmosphere absorbs is transformed into heat and the global temperature increases.

Planck's law is the basic concept in absorption and emission, see section 2.1.2. A photon, with a frequency such that h, Planck's constant, times the frequency is equal to the energy difference between two energy levels in the molecule, is absorbed by the system. There are three types of quantification *rotation*, *vibration* and *electron excitation*. The third one requires photons in the UV region and is therefore of no interest.

In order to achieve a rotation quantification the molecule must be a dipole, every two atomic molecule and the non symmetric molecules that consists of more than two molecules are dipoles.

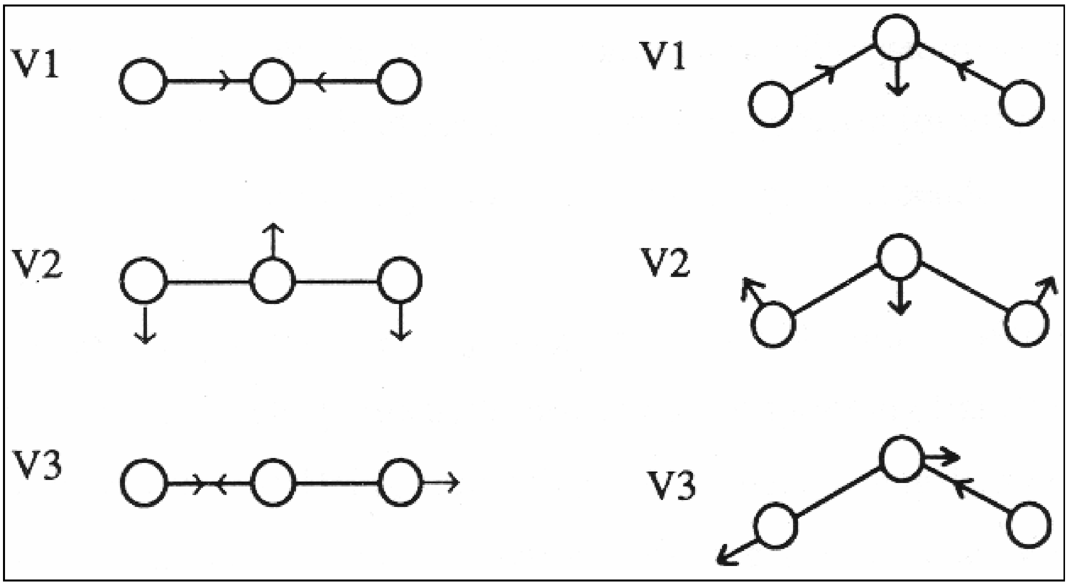


Figure 2-7 *Vibration modes for three atomic molecules, linear to the left and non linear to the right, (Nilsson 1994).*

Dipoles also vibrate and thereby create vibration quantification in certain vibration modes see Figure 2-7.

The two major constituents of the atmosphere are nitrogen and oxygen, which consist of two atoms without dipole moments and therefore have no infrared absorption bands. The IR active gases and their effect are shown in Figure 2-8. The two, by importance, outstanding contributors to gas absorption are carbon dioxide, CO_2, and water vapour, H_2O, which absorb whole bands of wavelengths.

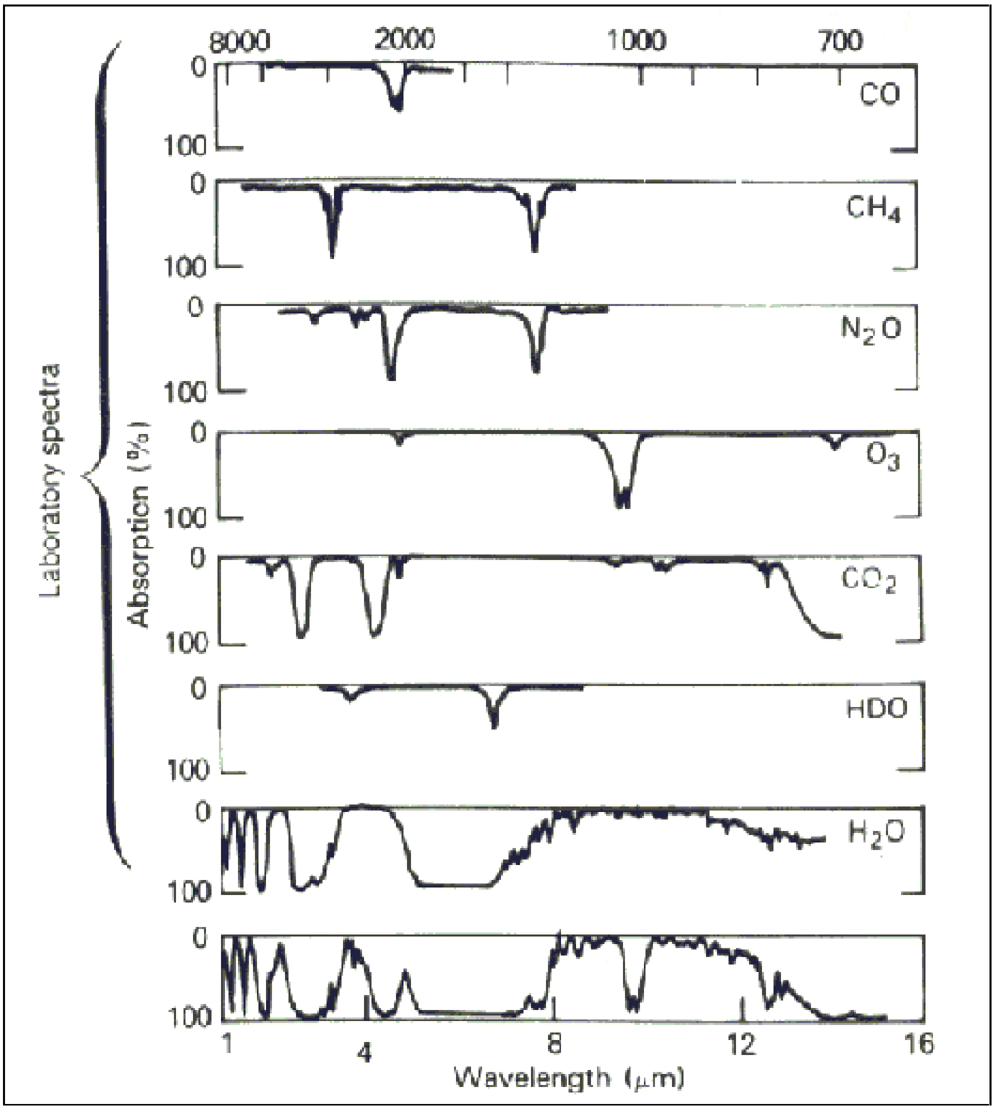


Figure 2-8 *The contributions from different gases in the atmosphere to the overall gas attenuation expressed in absorption versus wavelength, (Smith 1993).*

Water vapour, an asymmetric top molecule, has a strong dipole moment and the fact that each water vapour molecule consists of two light hydrogen atoms result in strong and broad absorption bands. Within the atmospheric windows we have both continuum and local line absorption due to water vapour.

Carbon dioxide, CO_2, is a symmetric linear molecule consisting of three atoms. This means that CO_2 has three vibration modes V1, V2 and V3 see Figure 2-7. The comparatively heavy atoms give CO_2 a narrower but more compact spectral range than water vapour. V3 causes nearly 100% absorption at 4.3 µm, which divides the 3 to 5 µm window into two parts. The other mode V2 causes a broad absorption band around 15 µm which coincide with the water bands.

Ozone, O_3, is an asymmetric-top polar molecule. The vibration mode V3 causes an absorption peak with approximately 60% absorption at 9,6 µm, in the middle of the 8-12 µm window. The other ozone absorption in the IR area drowns in the water band 5.5-7.5 µm. Ozone is, as we all know, most active in the UV wavelengths.

Methane, CH_4, is a spherical-top, non-polar molecule with three IR active rotational bands located at 3.3, 6.5 and 7.7 µm. (Smith 1993, Zissis 1993, Nilsson 1994)

2.6.2 Molecular scatter

This kind of scatter is often called Rayleigh scatter and is responsible for, among other things, the blue appearance of the clear sky. Rayleigh found that the scattering flux is proportional to the inverse fourth power of the wavelength, see equation (2-8).

$$\sigma_{sca}(z) = \frac{1}{\lambda^4} \cdot \frac{8\pi^3 (n^2-1)^2 N(z)}{3N^2(0)} \cdot \frac{(6+3\delta)}{(6-7\delta)} \ [\mathrm{km}^{-1}] \qquad (2\text{-}8)$$

where:

$\sigma_{sca}(z) =$ scattering coefficient.

$\delta =$ depolarisation factor.

$z =$ altitude.

$N(z) =$ number density of gas molecules at altitude z.

$n =$ index of refraction

$\lambda =$ wavelength

The Rayleigh approach is applicable for molecules as they are small compared to IR wavelengths. (Smith 1993)

2.7 Aerosol attenuation

Aerosols are atmosphere borne particles, dust, ice, salt, etc. There are many different underlying processes that generate aerosols, which means that there will be many different types and compositions of aerosol in the atmosphere.

The effect of aerosols depend greatly upon the size of the particles and on their composition. Aerosols are hygroscopic[7] and therefore change their size and the refractive index of the atmosphere when the relative humidity changes. This means that the attenuation effect from aerosols increase considerably with higher water vapour concentrations.

Normally, the absorption effect in aerosols is considerably smaller in comparison with the scattering effect, especially when considering IR wavelengths, (Hågård 1993).

There are quite large variations in the concentrations of the aerosols, from one day to another and even from one hour to another, which of course makes modelling rather difficult.

2.7.1 Aerosol scatter

Photons can of course ”bounce” several times on their way, but the behaviour of this multiple scatter is very difficult to predict therefore the single scatter approximation is normally used. This simplest form of aerosol scatter is covered by Mie theory. Mie theory assumes that the particles are spherical and that the particles are separated from each other in such a way that scatter from one neighbouring particle does not affect the others.

Real particles are not spherical but unless you study polarisation properties or measure backscatter this is a reasonable assumption. The Mie solution for scatter is a lengthy but straight-forward process. The result is an infinite series expression for the field components polarised perpendicular and parallel to the scattering plane. (Smith 1993)

[7] By hygroscopic (from the Greek words hygro´s wet moist, skope´ see, observe) is meant that they accumulate water especially when the relative humidity reaches the for this phenomena critical value of about 70%, (Hågård 1993).

2.8 Attenuation coefficient

When a beam of a certain wavelength travel through a medium we achieve attenuation depending on the composition of the medium. To calculate the attenuation we have defined an attenuation coefficient σ. This coefficient can be divided in order to take into account separate attenuation contributions. One common division consists of two parts, one absorption part and one scattering part.

$$\sigma_{ext} = \sigma_{abs} + \sigma_{sca} \ [\mathrm{km}^{-1}] \qquad (2\text{-}9)$$

Another common division consists of a gas part and a aerosol part,

$$\sigma_{ext} = \sigma_{gas} + \sigma_{aerosol} \ [\mathrm{km}^{-1}] \qquad (2\text{-}10)$$

or the combination of (2-9) and (2-10)

$$\sigma_{ext} = \sigma_{gas,abs} + \sigma_{gas,sca} + \sigma_{aerosol,abs} + \sigma_{aerosol,sca} \ [\mathrm{km}^{-1}] \qquad (2\text{-}11)$$

The attenuation coefficient is often called *extinction coefficient* and the unit is [km^{-1}]. The attenuation of a monochromatic beam with the power P_0 can be calculated with Beers law, (Smith 1993, Zissis 1993), in the following manner

$$P = P_0 \cdot e^{(-\sigma_{ext} \cdot R)} \ [\mathrm{W}] \qquad (2\text{-}12)$$

where

$P_0 =$ The initial power of the beam
$P =$ Remaining power after the beam has travelled the distance R

In this way we achieve a measure of the attenuation in the atmosphere per distance. This coefficient is normally wavelength dependent. Then, in order to calculate how much radiation that in fact penetrates the atmosphere, the atmospheric transmission, we need another measure.

2.9 Atmospheric transmission

The atmospheric transmission over a certain distance can easily be calculated if we know the extinction coefficient in the atmosphere that the radiation has to cross. The atmospheric transmission is expressed in the following manner:

$$\tau(\lambda) = \frac{P(\lambda)}{P_0(\lambda)} = e^{\left(-\sigma_{ext}(\lambda)\cdot R\right)} \text{ [-]} \qquad \textbf{\textit{(2-13)}}$$

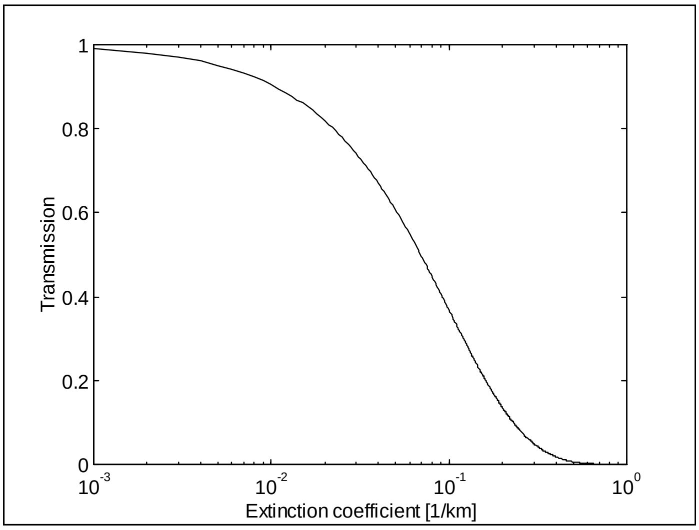
where

$P(\lambda) =$ wavelength dependent power [W]
$P_0(\lambda) =$ wavelength dependent initial power [W]
$\sigma(\lambda) =$ wavelength dependent extinction coefficient [km^{-1}]
$R =$ range [km]

To clarify the relation between transmission and extinction we have included Table 2-3 and the corresponding figure.

Table 2-3 *Transmission versus extinction coefficient*

$\tau_{10\ km}$	σ_{ext} [km^{-1}]
0.99	0.001
0.95	0.005
0.90	0.01
0.61	0.05
0.37	0.1
0.007	0.5
0	1



Due to the constrained effect of gases and particles discussed in the previous sections the IR-transmission reaches the highest average values in the wavelength windows 2-5 µm and 8-12 µm. The transmission of optical radiation has a complex relation to variations in weather situation, gas mix and density.

2.10 Range equation

With the previous theory we are now capable to deal with how to use and formulate a range equation. The range equation, i.e. an equation computing the maximum range at which a point target can be detected by an electro-optical system, is proposed in (Campana 1993) to be

$$R = \sqrt{\frac{\int_0^\infty \tau(\lambda)\cdot I_t(\lambda)\cdot d\lambda}{NEI}} \text{ [m]} \qquad (2\text{-}14)$$

where

R	Range from object to sensor	[m]
$\tau(\lambda)$	Atmospheric transmission	[-]
$I_t(\lambda)$	total radiant intensity	[W]
NEI	Noise Equivalent Irradiance	[W/m^2]

NEI is a measure of the sensor effectiveness as a photon detector. Inherent in every sensor are sources of noise, due to thermal generation and other factors. ”High noise levels” means that more photons per second have to reach the detector elements in order to produce a discernible signal. NEI is then simply the amount of photons, expressed in power terms, required to produce a signal of the same amplitude as the Root Mean Squared, RMS, noise signal.

$I_t(\lambda)$ determines the characteristics of the object signature, the heat footprint of the object, which of course is dependent upon wavelength.

At a first glance this equation can seem simple enough, but there are some troublesome parts that we have to investigate further, see section 5.5.

3 Problem Description

The objective for this master thesis is to consider the atmospheric transmission or rather the factors which influence atmospheric transmission, qualitatively and quantitatively in order to calculate sensor ranges. To accomplish this we must solve the following problems:

- First we got to obtain basic knowledge about the atmosphere and atmospheric effects on IR radiation.

- The second step is to derive and present a range equation for optical sensors acting in this environment.

- Then in order to use this range equation we must investigate the included relevant parameters further with special interest of the atmospheric variations in time and space.

3.1 Information sources

The major sources of information available to us during this study are the following:

- Various books and articles covering IR-radiation basics.
- Measured data concerning atmospheric properties at high altitude, (Vaughan 1995, Alejandro 1995)
- Measurements made from ground towards the sky, (Nilsson 1990).
- Theoretical analyses of test runs made in MODTRAN/LOWTRAN

3.2 Basic considerations

Below we have collected some of the fundamental questions and basic considerations that are to be investigated during this study.

- Which atmospheric parameters regarding atmospheric transmission have the largest impact on the sensor range ?

- Which are the reasonable intervals of the parameter values expected to be found under operating conditions ?

- Is it possible to derive a model for practical use taken natural variations of atmospheric conditions into account? And if so, which alternative ways are available to accomplish such a model ?

4 MODTRAN

The models and theories discussed in Chapter 2 could be put together in some kind of computer code in order to make the calculations of atmospheric transmission easier and more straight-forward. The codes that are most commonly used are, LOWTRAN, MODTRAN and FASCODE, (Smith 1993). We have used MODTRAN in the shape of PCMODWIN3 during this study.

4.1 What is MODTRAN

The codes above are developed by the Phillips Laboratory former Air Force Geophysics Laboratory, AFGL. AFGL has been the centre in the United States for atmospheric modelling since the late 1960s. All of these codes can calculate atmospheric transmission and radiance for various scattering and absorption phenomena, both in slant and horizontal paths. The major difference between these codes is that they have different spectral resolution, see section 4.2. LOWTRAN uses low resolution, 20 cm^{-1}, MODTRAN uses moderate resolution, 2 cm^{-1} and FASCODE uses high resolution. FASCODE uses a database called HITRAN directly, while LOWTRAN/MODTRAN uses HITRAN indirectly for calculation of the model parameters. (Smith 1993)

4.2 MODTRAN Method

The predecessor of MODTRAN is LOWTRAN. The first available version of this code was LOWTRAN2, in 1972. Since then several improvements have gradually been introduced with the updated versions.

The model covers a spectral range from 0 to 50000 cm^{-1} and delivers a resolution of 2 cm^{-1}. The wavenumber resolution can be transformed to wavelength resolution at a specific wavelength by deriving the wavenumber equation (4-1) with respect to wavelength which yields equation (4-2) which can be rewritten as (4-3).

From this final equation the wavelength resolution corresponding to 2 cm^{-1} (maximum resolution) at 0.5 µm can be calculated to be 0.00005 µm and correspondingly at 10 µm it will be 0,02 µm

$$\nu = \frac{0.01}{\lambda} \tag{4-1}$$

$$\frac{d\nu}{d\lambda} = -\frac{0.01}{\lambda^2} \tag{4-2}$$

$$d\lambda = \left|\frac{\lambda^2}{0.01}\right| \cdot d\nu \tag{4-3}$$

The atmosphere is described as 32 layers from 0 to 100 km altitude. Layer thickness varies somewhat, but up to the altitude of 25 km each layer is 1 km thick. Each layer is physically characterised by standard models valid for various geographical regions and seasons. MODTRAN supports six different reference model atmospheric profiles which specifies gas contents etc. for each layer.

- Tropical (15°N Latitude Annual average)
- Mid-Latitude Summer (45°N Latitude July)
- Mid-Latitude Winter (45°N Latitude January)
- Sub-Arctic Summer (60°N Latitude July)
- Sub-Arctic Winter (60°N Latitude January)
- US Standard

Sub-Arctic Summer, SAS and Sub-Arctic Winter, SAW are most relevant models considering Swedish conditions. Therefore we have preferably used these models during this study.

There are also possibilities to define an atmosphere of your own, and we have made use of this feature, see section 4.3. Attenuation is calculated for each layer and then summed along the specified path. MODTRAN uses an approximate exponential function, equation(4-4) to calculate transmittance.

$$\tau = e^{-(CW)^a} \qquad (4\text{-}4)$$

$$W = \left(\frac{p}{p_0}\right)^n \cdot \left(\frac{T_0}{T}\right)^m \cdot U \qquad (4\text{-}5)$$

$$C = 10 \cdot C' \qquad (4\text{-}6)$$

Equation (4-7) is used for all absorbers except water vapour that uses equation (4-8) instead.

$$U = 0.7732 \times 10^{-4} \cdot r \cdot \rho_a \cdot Z \qquad (4\text{-}7)$$

$$U = 0.1 \cdot \rho_w \cdot Z \qquad (4\text{-}8)$$

Parameters in these equations are:

p, p_0	Pressure, [atm]
T, T_0	Temperature, [K]
r	Mixing ratio, [PPMV]
ρ_a, ρ_w	Density, index a for air, w for water [g/m^3] U Absorber amount, [atm cm] for equation (4-7) and [g/cm^2] for equation (4-8).
Z	Path length, [km]

The model is then further defined with the absorber parameters a, n, m and C´. The first three parameters cover the spectrally independent features of the absorber and the C´ covers the spectral dependency. C is redefined in terms of C´ for computational convenience. These parameters are listed in (Abreu 1996).

4.3 MODTRAN accommodation

In MODTRAN there are several pre-defined models using standard atmospheres and interpolations of these. In order to adapt to conditions differing from pre-defined standard conditions MODTRAN atmospheric model can be adjusted, and it is thereby possible to define an atmosphere of our own.

This is done by specifying a set of atmospheric layers. These layers are defined at their boundaries by temperature, pressure density etc. Then MODTRAN interpolates values in each layer depending on the parameter settings at the boundary.

Since we have used MODTRAN with some difficulty we have included a users guide to PCMODWIN3, that is a program that runs MODTRAN in Microsoft Windows environment, see MODTRAN users guide.

In this users guide we have included the operations that are necessary for elementary use of the program. But we have also included some more advanced applications such as defining an atmosphere of your own.

5 Atmospheric investigations

This chapter covers the range equation and the further atmospheric investigations necessary to use this equation. We start with a minor adaptation of MODTRAN. Then we proceed with more thorough investigations of gases, aerosols and clouds. Finally we build the bricks together to form a concluding range equation.

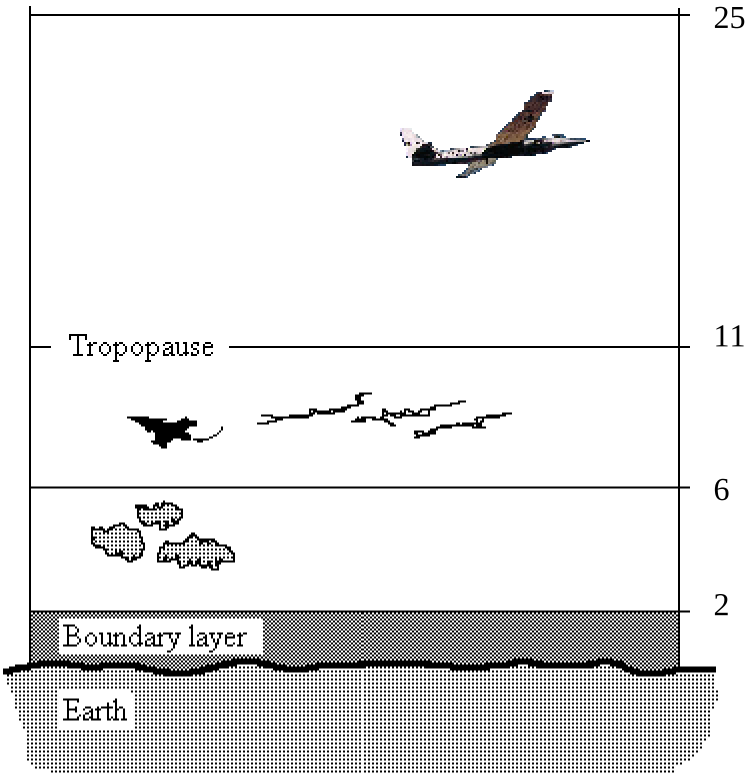


Figure 5-1 *Our model atmosphere consisting of four atmospheric layers with indicated boundaries in kilometres.*

5.1 MODTRAN test platform

As mentioned in section 4.3 it is possible to adapt MODTRAN by defining an atmosphere of your own. The test model atmosphere we mostly used consists of four layers, see Figure 5-1, and thereby five boundaries whereas the original MODTRAN model atmosphere has 32 layers.

Since one have to specify all parameters for each layer we have limited the model to include four layers in order to reduce the workload generated when changing single parameters. On the other hand we have chosen the layers with some care to include natural variations of the atmosphere.

The first layer, often referred to as the boundary layer, reaches from 0-2 km. In reality the boundary layer top altitude changes during a normal day, but the boundary layer is in MODTRAN defined to be at 2 km. This layer is characterised by a quite ”thick” atmosphere caused by relatively large concentrations of both gases and aerosols. Consequently, the magnitudes of the parameters in this layer are rather different than above the boundary layer and it is a good idea to treat this layer separately.

The second layer, 2-6 km is rather arbitrarily chosen but we wanted a controllable boundary between the boundary layer and the tropopause.

Then the third layer reaches from 6-11 km, this choice might seem a bit odd since we primarily are interested in altitudes between eight to twelve kilometres. However, MODTRAN estimates that the tropopause is located at 11 kilometres and this justifies this boundary.

The last layer in our model reaches from 11-25 km. Even if the upper limit primarily is set to 12 km we have decided to include altitudes up to 25 km in order to make sure that we cover all, for our purposes, interesting parts of the atmosphere.

Then we used this model atmosphere to perform tests to see which parameters that have the greatest impact on the transmission. We let one parameter change progressively while the others were kept constant and then registered the results. For instance, you can change the water vapour content in the layer your are interested in and let all other parameters be constant. This can only be done in a single atmospheric layer since all parameters change with altitude. more about the results from these investigations in sections 5.2 and 5.3.

5.2 Gases

To what extent gases attenuate depends on both molecular effects and the actual concentration of the gas. The concentration of all atmospheric gases vary more or less with altitude, see Figure 5-2.

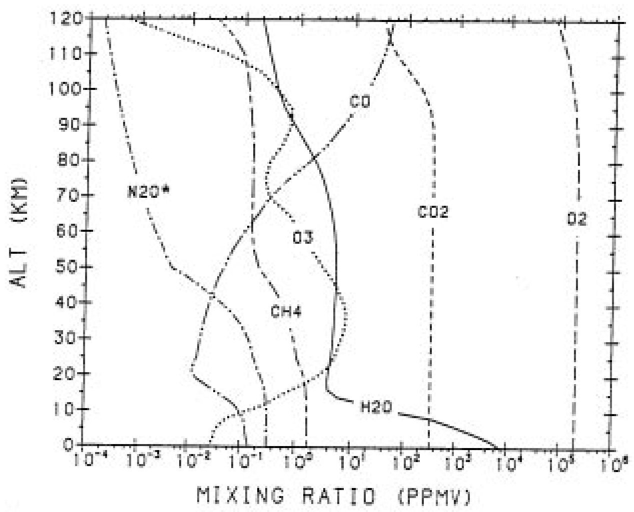


Figure 5-2 *The different IR active gases of our atmosphere have varying concentrations with altitude. USA standard atmosphere, (Abreu 1996).*

After having performed numerous simulations with MODTRAN and after theoretical research see section 2.6, we have isolated the gases which have the greatest effect on the transmission in the 3-12 μm band.

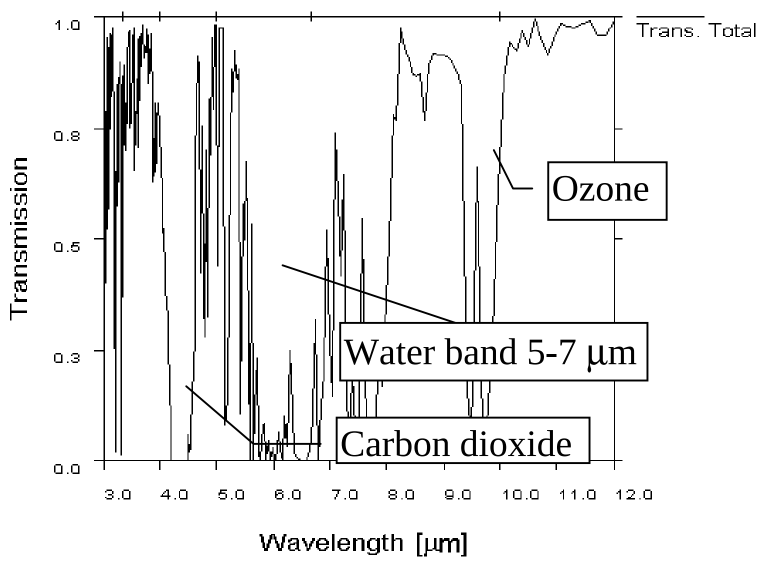


Figure 5-3 *A transmission plot from MODTRAN. At 10 km altitude over a range of 100 km with the SAS standard model, on which we have indicated the primary causes for decrease of transmission. This plot shows the total transmission from gases.*

We found that the three gases water vapour, carbon dioxide and ozone, see Figure 5-3 had the greatest impact in this band.

5.2.1 Water vapour

As mentioned in the theory chapter section 2.6, water vapour, H_2O is an important absorber in the 3-12 µm band. In Figure 5-4 a typical transmission plot is shown, in which we can see that the absorption lines due to vibration, rotation and the combination of them both, are very close to each other and therefore eliminates almost all IR radiation in the 5-7 µm region. In Figure 5-4 we can also see the effect of the H_2O continuum absorption.

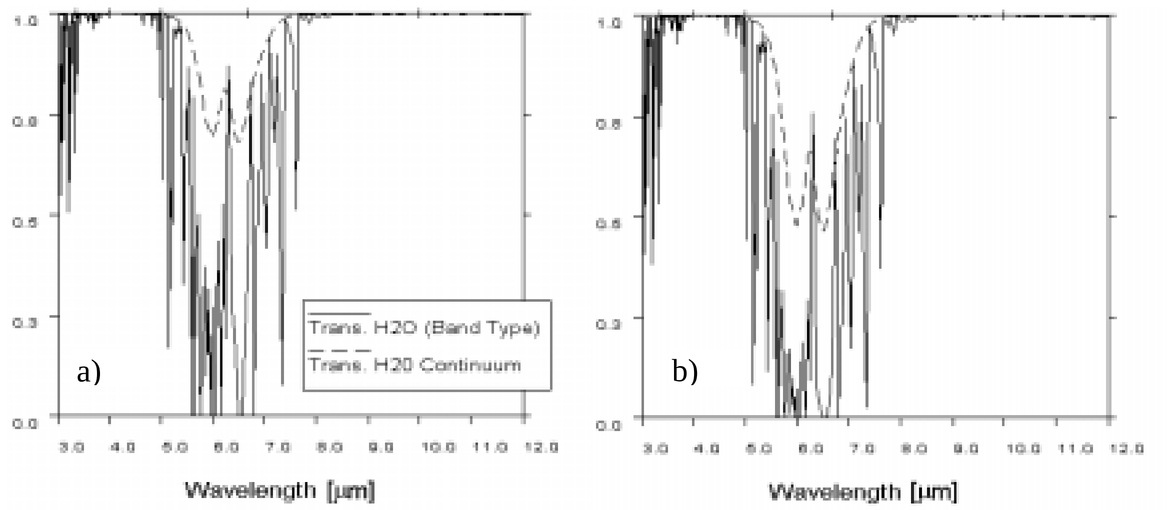


Figure 5-4 *Water vapour transmission for the SAS model in MODTRAN at 10 km altitude over two distances, a) 50 km and b) 100 km. Both continuum and band effects are shown.*

This specific plot was calculated for a distance of 100 km but if we increase the distance then both the continuum and the band curves will deepen increasingly with distance but just broaden marginally over wavelength. The air mass origin and seasonal effects are also important factors.

The H_2O content changes with temperature and pressure and will therefore change with altitude, in Table 2-1 page 11, we can see the dramatic change in H_2O content with altitude for two MODTRAN models concerning summer and winter conditions. This means that the H_2O content can change significantly between a cold and a warm day, in particular in the boundary layer. If the H_2O content at the altitude of interest is known then the transmission loss due to H_2O can be accurately calculated. Since water vapour hardly attenuates within the atmospheric windows, 3-5 µm and 8-12 µm, H_2O just marginally affect the *effective transmission*, see section 5.5.1 page 46. This means that the direct effects of water vapour could be disregarded because that sensors are designed to avoid this H_2O problem by ”looking” in the atmospheric windows instead. H_2O also contributes to attenuation indirectly and these effects cannot be disregarded and H_2O must be considered to be a highly relevant parameter to model, see sections 5.3 and 5.4.

5.2.2 Carbon dioxide

Carbon dioxide, CO_2, causes nearly 100 % absorption around 4.3 µm, see Figure 5-5. CO_2 also have a few other but not as powerful absorption bands at 9.5 µm and 10.5 µm.

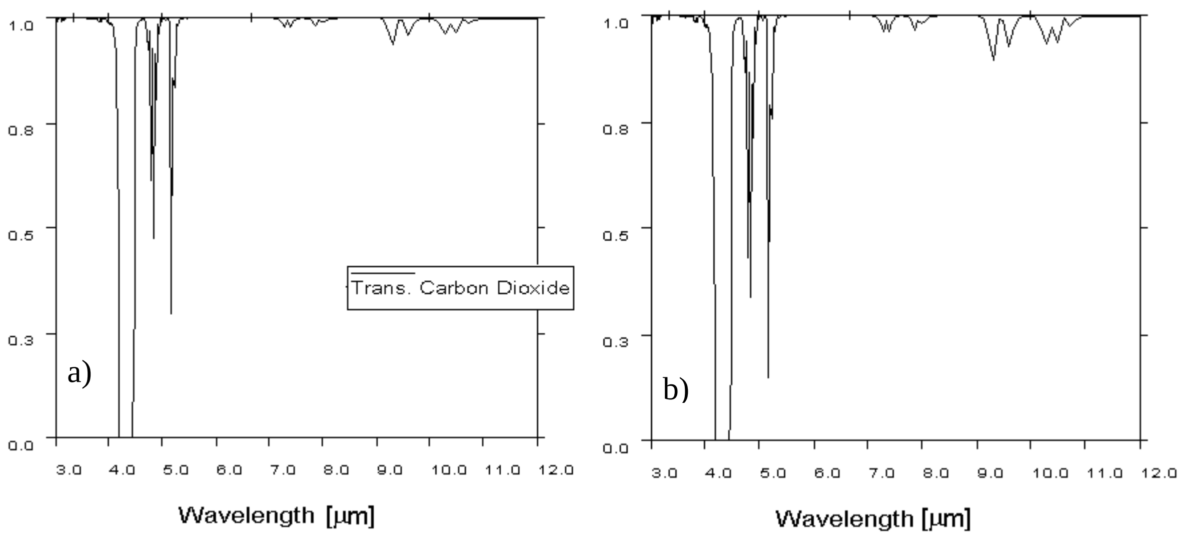


Figure 5-5 *Transmission losses caused by carbon dioxide for the SAS model in MODTRAN at 10 km altitude over two distances, a) 50 km and b) 100 km.*

The transmission losses due to CO_2 increases with range in the same fashion as water vapour does, but in contrast to water vapour the relative concentration of carbon dioxide is more or less constant with altitude, see Figure 5-2, and the seasonal effects are quite modest see (Abreu 1996).

5.2.3 Ozone

Ozone, O_3, is as we know from the theory chapter section 2.6 mostly active in the UV region, but also has a strong band around 9.6 µm see Figure 5-6.

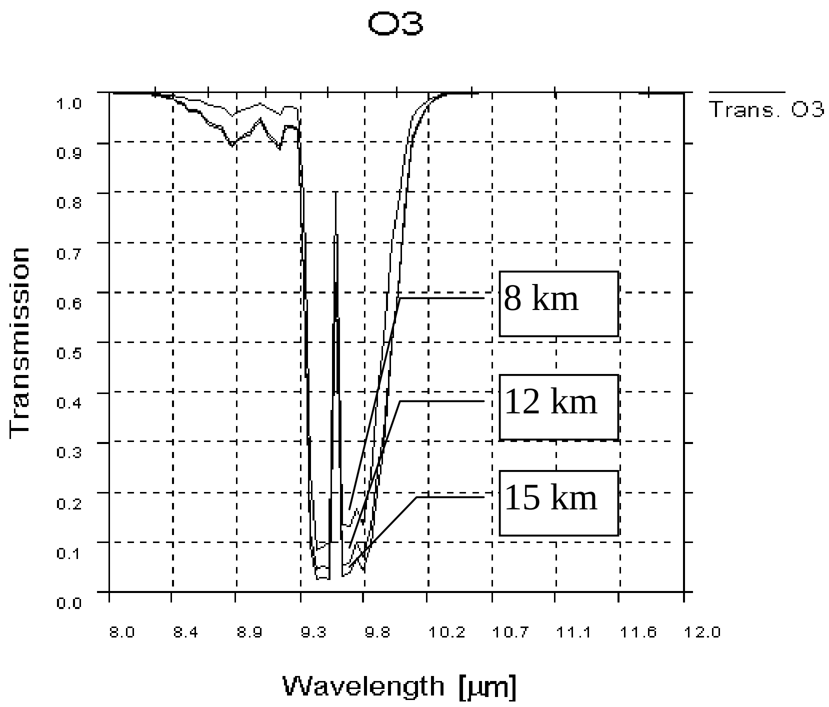


Figure 5-6 *The ozone concentration varies with altitude and has got a maximum at about 22 kilometres of altitude, the so called ozone layer. For the band at 9.6 µm the maximum seems to be at 12-15 kilometres of altitude, this plot contains three graphs at altitudes from 8 to 15 km but all of them are calculated for a distance of 100 km and the SAS model with the MODTRAN program.*

Unlike most other gases O_3 concentration increases with altitude, see Figure 5-2, but similar to carbon dioxide, the concentration is quite constant over time. Therefore O_3 transmission effects should also be rather accurately determined with MODTRAN.

5.2.4 Gas summary

There are three major attenuation gases, water vapour carbon dioxide and ozone. Water vapour is identified as an important parameter to include in an atmospheric model. The transmission losses due to direct attenuation by gases can be calculated with satisfactory accuracy with the LOWTRAN/MODTRAN computer codes, (Nilsson 1986, Hågård 1992).

5.3 Aerosols

In difference to the well explored molecular effects, the contribution due to atmospheric aerosols in relation to meteorological variables is not firmly established. There are many different underlying processes that generate aerosols, which means that there will be many different types and compositions of aerosol in the atmosphere.

However assuming that we have spherical particles and that the size distribution of the aerosols and the refractive index is known, we can calculate the aerosol extinction coefficient with Mie theory, see section 2.7.1 or (Smith 1993).

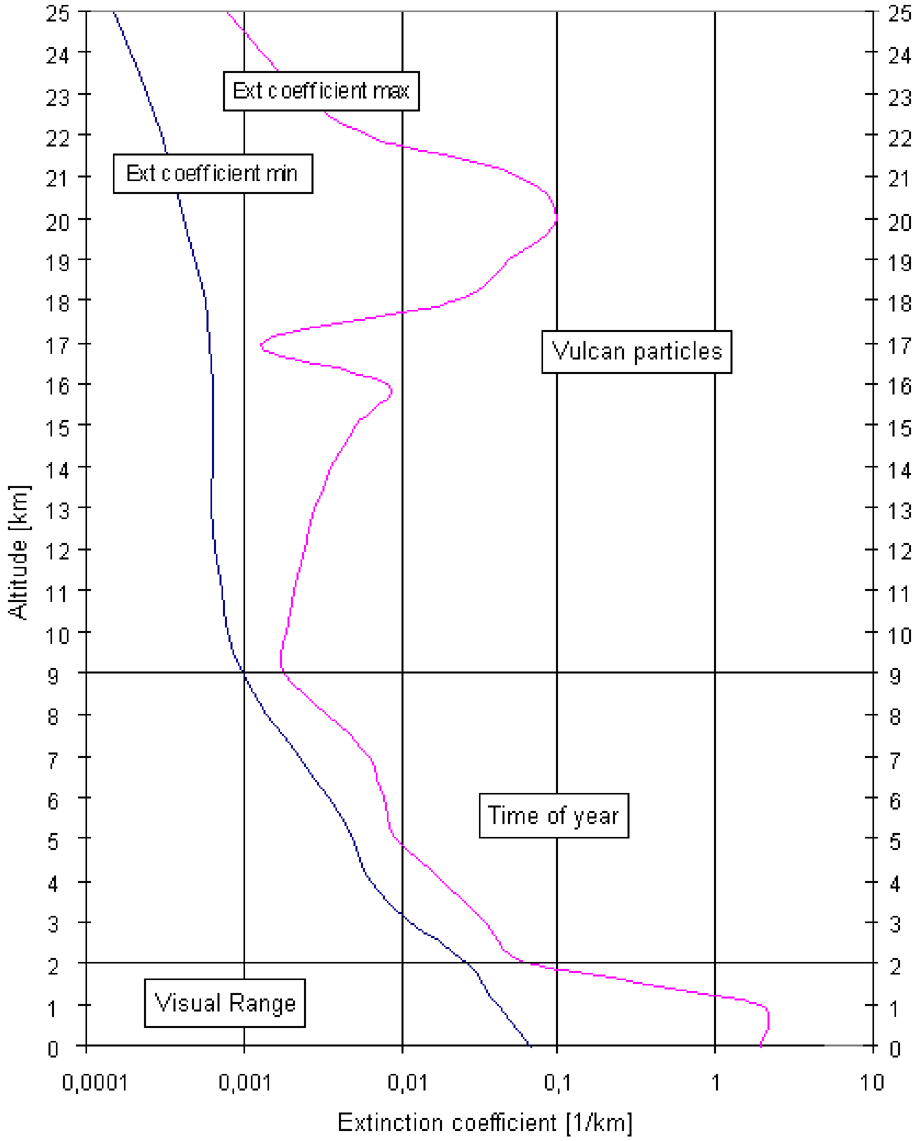


Figure 5-7 *Vertical distribution aerosol extinction used in MODTRAN. The important parameter, visual range, time of year or Vulcan particle concentration are indicated in each layer, (Jursa 1985).*

In Figure 5-7 a vertical aerosol extinction coefficient distribution is shown.

5.3.1 Wavelength independence

Tests with MODTRAN indicates that it would not be a too rough approximation to consider the aerosol extinction qualities as independent of wavelength, at least within a single atmospheric IR-window. In Figure 5-8 a plot from one of our test runs is included. However, if we consider larger intervals of wavelengths, see Figure 5-10, a wavelength dependency is present but with our limitations this is a valid statement.

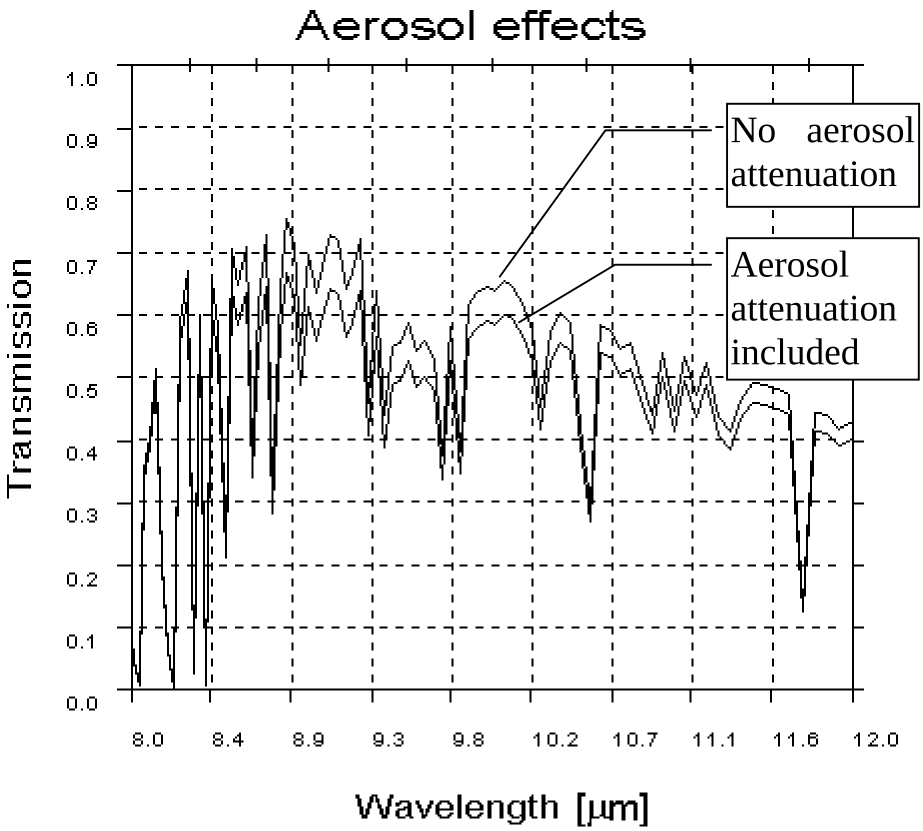


Figure 5-8 *Aerosol wavelength independence. The upper curve shows the atmospheric transmission without aerosol effects and in the curve below is the aerosol effect included. The curves follow each other quite well but are separated somewhat in the vertical plane illustrating the wavelength independence assumption. This MODTRAN plot is generated with MODTRAN set at 1 km of altitude, 10 km pathlength and 23 km visual range in the rural aerosol model using the SAS atmospheric model.*

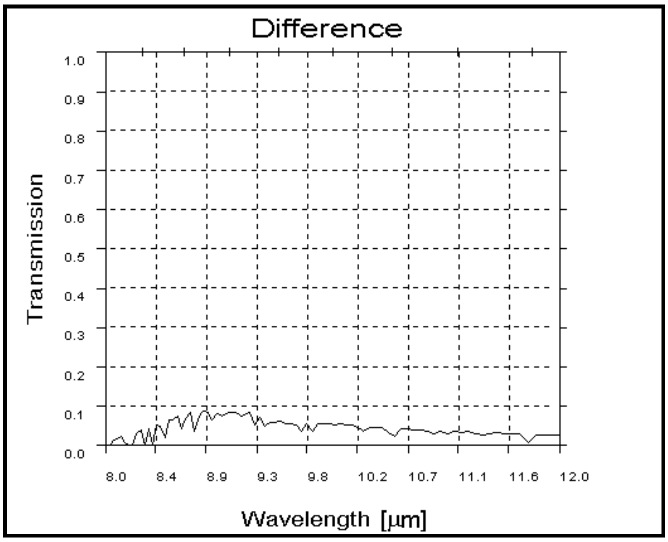


Figure 5-9 *differential plot of curves shown in Figure 5-8.*

If we plot the difference between these graphs, see Figure 5-8, the assumption of wavelength independence can be supported. Test run, similar to the one shown in figures Figure 5-8 and Figure 5-9 have also been made for wavelengths between 3 and 5 µm with similar result. The effect of the aerosols is approximately the same for all wavelengths within the atmospheric windows.

5.3.2 Effects of Humidity Variations on Aerosol Properties

The basic effect of changes in the relative humidity on the aerosols, is that as the relative humidity increases, the water vapour condenses out of the atmosphere onto the existing atmospheric particles.

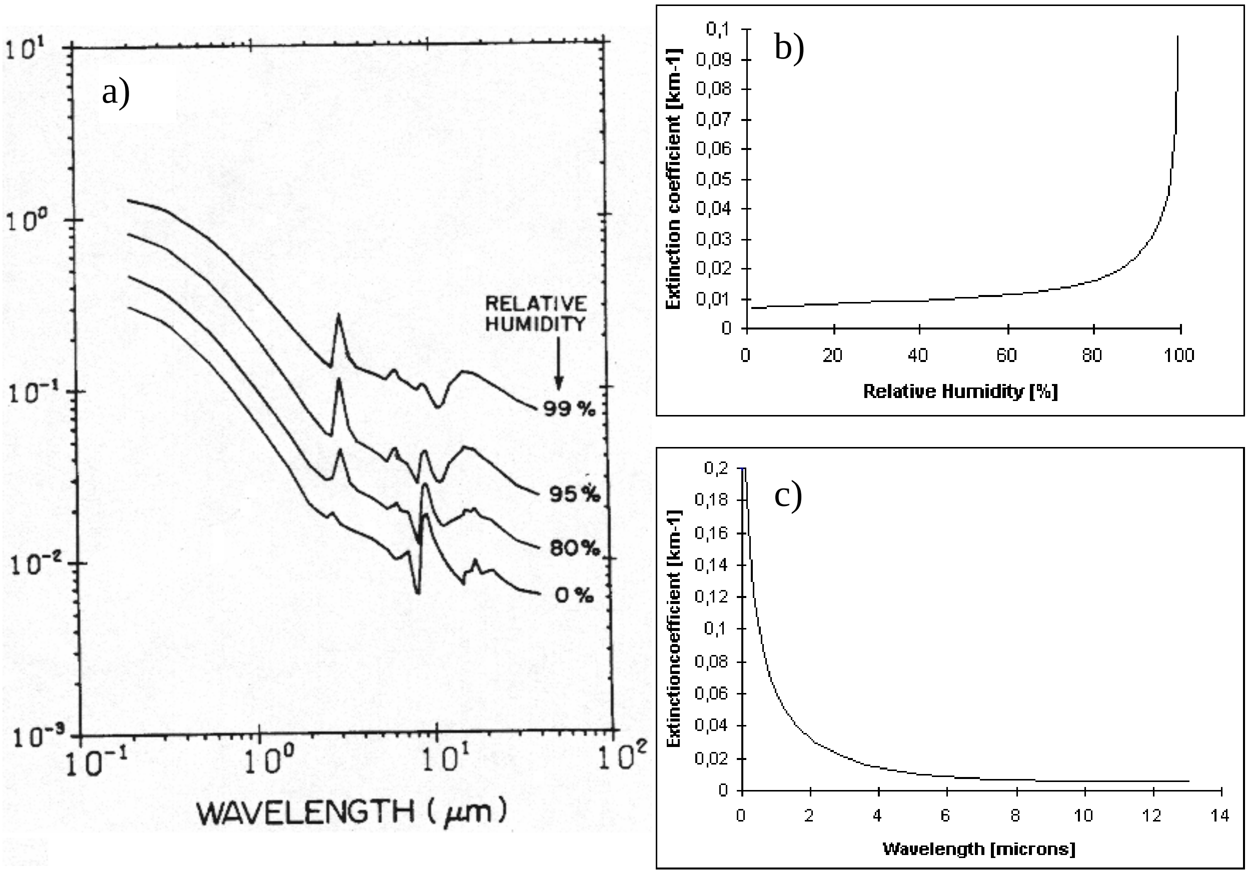


Figure 5-10 *The aerosol extinction coefficient changes with humidity rather dramatically. 5-10 a) is a summarisation of 5-10 b) & c) showing the aerosol extinction coefficient variations with both wavelength and relative humidity, with the rural aerosol model (Jursa 1985). 5-10 b) shows only extinction versus relative humidity and 5-10 c) shows only the spectral effects upon extinction coefficient.*

This condensed water increases the size of the aerosols, and changes their composition and their effective refractive index. The resulting effect of the aerosols on the absorption and scattering of radiation will correspondingly be modified. In Figure 5-10 we can see that as the water vapour content increases, the aerosol extinction coefficient increases in a logarithmic fashion, see especially Figure 5-10 b), but seems to be approximately linear with the same inclination with respect to wavelength, at least in the 3-12 μm band.

5.3.3 Backscatter coefficient

The most common way of measure aerosol extinction is to emit radiation with for instance a laser and then measure the amount of radiation that gets reflected back by the aerosols. This measure is called the backscatter coefficient.

The most recent relevant data that we have come across are actually a measurement of backscatter coefficient. A small excerpt from the extensive material is shown in Table 5-1.

Rensch and Long, (Rensch 1970), investigated the relationship between extinction and backscatter in the seventies. From their investigations we have derived the approximate equation (5-1)

$$\beta = \frac{\sigma_{ext,\ ero}}{2.5 \times 10^{-2}} \ [\mathrm{km}^{-1}\ \mathrm{sr}^{-1}] \qquad (5\text{-}1)$$

This simple relation was also supported by (Hågård 1998), associate professor at Defence Research Establishment, Department 3, Linköping Sweden.

Table 5-1 *Backscatter coefficients, β [km^{-1} sr^{-1}], measured in the Northeast Atlantic and in United Kingdom during summer. Within each β interval (the first row of the table) the percentage of the total number of measurements, M, performed during the indicated number of flights, Flt, is presented. The percentage does not add up to 100 because of failed measurements of β, (Vaughan 1995).*

Alt [km]	β	*< 6.3E-09*	*6.3E-09 2E-08*	*2E-08 6.3E-08*	*6.3E-08 2E-07*	*2E-07 6.3E-07*	*6.3E-07 2E-06*	*2E-06 6.3E-06*	*Flt*	*M.*
11-12		0.41	29.72	21.83	4.21	1.56	1.27	1.48	14	6366
10-11		0.18	26.47	24.83	4.21	3.60	2.05	2.30	16	15797
9-10		0.22	9.41	8.81	6.39	14.01	3.18	3.88	16	12253
8-9		0.02	11.07	15.33	10.06	10.68	5.92	2.10	16	4643
	β	*6.3E-06 2E-05*	*2E-05 6.3E-05*	*6.3E-05 2E-04*	*2E-04 6.3E-04*	*6.3E-04 2E-03*	*2E-03 6.3E-03*	*6.3E-03 >*	*Flt*	*M*
11-12		1.76	2.75	4.15	2.72	3.61	3.75	12.88	14	6366
10-11		2.96	3.51	3.61	3.16	3.54	2.11	8.83	16	15797
9-10		6.15	9.22	4.46	4.61	6.62	6.89	12.95	16	12253
8-9		4.42	5.92	1.90	3.02	5.64	4.44	15.74	16	4643

A first conclusion drawn from this material is that the there are quite large variations in the concentrations of the backscatter coefficients, and thereby in $\sigma_{ext,\ aerosol}$. Furthermore, if we study single flights we can conclude that these large variations occur even over shorter periods of time. In the extremes the backscatter coefficient can vary with 5-7 powers of ten which means that accurate models are very difficult to develop, if we do not have a measurement of any parameter related to σ_{ext}, or σ_{ext} itself.

5.3.4 Aerosol summary

The aerosol extinction can, as a first approximation, be considered to be wavelength independent within a single transmission band. Water vapour content, especially when the Relative humidity exceeds 70%, has got a tremendous impact on aerosol extinction coefficient since aerosols are hygroscopic. Large variations in aerosol attenuation with time and altitude make simple modelling difficult if we do not have an accurate up to date measurement of any parameter related to σ_{ext}, or σ_{ext} itself.

5.4 Clouds

As we all know, clouds decrease the sunlight more or less. Clouds also have a high influence on infrared radiation. In Table 5-2 the extinction coefficient in different types of clouds for three infrared wavelength bands are shown. According to this the transmission through clouds is rather low, except for Cirrus clouds.

Table 5-2 *Extinction coefficients for different types of clouds, fog and precipitation in our atmosphere, (Nilsson 1990)*

Altitude [km]	*Cloud / precipitation*	*Extinction coefficient σ_{ext} [km^{-1}] for three wavelength bands*		
		2.5 - 3.5	4.0 - 5.5	8.0 - 12.0
0.05	Fog (0.5)[8]	9.8	8.9	2.4
	Fog (0.2)	20.6	21.3	22.4
	Drizzle	0.7	0.6	0.6
	Light rain	1.2	1.1	1.1
	Moderate rain	1.9	1.9	1.9
	Heavy rain	2.9	2.9	2.8
1	Stratus	35.7	39.6	28.7
	Cumulus	46.7	49.1	44.8
	Stratocumulus	38.8	44.4	26.2
	Nimbostratus	8.6	9.2	8.4
3	Cumulus	24.4	25.6	24.4
	Altostratus	80.5	89.2	55.1
8	Cirrus	0.3	0.3	0.3
12	Cirrus	0.3	0.2	0.3

With support from our test with MODTRAN, which includes models for the most common types of cloud and rain, in combination with the results in Table 5-2 it is apparent that IR sensor ranges through all types of clouds except

[8] The value in the parenthesis is the visual range in kilometres.

cirrus and cirrostratus are to short to be of any practical use. If, for instance, σ is equal to 20 then the transmission over a distance of 100 meters will be 0.14, see Table 2-3.

Another conclusion which we are able to draw from Table 5-2 is that there is not all that many types of cloud present at altitudes beyond 8 kilometres, in fact Cirrus and Cirrostratus are most likely the only clouds present at these altitudes.

Because of this we concentrate our further efforts on Cirrus clouds. The following sections concerning Cirrus clouds are mainly derived from (deBlij 1996, Scorer 1972).

Cirrus is a cloud of fibrous appearance and this structure is due to wind shear and/or falling particles. The cloud consists of ice crystals. Cirrus of some sort appears when almost any cloud is glaciated. There are generally speaking three different kinds of Cirrus, fibrous patches, falling cirrus and extensive cirrus, where extensive cirrus practically can cover the sky.

Cirrus clouds are most often formed due to frontal movements, see section 2.4.2. When the warmer air overrides the colder air a boundary is produced, called a *warm front*. Warm fronts, because of their gentle upward slope, are associated with wide areas of light to moderate precipitation. The Cirrus cloud evolves slowly from Nimbostratus, Altostratus, Cirrostratus until it finally forms Cirrus at altitudes from six to twelve kilometres.

Consequently, the formation of Cirrus clouds is a quite slow process, but on the other hand, they can cover large areas.

Table 5-3 *Relative frequency of high clouds, above 6 km, at station Malmslätt, Sweden during the period 1961-01-01 - 1997-12-31,* ***(SMHI 1998).***

Type cloud/weather	*Relative frequency*
Clear	48,7
Cirrus	36,4
Other	14,9

At middle and upper northern latitudes[9], air masses with significantly different temperatures commonly come together, because the general atmospheric circulation causes poleward-flowing tropical air to collide with polar air

[9] Sweden is located between 56°N and 68°N Latitude.

moving toward the equator. This means that Cirrus clouds are quite common in our northern region. This is supported by data from SMHI, see Table 5-3.

5.4.1 Clouds summary

We conclude that no clouds except Cirrus and Cirrostratus are IR transparent and that Cirrus and Cirrostratus are most likely the only clouds present at 8-12 km of altitude. Because of the general atmospheric circulation clouds are quite common in our northern region.

5.5 Range

The next step is to adapt the range equation, (2-14) at page 26, to fit our purposes by applying the knowledge obtained during the atmospheric investigations.

$$R = \sqrt{\frac{\int_0^\infty \tau(\lambda) \cdot I_t(\lambda) \cdot d\lambda}{NEI}} \qquad (2\text{-}14)$$

This equation uses the total radiant intensity of an object $I_t(\lambda)$ for the determination of the object signature characteristics. A for our purposes more suitable version of this equation should take into account the relation between object and background radiation, see equation (5-2).

$$\Delta I(\lambda) = \left(L_{obj}(\lambda,T) - L_{bgr}(\lambda,T)\right) \cdot A_{obj} \text{ [W/m sr]} \qquad (5\text{-}2)$$

where

L_{obj}	Spectral object radiance	[W/m^2 m sr]
L_{bgr}	Spectral background radiance	[W/m^2 m sr]
A_{obj}	Physical object area in the sensor direction	[m^2]

$I_t(\lambda)$ is therefore replaced by $\Delta I(\lambda)$ according to equation (5-2). One can see from this equation that if both the object and background have identical radiation characteristics the difference will end up in zero[10], in spite of the fact that $I_t(\lambda) \neq 0$ for the object. The term to use should therefore preferably be the relative intensity $\Delta I(\lambda)$ of the object in the background in question. This

[10] To achieve zero difference between object and background radiance is the basic thought behind stealth technology.

number is normally expressed in some power term; for point objects we use [W/sr].

In equation (2-14) it is assumed that the Signal to Noise Ratio, SNR, is equal to one (1) when determining NEI. A more general formulation allowing SNR to be defined to a more realistic value for object detection by automatic signal processing algorithms, i.e. SNR > 1, can be included in (2-14) by letting SNR be a parameter.

The reformulation of (2-14) taking into account both $\Delta I(\lambda)$ and SNR > 1, then leads to equation (5-3). A more sophisticated analysis of (2-14) leading to (5-3) is supplied in (Dudzik 1993).

$$R = \sqrt{\frac{\int_0^{\infty} \tau(\lambda) \cdot \left(L_{obj}(\lambda, T) - L_{bgr}(\lambda, T) \right) \cdot A_{obj} \cdot d\lambda}{NEI \cdot SNR_{\min}}} \text{ [m]} \qquad \textit{(5-3)}$$

the parameters involved are:

R	Range from object to sensor	[m]
$\tau(\lambda)$	Atmospheric transmission	[-]
$L_{obj}(\lambda,T)$	Spectral object radiance	[W/m^2 m sr]
$L_{bgr}(\lambda,T)$	Spectral background radiance	[W/m^2 m sr]
A_{obj}	Physical object area in the sensor direction	[m^2]
NEI	Noise Equivalent Irradiance	[W/m^2]
$SNR_{\min}$	Minimal SNR for object detection	[-]

SNR_{min} could be described as the smallest amplitude of a signal required for the detection of an object in a noisy image, thus being a measure of the signal processing efficiency of the equipment. For further explanations of the other parameters see section 2.10.

5.5.1 Effective transmission

Unfortunately there are physical limitations of all sensors. The detector elements in the sensor can only detect within a narrow spectral band, which means that the response function for the sensor is separated from zero only at some of the wavelengths between zero and infinity.

This means that we should extend the equation further to include the in-band response function of the particular sensor, $R_e(\lambda)$. The in-band response is described by the normalised response function of the sensor, see Figure 5-11. It describes the wavelength dependent sensitivity of a sensor, with a maximum sensitivity normalised to one.

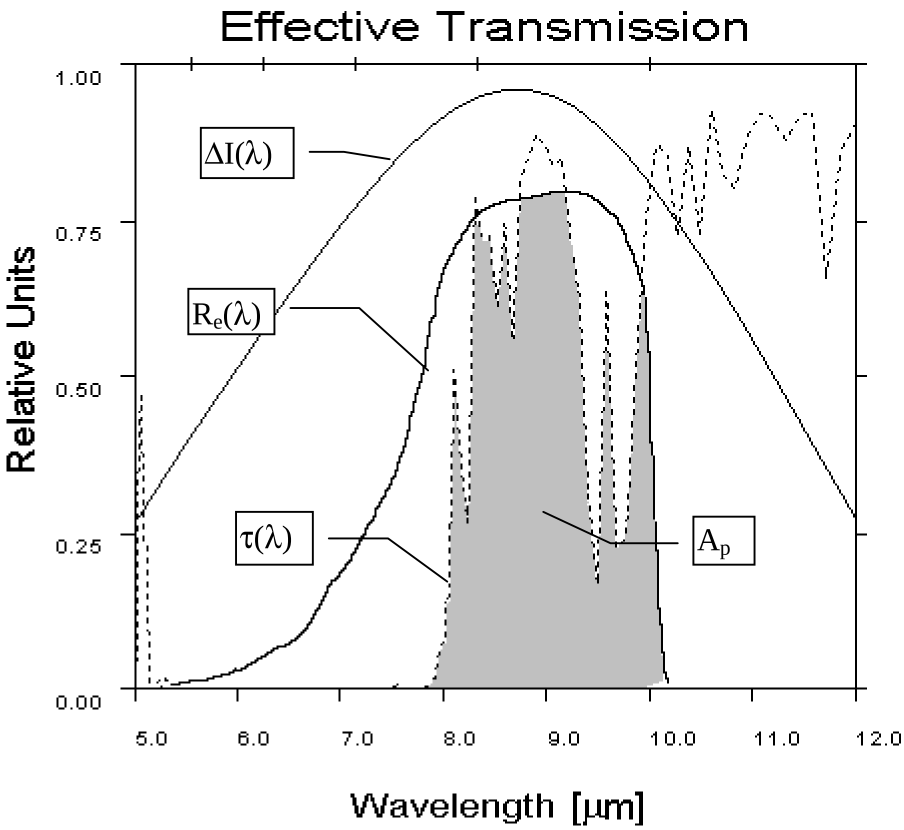


Figure 5-11 *The useful area of detection, A_p, greyish in the figure, is narrowed by several factors. $\tau(\lambda)$, atmospheric transmission from MODTRAN, $R_e(\lambda)$, the spectral response function for the sensor and finally the object radiance compared with the background, $\Delta I(\lambda)$.*

This, together with the fact that the object only radiates within a restricted spectral band, that do not always coincide completely with the response function means that the spectral envelop could be sharpened even more see Figure 5-11. Equation (5-4) is quite similar to (5-3) but now the spectral response function $R_e(\lambda)$ is included.

$$R = \sqrt{\frac{\int_0^\infty \tau(\lambda)\cdot R_e(\lambda)\cdot\left(L_{obj}(\lambda,T)-L_{bgr}(\lambda,T)\right)\cdot A_{obj}\cdot d\lambda}{NEI\cdot SNR_{\min}}}\ \text{[m]} \qquad (5\text{-}4)$$

By remembering equation (2-13) the conclusion formulated in equation (5-5) that atmospheric transmission is in fact a function of our present range, from object to sensor, becomes obvious.

$$\tau(\lambda) = e^{-\sigma_{ext}(\lambda)\cdot R} = \tau(\lambda, R) \qquad (5\text{-}5)$$

The fact that we have the range on both sides of the equal sign increases the complexity of the range equation. This leads to an iterative numerical solution for instance the simple one suggested below.

$$R_i = \sqrt{\frac{\int_0^\infty \tau_{gas}(\lambda, R)\cdot \tau_{aero}(\lambda, R)\cdot R_e(\lambda)\cdot \left(L_{obj}(\lambda,T) - L_{bgr}(\lambda,T)\right)\cdot A_{obj}\cdot d\lambda}{NEI\cdot SNR_{\min}}}$$

$$R_{i+1} = \sqrt{\frac{\int_0^\infty \tau_{gas}(\lambda, R_i)\cdot \tau_{aero}(\lambda, R_i)\cdot R_e(\lambda)\cdot \left(L_{obj}(\lambda,T) - L_{bgr}(\lambda,T)\right)\cdot A_{obj}\cdot d\lambda}{NEI\cdot SNR_{\min}}} \qquad (5\text{-}6)$$

etc.

The range equation work up to this point can be summarised with the following bullets:

- The atmospheric transmission is to be calculated with MODTRAN, and this calculation is rather complex.
- The expression, $\left(L_{obj}(\lambda,T) - L_{bgr}(\lambda,T)\right)$, is rather troublesome to solve and fast changes in both object and background radiation adds to the total complexity of the range equation.
- Most often the range equation has to be solved iterative, this could be time consuming.

The conclusion so far is that a real-time solution of this complex range equation is impossible for practical use. Therefore we have to develop and simplify the equation further to make calculations faster and less demanding.

First by realising that we can divide the atmospheric transmission function into one gas and one aerosol part according to equation (2-10), and that the transmission also is a function of our present range, see equation (2-13) we can rewrite the range equation by using equation (5-7) which is a further development of (5-5).

$$\tau(\lambda) = e^{-\sigma_{ext,tot}(\lambda)\cdot R} = e^{-\left(\sigma_{ext,gas}(\lambda) + \sigma_{ext,aero}(\lambda)\right)\cdot R} = \tau_{gas}(\lambda, R)\cdot \tau_{aero}(\lambda, R) \qquad (5\text{-}7)$$

In section 5.3.1 we stated that the transmission losses due to aerosols as an approximation can be considered to be wavelength independent. This means that we can extract the aerosol part from the integral in the numerator of the expression.

$$R = \sqrt{\frac{\tau_{aero}(R) \cdot \int_0^\infty \tau_{gas}(\lambda, R) \cdot R_e(\lambda) \cdot \left(L_{obj}(\lambda, T) - L_{bgr}(\lambda, T)\right) \cdot A_{obj} \cdot d\lambda}{NEI \cdot SNR_{\min}}} \qquad \textbf{\textit{(5-8)}}$$

The effective transmission discussion indicates that we should weigh τ with the actual sensor response in order to take into account whether the sensor operates in for instance the 3-5 μm or 8-12 μm band. And to get a single value of $\tau(\lambda)$ to use in the range equation some sort of mean of $\tau(\lambda)$ must be produced. The simplest form is the arithmetic mean see equation (5-9) which however does not take into account the spectral content of the object radiation $I(\lambda)$ or the sensor response function, $R_e(\lambda)$.

$$\tau_{mean}(\lambda) = \frac{\tau(\lambda_1) + \tau(\lambda_2) + \ldots + \tau(\lambda_n)}{n} \qquad \textbf{\textit{(5-9)}}$$

A mean where this effect is taken into account is produced by equation (5-10) which gives a weighted mean of $\tau(\lambda)$ where $\tau(\lambda)$ coincident with high levels of $R_e(\lambda) \cdot L(\lambda)$ will have a greater impact on $\langle \tau \rangle$, than will $\tau(\lambda)$ at low levels of $R_e(\lambda) \cdot L(\lambda)$. In order to separate these weighted measures from the originals we have surrounded the parameter with hooks, $\langle\ \rangle$.

$$\langle \tau(R) \rangle = \frac{\int_0^\infty \tau_{gas}(\lambda, R) \cdot R_e(\lambda) \cdot \left(L_{obj}(\lambda, T) - L_{bgr}(\lambda, T)\right) \cdot d\lambda}{\int_0^\infty R_e(\lambda) \cdot \left(L_{obj}(\lambda, T) - L_{bgr}(\lambda, T)\right) \cdot d\lambda} \qquad \textbf{\textit{(5-10)}}$$

To make real-time calculations of range possible we suggest that equation (5-10) should be solved in advance. This means that tables of $\langle \tau(R) \rangle$ should be developed. Entries to these tables $\langle \tau(R) \rangle_{tab}$ could be for instance altitude and RH etc.

Since $\langle\tau(R)\rangle_{tab}$ is wavelength independent we can move $\langle\tau(R)\rangle$ out of the integration which leads us to equation (5-11).

$$R = \sqrt{\tau_{aero}(R) \cdot \frac{\langle\tau(R)\rangle_{Tab} \cdot \int_0^\infty \cdot R_e(\lambda) \cdot \left(L_{obj}(\lambda,T) - L_{bgr}(\lambda,T)\right) \cdot A_{obj} \cdot d\lambda}{NEI \cdot SNR_{\min}}} \tag{5-11}$$

And in the same way as with the atmospheric transmission we also suggest that the integral over the object intensity should be solved in advance. This means another table, ΔI_{Tab}, entries to this table could be for instance object speed, object attitude etc.

$$\Delta I_{Tab} = \int_0^\infty \cdot R_e(\lambda) \cdot \left(L_{obj}(\lambda,T) - L_{bgr}(\lambda,T)\right) \cdot A_{obj} \cdot d\lambda \tag{5-12}$$

This finally brings us to this neat equation

$$R = \sqrt{\frac{\tau_{aero,R} \cdot \langle\tau\rangle_{R,Tab} \cdot \Delta I_{Tab}}{NEI \cdot SNR_{\min}}} \tag{5-13}$$

5.5.2 Range Summary

Most probably the range equation must be solved in an iterative way, this could be time consuming depending upon the choice of iterative method. Rapid changes of $\tau_{aero,R}$ and ΔI or rather $\left(L_{obj}(\lambda,T) - L_{bgr}(\lambda,T)\right)$ extends the complexity even further. If we for instance enter a cloud $\tau_{ro,}$ will change momentarily, but $\tau_{ro,}$ can also vary gradually if for instance the water vapour content increases. On the other hand $L_{obj}(\lambda,T)$ can change several powers of magnitude if for instance the engine thrust changes or if the aspect angle changes. This means that the range equation must be updated rather often.

6 Discussion

In this chapter we discuss the outcome of this thesis and answer the basic questions formulated in the problem description. Moreover, suggestions of future work and improvements are made.

6.1 Important parameters

There are consequently three major contributors to the overall atmospheric transmission; gases, aerosols and clouds. These contributions can be treated individually, (Nilsson 1989, Hågård 1992), and then combined using Beer's law, see section 2.8.

All the three major attenuation gases, water vapour carbon dioxide and ozone should be considered important to include in a model but water vapour is identified as the most important parameter. The transmission losses due to direct attenuation by gases can be calculated with satisfactory accuracy with the LOWTRAN/MODTRAN computer codes, (Nilsson 1986, Hågård 1992).

We have stated that the aerosol contribution could be approximated to be wavelength independent and water vapour content has got a tremendous impact on aerosols since they are hygroscopic. The transmission loss due to aerosols could be modelled by the extinction coefficient with a simple exponential function. The major obstacle on this path is that the concentration of aerosols are changing constantly, this changes in turn the extinction coefficient. This problem can though be remedied if we feed back a measure of the current atmosphere or preferably the present extinction coefficient.

Clouds are often present in our northern region and the transmission of IR radiation through clouds are extremely low except for Cirrus clouds. Since Cirrus clouds consists of particles in the atmosphere it is quite natural to consider Cirrus as a kind of aerosol when that is what it is. In order for clouds to form the relative humidity have to be 100 %.

Water vapour content effect the size of the aerosol particles and thereby the attenuation caused by aerosols, water vapour also effects the range directly, in the band 5-7 μm water vapour absorbs approximately 100% of the radiation.

The water vapour content is also a major contributing factor for the formation of cloud. Therefore we can assuredly state that water vapour is the single most import parameter considering atmospheric transmission for IR radiation.

The range equation must be solved in an iterative way, this could be time consuming. Due to the swiftly varying components of the range equation the update rate must be rather high.

6.2 Atmospheric model approaches

After having studied the collected information and achieved knowledge about the atmosphere, three major paths of model developing came into our minds.

- Using available computer transmission codes directly and accommodating them for range calculations, *available code accommodation*.
- Develop a model of our own, *model from scratch*.
- A combination, develop some parts by ourselves and use others from available transmission codes, *combined further development*.

6.2.1 Available code accommodation

There are several codes available for calculation of atmospheric transmission, for instance LOWTRAN, MODTRAN, FASCODE and HITRAN. There are also many specialised codes, developed by aerospace and defence organisations all over the world, of which only a few codes are available. These codes perform better in special applications but are not as prevalent and adaptive as the ones mentioned above.

Among these alternatives MODTRAN/LOWTRAN qualifies to be the most appropriate choice considering availability, suitability and resolution. The advantage of using MODTRAN/LOWTRAN would be that it is widely used for calculating atmospheric transmission, available and validated to be a good atmospheric modelling tool, (Ben-Shalom 1988, Hågård 1992, Nilsson 1986).

However these programs have limited adaptive capabilities. For instance there are only a few aerosol models included. This yields a risk that the aerosol parts become inaccurate when studying conditions beyond these models, (Nilsson 1986, Hågård 1992).

Unfortunately, MODTRAN demands a lot from the intended computer, at least when considering airborne applications. MODTRAN occupies 5 Mb disk space and requires at least 16 Mb RAM in order to work properly. We performed a test with a Pentium 166 MHz, 64 Mb RAM performing 310 MIPS and 98 MFLOPS. We designed two test cases, one simple and one more demanding. If we let the program consume 100 % of the central processing units available time, the first test case took 7 s and the second one took 8 s.

Furthermore in order to use MODTRAN in real-time, equation (5-11) must be solved, this means that the integral has to be performed since $\left(L_{obj}(\lambda,T)-L_{b}\ (\lambda,T)\right)$ and $\tau_{\ o,}$ can vary rapidly. Solving equation (5-11) must be an iterative process, since the range, R, are present on both sides of the equal sign. This also adds to the processor workload.

6.2.2 Model from scratch

This is probably the most challenging alternative of them all and of course the most difficult way to reach the goal. But on the other hand we would get a tailor made model perfectly suited for our purposes.

The atmosphere is, as we have discussed previously, a very complex and dynamic environment to model. After having spent a long time trying to dig down to the fundamental issues and basic concepts of the atmosphere we soon realised that in order to get reasonable accuracy, deep and thorough investigations of literature had to be made and above all, relevant atmospheric data have to be provided. This has to be done in such a way that the work required would exceed the limits of a master thesis.

6.2.3 Combined further development

To analyse and to evaluate the already existing models in order to improve them in presumed weak areas and to add missing functions seemed to be the most viable approach. This approach would mean that we could achieve as many advantages as possible presented in the alternatives above and lessen the disadvantages and thereby getting an excellent model.

6.3 A way towards a model implementation

Our suggestion is to follow the third path *combined further development*. Due to the uncertainties of the aerosol and cloud models together with the computer demands for MODTRAN, unfortunately real-time use of MODTRAN is ruled out.

A way around these problems is to create tables with calculated values of gas transmission, with the MODTRAN computer code preferably. Then by using the assumption that cirrus clouds approximately can be considered to be aerosols and that aerosols can be modelled with a simple exponential function we can calculate the aerosol (and cloud) attenuation if we provide the function with the present aerosol (cloud) extinction. Depending upon the values of the aerosol extinction this would be a good approximation of the aerosol attenuation.

Then by using the range equation (5-13) sensor ranges can be calculated if we add sensor and target information.

6.4 Range equation application

We have identified two fundamentally different cases for applying the range equation. The obvious difference is if you know where an object is or not.

Assume that you of some reason know where an object is, this information could be achieved from intelligence reports, another sensor or some other source. Anyway now we want to use the range equation to make a calculation if we are capable to ”see” this specified object at this range. If we can’t see that far then there is no point in looking in that direction, and we can for instance continue our search for other objects *within* our range. This application does not need an iterative solution of the range equation since we know the range ”within” the equation.

The other case, probably the most common, is when we want to know how wide our present ”safe” surroundings are. This is made by specifying certain target intensity levels, for instance a missile in boost phase[11] emits rather much, this means that we will have a longer range towards such a radiator than from a cruising fighter. This will increase the pilot’s SA considerably. However it may be troublesome to choose standard levels of emittance since factors as aspect angle and thrust setting plays great parts.

6.5 Future work

Since this master thesis is the first one that considers development of an operational model for optical sensor ranges in the atmosphere performed at Saab AB in Linköping, there are still many roads to follow up, adjacent to the path this thesis covers. Here are some of our suggestions for future work.

[11] Directly after launch, a missile accelerates by burning its engine until the fuel is consumed, this produces a quite intense radiation source, then it glides towards the target with only the, due to the velocity, heated skin to reveal its presence to the IR sensor.

6.5.1 Model implementation

The most obvious extension is to build the model we have suggested completely. First create tables with calculated values of transmission for at least the simplest flight missions. Then implement the range equations and an interface able to read out the parameters from the tables and deliver them to the range equation function. Together with simple implementations of sensor and target see 6.5.2 and 6.5.3, we would achieve a fully functional model to simulate infrared sensors ranges in the atmosphere.

Finally, of course, this implementation must be validated in some way preferably against real data from flights with relevant equipment, but at least against other atmospheric transmission codes and available data.

6.5.2 Sensor model

In order to make the sensor model as simple as possible we suggest to model the sensor by its parameters. By this we mean to specify NEI, SNR and finally the sensor response function R_e. In order to define a sensor and include it into the model, those parameters must be provided.

6.5.3 Target model

In resemblance with the sensor model we have tried to model the target as simple as possible. The simplest target model in our opinion is to model the target as a blackbody radiator at one specific temperature, with a specific area. This might seem to be a rather rough model but on the other hand it is not all that troublesome to exchange this part with a more sophisticated model in the future. This blackbody function together with an object (target) area are enough information to model our target.

6.5.4 Sensor measurements

In order to achieve realistic aerosol attenuation from an atmospheric model we suggest that a method to calibrate the transmission model with continuos measurements, with the actual sensor equipment, against a known object, with well documented properties, for instance a wingman should be added to the model. Since the amount of aerosols constantly changes in the atmosphere we conclude that models without feed back would be inaccurate even though the average value of the transmission could be quite accurate.

6.5.5 Model improvements

More thorough investigation of atmospheric aerosols could prove itself as a viable approach to improve the aerosol part of the model.

Both target and sensor models can be improved. For instance targets generally consists of more than one part and these parts are at different temperatures.

Aircraft also exhaust hot gases in large quantities and depending upon the aspect angle this exhaust could affect more or less.

Another ”improvement” is to develop an interface program that could handle data to MODTRAN. This would be quite useful when creating the gas transmission tables, especially if one wants to provide MODTRAN with atmospheric data beyond the integrated models

6.5.6 Integration with other models

There are many projects in progress adjacent to this, for instance a recently developed multisensor taskmanager, (Jensen 1997), lack models for calculating the range of infrared sensors in different weather conditions.

7 Conclusions

The following list constitutes the major conclusions from this thesis work:

- The single most important parameter in an atmospheric transmission model is the *water vapour content*. Water vapour affects the transmission both directly and indirectly. Directly by absorption and indirectly by affecting size of atmospheric particles and presence of clouds.

- *Clouds* in general have a very strong absorbing effect on infrared radiation. However clouds that appear at high altitudes consist mostly of ice and are less dense than low altitude clouds and therefore transparent to some extent. We can expect to achieve sensor ranges of practical use in these. The formation of clouds are highly dependent upon the water vapour content.

- Another crucial parameter is the amount of particles dissolved in the atmosphere, *aerosols*. This amount changes constantly and this makes accurate modelling difficult. The size of these particles changes with water vapour content in the atmosphere and this effects the attenuation. However, the effects can be considered approximately to be wavelength independent.

- Since water vapour plays such an important role in the atmosphere, we state that water vapour should be measured continuously to feed an atmospheric model with relevant data.

- Available models for aerosols are not good enough and probably impossible to develop since the concentration of aerosols change rapidly. Some kind of calibration of the aerosol model has to be done, perhaps with a measurement against a well known object to determine the present aerosol concentration.

- The suggested range equation includes atmospheric transmission and simple sensor and object parameters. The atmospheric transmission is separated into an aerosol and a gas part. Most likely this equation must be solved iteratively. Rapid changes of important included parameters requires that the update rate of the range equation should be rather high.

References

Abreu L. W. et al (1996) *MODTRAN Report*, Ontar Corporation, North Andover, Ma, USA.

Alejandro S. B. et al *Atlantic atmospheric aerosol studies*, Journal of Geophysical Research, Vol. 100 (1995), pp 1035-1041.

Anthes R. A. et al (1975) *The Atmosphere*, Bell & Howell Company, Columbus, Ohio USA.

Ben-Shalom A. et al *Experimental validation of atmospheric transmittance codes*, SPIE Optical, Infrared and Millimeter Wave Propagation Engineering, Vol. 926 (1988), pp 54-64.

deBlij H. J., Muller P. O.(1996), *Physical Geography of the global environment*, second edition John Wiley & Sons, Inc. USA.

Campana S. B. et al (1993) *Passive Electro-Optical Systems*, volume 5 of The Infrared & Electro-Optical Systems Handbook, Infrared Information Analysis Center, Ann Arbor, Michigan USA & SPIE Optical Engineering Press, Bellingham, Washington USA.

Dudzik M. C. et al (1993) *Electro-Optical Systems Design, Anaysis and testing*, volume 4 of The Infrared & Electro-Optical Systems Handbook, Infrared Information Analysis Center, Ann Arbor, Michigan USA & SPIE Optical Engineering Press, Bellingham, Washington USA.

Endsly M. R. *Design and Evaluation for Situation Awareness enhancement*, Proceedings of the human Factors Society 32nd Annual Meeting, (1988), pp 97-101.

Hågård A. (1998) *Private conversation* at Defence Research Establishment, Department 3, FOA3, Linköping, Sweden.

Hågård A. (1993) *Optisk transmission i atmosfären*, Appendix FOA3, Unpublished

Hågård A., Persson R. *Infrared transmission measurement in the atmosphere*, SPIE-proceedings, Vol. 1762 (1992), pp 266-275.

Hågård A. (1986) *En metod för snabb approximativ beräkning av atmosfärstransmission i sneda banor* PM FOA3, Unpublished

Jensen T. ,Karlsson M. (1997) *Sensor Management in a Complex Multisensor Environment*, Master Thesis LiTH-ISY-EX-1831, Department of Electrical Engineering, Linköping University, Linköping, Sweden

Jursa A. S. et al (1985) *Handbook of Geophysics and the space environment*, Air Force Geophysics Laboratory, Air Force Systems Command, United States Air Force

Kneizys F. X. et al (1983) *Computer code LOWTRAN,* AFGL, Hancom, Ma, USA

Lovell D. J (1981) *Optical Anecdotes*, The International Society for Optical Engineering, Bellingham, Washington, USA

Nilsson B. A. *Meteorological influence on aerosol extinction in the 0.2-40 µm wavelength range*, Applied Optics, Vol. 18 (1979), No. 20, pp 3457-3473.

Nilsson B. A. (1990), *IR transmissionens vertikala fördelning i Sverige* FOA report C 30566-3.1 ISSN 0347-3708, Defence Research Establishment, Department 3 Linköping, Sweden.

Nilsson B. A. (1986), *Analyses of the Atmospheric Aerosol Extinction in the 0.5-14 µm region,* FOA Report C 30396-E1,E3, Defence Research Establishment, Department 3, FOA3, Linköping, Sweden.

Nilsson P. (1994) *Spectral sky background in the IR -measurements with FTIR*, Master Thesis LiU-IFM-Fy-Ex 397, Department of Physics and Measurement Technology, Linköping University, Linköping, Sweden

Ontar Corporation (1997) *PcModWin Manual*, Ontar Corporation North Andover, Ma, USA

Rensch D. B., Long R. K. *Comparative Studies of Extinction and Backscatter by Aerosols, Fog and Rain at 10.6 µm and 0.63 µm*, Applied Optics, vol. 9 (1970), No. 7, pp 1563-1573.

Schwiesow R. L. et al *Aerosol Backscatter Coefficient Profiles Measured at 10.6µm*, Journal of Applied Meteorology, vol 20 (1980), pp 184-194.

Scorer R. S. (1972) *Clouds of the world*, David & Charles Publishers Ltd, Newton Abbot, Devon, Great Britain

Smith F. G. et al (1993) *Atmospheric Propagation of Radiation*, volume 2 of The Infrared & Electro-Optical Systems Handbook, Infrared Information Analysis Center, Ann Arbor, Michigan USA & SPIE Optical Engineering Press, Bellingham, Washington USA

SMHI (1998) *Relativa frekvenser av höga moln*, Station Malmslätt, Period 1961-01-01 to 1997-12-31, SMHI, Norrköping, Sweden.

Spiro I, Schlessinger M. (1989) *Infrared Technology Fundamentals*, Marcel Dekker, NY, USA

Vaughan J. M. et al *Atlantic atmospheric aerosol studies, Compendium of airborne backscatter measurements at 10,6 µm*, Journal of geophysical research, vol 100 (1995), pp 1043-1065.

Wolfe W. L., Zissis G. J. (1993) *The Infrared Handbook*, Infrared Information Analysis Center, Ann Arbor, Michigan USA

Zissis G. J. (1993) *Sources of Radiation*, volume 1 of The Infrared & Electro-Optical Systems Handbook, Infrared Information Analysis Center, Ann Arbor, Michigan USA & SPIE Optical Engineering Press, Bellingham, Washington USA

Appendix

MODTRAN users guide

To help us use PCModWIN3 and to write this users guide we have used information from the following sources (Abreu 1996, Kneizys 1983, Ontar 1997). MODTRAN is further discussed in Chapter 4 in this thesis.

This is an attempt to make further use of MODTRAN3/PCModWin3 as easy as possible. This users guide has been developed for a PC using Microsoft's Windows NT 3.51 operating system. There might be minor differences if another operating system is used.

To be able to use this program you have two major obstacles to overcome. First the input routines of PCModWIN3 and then the input itself. This appendix considers the first part but sufficient information about the other part must be obtained by the reader. The theory chapter in this thesis is a good place to start your quest.

Overview

PCmodWin3 is a windows based application and the appearance is quite similar to other more commonly used applications. We have decided to concentrate this effort on the following elementary functions and our intention is that this users guide together with experience collected during contact with other windows applications would be sufficient to handle the program rudimentary.

- Create and save an input file
- How to run an input file
- Create and save output plots
- How to view and save an output file
- Restore a saved input file
- Restore a saved plot
- Some Advanced applications
- Help

Create and save an input file

When you are going to perform your first simulation in PCModWIN3 you start by changing and setting the parameters under the menu ”Modtran Input”. Start preferably from the top of the list with ”Model Atmosphere”. Then, depending on what you have chosen, various items on the ”Modtran Input” menu will be grey and thereby not accessible. This is in fact a great help as you do not have to provide the program with unnecessary input.

To create or rather to save an input file you simply change the parameters (under the menu ”Modtran Input”) to the values you wish to have in the usual fashion. However make sure to change the path length (menu ”Modtran input” item ”Geometry and Spectral band”) to a value separate from zero. Otherwise the Modtran will calculate the transmission to be zero, see chapter 4. When you consider yourself ready, save (and thereby create) your file by choosing ”Save as” under either the ”File” or ”Modtran Input” menu. You must of course choose a name and a place for your file and make sure you know *where* you have saved the file (if you want to find it again see 0 Restore a saved input file).

This operation will create an input file in the directory you have chosen called *something.ltn* (where ”something” of course is the name of your file. We have decided to use *something* as a notation for an arbitrary name chosen by yourself). PCModWIN3 also creates a file called *something.plt* during this operation but you can safely ignore this file as it is of no interest to your purpose. However, keep them together.

How to run an input file

Now, when you have an input file created, restored or just defined by parameter settings, you can perform an execution of MODTRAN with this particular file by choosing ”Run modtran” under the menu called ”Run model”.

When this is done your input file is ”sent” to the MODTRAN program which by itself generates and stores the output in the three output files Modout 1-3 located in the MODWIN3 directory. Now, another file called *something.fl7* is generated by PCModWIN3 together with the *.ltn* and *.plt* file. It is important to keep these files together if you want PCmodWIN to work properly.

Create and save output plots

There are two ways available in order to create a plot from MODTRAN, either by using the file *Modout2* or by using so called ”Plot cards”. If you use ”Plot cards" you can save your plot settings (and even save several plots with different settings) instead of using the more direct approach through *Modout2*.

Modout2
The simplest way to create a plot from MODTRAN is to (after you have made a run according to the previous section) choose "Interactive" under the "Plot" menu, a dialogue box (Open File to Plot) will then appear on the screen. Fortunately modout2 is already selected as the default file to open so all you have to do is to choose "OK" (or punch "Enter" on your keyboard). This makes the plot dialogue box appear and here you can adapt your plot in numerous ways, see Plot dialogue box below.

Plot cards
It is often wiser to use Plot cards instead, as if you do so you can save your plot(s) together with your input file. You create Plot cards by choosing "Plot Cards" under the "Modtran Input" menu. This makes a dialogue box appear and in this box you can set the total number of plots you wish to save with the input file. When you have pressed OK a plot dialogue box appears which is similar to the one referred to earlier. However, if you choose more than one plot card you can access the different plot card (dialogue boxes) by clicking on the "Next" and "Prev" buttons. Suggestion: if you want to separate the plots from each other, give them a title! How to use the plot dialogue box is described in the next section. Don't forget to save your input file in order to include your plot settings.

Plot dialogue box
On the left part of the box you can choose what you want to plot, and on the right side you can change scales etc. If you want to use the features on the right side you must remove the "Auto Scale" selection by clicking with the left mouse button on the box beside "Auto Scale" in such a way that the x in the box disappears (if this feature is used make sure that Min/Max X and Min/Max Y includes your actual output from MODTRAN!)

How to view and save an output file

To view the output from MODTRAN you can easily open them by selecting "Edit File" under the "Edit" menu, then you only have to choose one of modout 1-3 and press OK. Modout1 is the one of most interest and it includes all output and input from MODTRAN. Modout2 includes only the plotable output and Modout3 finally includes the input data and the total average transmission. Remember that these files are read by a DOS application that requires that you use menu "File" item "Exit" to exit the application.

There are no method available to save the output file in PCModWIN (but you can of course make a copy by yourself in a word processing tool). The only way to access the modout1-3 files connected to a specific input file, is to run the input file through MODTRAN and view modout1-3 as mentioned above.

Restore a saved input file

To restore a input file you only have to choose ”Open” from either the ”File” or the ”Modtran Input” menu and choose your input file called *something.ltn*

Restore a saved plot

To restore a plot saved together with an input file you simply select ”Database” from the ”Plot” menu and all your plots created by plot cards will emerge in the PCModWIN window. However you must run your input file first.

Some advanced applications

There are many advanced capabilities available when using this program, but of special interest is the ability to adapt the atmosphere used by the program. This feature is very useful if you have relevant atmospheric data over your region of interest and/or you want to have control over the gas composition in the different atmospheric layers.

You get access to your own atmosphere by choosing ”Model Atmosphere” under the ”Modtran Input” menu. On this MODTRAN card you can choose ”New Model Atmosphere” in the ”Model Atmosphere” item in the list.

This enables the MODTRAN cards ”New Model Atmosphere” on which you can choose the number of atmospheric layer you wish to have and also specify what kind of information you want to provide ”your” atmosphere with. For each atmospheric layer you get a layer card called ”User Supplied Profile” on which you are obliged to fill in all the gaps.

Help

If you need further instructions, help or just wonder about something, the on-line help tool is very nice. For instance if you have a question about a parameter, you can get access to the on-line help by clicking on the parameter name with the mouse and a brief explanation will occur.

Institution, Avdelning
Department, Division

Department of Electrical Engineering

Division of Automatic Control

Datum
Date

1998-12-18

Språk
Language

☐ Svenska/Swedish
☒ Engelska/English
☐ _______________

Rapporttyp
Report category

☐ Licentiatavhandling
☒ Examensarbete
☐ C-uppsats
☐ D-uppsats
☐ Övrig rapport
☐ _______________

ISBN

ISRN

Serietitel och serienummer
Title of series, numbering

LiTH-ISY-EX-1909

ISSN

URL för elektronisk version
http://www.rt.isy.liu.se/

Title: **Atmospheric Transmission Models for Infrared Wavelengths**
Titel: Atmosfärstransmissions modeller för IR våglängder

Författare : **Björn Hässler**
Authors:

Sammanfattning
Abstract

In the demanding environment in which modern combat aircraft perform, it is vital for the pilot to uphold situation awareness of his surroundings; are there other objects in the vicinity of the aircraft and if so is there any risk that they are hostile? Of equally vital importance is the extent of the somewhat vague term ”surroundings”. Different types of sensors have different range capabilities under different conditions, weather and time for instance. This means that the size of the volume in which it is possible to uphold situation awareness will depend on the type of sensors included in the aircraft sensor suite.

This thesis investigates the atmosphere with the purpose of finding factors which influence the range of sensors that detect infrared radiation. The result is expected to form a basis for models concerning ranges of infrared sensors and atmospheric transmission.

A range equation considering atmospheric transmission are suggested for infrared sensors. The single outstanding most important parameter in an atmospheric transmission model is the water vapour content, water vapour effects the transmission both directly and indirectly. Another crucial parameter is the amount of particles dissolved in the atmosphere, this amount changes constantly and this makes modelling difficult. Clouds have a dramatic attenuation effect upon infrared radiation, and the random nature of clouds also adds to the complexity of this matter.

Nyckelord
Keywords

Atmospheric Transmission, IR, MODTRAN, Situation Awareness, Atmospheric Aerosol