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Atmospheric Propagation of Terahertz Radiation

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1. Introduction

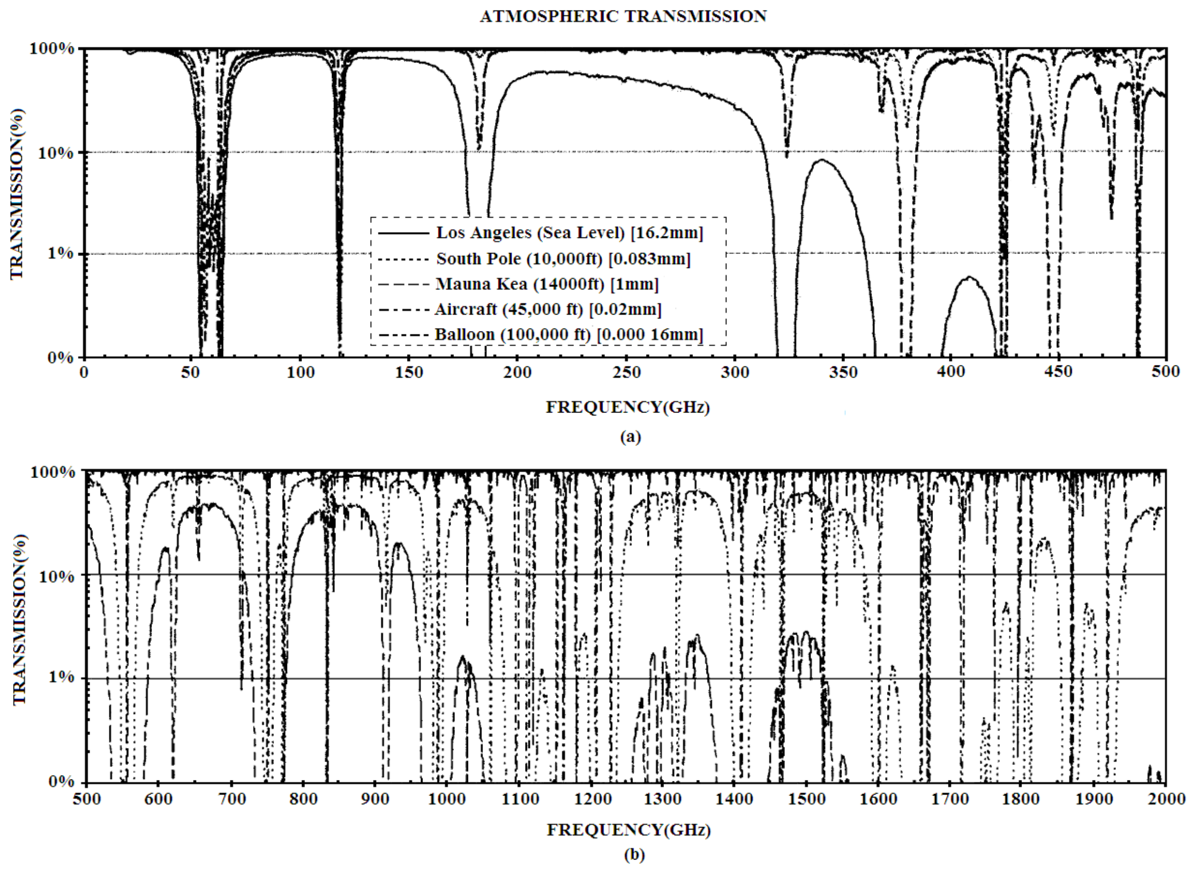
Terahertz (THz) radiation, sandwiched between traditional microwave and visible light, is the electromagnetic spectrum with the frequency defined from 0.1 to 10 THz ($1THz=10^{12}Hz$). Until recently, due to the difficulty of generating and detecting techniques in this region, THz frequency band remains unexplored compared to other range and tremendous effort has been made in order to fill in "THz gap" . (Zhang & Xu, 2009)

Recent advances provide new opportunities and widespread potential applications of THz in information and communication technology (ICT), material identification, imaging, non-destructive examination, global environmental monitoring as well as many other fields. The rapid development can be attributed to the nature of terahertz radiation, which offers the advantages of both microwave and light wave. The characteristics of THz atmospheric propagation now rank among the most critical issues in the principal application of space communication and atmospheric remote sensing. (Tonouchi, 2007)

Terahertz communication will benefit from the high-bit-rate wireless technology which takes advantage of higher frequency and broader information bandwidth allowed in this range than microwave. It is possible for such a system to achieve data rate in tens of gigabits per second. (Lee, 2009) However, as shown in Figure 1, the atmospheric opacity severely limits the communication applications at this range (Siegel, 2002) and it is the commercial viability rather than technological issues that will undoubtedly determine whether THz communication will be carried out into practical application.

The overview of the THz remote sensing from the National Institute of Information and Communications Technology (NICT) in Japan is given in Figure 2. (Yasuko, 2008) Many biological and chemical compounds exhibit distinct spectroscopic response in THz range, which presents tremendous potential in the environmental monitoring of atmospheric chemical compositions (water, oxygen, ozone, chlorine and nitrogen compounds, etc.) and the identification of climate evolution in the troposphere and lower stratosphere. (Tonouchi, 2007) The knowledge about atmospheric attenuation will illustrate the optimum frequency bands for sensing systems while the material database will discriminated atmospheric components.

Based on these considerations, there are three fundamental problems as follow: (Foltynowicz et al., 2005) (1)To confirm the atmospheric transparency in the THz range and



a) 0-500 GHz, (b) 600-2000GHz

Fig. 1. Atmospheric transmission in the terahertz region at various locations and altitudes

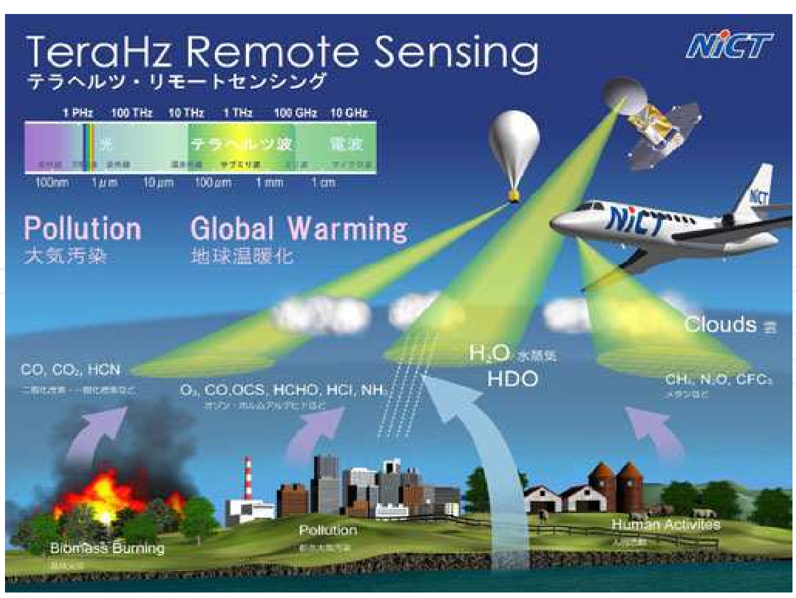


Fig. 2. Overview of NICT THz remote sensing

find out the air transmission windows for communicating and sensing system. (2)To collect the spectroscopic fingerprinting of atmospheric molecules for Terahertz atmospheric monitoring. (3)To improve the signal to noise ratio and restore the original signal from the observed signal by the process of deconvolution. (Ryu and Kong, 2010) It is essential to understand the actual effects on the amplitude and phase of THz radiation propagating through the atmosphere, which depends on the frequency of incident wave, gas components, and ambient temperature or barometric pressure in different atmospheric conditions.

This chapter aims to provide the theoretic instructions for the applications above and illuminate characteristics of THz atmospheric propagation. The fundamental theory has been systematically introduced, with the physical process of Lamber-beer law, Mie scattering theory and so on. The atmospheric absorption, scattering, emission, refraction and turbulence are taken into account and a special focus is put on the detailed derivation and physical significance of radiative transfer equation. Additionally, several THz atmospheric propagation model, including Moliere, SARTre and AMATERASU, are introduced and compared with each other. The conclusions are drawn by giving the future evolutions and suggestions of further study in this region.

2. Fundamental theories of terahertz atmospheric propagation

The framework of fundamental physical concepts and theories in the process of THz atmospheric propagation is shown in Figure 3. The three fundamental physical concepts (atmospheric extinction, atmospheric emission and background radiation) on the left can be uniformly expressed in the radiative transfer equation, which is the foundation of THz atmospheric propagation mode and describes the processes of energy transfer along a given optical path. Other elements (atmospheric refraction and turbulence) results in a correction and optimization of the integration path-length and radiative transfer algorithm in practical solution procedure.

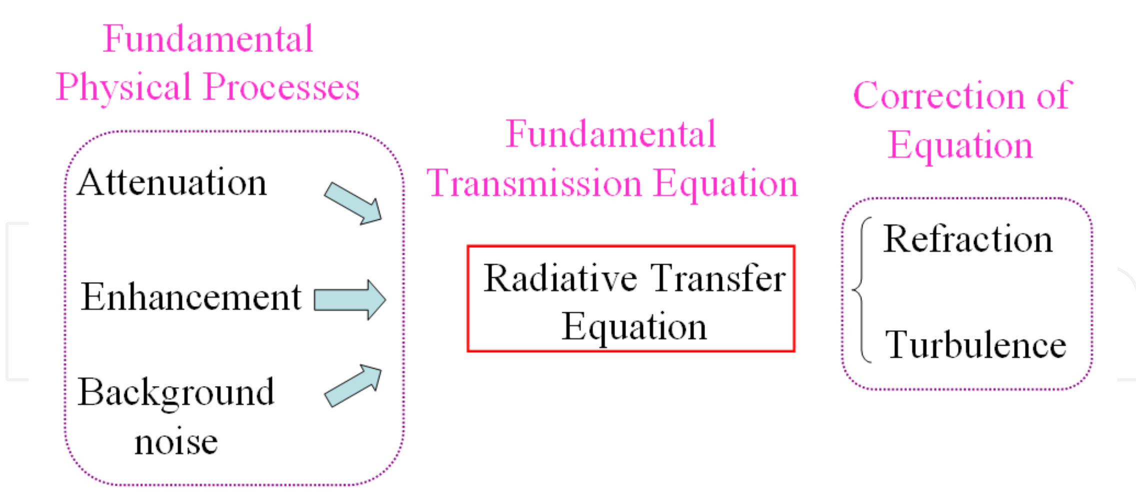


Fig. 3. The fundamental physical concepts and theories

2.1 Fundamental physical processes

2.1.1 Atmospheric extinction

In the process of the interaction between electromagnetic wave and medium, THz radiation is attenuated by absorption as well as scattering out of their straight path. The atmospheric extinction is illustrated by Lamber-beer law and mainly causing the energy attenuation of incident wave. The differential and integral forms of the mathematical expression is

$$dI(v) = -\alpha_v(z)I(v)dz \qquad I_{r_1}(\nu) = I_{r_0}(\nu)e^{-\int_{r_0}^{r_1}\alpha_\nu(z)dz} \tag{1}$$

$I_{r0}(v)$ denotes the incident radiance entering the optical path (r_0,r_1) at the frequency v and $I_{r1}(v)$ is the outgoing radiance. The opacity or optical thickness is defined as

$$\tau_\nu(r_0,r_1) = \int_{r_0}^{r_1}\alpha_\nu(z)dz \tag{2}$$

and the transmission is

$$\eta_{r_0,r_1} = \frac{I_{r_1}}{I_{r_0}} = e^{-\tau_v(r_0,r_1)} \tag{3}$$

Extinction coefficient $\alpha_v(z)$ can be expressed mathematically as the summation of the absorption and scattering coefficient, α_a and α_s, separately

$$\alpha_e = \alpha_a + \alpha_s \tag{4}$$

The atmospheric absorption, particularly from water vapor, involves the linear absorption and continuum absorption, while the atmospheric scattering mainly depends on aerosols.

2.1.1.1 The absorption of water vapor

The linear and continuum absorption constitutes the THz atmospheric absorption, which is dominated by water vapor. The former is comprised most of the absorption lines in the air, which is due to the molecular rotational transitions. The absorption lines of water vapor are characterized by spectroscopic parameters, including the center frequency, oscillator intensity, and pressure broadening coefficient. (Yasuko and Takamasa, 2008) Most of these optical properties have been conveniently catalogued into databases, such as JPL (Jet Propulsion Laboratory) and HITRAN (Rothman et al., 2009) to stimulate the line by line absorption.

The atmospheric absorption spectrum doesn't correspond to the accumulation of water vapor absorption lines. The continuum absorption is what remains after subtraction of linear contributions from the total absorption that can be measured directly. (Rosenkranz, 1998) It may be observed in wide electromagnetic spectrum (from microwave to infrared) and cannot be described by water vapor absorption lines. Its generating mechanism is not sufficiently understood while several theories have been proposed, including anomalous far-wing absorption, (Ma and Tipping, 1992) absorption by dimmers and larger clusters of water vapor, and absorption by collisions between atmospheric molecules. (Ma and Tipping, 1992) A semi-empirical CKD model is applicable in a wide frequency range and has been proven successful in some aspects. (Clough et al., 1989) For the simulation at frequencies below 400GHz, Liebe model could be used for dry air and water vapor continua. (Liebe, 1989) Figure 4 illustrates the discrepancy between radio-wave and infrared wave propagation models. The radio-wave model is calculated with JPL line catalog and

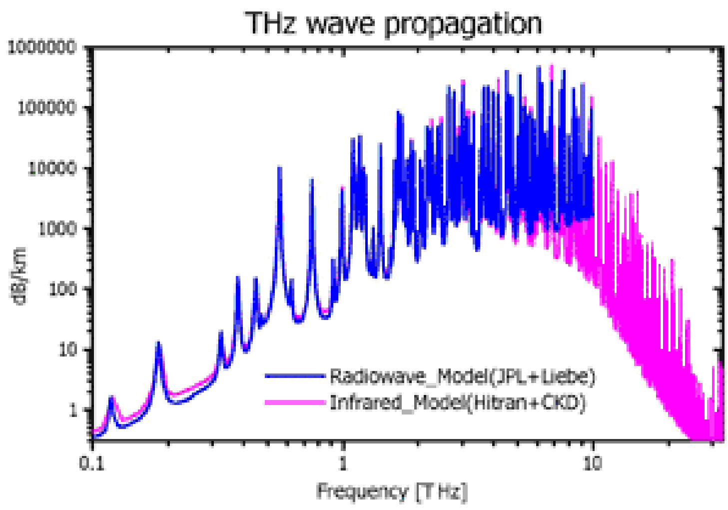


Fig. 4. The linear and continuum absorption of THz wave from NICT

Liebe model for continuum absorption while the infrared model is on the basis of HITRAN line catalog and CKD continuum model. (Yasuko and Takamasa, 2008)

2.1.1.2 The scattering of aerosol

In parallel, scattering effect also results in the energy attenuation along the optical path. It comprises the molecular Rayleigh scattering and the Mie scattering by aerosols and water vapor coagulum. As the wavelength of THz radiation lies in the order of aerosols, only Mie scattering should be taken into consideration. Aerosol particles mainly refer to the solid and liquid particles suspending in the atmosphere, for example, dusts, salts, ice particles and water droplets, and the Mie scattering effect mainly depends on their size-distribution, complex refractive index and the wavelength of incident radiation.

It is difficult to simulate the scattering by aerosols due to their large scale change in time and space domain. The scale distribution is an important concept to describe aerosols, and the spectrum pattern commonly includes:

2.1.1.2.1 Revision spectrum

$$\frac{dN(r)}{dr} = ar^{\alpha} \exp(-b^{\gamma}) \tag{5}$$

Where N is granule number in the unit volume, r is the radius of particle, a, b, a, γ is the constant which depends the origin of aerosol, including Mainland (Haze L), Sea (Haze M) and High Stereotype (Haze H).

2.1.1.2.2 Junge spectrum

$$\frac{dN}{d\log r} = cr^{-v} \tag{6}$$

In the expression above, v is the spectrum parameter, usually taking 2~4. The parameter c relates to the total density of aerosols.

2.1.1.3 Terahertz spectroscopic measurement technology

The THz spectroscopic parameters above will directly influence the accuracy of atmospheric propagation model and should be precisely measured in laboratory experiments. Currently, Terahertz Time-domain Spectroscopy (THz-TDS) technology and Fourier-transform Infrared Spectroscopy (FT-IR) have attracted a great deal of attention. A typical THz-TDS arrangement includes a femtosecond (fs) laser, a THz emitter source, a THz detector, focusing and collimating parts, a motorized delay line, a lock-in amplifier, and a data acquisition system.

As shown in Figure 5, the femtosecond laser is split into THz generation and detection arms. Coming from the same source, the pump and probe pulses have a defined temporal relationship. The THz radiation is excited by focusing the pulse onto a photoconductive antenna and the emitted THz pulses are collimated and focused onto the sample by a pair of parabolic mirrors; samples can be scanned across the focus to build up a two-dimensional image, with spectral information recorded at each pixel. (Baxter, 2011) The reflected or transmitted THz pulse is then collected and focused with another pair of parabolic mirrors onto a detector, which is a second photoconductive antenna or a sampling electro-optical crystal. The probe beam is measured with a quarter wave-plate, a Wollaston polarization (WP) splitting prism, and two balanced photodiodes. Lock-in techniques can be used to measure the photodiode signal with the modulated bias field of the photoconductive emitter as a reference. Furthermore, by measuring the signal as a function of the time delay between the arrival of THz and probe pulses, the THz time-domain electric field can be reconstructed. A computer controls the delay lines and records data from the lock-in amplifier, and the Fourier transform expresses the frequency spectrum of THz radiation. (Davies el al., 2008)

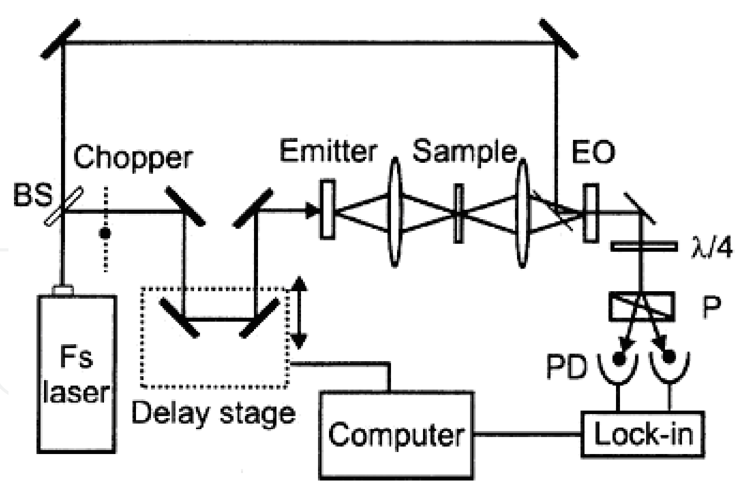


Fig. 5. Schematic experimental setups for THz-TDS system

Fourier transform infrared (FTIR) spectroscopy is a technique to obtain an infrared spectrum of absorption, emission, photoconductivity or Raman scattering of the samples. It consists of an incoherent high-pressure mercury arc lamp, a far-IR beam splitter (free-standing wire grid or Mylar), focusing and collimating optical parts for far infrared, a thermal detector, a motorized delay line, and a data acquisition system, just as Figure 6 plots. The source is generated by a broadband light source containing the full spectrum of wavelengths. The

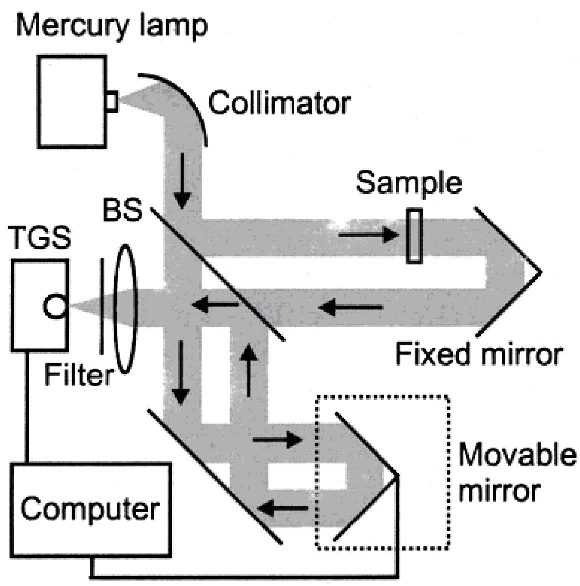


Fig. 6. Schematic experimental setups for far-IR Fourier transform spectroscopy

light shines into a Michelson interferometer, that allows some wavelengths to pass through but blocks others due to wave interference. Computer processing is required to turn the original data into the desired result.

Compared to other spectroscopic techniques, THz-TDS presents a series of advantages. THz pulse has ps pulse duration, resulting in the intrinsic high temporal resolution and is very suitable for the dynamic spectroscopic measurement. THz-TDS provides coherent spectroscopic detection and a direct record of the THz time-domain pulse. It enables the determination of the complex permittivity of a sample, consisting of the amplitude and phase, without the requirement of Kramers-Kronig relationship. (Zhang & Xu, 2009) Additionally, time-gating technology in sampling THz pulses has been employed, which dramatically suppresses the background noise. It is especially useful to measure spectroscopy with high background radiation which is comparable or even stronger than the signal. In terms of signal-to-noise ratio, THz-TDS is advantageous at low frequencies less than 3 THz, while Fourier transform spectroscopy works better at frequencies above 5 THz. (Han et al., 2001)

2.1.2 Atmospheric emission

THz radiation propagating in the atmosphere also experiences the process of enhancement. THz emission is defined as source term J, comprising the thermal emission J_B and the scattering source term J_S. Compared with the attenuation by scattering out of the line-of-sight, scattering into the path is considered as a source of radiation as well, including the source sole scattering on direct radiation condition J_{SS} and the multiple scattering source J_{MS}. (Mendrok, 2006) The expression of source terms is

$$J = J_B + J_S = J_B + J_{SS} + J_{MS} \tag{7}$$

The thermal emission term is defined as

$$J_B = (1 - \omega_0) B(T) \tag{8}$$

B(T) denotes the Planck emission term which is given by Planck's function describing the radiation of a black-body at temperature *T*:

$$B_v(T) = \frac{2hv^3}{c^2} \frac{1}{e^{hv/k_B T} - 1} \tag{9}$$

where h is Planck's constant, c the speed of light, and k_B denotes Boltzmann's constant. w_0 is the scattering albedo of the "mixed" atmospheric medium along the line-of-sight, which is calculated from molecular and particle optical properties:

$$\omega_0 = \frac{\alpha_s^{par}}{\alpha_s^{par} + \alpha_a^{par} + \alpha_s^{mol}} \tag{10}$$

where α_s and α_a are scattering and absorption coefficients with superscripts 'mol' and 'par' denoting properties of molecular and particulate matter, respectively.

The scattering source term into the optical path is described as:

$$J_s(\Omega) = \frac{\alpha_s}{\alpha_e} \frac{1}{4\pi} \int_0^{4\pi} P(\Omega,\Omega')I(\Omega')d\Omega' \tag{11}$$

It comprises radiation incident from all directions Ω' scattered into the direction of interest Ω. While the scattering coefficient α_s accounts for the scattered fraction of radiation, the phase function $P(\Omega,\Omega')$ can be interpreted as the probability of incident radiation being scattered from direction Ω' into direction Ω with the normalizing condition:

$$\frac{1}{4\pi} \int_0^{4\pi} P(\Omega,\Omega')d\Omega' = 1 \tag{12}$$

$I(\Omega')$ describes the incident radiation field in terms of incident direction for the calculation of the scattering source term.

2.1.3 Background radiation

Remote observations of the atmosphere can be performed at different geometries, as Figure 7 shows. The case that the line-of-sight goes through a long tangential atmospheric path above the ground is commonly referred to as limb-sounding geometry. If the line-of-sight crosses the surface, it is called nadir-sounding geometry. The up-looking case can be obtained by inverting the sense of the nadir observation. The background radiation of THz wave in the atmosphere mainly results from many kinds of electromagnetic radiation in the interstellar space or from the planet surface. For limb-sounding and up-looking, it is the cosmologic radiation at 3K, and for nadir-sounding (or down-looking), it is the earth surface emission.

2.2 Radiative transfer equation

Radiative transfer is the physical phenomenon of energy transferring in the form of electromagnetic radiation. The propagation of radiation through a medium is affected by the

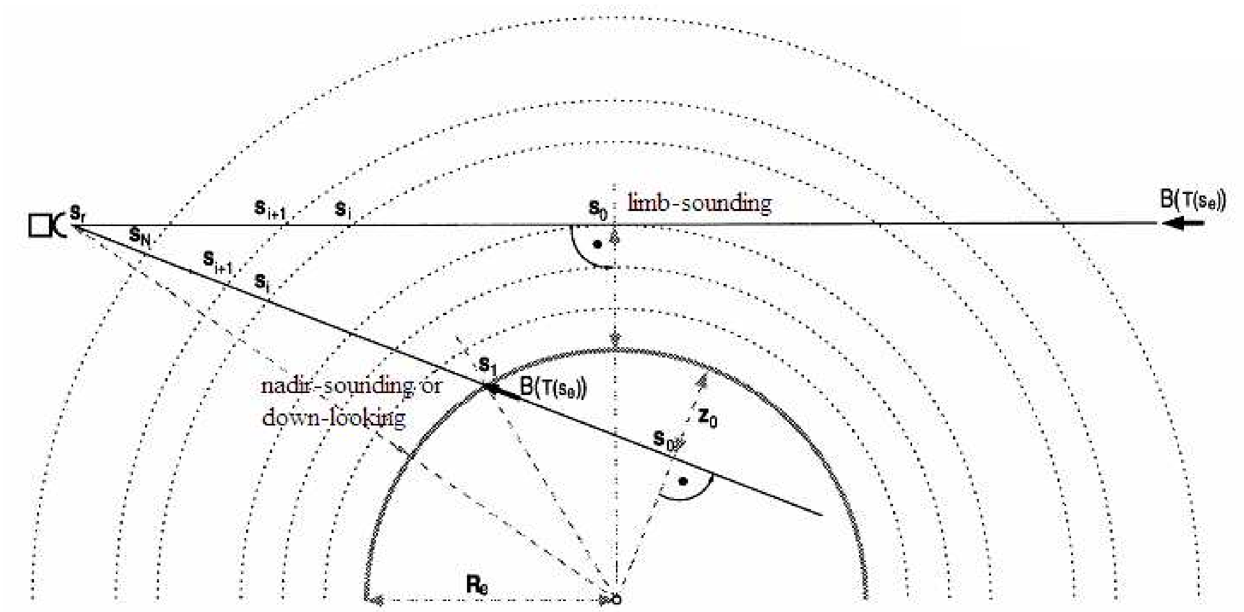


Fig. 7. Geometry inlcuding limb-sounding and nadir-sounding

three concepts (attenuation, enhancement, and background radiation) occurring along the line-of-sight and the equation of radiative transfer describes these interactions mathematically. It is the foundation of THz atmospheric propagation model, and the derivation is as follow: (Thomas & Stamnes, 2002)

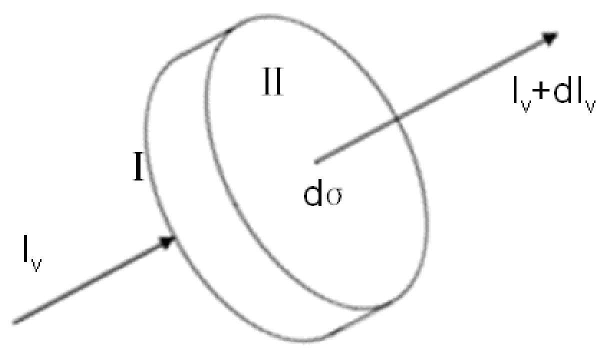


Fig. 8. The input and output optical intensity

The fundamental quantity which describes a field of radiation is the spectral intensity. Let's think of a very small area element in the radiation field, as the Figure 8 above, the radiant energy of incident light in the surface I of an infinitesimal volume is:

$$dE^{in} = I_v d\omega dv d\sigma dt \tag{13}$$

where I_v is radiant intensity, dw solid angle, dv frequency interval, $d\sigma$ basal area, and dt denotes the time of radiation (polarization will be ignored for the moment). And the emergent radiant energy from surface II is:

$$dE^{out} = (I_v + dI_v) d\omega dv d\sigma dt \tag{14}$$

According to the Lamber-beer law, with the absorption coefficient α_v, the radiant energy absorbed by the medium is:

$$dE_\alpha = -\alpha_\nu dE^{in} dr = -\alpha_\nu I_\nu d\omega d\nu d\sigma dt dr \quad (15)$$

With the emission coefficient j_v, the radiant energy of medium emission is:

$$dE_e = j_\nu d\omega d\nu d\sigma dt dr \quad (16)$$

In accordance with energy conservation law, we get:

$$dE^{out} = dE^{in} + dE_e + dE_\alpha \quad (17)$$

Substituting equation (8)~(11) into equation (12):

$$dI_\nu d\omega d\nu d\sigma dt = j_\nu d\omega d\nu d\sigma dt dr + (-\alpha_\nu I_v) d\omega d\nu d\sigma dt dr \quad (18)$$

A particularly useful simplification of the radiative transfer equation occurs under the conditions of local thermodynamic equilibrium (LTE). In this situation, the atmosphere consists of massive particles which are in equilibrium with each other, and therefore have a definable temperature. For the atmosphere in LTE, the emission coefficient and absorption coefficient are functions of temperature and density only, and the source function is defined as $S_v \equiv j_v / \alpha_v$. It equals the Planck function according to Kirchhoff's law:

$$S_v \equiv j_v / \alpha_v = B_\nu(T) \quad (19)$$

Given the definition of opacity or optical thickness: $d\tau_v = \alpha_v dr$, we get the differential form of radiative transfer equation from equation (18):

$$\frac{dI_v}{d\tau_v} = S_\nu - I_\nu \quad (20)$$

To solve this single-order partial differential equation along integral path (r_0,r_1), with the integral variable r, we get the integral form of radiative transfer equation:

$$I_\nu(r_1) = I_\nu(r_0) e^{-\int_{r_0}^{r_1} \alpha_\nu(r) dr} + \int_{r_0}^{r_1} e^{-\int_r^{r_1} \alpha_\nu(r') dr'} S_\nu(r) \alpha_\nu(r) dr \quad (21)$$

Under the assumption of LTE, the equation can be written as:

$$I_\nu(r_1) = I_\nu(r_0) e^{-\int_{r_0}^{r_1} \alpha_\nu(r) dr} + \int_{r_0}^{r_1} B_\nu(T) \alpha_\nu(r) e^{-\int_r^{r_1} \alpha_\nu(r') dr'} dr \quad (22)$$

The physical significance of radiative equation lies in the processes of absorption and emission of atmosphere at the position r along a given optical path (r_0,r_1), with the first term on the right side describing the background radiation attenuated by atmosphere while the second one standing for atmospheric emission and absorption. $I_v(r_1)$ is the outgoing radiance arriving the sensor at the frequency v and $I_v(r_0)$ corresponds to the background radiance entering the optical path.

As the radiative transfer equation results from energy conservation law, it is applicable to the whole electromagnetic spectrum, from radio wave to visible light. In the course of this work, radiation has only been discussed in terms of scalar intensity. Considering the polarization, the radiation is described by four components (I, Q, U, V) of the Stokes vector and a complete description of interaction between the medium and the radiation will be expressed. However, scalar radiative transfer is usually a good approximation for most situations in radiative transfer modeling.

2.3 Elements to promote the algorithm

2.3.1 Atmospheric turbulence

Turbulence is a flow regime characterized chaotically and stochastically, the problems of which are thus treated statistically rather than deterministically. The turbulent atmospheric optical property is changing with the temporal and spatial variation, resulting in the fluctuation of atmospheric refractive index. The essence of turbulence effect is the influence of medium disturbance on the transmission of incident THz radiation, including the beam drift, jitter, flickering, distortion, and degeneracy of the spatial coherence.

The turbulent consequence mainly depends on the relationship of turbulent scale l and the characteristic dimension of the incident radiation d_B.

On condition that $l >> d_B$, THz beam deflects during the process of the propagation in turbulence and mainly cause beam drifting on the receiver. When turbulent scale l is equal to the characteristic dimension d_B, the light beam will also experience stochastic deflection, resulting in the image spot jitter. If $l << d_B$, the influence of scattering and diffraction leads to the intensity flickering of THz beam. (Yao & Yu 2006)

Additionally, in terms of incident radiation, fully coherent light beams are sensitive to the properties of the medium through which they are propagating and the turbulence-induced spatial broadening is the major limiting factor in most applications. Partially coherent beams are less affected by atmospheric turbulence than fully ones. (Shirai 2003)

2.3.2 Atmospheric refraction

The atmospheric refraction results from the uneven distribution of air in horizontal and vertical directions. When passing through the atmosphere, the line of sight is refracted and bended towards the surface of the planets. Taking refraction into account will correct and promote the radiative transfer path with some elementary geometrical relationships, as plotted in Figure 9.

In conclusion of Section 2, the general idea to solve these problems above is to study the various effects independently and superpose them. Currently, most researches are mainly focused on the atmospheric extinction and the establishment of radiative transfer model.

3. THz atmospheric propagation model

3.1 Moliere

Microwave Observation Line Estimation and Retrieval (Moliere), developed at the Bordeaux Astronomical Observatory (France), is the versatile forward and inversion model for

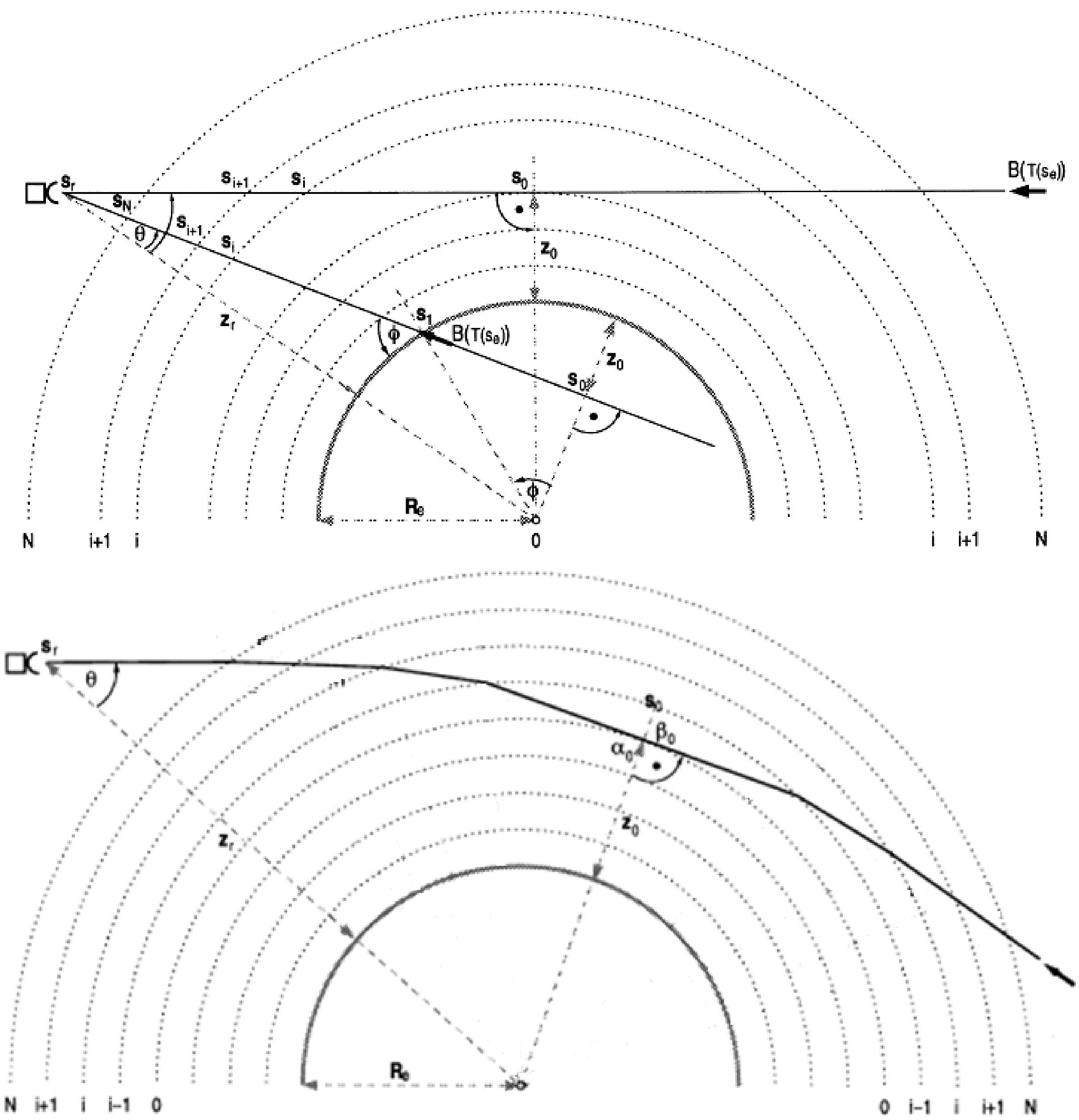


Fig. 9. The radiation path and its modification due to atmospheric refraction

millimeter and sub-millimeter wavelength observations on board the Odin satellite, including a non-scattering radiative transfer model, a receiver simulator and an inversion code. The forward models comprise spectroscopic parameters, atmospheric radiative transfer model, and instrument characteristics in order to model and compute the searched atmospheric quantities. In parallel, inversion techniques have been developed to retrieve geophysical parameters such as temperature and trace gas mixing ratios from the remotely measured spectra. (Urban et al., 2004)

Moliere is presently applied to data analysis for ground-based and space-borne heterodyne instruments and definition studies for future limb sensors dedicated to Earth observation and Mars exploration. However, this code can not be used when both up-looking and down-looking geometries should be considered together, and for limb geometry if the receiver is inside the atmosphere, such as balloon and airplane.

3.2 SARTre

The new radiative transfer model [Approximate] Spherical Atmospheric Radiative Transfer model (SARTre) has been developed to provide a consistent model that accounts for the influence of aerosols and clouds, e.g. water droplets or ice particles. It includes emission and absorption as well as scattering as sources/sinks of radiation from both solar and terrestrial sources in the spherical shell atmosphere and is able to analyze data measured over the spectral range from ultraviolet to microwaves. (Mendrok et al., 2008) SARTre is designed for monochromatic, high spectral resolution forward modeling of arbitrary observing geometries, especially for the limb observation technique.

The line-by-line calculation of molecular absorption cross sections has been adapted from the radiative transfer package MIRART (Modular Infrared Atmospheric Radiative Transfer). And the DISORT (Discrete Ordinate Radiative Transfer Model) package is used for the calculation of the incident radiation field when taking multiple scattering into account, under the assumption of a locally plane-parallel atmosphere. (Mendrok et al., 2008)

3.3 AMATERASU

The Advanced Model for Atmospheric Terahertz Radiation Analysis and Simulation (AMATERASU) is developed by the National Institute of Information and Communications Technology (NICT) THz project. This project aims to develop THz technology for various applications concerning the telecommunications, atmospheric remote sensing to retrieve geophysical parameters and the study of the thermal atmospheric emission in the Earth energy budget. The framework of AMATERASU has been shown in Figure 10, mainly consisting of the spectroscopic parameters and the radiative transfer equation, as mentioned above.

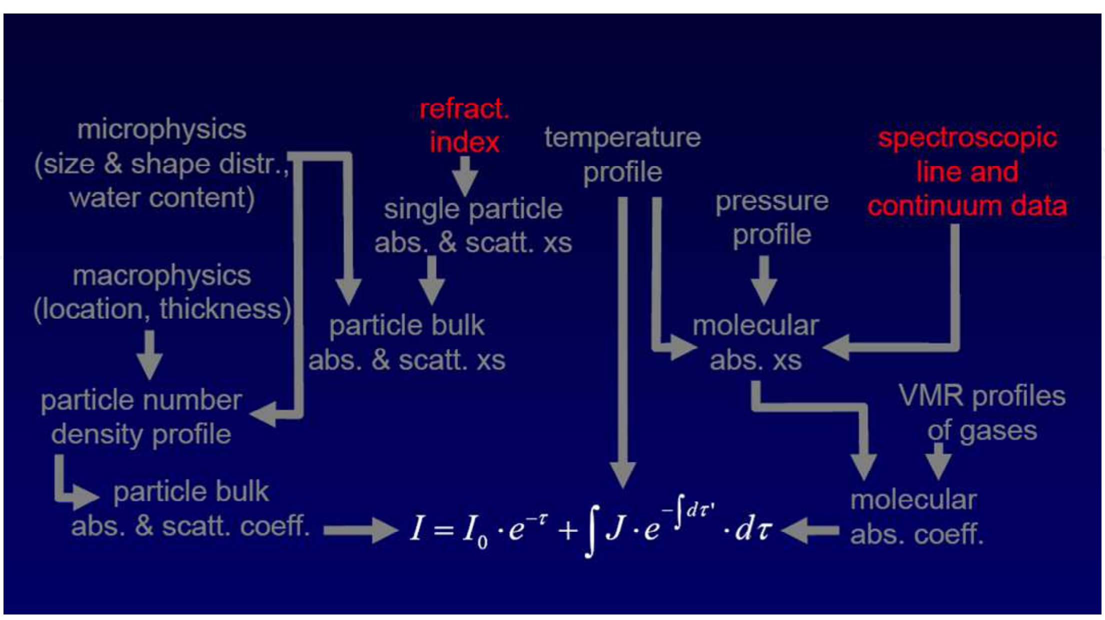


Fig. 10. The framework of AMATERASU from NICT

The AMATERASU has a strong heritage from the two models above, respectively in the non-scattering and scattering case. The first stage concerns a non-scattering and homogeneous atmosphere, based on the original Moliere receiver simulator and retrieval codes. The absorption coefficient module has been extent to THz region and a more general radiative transfer module has been implemented to handle different geometries of optical paths and any location for the receiver. (Baron et al., 2008) The advanced version has taken the scattering effect into consideration. Modules related to optical properties of atmospheric particles and to scattering have been adapted from SARTre. The complex refractive index data of aerosols in THz region should be emphasized as a crucial parameter for radiative transfer algorithms. (Mendrok et al., 2008)

As for the practical applications, the THz atmospheric propagation models above should be compared with each other and validated against the real laboratory measurements in order to verify the data accuracy and correctness of the algorithm hypothesis. (Wang et al., 2011)

4. Conclusion

In this chapter, we have discussed the fundamental theory in the process of THz atmospheric propagation. Several kinds of THz atmospheric propagation models have been introduced as well. The critical issues lie in the construction of radiative transfer algorithm, the collection of accurate spectral parameters, such as linear and continuum absorption and complex refractive index in THz region, and the standardization of measurement procedures. The ultimate objective is to construct the atmospheric propagation model in different kinds of climatic conditions on the basis of the theoretical analysis and the material database.

5. Acknowledgment

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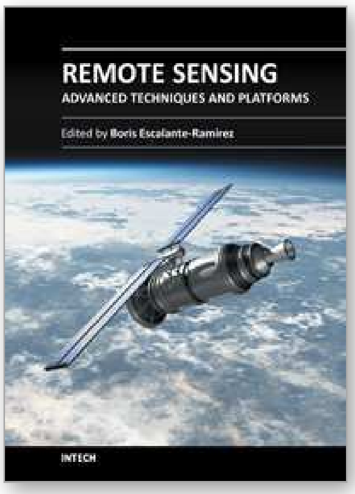

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This dual conception of remote sensing brought us to the idea of preparing two different books; in addition to the first book which displays recent advances in remote sensing applications, this book is devoted to new techniques for data processing, sensors and platforms. We do not intend this book to cover all aspects of remote sensing techniques and platforms, since it would be an impossible task for a single volume. Instead, we have collected a number of high-quality, original and representative contributions in those areas.