Techniques for Remote Sensing of Molecular Species

Thermal Emission Remote Sensing

Passive Micro Wave Remote sensing
Remote sensing of Molecular Species by differential Spectral/Emission Techniques

**APPROACH 1**
Differential Scattering

- DIAL (Differential Absorption Lidar)
- SBUV (Solar Backscattered Ultraviolet)
Remote sensing of Molecular Species by differential Spectral/Emission Techniques

APPROACH 2
Differential Transmission

• Ground Based Solar Radiometry
  – Ozone and water vapor retrieval.

• Limb-Scan Satellite Solar Radiometry
  – SAGE satellite for ozone and water vapor retrievals
Remote sensing of Molecular Species by differential Spectral/Emission Techniques

APPROACH 3
Differential Emission

• Ground Based IR & Microwave Radiometry
  – (NOAA & PSU/UA Microwave Profilers)

• Satellite IR & Microwave Radiometry
  – (GOES and TIROS-N IR & Microwave sounders
  – HIRS & MSU for temperature and water vapor retrievals
Different Configurations for Atmospheric Sounding
Figure 8-2. Absorption along a vertical atmosphere path by a variety of constituents in the spectral region from 1.0 to 16 μm. (From J. H. Shaw, 1970.)
Equation of Radiative Transfer

Interaction between radiation and matter is described by extinction and emission.

Consider a ‘pencil’ or cylinder along path $s$ of length $ds$ which radiation $I$ enters and exits along $s$. Due to scattering, absorption and Planck emission, $I(s+ds)$ differs from $I(s)$.
**Extinction**

\[ \text{extinction} = \text{scattering} + \text{absorption} \]

\[ \alpha_e = \text{extinction coefficient (m}^{-1}) \]

\[ = \alpha_s + \alpha_a; \text{scattering} + \text{absorption} \]

\[ dI(\text{ext.}) = -\alpha_e I \, ds \]
Emission

Emission will in general be due to both scattering and thermal (Planck) emission

\[ dI_{\text{(emission)}} = \alpha_s J + \alpha_a B \]

\( J \) = source function accounting for scattering from other directions into direction \( s \)

\( B \) = Planck function
Differential Relation

\[ dI = dI_{\text{emission}} - dI_{\text{extinction}} \]
\[ = (\alpha_s J + \alpha_a B - \alpha_e I) \, ds \]

and

\[ ds = dz / \cos \theta \]
\[ d\omega = \alpha_e \, dz \]
\[ \omega = \frac{\alpha_s}{\alpha_s + \alpha_a} = \frac{\alpha_s}{\alpha_e} \]

\[ \therefore \int_0^\infty \frac{dI}{dT} = \omega J + (1-\omega) B - I \]
No Emission Case

If contributions from $\alpha J$ and $\alpha B$ are negligible, the radiative transfer equation reduces to Beer's law.

$$ -\frac{dI}{dx} = -I $$

or

$$ I(x) = I_0 e^{-mx} $$

$m = 1/a$, relative air mass $\approx \sec \phi$

$\phi = \text{zenith path optical depth}$

$$ \phi = \frac{\sqrt{I_0}}{I(x)} \left\{ \text{layer of optical depth } \phi \right\} $$
No Scattering Case

If contribution from \( g_s T \) is negligible, the radiative transfer equation reduces to

\[
\nu \frac{dI}{d\tau} = B - I
\]

and has a solution of the form

\[
I(\tau) = I_0 e^{-\tau/\lambda} + \int_0^\tau B e^{-(\tau - \tilde{\tau})/\lambda} d\tilde{\tau}
\]

\[
I(0) = \frac{\sqrt{I_0}}{\sqrt{I(\tau)}} \quad \tau = 0
\]

\[
\frac{\sqrt{I(\tau)}}{\sqrt{I_0}} \quad \tau = \tau_0
\]

\[
e^{-(\tau_0 - \tilde{\tau})/\lambda} = T(\tau); \text{ transmittance from level } \tilde{\tau} \text{ to } \tau_0
\]

\[
I(\tau) = I_0 e^{-\tau/\lambda} + \int \frac{I(\tau)}{I(0)} B d\tau
\]
If the medium is optically thick or there is no source term, the transfer equation solution reduces to

\[ I(\mathbf{r}_0) = \int_{\mathbf{r}_0}^{\mathbf{r}_0} B \cdot dI(\mathbf{r}) \]

which is the basis for most IR and microwave remote sensing applications.
Remote Sensing Problem

Our integral relation is actually monochromatic or at least quasi-monochromatic. If we choose to work in frequency $\nu$, then we have

$$\frac{I}{I_0} = \int_{I_0}^{I(\nu)} B_\nu \ dI(\nu)$$

Also, $B_\nu$ is a function of temperature $T$ of the medium at position $x$, where $x$ may be any position coordinate (height, pressure, log pressure, etc.)
Thus, $I_r$ may be expressed in a position-dependent form

$$I_r = \int_{x_0}^{x'} B_r(x) \frac{dI_r}{dx} \, dx$$

Also, define $\frac{dI_r}{dx}$ to be $K(v, x)$

$$K(v, x) \triangleq \frac{dI_r}{dx}$$

The kernel function relating $I_r$ to $B_r$

$$I_r = \int_{x_0}^{x'} K(v, x) B_r(x) \, dx$$

The remote sensing problem is how to take a collection of measurements $I_r$, for a number of frequencies $v$, and "invert" them to retrieve $B_r(x)$ from which one can obtain $T(x)$.

To obtain good resolution in $B_r(x)$, the kernels must change significantly in $x$ for different $v$. 
The kernel function is different depending on whether one is looking up from the surface of the earth or looking down from the top of the atmosphere (satellite case).

One can show that \( \overline{I} \) is also of the form

\[
\overline{I}(x) = \int_{x_0}^{x_1} \frac{\alpha(x') B[z(x')]}{2\pi} e^{-\frac{x-x'}{2\sigma^2}} dx'
\]

\[
= \int_{x_0}^{x_1} K(x', x) B[z(x')] dx'
\]

\[0, \quad K(x', x) = \frac{\alpha(x') e^{-\frac{x-x'}{2\sigma^2}}}{\pi \sigma^2} \]

**Upward Looking**

\[x_1 = x_{top}, \quad x_0 = 0 \Rightarrow \text{integrate } \frac{\alpha(x')}{\pi \sigma^2} \text{ from } 0 \text{ to } x\]

**Down Looking**

\[x_1 = x_{top}, \quad x_0 = 0 \Rightarrow \text{integrate } \frac{\alpha(x')}{\pi \sigma^2} \text{ from } x \text{ to } x_{top}\]
Planck Function

\[ B_\nu = \frac{2 \pi \nu^3}{c^2} \left( \frac{1}{e^{\frac{\nu c}{kT}} - 1} \right) \text{Watts m}^{-2} \text{sr}^{-1} \text{Hz}^{-1} \]

\( h = \text{Planck's constant} \)
\( c = \text{speed of light} \)
\( T = \text{absolute temperature (°K)} \)

As \( \lambda \nu = c \), where \( \lambda \) is wavelength

\[ B_\nu = \frac{2 \pi h c}{\lambda^3} \left( \frac{1}{e^{\frac{h c}{\lambda kT}} - 1} \right) \]
Rayleigh–Jeans Law Approximation

For low frequencies or long wavelengths, as for the microwave region, where $\hbar \nu/kT \ll 1$, the Planck function reduces to

$$B_\nu = \frac{2f^2 kT}{c^2} = \frac{2kT}{\lambda^2} \left\{ \frac{\text{Watts}}{m^2 \cdot \text{sr} \cdot \text{Hz}} \right\}$$

$$B_\lambda = \frac{2c kT}{\lambda^4} \left\{ \frac{\text{Watts}}{m^2 \cdot \text{sr} \cdot \text{m}} \right\}$$
Fig. 4.5 Comparison of Planck's law with its low-frequency (Rayleigh-Jeans law) and high-frequency (Wien's law) approximations at 300 K.
Microwave Form of Transfer Equation

Solution for No Scattering

Using the Rayleigh-Jeans law, the transfer equation for no scattering may be expressed in the form

\[ T_{br} = T_{or} e^{-\frac{T_{or}}{kT_0}} + \int_{x_0}^{x_1} K(v,x) T(x) \, dx \]

\[ T_{br} = \text{Brightness temperature of the emitting medium plus the contribution of source term, } T_{or}, \text{ seen through the medium} \]

\[ T_{or} = \text{source brightness temperature (say of sun, if looking at sun)} \]

\[ T(x) = \text{temperature of medium at height } x. \]

In microwave radiometry, one measures \( T_{br} \) at several \( v \) values to invert for \( T(x) \). Can also be done to retrieve molecular profiles of say H₂O.
Figure 8-6. Absorption spectrum of water vapor at two pressures: 1 bar and 0.1 bar, at temperature 273°K and for a water vapor density of 1 g/m³ (Chahine et al., 1983).
Figure 4. Calculated brightness temperatures for ground-based viewing. After Hogg [7].
$T_b = T_b^{\text{ext}} \exp \left( - \int_0^s \alpha(s) \, ds \right) + \int_0^\infty T(s) \alpha(s) \exp \left( - \int_0^s \alpha(s') \, ds' \right) \, ds$

Measured Quantity  Cosmic Term (known)  Atmospheric Term

$T_b$ = Brightness Temperature Measured at Ground
$\alpha(s)$ = Absorption Coefficient at Coordinate s
$T(s)$ = Temperature at Position s
$T_b^{\text{ext}}$ = Brightness Temperature External to Atmosphere

Figure 2. Microwave radiative transfer for upward-viewing systems.
Figure 3. Microwave radiative transfer for downward-viewing systems.
Fig. 1 Atmospheric Absorption of Oxygen and Water Vapor
Combined MSU Profiler Temperature Weighting Functions
Figure 9-5 (Continued) Temperature weighting functions as a function of altitude above the surface for observations from space which view the nadir. The curves correspond to the emission by oxygen: (b) around 118 GHz (from Wilheit et al., 1977).
Fig. 1. Weighting functions for ground-based observations.
Figure 12. Weighting functions, normalized to unit maxima, for surface-based and satellite-based microwave temperature profiling. After Westwater and Grody [48].
Figure 9-5. Temperature weighting functions as a function of altitude above the surface for observations from space which view the nadir. The curves correspond to the emission by oxygen: (a) around 60 GHz (Lenoir, 1968). Continued on following page.
Figure 9-6. Normalized weighting function curves for water-vapor density in the atmosphere at three representative frequencies near and on the 22.235 GHz resonance of water vapor. The curves are derived for brightness temperature measurements from the surface of the Earth. (From Staelin, 1969.)