

Lecture 10.

Applications of passive remote sensing using emission:

Principles of sounding by emission and applications (temperature and atmospheric gases).

1. Concept of weighting functions: weighting functions for nadir and limb soundings.
2. Sounding of the atmospheric temperature. Examples: NOAA sounders.
3. Sounding of atmospheric gases.

Appendix: Concept of an inverse problem.

Required reading:

S: 7.5, 1.2, 7.5.4, 7.3.1, 7.3.2, 7.7, Patty: 8

Additional reading:

Sounders for atmospheric chemistry (NASA Aura mission):

<http://aura.gsfc.nasa.gov/>

1. Concept of weighting functions: weighting functions for nadir and limb soundings.

Recall Eq.[9.8] that gives the **upward intensity in the plane-parallel atmosphere with emission (neglecting scattering):**

$$I_v^\uparrow(\tau, \mu) = I_v^\uparrow(\tau^*, \mu) \exp\left(-\frac{\tau^* - \tau}{\mu}\right) + \frac{1}{\mu} \int_{\tau}^{\tau^*} \exp\left(-\frac{\tau' - \tau}{\mu}\right) B_v(\tau') d\tau'$$

and that

$$T_v(\tau', \tau, \mu) = \exp\left(-\frac{\tau' - \tau}{\mu}\right) \quad \text{and} \quad \frac{dT_v(\tau', \tau, \mu)}{d\tau'} = -\frac{1}{\mu} \exp\left(-\frac{\tau' - \tau}{\mu}\right)$$

where μ is the cosine of zenith angle of observation.

Eq.[9.8] can be re-written in terms of transmission function (see Eq. 9.15) as

$$I_v^\uparrow(\tau, \mu) = I_v(\tau^*)T_v(\tau^*, \tau, \mu) + \int_{\tau^*}^{\tau} B_v(\tau') \frac{dT_v(\tau', \tau, \mu)}{d\tau'} d\tau' \quad [10.1]$$

Eq.[10.1] can be expressed in different vertical coordinates such as z, P or $\ln(P)$.

Let's denote an arbitrary vertical coordinate by \tilde{z} , so Eq.[10.1] becomes

$$I_v^\uparrow(\tilde{z}, \mu) = I_v(\tilde{z}^*)T_v(\tilde{z}^*, \tilde{z}, \mu) + \int_{\tilde{z}^*}^{\tilde{z}} B_v(\tilde{z}')W(\tilde{z}', \tilde{z}, \mu)d\tilde{z}' \quad [10.2]$$

where the **weighting function** is defined in the general form as

$$W_v(\tilde{z}_1, \tilde{z}_2, \mu) = \left| \frac{dT_v(\tilde{z}_1, \tilde{z}_2, \mu)}{d\tilde{z}} \right| \quad [10.3]$$

Physical meaning of the weighting function:

Radiances emitted from a layer $d\tilde{z}'$ is determined by a blackbody emission, $B_v(\tilde{z}')$, of the layer weighted by the factor $W_v(\tilde{z}', \tilde{z}, \mu)d\tilde{z}'$

Let's re-write the solutions of the radiative transfer equation for upward and downward radiances in the altitude coordinate, z. Recall that the optical depth of a layer due to absorption by a gas in this layer is

$$\tau_v = \int_{u_1}^{u_2} k_v du$$

Let's express the optical depth in terms of a mass absorption coefficient of the absorbing gas and its density

$$\tau_v = \int_{z'}^z k_v \rho_{gas} dz'' \quad [10.4]$$

Thus transmission between z and z' along the path at μ is

$$T_v(z, z', \mu) = \exp\left(-\frac{1}{\mu} \int_{z'}^z k_v \rho_{gas} dz''\right) \quad [10.5]$$

and

$$\frac{dT_v(z, z', \mu)}{dz'} = -\frac{k_v \rho_{gas}}{\mu} \exp\left(-\frac{1}{\mu} \int_{z'}^z k_v \rho_{gas} dz''\right) \quad [10.6]$$

Therefore, for the **upward intensity and downward intensities** at the altitude z , we have

$$I_v^\uparrow(z, \mu) = I_v^\uparrow(0, \mu) T_v(z, 0, \mu) + \int_0^z B_v(T(z')) \left| \frac{dT_v(z, z', \mu)}{dz'} \right| dz' \quad [10.7]$$

$$I_v^\downarrow(z, -\mu) = \int_z^\infty B_v(T(z')) \left| \frac{dT_v(z, z', \mu)}{dz'} \right| dz' \quad [10.8]$$

and thus

$$I_v^\uparrow(z, \mu) = I_v^\uparrow(0, \mu) \exp\left[-\frac{1}{\mu} \int_0^z k_v \rho_{gas} dz'\right] + \frac{1}{\mu} \int_0^z \exp\left[-\frac{1}{\mu} \int_{z'}^z k_v \rho_{gas} dz''\right] B_v(T(z')) k_v \rho_{gas} dz' \quad [10.9]$$

$$I_v^\downarrow(z, -\mu) = \frac{1}{\mu} \int_z^\infty \exp\left[-\frac{1}{\mu} \int_{z'}^z k_v \rho_{gas} dz''\right] B_v(T(z')) k_v \rho_{gas} dz' \quad [10.10]$$

NOTE: Eq.[10.9] is fundamental to remote sensing of the atmosphere. It shows that the upwelling intensity in the IR is a product of the Planck function, spectral transmittance, and weighting function. Information on temperature is included in the Planck function, while the density profile of relevant absorbing gases is involved in the weighting function.



Thus, one can retrieve the profile of temperature if the profiles of relevant absorbing gases are known, or vice versa.

Weighting functions for near-nadir sounding:

From Eq.[10.7], upwelling radiance detected by a satellite sensor at $z = \infty$ is

$$I_v^\uparrow(\infty, \mu) = I_v^\uparrow(0, \mu) T_v(\infty, 0, \mu) + \int_0^\infty B_v(T(z')) \left| \frac{dT_v(\infty, z', \mu)}{dz'} \right| dz' \quad [10.11]$$

or

$$I_v^\uparrow(\infty, \mu) = I_v^\uparrow(0, \mu)T_v(\infty, 0, \mu) + \int_0^\infty B_v(T(z))W_v(\infty, z, \mu)dz \quad [10.12]$$

where

$$W_v(\infty, z, \mu) = \left| \frac{dT_v(\infty, z, \mu)}{dz} \right|$$

thus using Eq.[10.6] we have

$$W_v(\infty, z, \mu) = \left| \frac{T_v(\infty, z, \mu)}{dz} \right| = \frac{k_v \rho_{gas}}{\mu} \exp\left(-\frac{1}{\mu} \int_z^\infty k_v \rho_{gas} dz\right) \quad [10.13]$$

↑ decreases with altitude
 ↑ increases with altitude

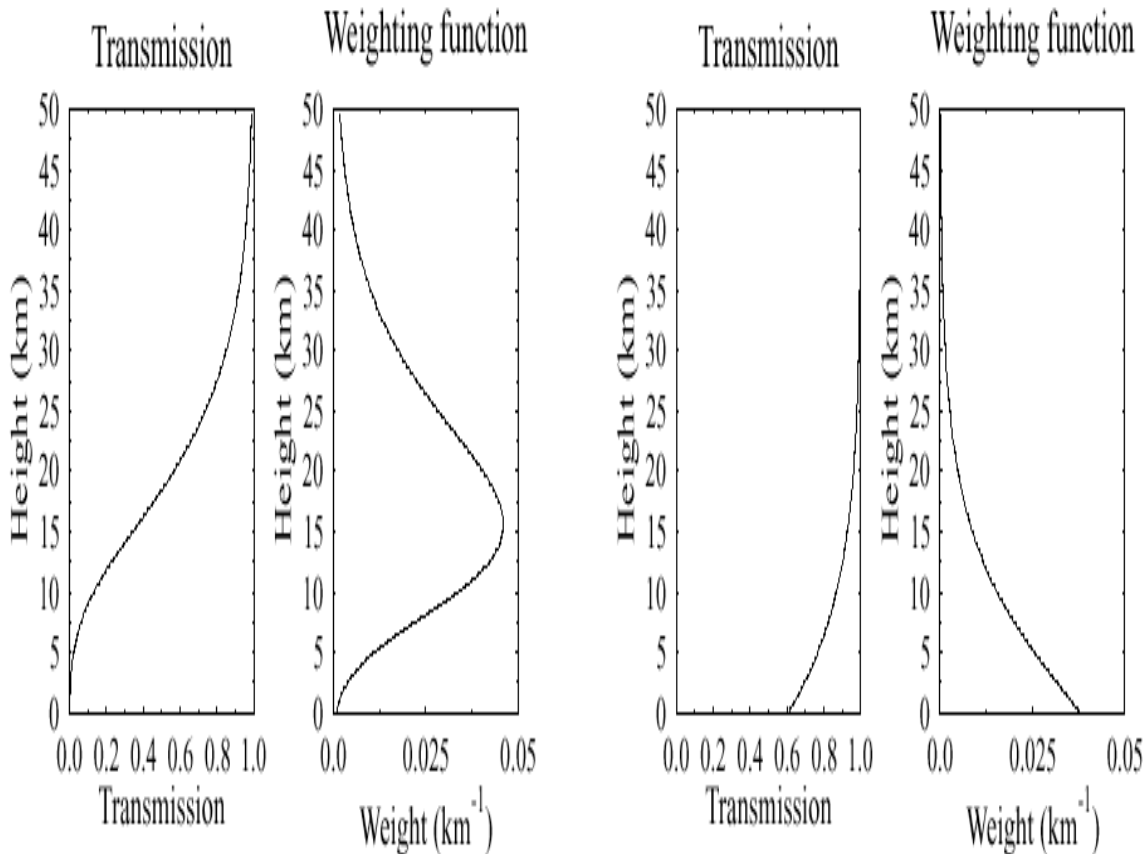


Figure 10.1 Examples of weighting functions for nadir sounding for optically thick (left pair) and optically thin (right pair) media.

Weighting functions for limb sounding:

The intensity measured by a satellite for limb viewing geometry is the integral of the emission along a line-of-sight

$$I_{\nu}(h) = \int_{\infty}^0 B_{\nu}(s) \frac{dT_{\nu}(s,0)}{ds} ds \quad [10.14]$$

h is the tangent altitude,

$T_{\nu}(s, 0)$ is the transmission function along the path of length s from the outer levels of the atmosphere at $s = \infty$.

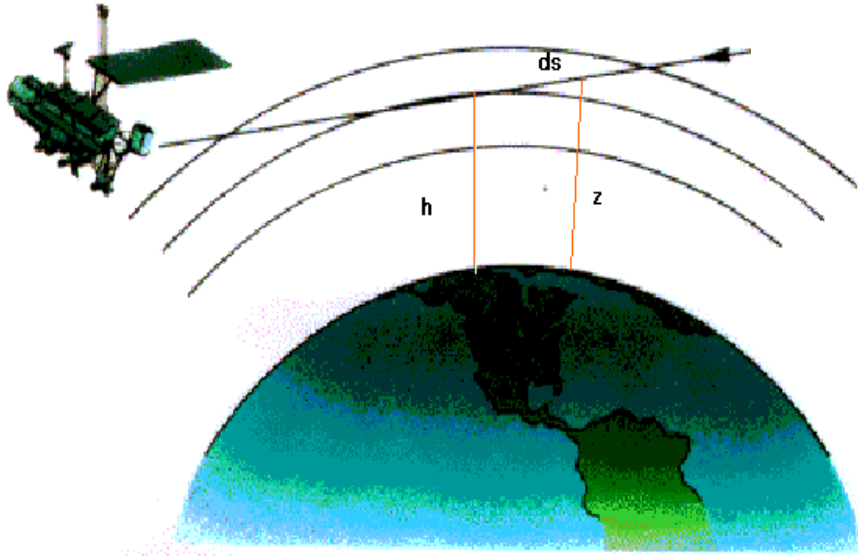


Figure 10.2 Viewing geometry of limb sounding.

We can relate s and z as

$$(R + h)^2 + s^2 = (R + z)^2 \quad [10.15]$$

where R is the radius of the Earth. Using that $R \gg h$, we have

$$s^2 \approx 2R(z - h) \quad [10.16]$$

Thus Eq.[10.14] becomes

$$I_{\nu}(h) = \int_h^{\infty} B_{\nu}(z') \frac{dT_{\nu}(z', \infty)}{ds} \frac{ds}{dz'} dz' \quad [10.17]$$

and

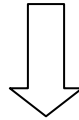
$$I_v(h) = \int_h^{\infty} B_v(z')W(h, z', \infty)dz' \quad [10.18]$$

where

$$W_v(h, z, \infty) = 0 \quad \text{for } z < h$$

$$W_v(h, z, \infty) = \frac{dT_v(z, \infty)}{ds} \sqrt{\frac{R}{2(z-h)}} \quad \text{for } z > h \quad [10.19]$$

↑
enhancement of the tangent path relative to a vertical path



Limb sounding has higher sensitivity to emission from trace gases (CO, NO, N₂O, CIO)

Advantages of limb sounding:

- Can measure emission from gases of low concentrations
- Surface emission does not effect limb sounding
- Good vertical distribution since it senses outgoing radiation from just a few kilometers above the tangent height (=> weighting functions have spikes, see S:fig.7.18)

Disadvantages of limb sounding:

- ✓ Can not be used below the troposphere
- ✓ Requires precise information of the viewing geometry

2. Sounding of atmospheric temperature.

Let's find the simplest solution of Eq.[9.A2] (see Appendix), assuming that transmittance (and hence weighting functions) does not depend on temperature. Thus Eq.[9.A2] is linear in $B(\bar{\nu}, T(z))$.

A standard approach is to express $B(\bar{\nu}, T(z))$ as a linear function of N variables, b_j :

$$B(\bar{\nu}, T(z)) = \sum_{j=1}^N b_j L_j(z) \quad [10.20]$$

where $L_j(z)$ is a set of representation functions such as polynomials or sines and cosines.

Eq.[9.A2] becomes

$$I_{\nu_i}^{\uparrow} = \sum_{j=1}^N b_j \int_0^{\infty} L_j(z) W_{\nu_i}(z) dz = \sum_{j=1}^N C_{ij} b_j \quad [10.21]$$

where the square matrix C whose elements $C_{ij} = \int_0^{\infty} L_j(z) W_{\nu_i}(z) dz$ can be easily

calculated. Thus for the N unknown b_j , there are N equations which can be solved. The solution of Eq.[10.21] is called an **exact solution to the linear problem**.

Problems:

Eq.[10.21] is ill-conditioned (i.e., any experimental error in the measurements can be greatly amplified and the solution can be physically meaningless, though it satisfies Eq.[10.21]).

Strategy: instead of **an exact solution**, find the solution that lies within the experimental error of measurements => it gives us more freedom in a choice of a solution, but a new problem is how to make this choice.

Thus the problem of retrieval can be re-stated as:

Given the measured radiances, the statistical experimental error, the weighting functions, and any other relative information, what solutions for $B(\bar{\nu}, T(z))$ are physically meaningful?

A priori information is often used to provide “other relative information”.

A priori information for the retrievals of temperature:

- Radiosonde data
- Forecast atmospheric dynamical models

Example: GOES soundings are generated every hour, using a numerical weather prediction model forecast as a 'first guess'

NOAA sounders:

HIRS/2 (High Resolution Infrared Radiation Sounder 2): 20 channels, resolution 19 km (nadir)

MSU (Microwave sounding Unit): 4 channels, resolution 111 km (nadir)

SSU (Stratospheric Sounding Unit): 3 channels (in the 15- μm CO₂ band), resolution 111 km (nadir)

[HIRS+MSU+SSU] is called **TOVS** (TIROS N Operational Vertical Sounder)

NOTE: MSU+ SSU were replaced by AMSU-A and AMSU-B (Advanced Microwave Sounding Units) on NOAA K, L, M series.

Retrieval methods for temperature sounding:

- Physical retrievals
- Statistical retrievals
- Hybrid retrievals

Physical retrievals:

use the forward modeling to do an iterative retrieval of the temperature profile

Steps:

- 1) Selection of a first-guess initial temperature profile.
- 2) Calculation of the weighting functions.
- 3) Forward modeling of the radiance in each channel of a sensor.
- 4) If the calculated radiance agrees with the measured radiance within the noise level of the sensor, the current profile gives the solution.

- 5) If convergence has not been achieved, the current profile is adjusted, and steps 2 through 5 are repeated until a solution is found.

Advantages:

- Relevant physical processes are taken into account at each step.
- No data is necessary

Disadvantages:

- Computationally intensive
- Requires accurate predictions of the transmittance

Statistical retrievals:

Do not solve the radiative transfer (i.e., no forward modeling). Instead a training data set – a set of radiosonde soundings that are collocated in time and space with satellite soundings – is used to establish a statistical relationship between the measured radiances and temperature profiles. These relationships are then applied to other measurements of the radiances to retrieve the temperature.

Advantages:

- Computationally easy and fast (does not require to solve the radiative transfer equation).

Disadvantages:

- A large training data set (covering different region, seasons, land types, etc.) is required.
- Physical processes are hidden in the statistics.

Hybrid retrievals: (also called inverse matrix methods)

Use the weighing functions (but do not solve the radiative transfer equation) and available data (but for a limited data set).

3. Sounding of atmospheric gases.

Strategy: make satellite measurements at frequencies in absorption bands of atmospheric gases.

The principles of the methods for gas retrievals are generally the same as for temperature retrievals, but gas inversion is more difficult:

- The inverse problem is more nonlinear for constituents (because they enter the radiative transfer equation through the mixing ratio profile in the exponent. It is not possible to separate the radiative transfer equation into the product of a simple constituent function and one which is constituent-independent).
- The second main problem is that, in some cases, the radiances are insensitive to changes in the mixing ratio. (For instance, for an isothermal atmosphere at temperature T , any mixing ratio profile will result in the same radiances (i.e. $B_v(T)$). In practice, we find this problem in the retrieval of low-level water vapor; because the temperature of the water vapor is close to that of the surface, infrared radiances are relatively insensitive to changes in low-level water vapor).

Examples of sounders and other sensors for remote sensing of gaseous species:

GOME (Global Ozone Monitoring Experiment), ESA-ERS

retrievals of O₃, NO₂, H₂O, BrO, SO₂, HCHO, OCLO

http://www.doas-bremen.de/no2_from_gome.htm#Links

SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography), ESA-ENVISAT, 2001-present,

retrievals of O₂, O₃, NO, NO₂, N₂O, H₂O, BrO, SO₂, HCHO, H₂CO, CO, OCLO, CO₂, CH₄

<http://www.iup.uni-bremen.de/sciamachy/>

<http://www.temis.nl/products/>

MOPITT (Measurements Of Pollution In The Troposphere), NASA Terra, 1999-present
retrievals of CO and CH₄ (retrieval algorithm involves weighing function)

<http://www.eos.ucar.edu/mopitt/>

NASA satellite mission for atmospheric chemistry:

EOS Aura: launched July 15, 2004.

<http://aura.gsfc.nasa.gov/>

Aura includes HIRDLS, MLS, TES, and OMI instruments.

HIRDLS (High Resolution Dynamics Limb Sounder)

<http://aura.gsfc.nasa.gov/instruments/hirdls.html>

an infrared limb-scanning radiometer designed to sound the upper troposphere, stratosphere, and mesosphere to determine temperature; the concentrations of O₃, H₂O, CH₄, N₂O, NO₂, HNO₃, N₂O₅, ClONO₂, CFC₁₂, CFC₁₃, and aerosols; and the locations of polar stratospheric clouds and cloud tops. HIRDLS performs limb scans in the vertical at multiple azimuth angles, measuring infrared emissions in 21 channels ranging from 6.12 μm to 17.76 μm.

MLS (Microwave Limb Sounder) <http://aura.gsfc.nasa.gov/instruments/mls.html>

measures lower stratospheric temperature and concentrations of H₂O, O₃, ClO, BrO, HCl, OH, HO₂, HNO₃, HCN, and N₂O.

MLS observes in spectral bands centered near the following frequencies:

118 GHz, primarily for temperature and pressure;

190 GHz, primarily for H₂O, HNO₃, and continuity with UARS MLS measurements;

240 GHz, primarily for O₃ and CO;

640 GHz, primarily for N₂O, HCl, ClO, HOCl, BrO, HO₂, and SO₂; and

2.5 THz, primarily for OH.

OMI (Ozone Monitoring Instrument) <http://aura.gsfc.nasa.gov/instruments/omi.html>

continues the TOMS record for total ozone, also will measure NO₂, SO₂, BrO, OCIO, and aerosol characteristics.

TES (Tropospheric Emission Spectrometer)

<http://aura.gsfc.nasa.gov/instruments/tes.html>

a high-resolution infrared-imaging Fourier transform spectrometer with spectral coverage of 3.2 to 15.4 μm at a spectral resolution of 0.025 cm^{-1} . TES provides simultaneous measurements of NO_y , CO , O_3 , and H_2O .

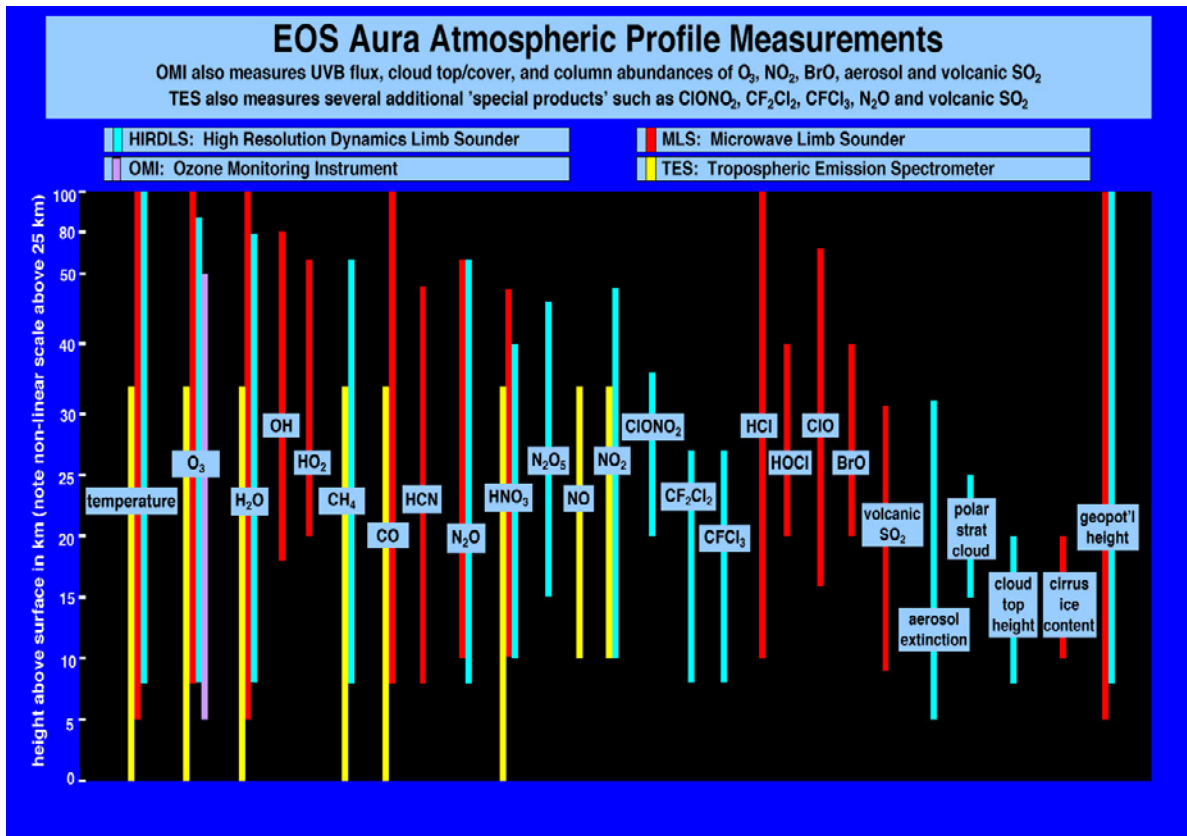


Figure 10.3 The atmospheric parameters measured by HIRDLS, MLS, OMI, and TES. The altitude range where these parameters are measured are shown as the vertical scale. In several cases the measurements overlap which provides independent perspectives and cross calibration of the measurements.

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APPENDIX. Concept of an inverse problem.

Advanced reading:

C. D. Rodgers, Inverse methods for atmospheric sounding: Theory and practice. 2000.

Eq.[10. 11] which gives the solution of the radiative transfer equation with emission for the **outgoing intensity** at the top of the atmosphere $z = \infty$

$$I_{\nu}^{\uparrow}(\infty, \mu) = I_{\nu}^{\uparrow}(0; \mu, \mu) T_{\nu}(\infty, 0, \mu) + \int_0^{\infty} B_{\nu}(T(z)) W_{\nu}(\infty, z, \mu) dz$$

where

$$W_{\nu}(\infty, z, \mu) = \left| \frac{dT_{\nu}(\infty, z, \mu)}{dz} \right| \text{ is the weighting function.}$$

Forward problem is to calculate outgoing radiances for given temperature and gas concentration profiles.

Inverse problem in remote sounding is to determine what temperature and gas concentration profiles could have produced a set of radiances observed at closely spaced wavenumbers.

Let's assume that $T_{\nu}(\infty, 0, \mu)$ is negligible small. The for nadir sounding we have

$$I_{\nu_i}^{\uparrow}(\infty) = \int_0^{\infty} B_{\nu_i}(T(z)) W_{\nu_i}(\infty, z) dz \quad [9.A1]$$

where $\nu_i, i=1, 2 \dots N$, is the wavenumbers (i.e., centers of the finite spectral bands of a spectrometer).

We can ignore the frequency dependence of the Planck function if ν_i are closely spaced.

Eq.[9.A1] becomes

$$I_{\nu_i}^{\uparrow}(\infty) = \int_0^{\infty} B(\bar{\nu}, T(z)) W_{\nu_i}(\infty, z) dz \quad [9.A2]$$

Consider that measurements are done in the CO₂ absorbing band, so the weighting function are known and $B(\bar{\nu}, T(z))$ is unknown. Thus we want to solve Eq.[9.A2] to find $B(\bar{\nu}, T(z))$ and hence $T(z)$.

Eq.[9.A1] is a so-called **Fredholm integral equation of the first kind**, which has long been known for many associated difficulties. The general form of the Fredholm integral equation (because the limits of the integral are fixed, not variable) of the first kind (because $f(x)$ appears only in the integral) is

$$g(y) = \int_a^b f(x)K(y, x)dx \quad [9.A3]$$

where

$f(x)$ is unknown (in our case $B(\bar{\nu}, T(z))$)

$K(y, x)$ is called the kernel (or kernel function), (in our case $W_{\nu_i}(\infty, z)$)

$g(y)$ is known (in our case $I_{\nu_i}^{\uparrow}(\infty)$)

Problems in solving the inverse problem (i.e., problems in solving Eq.[9.A2])

- The inverse problem is **ill-posed** (i.e., underconstrained) because there are only a finite number of measurements and the unknown is a continuous function.
- This inverse problem is **ill-conditioned** (i.e., any experimental error in the measurements of radiances can be greatly amplified, so that the solution becomes meaningless)