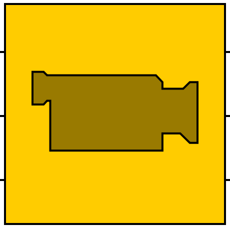
PHY2505S
Atmospheric Radiative Transfer and Remote Sounding

Lecture 12

- Atmospheric Scattering (continued)
- Atmospheric Remote Sounding

Scattering of Sunlight



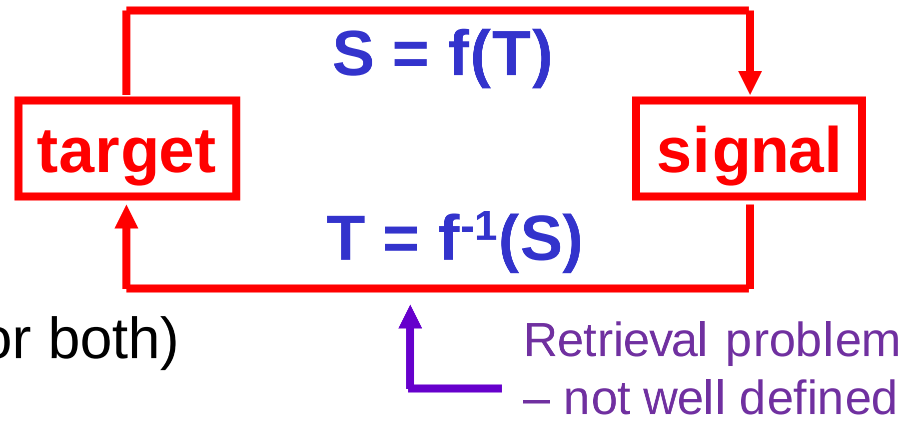
Remote Sensing / Sounding*

"Measurement at a distance"

- Information is carried by electromagnetic radiation
- Provides a method of obtaining information about the properties of the atmosphere without coming into physical contact with it
  - → in contrast to extractive or in situ techniques
- Advantages
  - → no perturbation of the sample being observed
  - → sensitive to many gases and surfaces
  - → can provide point, column or profile data
- Disadvantages
  - → limited spatial resolution
  - → interpretation of data can be difficult
  - → indirect so some uncertainty about what is being measured
- remote <u>sensing</u> → generally applies to observations of the surface
- remote <u>sounding</u> → generally applies to observations of the atmosphere

Remote Sounding

- Using formalism from Liou:
- If we measure the signal at a detector after it interacts with the target (either molecules or particles or both)



- The direct or forward problem:
  - → A detector measures a signal S = f(T) which is generated by the interaction of radiation with the target (e.g., surface, atmosphere, clouds, etc.). Given properties of the target, calculate the signal.
- The inverse problem:
  - → Want to determine properties of the target, given by the inverse function $T = f^{-1}(S)$. Given signal, calculate properties of the target.
- Example:
  - → direct problem – describe tracks that a dog would leave in the snow
  - → inverse problem – describe the animal that left the observed tracks

Challenges with the Inverse Problem

Solving the inverse problem is complicated by several difficulties.

(1) Non-uniqueness of the solution caused by several unknown parameters, which can be combined in different ways to generate the same observed signal.

i.e., have several solutions $T_1 = f^{-1}(S)$, $T_2 = f^{-1}(S)$, etc.

(2) Discreteness of the measurements when the measured quantity is a smoothly varying function.

e.g., T is a function of height z, while S is measured at discrete levels over some range of heights, so

$$S = \int_a^b K(z)T(z)dz$$

where K(z) is called a kernel function or a weighting function.

(3) Instability of the solution due to errors in the observations S.

e.g., If ε is the error on S, then $S + \varepsilon = \int_a^b K(z)T(z)dz$

where ε can produce a large change in the retrieval of T(z).

Advantages of Remote Sounding

So why use remote sounding at all, given these difficulties?

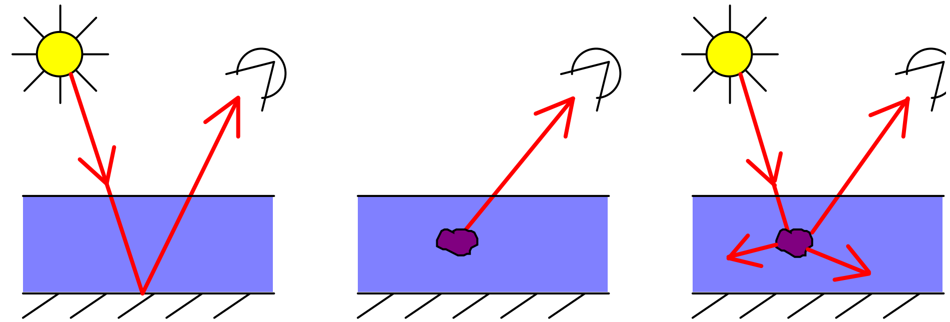
Additional advantages:

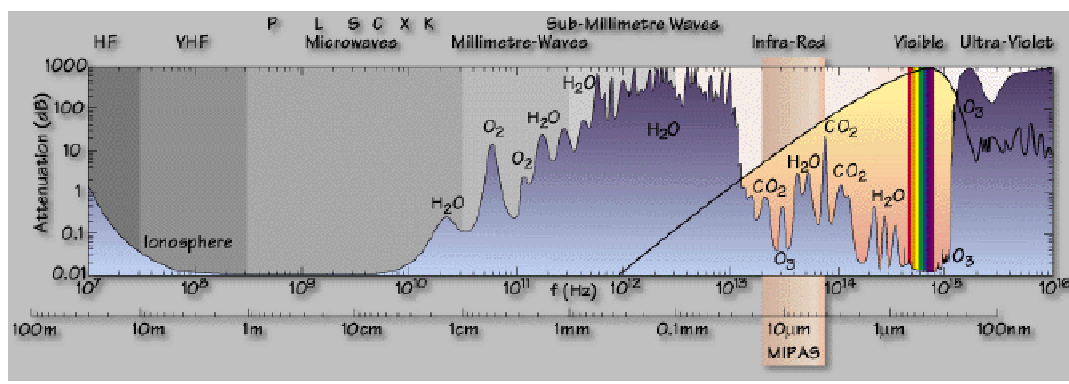
- Allows the sampling of regions that are difficult or impossible to reach
- Can measure unstable species that would decompose with in situ or extractive techniques
- Provides geographical coverage (primarily from satellites) measuring over areas where there is little population

Remote Sounding Approaches

Remote sounding techniques can be classified by:

1) Radiation source
   - → passive – use natural radiation (solar, stellar, terrestrial)
   - → active – use artificial sources of radiation (lasers, radar)
2) Type of interaction between radiation and the atmosphere
   - → absorption
   - → emission
   - → scattering
3) Spectral region
   - → ultraviolet
   - → visible
   - → infrared
   - → microwave





Remote Sounding Platforms

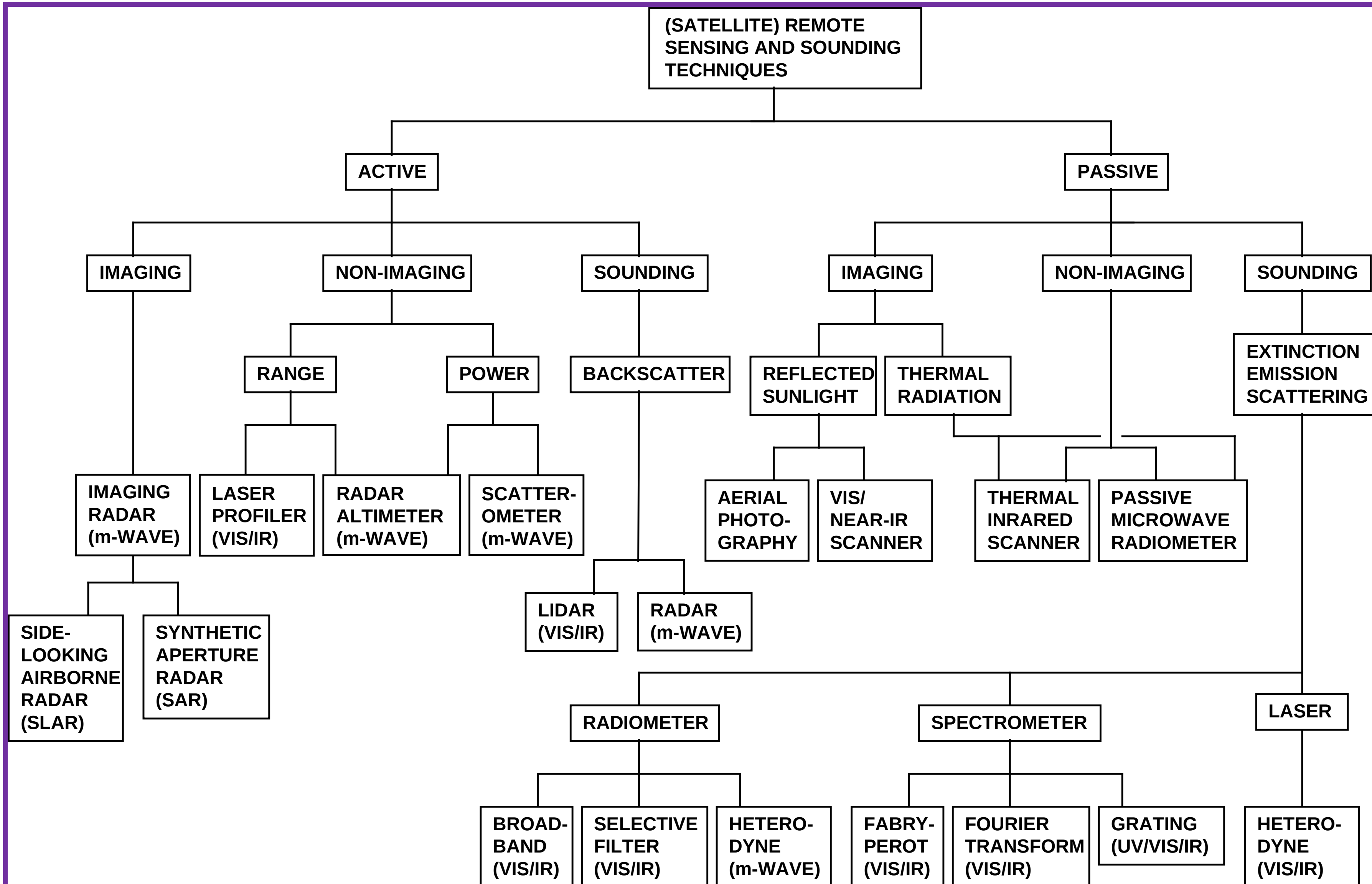
Remote sounding can be performed from many platforms:

- Ground
- Balloons
- Aircraft
- Rockets
- Space shuttle
- Satellites
- Interplanetary spacecraft

All the location does is change the frame of reference for the retrieval problem.

We will look at some examples of radiative remote sounding techniques.

Remote Sensing/Sounding Techniques



Ground-Based Measurements

Advantages:

- Can provide long time series and high temporal resolution
- Enable simultaneous measurements of many trace gases under well-calibrated conditions
- Allow comparison and development of different techniques
- Essential for the validation of new satellite instruments
- Inexpensive compared to balloons, rockets, satellites

Disadvantages:

- Poor global coverage
- Interference from the dense atmophere above

Transmission Techniques

Recall Schwarzchild's Equation:

$$\frac{dI}{k \rho \, dx} = -I + J$$

In its integral form:

$$I(b) = I(a)\,\tau(a,b) + \int_{path} J(x)\,\frac{d\tau(b,x)}{dx}\,dx$$

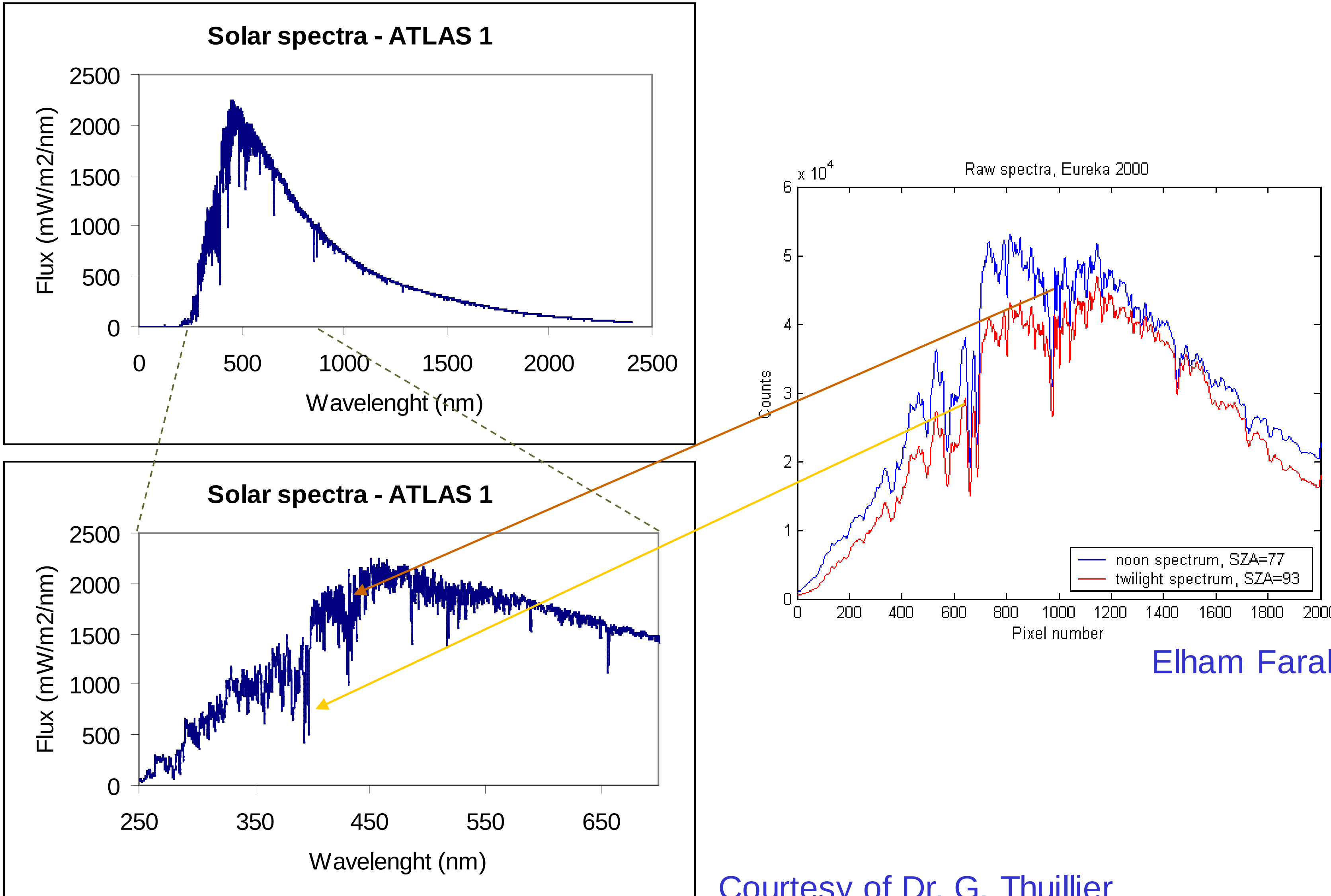
emission

transmission

Transmission techniques require a source of light, such as:

- Sun, Star, Moon, Laser, Calibrated lamp

Solar spectra outside (left) and inside the terrestrial atmosphere



Elham Farahani

Courtesy of Dr. G. Thuillier

Transmission Techniques

- All transmission techniques require a source of radiation (active or passive)

Example: The <u>Dobson Ozone Spectrophotometer</u> (G.M.B Dobson, 1924)

- Utilizes the absorption of O_3 in the UV-visible to infer the column density of ozone in the atmosphere
  - → measures how many molecules there are along the path
  - → the technique is to select a wavelength in the UV-visible for which there is a significant O_3 absorption and use a simple spectrometer to observe the sun
  - → the measured intensity is:

$$I(0,\tilde{\nu}_1) = I(\infty,\tilde{\nu}_1)\ \exp\left(-\int_0^{\infty} k\rho dz/\cos\theta\right)$$

The National Oceanic and Atmospheric Administration (NOAA) world standard Dobson Spectrophotometer in Boulder, Colorado.

The Dobson Spectrophotometer - 1

- Ideally the transmission term would be characteristic of ozone, but in fact there are at least two other effects
  - → Rayleigh scattering
  - → aerosol scattering
- However these tend to occur at lower altitudes than the ozone layer in the mid-stratosphere and in that case we can separate the transmission into a product:

$$\exp\left(-k_3\Omega_3/\cos\theta\right) . \exp\left(-k_a m_a/\cos\theta\right)$$

where
  - → k_3 is the ozone absorption coefficient,
  - → Ω_3 is the total equivalent vertical ozone amount (i.e. $\Omega_3/\cos\theta$ is the total amount of ozone in the path from the instrument to the sun),
  - → k_a is the extinction coefficient for the rest of the scattering, and
  - → m_a is the total vertical amount of material in the path

Note: k_a here is really k_s as used earlier in the notes - sorry!

The Dobson Spectrophotometer - 2

- If we consider another wavelength such that it is close to the ozone absorption line and therefore shares common values of most variables except the ozone absorption:

$$I(0,\tilde{\nu}_2) = I(\infty,\tilde{\nu}_2)\,\exp\left(-k_a m_a/\cos\theta\right)$$

- By ratioing the two measurements and assuming common values of everything except ozone absorption we find that:

$$\frac{I(0,\tilde{\nu}_1)}{I(0,\tilde{\nu}_2)} = \exp\left(-k_3\Omega_3/\cos\theta\right)$$

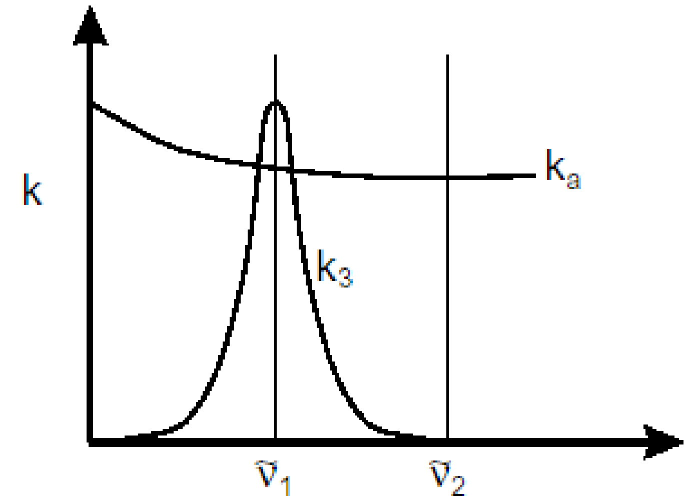


Figure 75: Ozone Absorption Experiment

- By knowing the value of k_3 we can evaluate the total ozone concentration above the instrument
- Dobson wavelengths are 325.4 nm and 339.8 nm

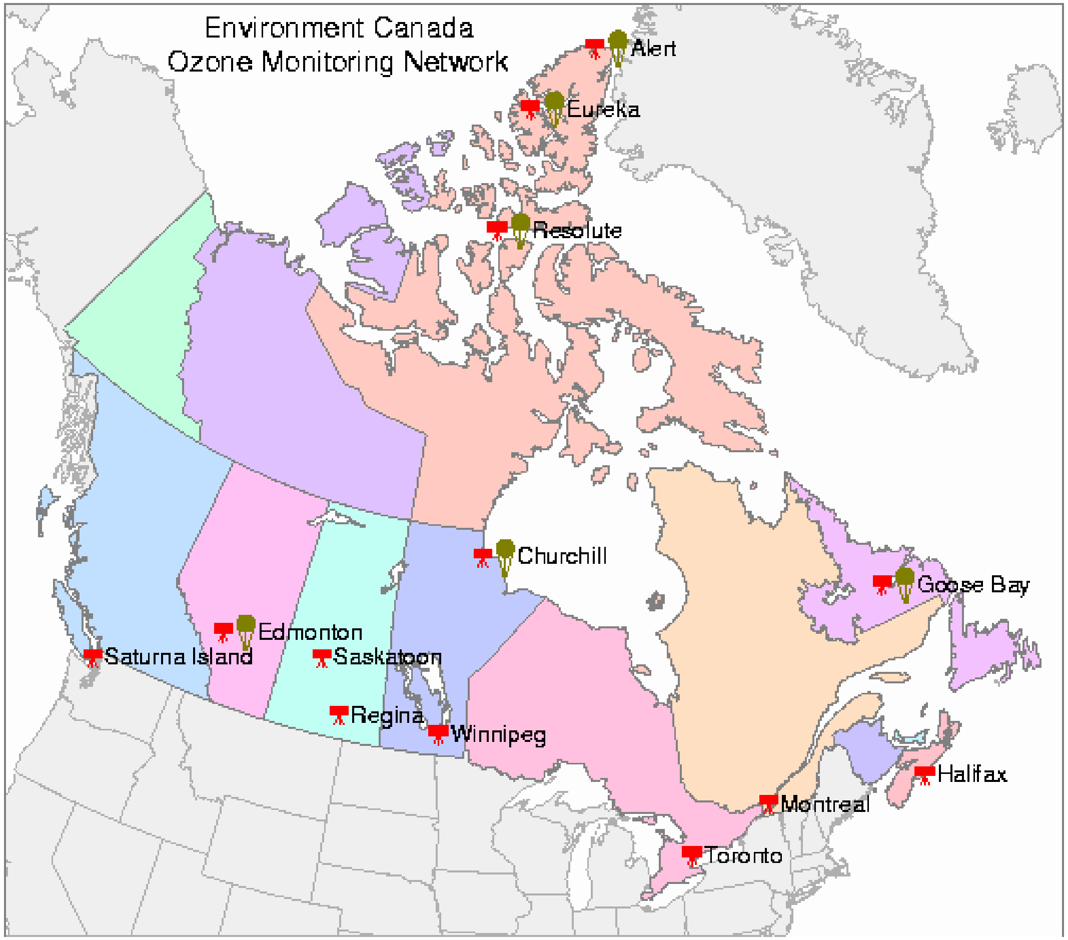
The Dobson Spectrophotometer - 3

- That was really too simple an explanation!
  - → Corrections have to be made to account for the fact that the wavelengths are not truly identical.
- The basis of the measurement is still to take out the majority of the unwanted dependencies by this differential technique and then correct the answer as necessary.
  - → Corrections also have to be made for the instrument performance!
- There is a big international effort for inter-comparing ozone-measuring instruments in order to achieve a “consistency” level.
- The Brewer grating spectrophotometer is similar in its principle to the Dobson, but it has an improved design and is fully automated.
  - → The ozone column is obtained from using five wavelengths between 306 and 320 nm. Since the 1980s, Brewer instruments have been deployed in a worldwide network.
  - → Developed here at the University of Toronto, at Environment Canada, and Sci-Tec (Alan Brewer, Tom McElroy, Jim Kerr, …)

The Brewer Spectrophotometer

Brewers on the roof of the Environment Canada building, Toronto

Brewer on the roof of the Physics building - on loan from EC



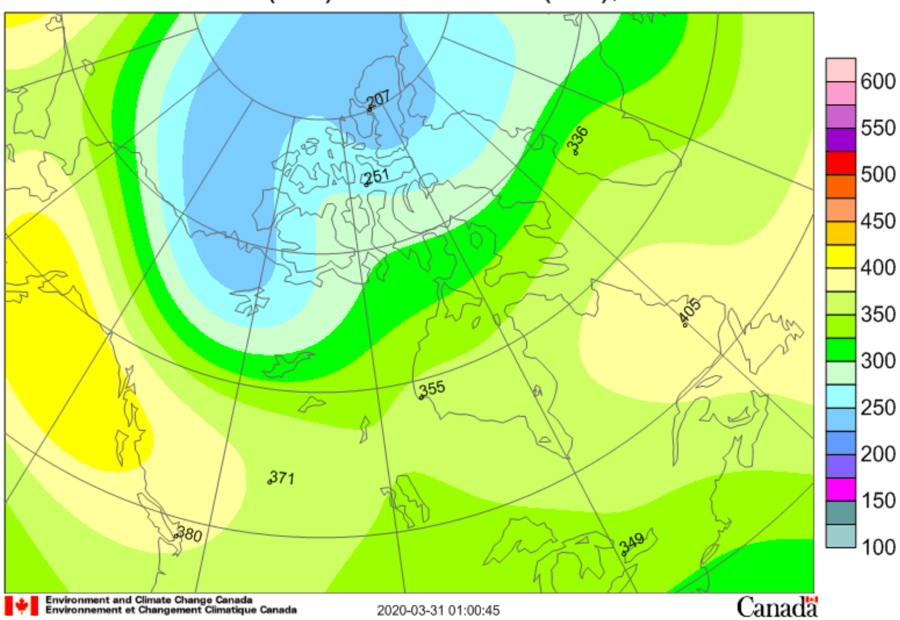
World Ozone and UV Data Centre

Based at Environment Canada: https://woudc.org/home.php

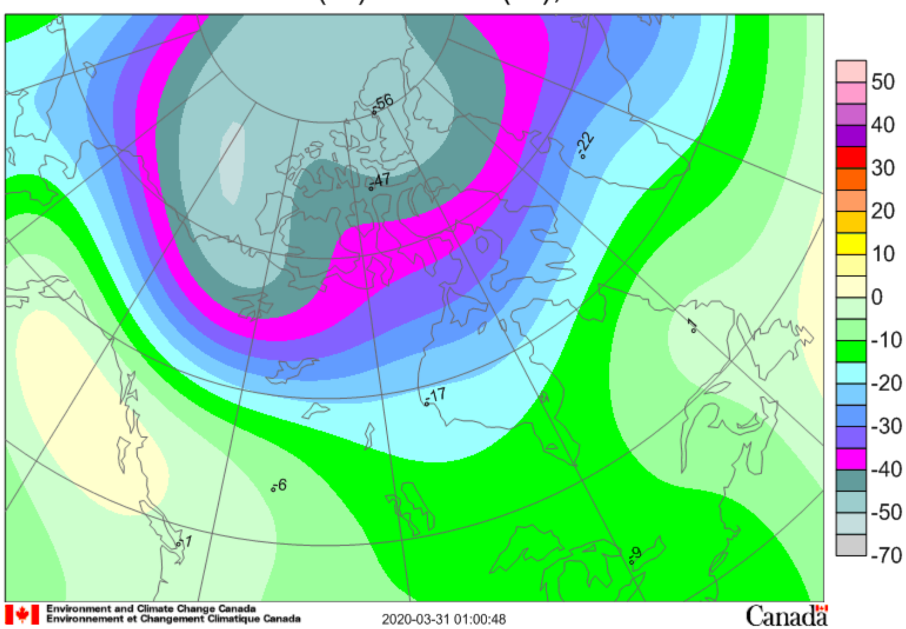
Total Ozone Maps for Canada

Maps of deviations represent total ozone deviations from the 1978-1988 level estimated using TOMS data. The total ozone maps for the northern hemisphere are based on near-real time NASA Earth Probe Total Ozone Mapping Spectrometer (TOMS) gridded satellite data available from the NASA TOMS home page, NOAA SMOBA (Stratosphere Monitoring Ozone Blended Analysis) data (if TOMS data are not available) and on ground-based measurements. Ground-based data are provided by Environment Canada, by the Russian Central Aerological Observatory, and by other agencies. Over the polar night area Dobson and Brewer moon observations and/or NOAA's TIROS Operational Vertical Sounder (TOVS) satellite data are used. TOVS data are also used when the more reliable TOMS data are not available. To see ozone maps from the individual data sources (TOMS, SMOBA, TOVS and ground-based) click here. The mapping algorithm is similar to those used by the WMO Ozone Mapping Centre . Total ozone values are given in Dobson Units.

Total ozone (DU) / Ozone total (UD), 2020/03/29



Deviations (%) / Ecarts (%), 2020/03/29



Dobson Unit = vertical thickness of ozone at STP in hundredths of a mm.
So an ozone column of 300 DU is equivalent to a 3 mm layer of at STP.

Differential Optical Absorption Spectroscopy (DOAS)

Top to bottom:

- Zenith sky spectrum at noon
- Zenith sky spectra at twilight
- Ratio of the spectra (SZA=95/20)
  - → the tilting arises from the reduction of multiple scattering at twilight
- Ratio of spectrum at SZA=80 seen through an NO_2 filled cell to spectrum with the cell empty

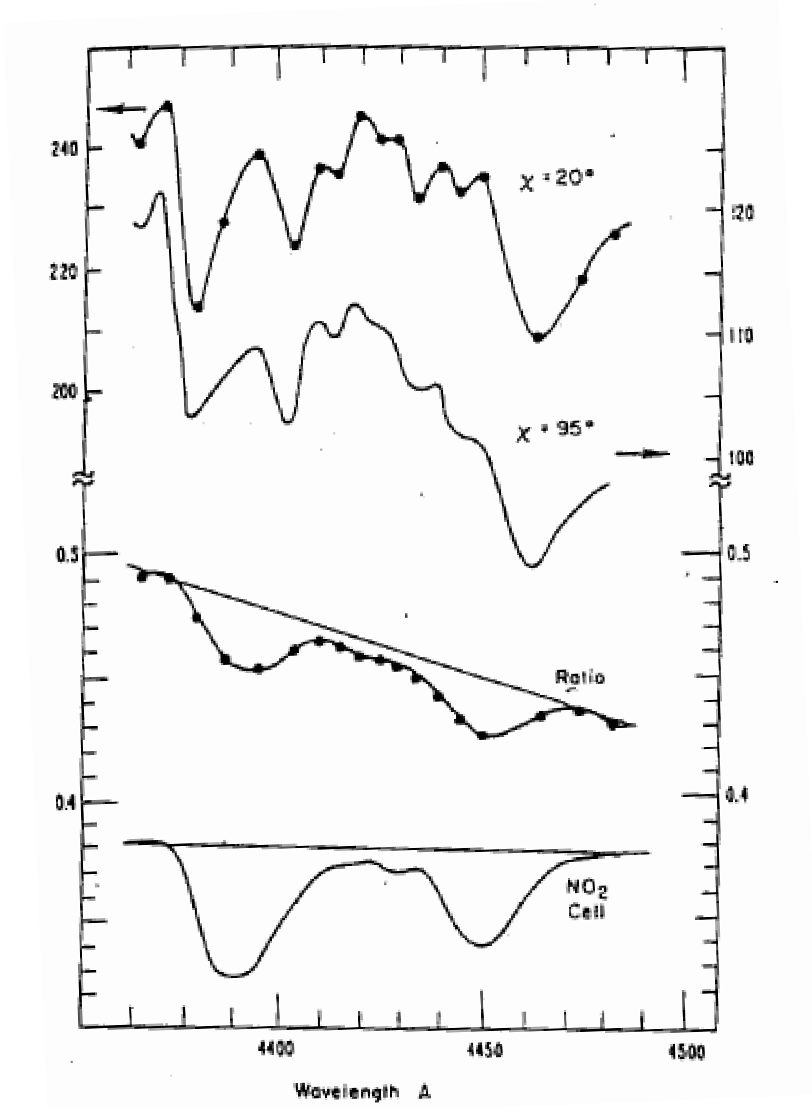


Figure from Noxon et al., JGR 84, 1979

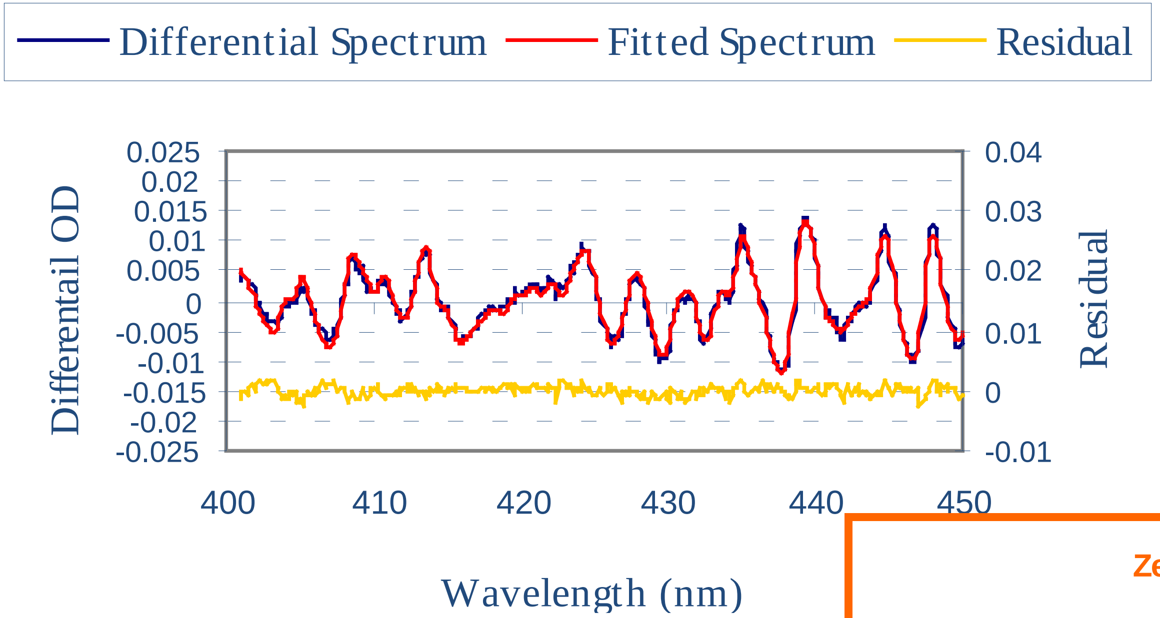
Differential Optical Absorption Spectroscopy (DOAS)

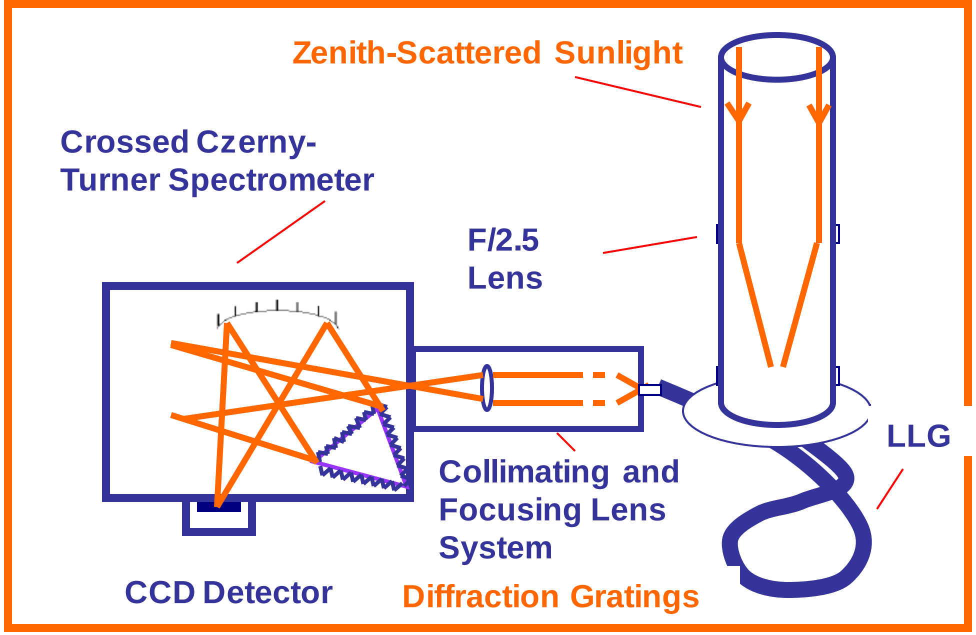
Record sunlight scattered from the zenith-sky at a series of solar zenith angles to obtain vertical column amounts.

- well-established technique to measure stratospheric constituents
- uses narrow absorption features after removal of the broad band signal where scattering processes interfere
- enhances optical path of the scattered light 20-30 times the vertical path, allowing detection of weakly absorbing species
- allows simultaneous measurements of different species such as ozone, NO_2, O_4, H_2O, OClO, BrO

Based on this technique, UV-visible DOAS spectrometers have performed network operations since the late 1980s and have monitored columns of ozone and NO_2 from the Arctic to Antarctica, with an accuracy of about 3-5% for ozone and 10% for NO_2.

Retrieval of NO_2 Using DOAS



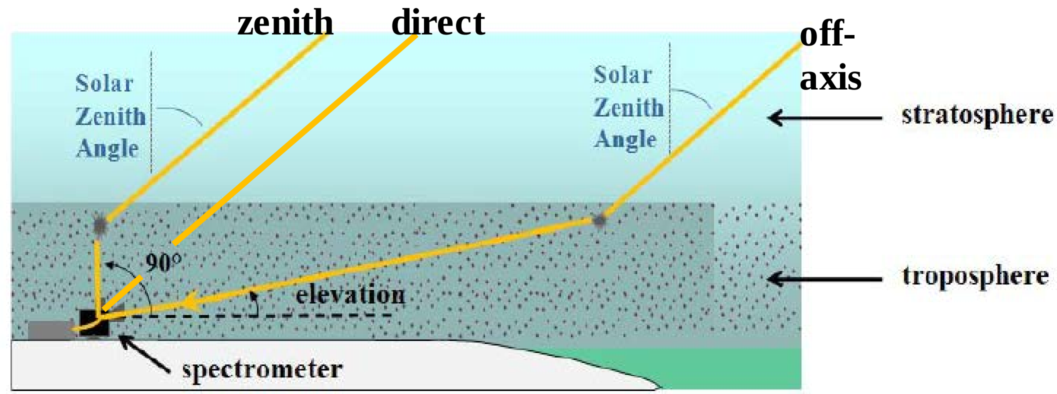


Elham Farahani

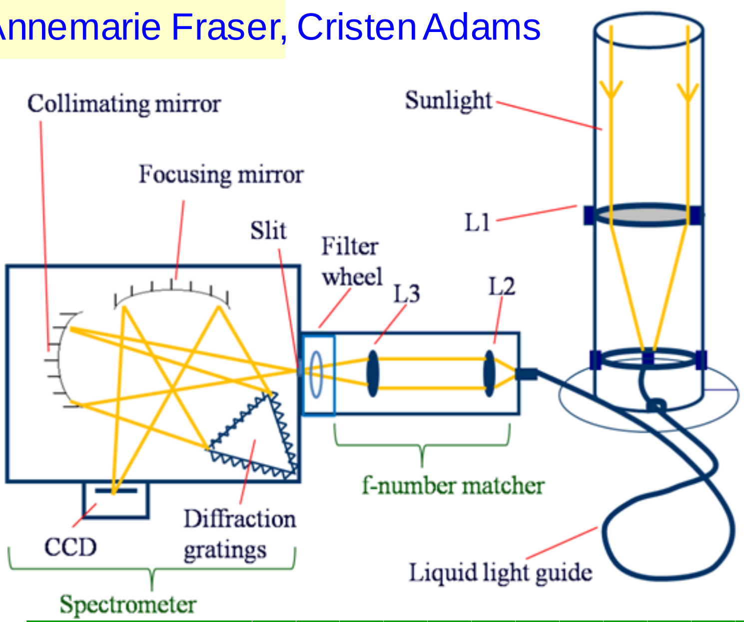
DOAS: Additional Slides – 1

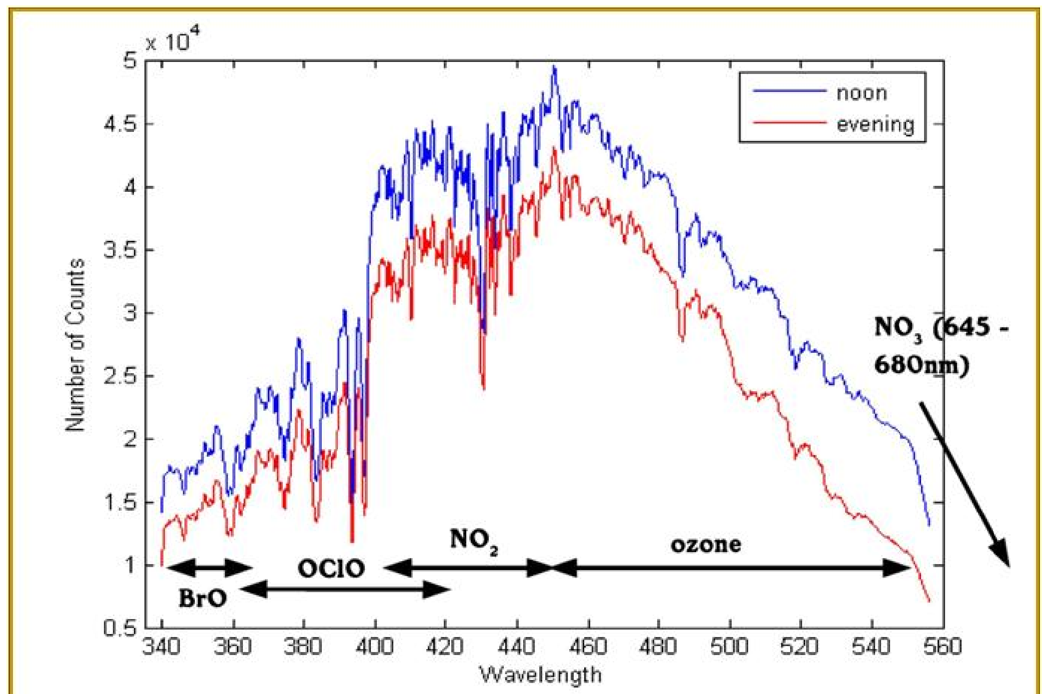
Photo by Pierre Fogal

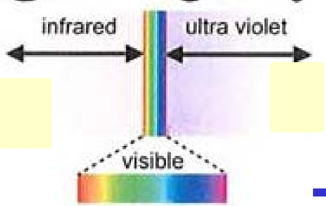
Annemarie Fraser, Cristen Adams



Adapted from Roscoe et al., AMT, 2010







DOAS: Additional Slides – 2

1) Wavelength calibrate one noon and one twilight spectrum. These obey Beer's Law:

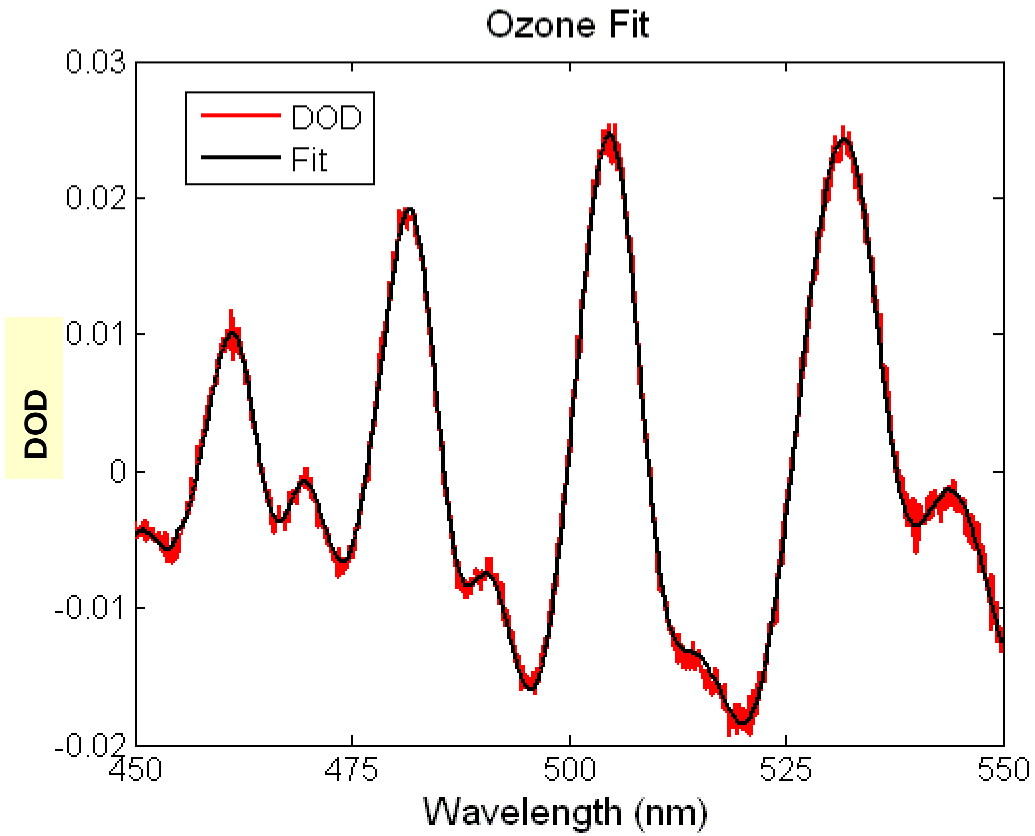
$$dI(\lambda) = -\sigma(\lambda)\, I(\lambda)\rho(z)dz$$

2) Take the negative ln of the ratio of twilight and noon spectra:

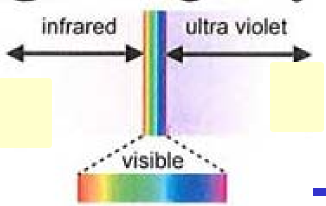
$$-\ln(I/I_o) = \Sigma\, \sigma_i(u_{i1}-u_{i2}) + \text{slow varying}$$

3) Subtract polynomial to get differential optical depth (DOD) and fit absorption cross-sections

UV-Visible Spectral Fitting

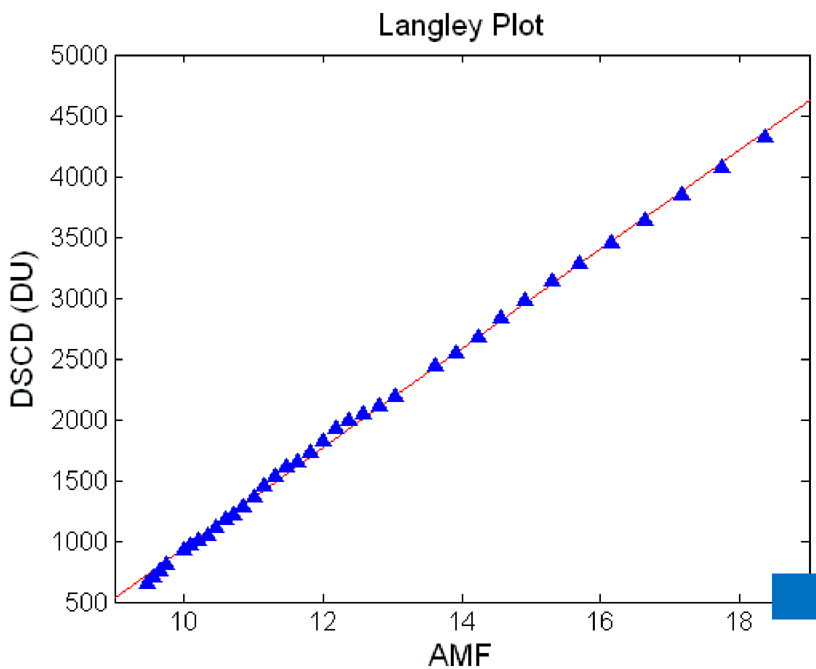


Xiaoyi Zhao, Cristen Adams



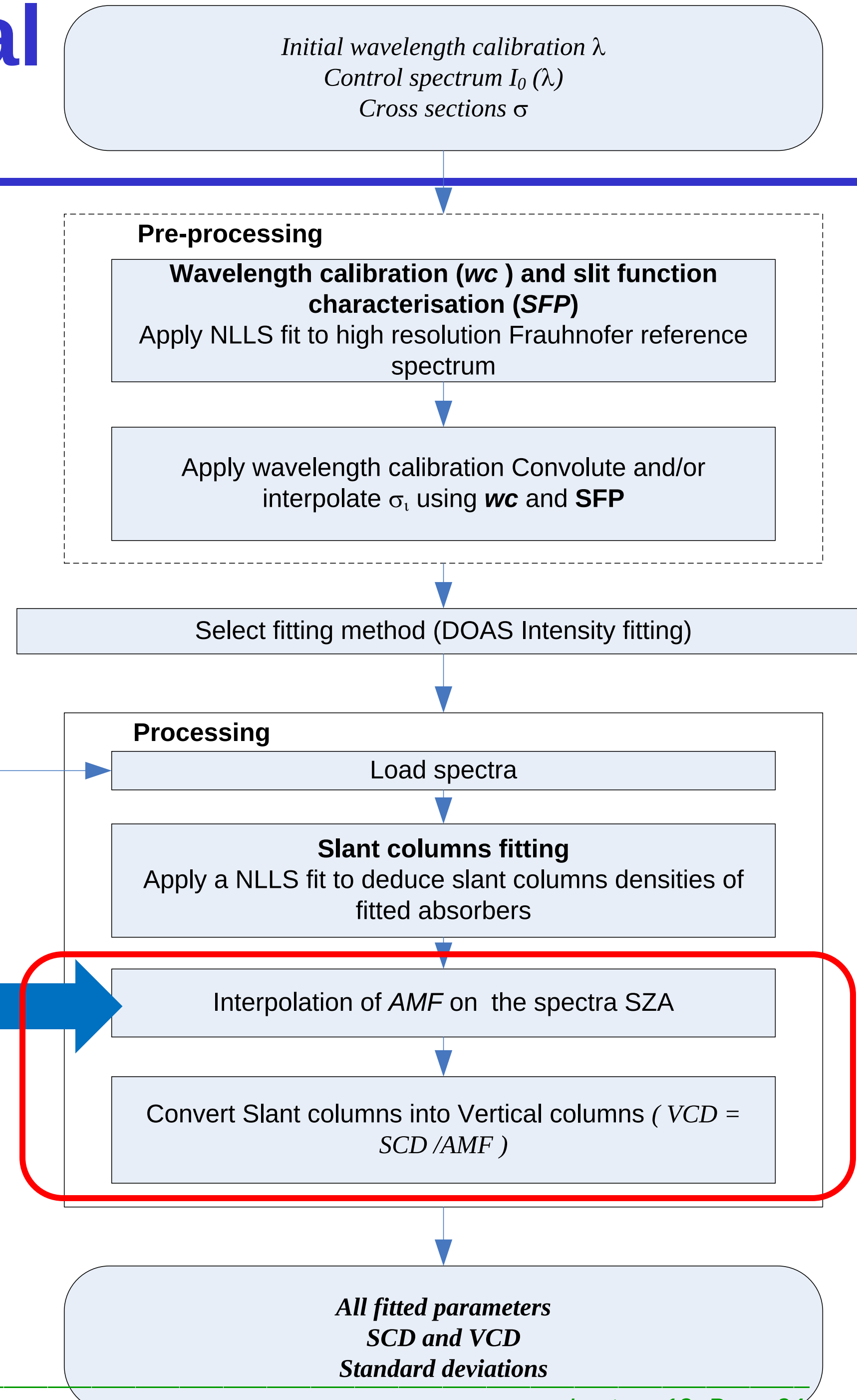
DOAS: Additional Slides – 3

- DSCD = differential slant column
- VCD = vertical column density



Plot DSCD vs airmass factor for a number of solar zenith angles:
Slope = VCD
y-intercept = -RCD

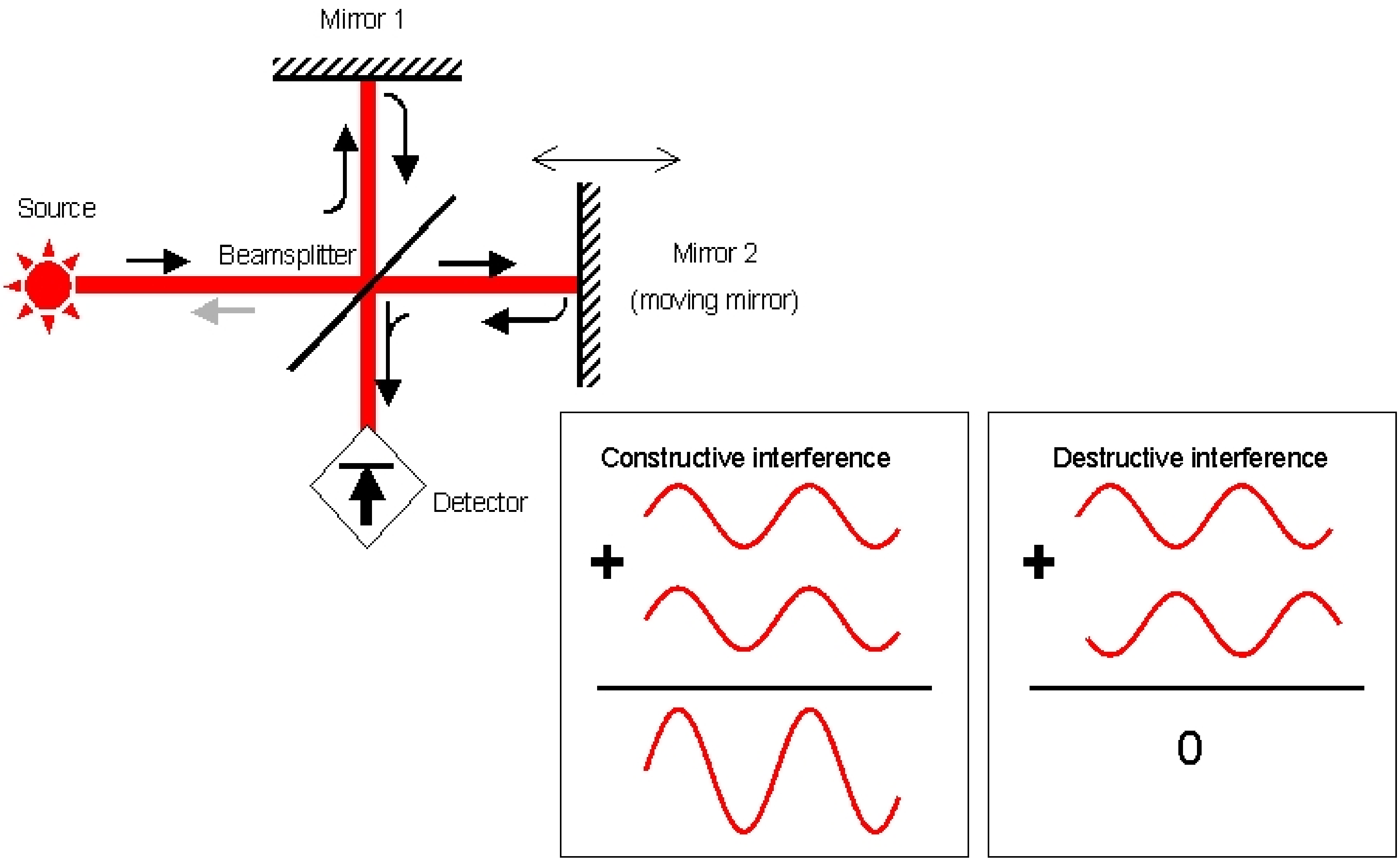
Xiaoyi Zhao,
Caroline Fayt,
Michel van Roozendael



Fourier Transform Infrared Spectrometers (FTIR/FTS)

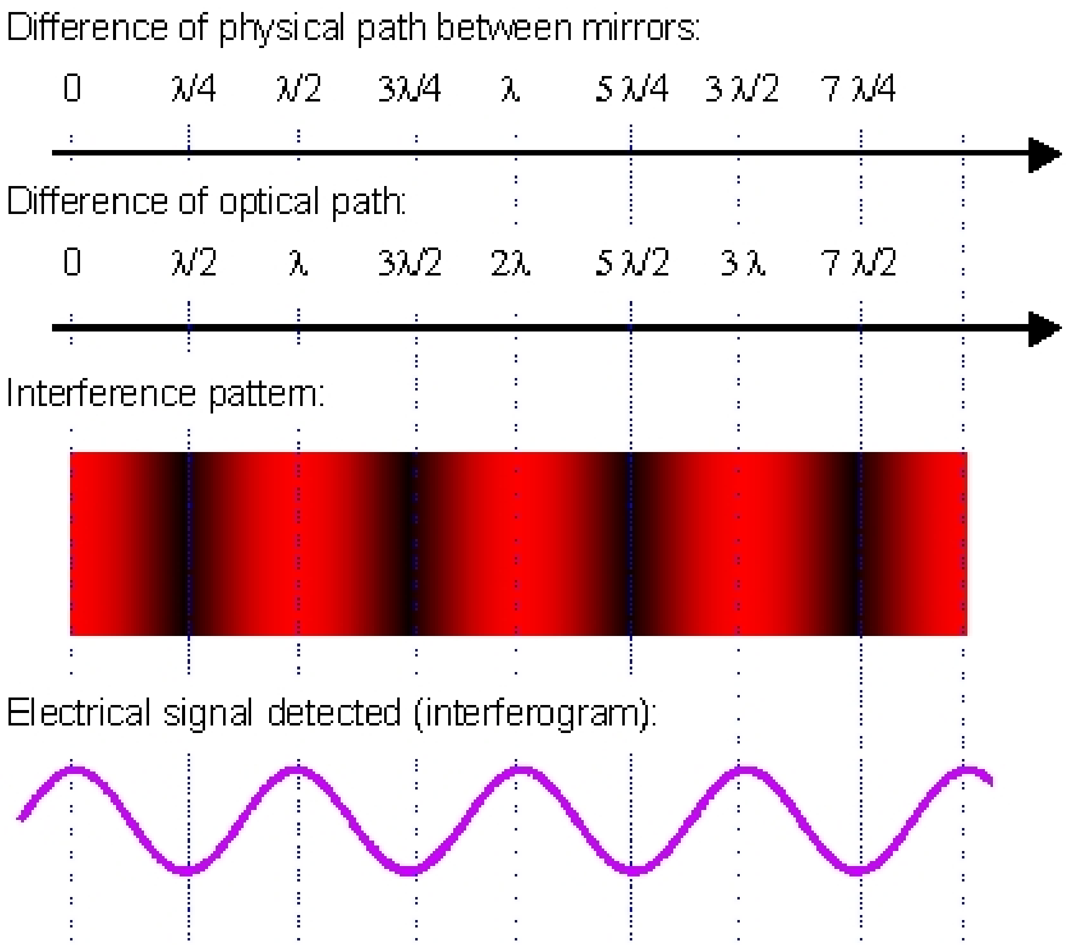
- Used to derive the column amounts of a large number of atmospheric trace constituents that have absorption features in the infrared range, including ozone, nitrogen compounds, HCl, HF, CO, CH_4, CFCs, etc.
- These are retrieved from high spectral resolution measurements of the solar spectrum
- Typical relative uncertainties are currently around 5% for ozone, HCl, HF and HNO_3, 10% for NO and NO_2, and 25% for $ClONO_2$

The Principle of FT Spectroscopy - 1



Former link: http://envisat.esa.int/dataproducts/mipas/CNTR1-1-4.htm

The Principle of FT Spectroscopy - 2



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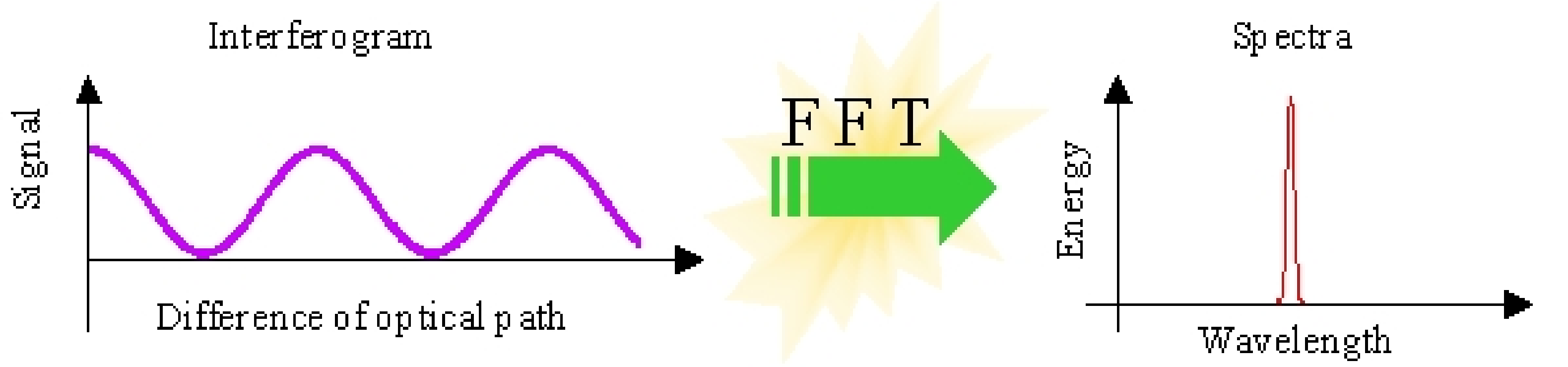
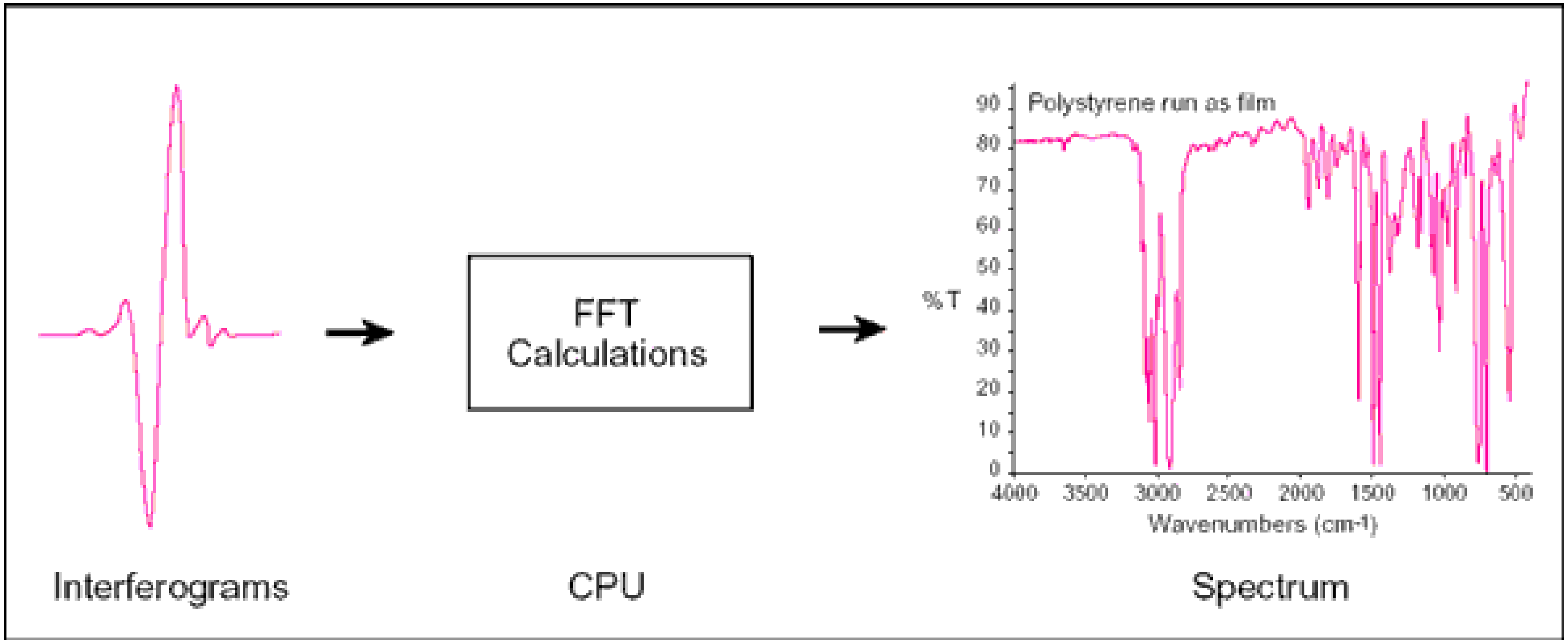
The Principle of FT Spectroscopy - 3





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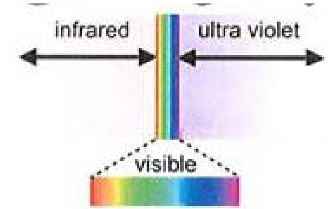
FTIR Retrieval Algorithm



SFIT2

Temperature
Pressure
VMR profiles

Ray tracing program (fscatm)

Model atmosphere:

density-weighted effective pressure, temperature and VMR profiles, and airmass factors for each layer

Forward model calculates

HITRAN spectral database

Calculated infrared absorption spectrum of the target gas

compare

Measured spectrum

Adjust the profile

New iteration

Difference > Estimated error * tolerance factor

Difference < Estimated error * tolerance factor

Profile

Forward model **F** describes the physics of the measurement process: $\mathbf{y} = \mathbf{F}(\mathbf{x},\mathbf{b}) + \boldsymbol{\varepsilon}$

where **x** = state vector (profile), **b** = parameters, **y** = measurement vector (spectrum), **ε** = error

Rodica Lindenmaier

LIDAR – LIght Detection And Ranging

- Uses short pulses of powerful lasers to probe the atmosphere
- Time-resolved detection of the backscattered light allows precise determination of the altitude z of the scattering process:

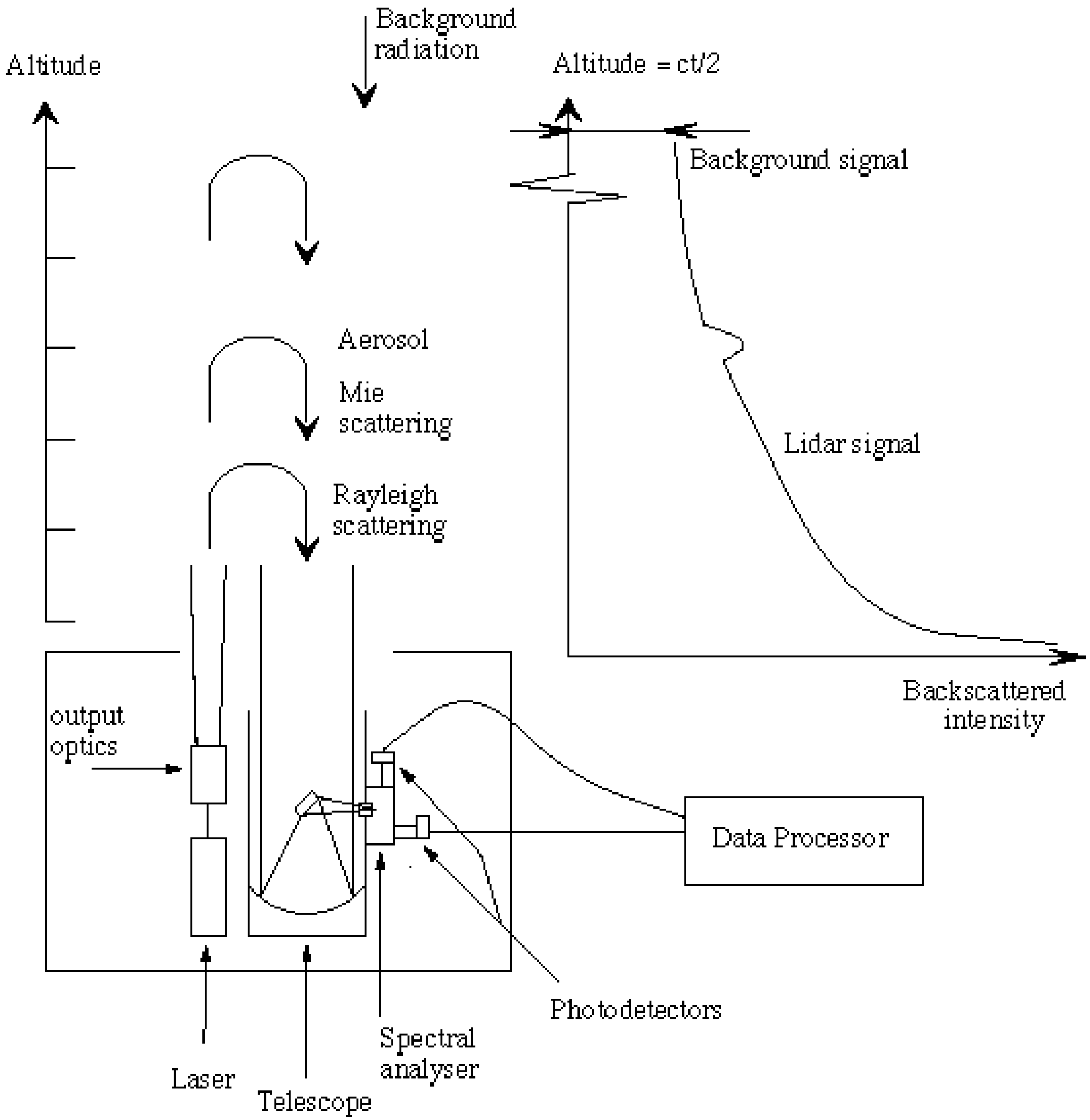
$$z = c / 2 * t,$$

- where c is the velocity of light and t the time.

The primary components of a lidar system:

- one or several laser sources with optical devices to reduce the divergence of the beam
- telescope to collect the light scattered back by the atmosphere
- an optical analyzing system with detectors such as photomultipliers to detect the optical signal
  - → for DIAL systems characterized by the emission of two laser wavelengths, the optical receiving system comprises spectral analyzing optics, such as interference filters or spectrometers
- an electronic acquisition system

Schematic View of a Lidar System



From Stratospheric Processes And their Role in Climate
A project of the World Climate Research Programme

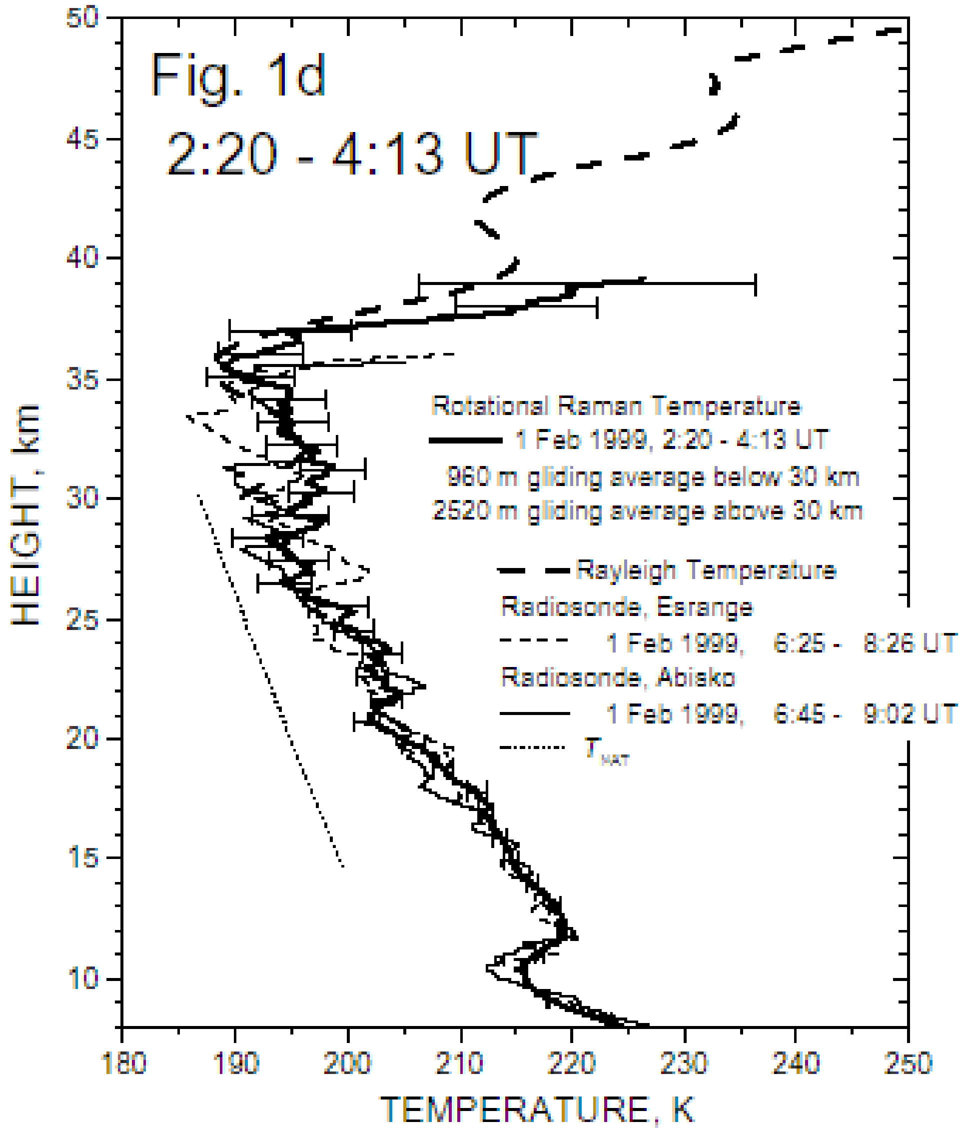
Rayleigh and Raman Lidar

- Rayleigh LIDAR
  Below 30 km, the received signal will contain a significant amount of aerosol scattering. However, above 30 km, lidar measurements consist primarily of elastic molecular backscattering. In the absence of aerosols and when scaled by the square of the altitude, the backscattered signal is proportional to the atmospheric density. Manipulation of the equation of hydrostatic equilibrium and the ideal gas law leads to a measurement of temperature.
- Raman LIDAR
  Raman scattering is the theory of light scattering by molecules, where the wavelength is changed by the scattering. The change in wavelength depends on the temperature of the air and the type of molecule from which the scattering takes place. Raman scatter lidar is used to measure water vapour concentration and air temperature.

E.g., Rayleigh and Raman Temperatures

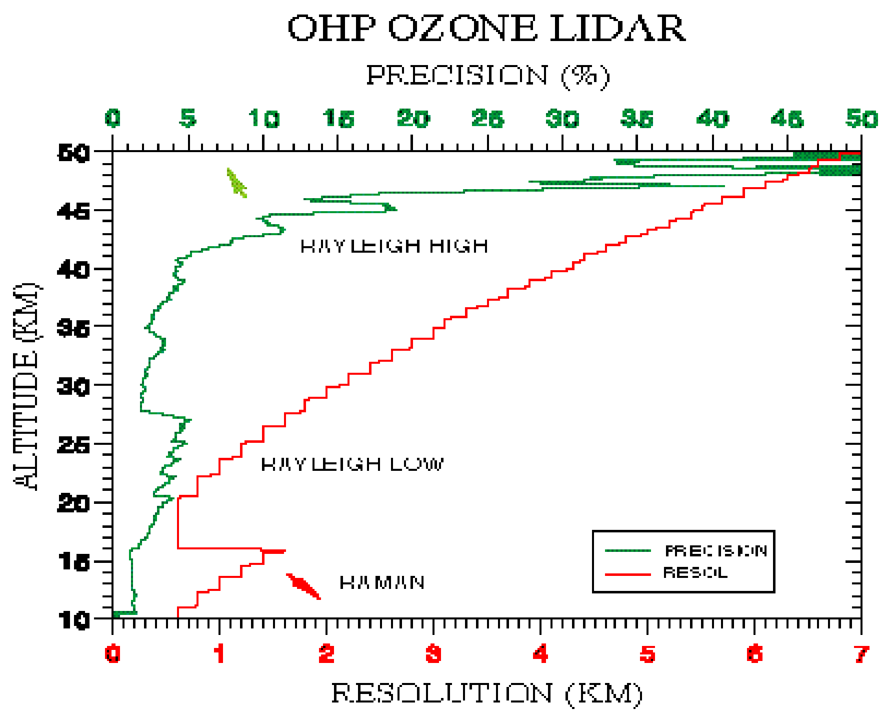
Temperature profiles measured with rotational Raman and Rayleigh integration technique at Esrange, Sweden, compared with profiles from radiosondes.

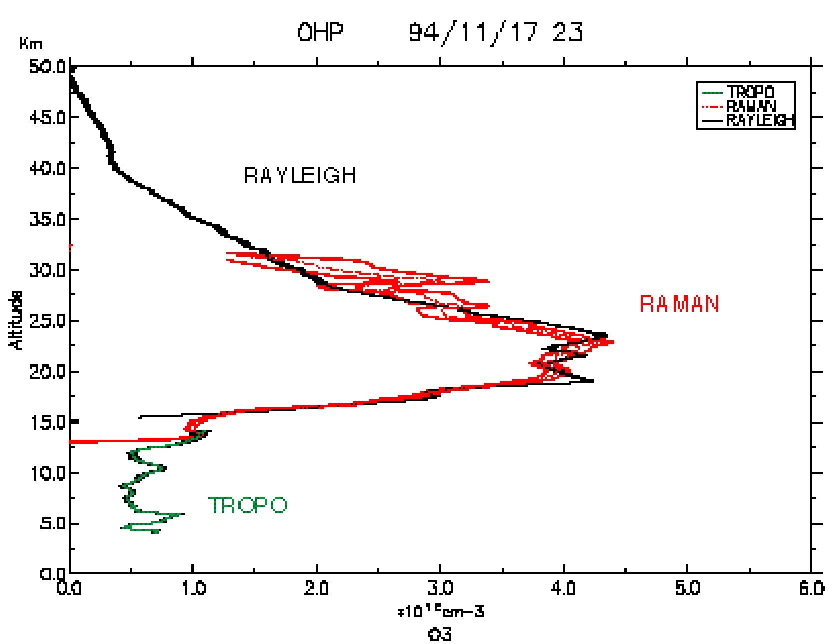
From: Tropospheric and stratospheric temperature measurements with lidar above Esrange in January and February 1999, by Andreas Behrendt, Jens Reichardt, Joerg Siebert, K.-H. Fricke, and Claus Weitkamp.



Lidar Profiles of Ozone

Precision and vertical resolution profile of an ozone measurement in the case of the OHP lidar instrument. Both the precision and the vertical resolution profile depend on the experimental configuration. The precision can vary from one measurement to the other.





Example of Rayleigh and Raman ozone lidar profiles. These measurements are compared to a tropospheric lidar profile obtained on the same site with a different lidar instrument.

Differential Absorption Lidar (DIAL)

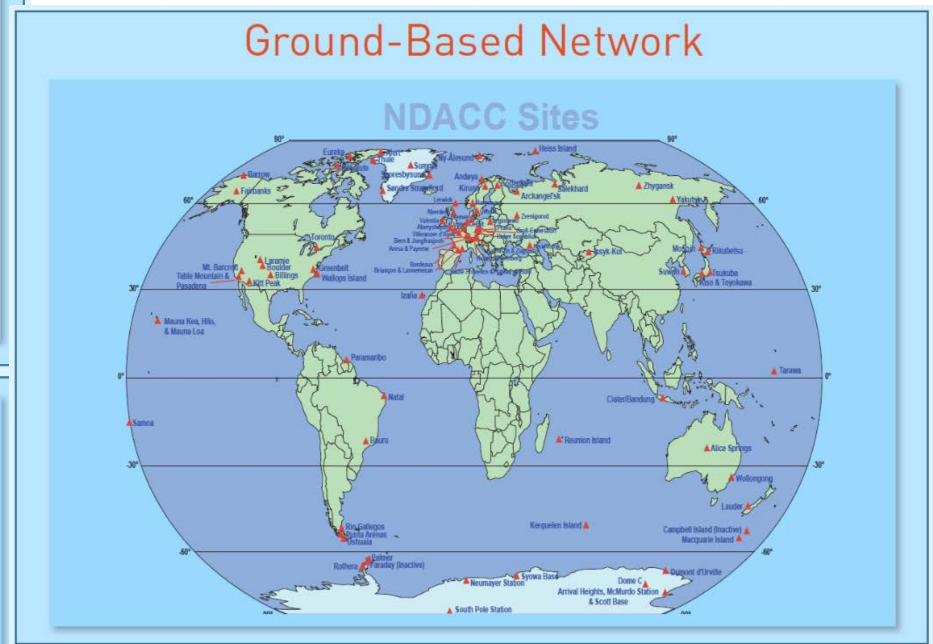
- Uses two laser wavelengths to measure ozone profiles.
  - → One wavelength is strongly absorbed by ozone, while the second wavelength is less absorbed.
  - → The two wavelengths travel through the atmosphere and are scattered back to two receivers.
  - → The signals are compared to give a measure of the concentration of ozone at a range of heights.
- This technique provides accurate vertical distributions of ozone.
- A stratospheric lidar yields an accuracy within 3% over 15-45 km and a precision varying typically from 0.5% to 10% corresponding to the related vertical resolution which varies from 0.5 to 8 km with increasing altitude.
- These observations require essentially clear sky conditions.

Network for the Detection of Atmospheric Composition Change (NDACC)

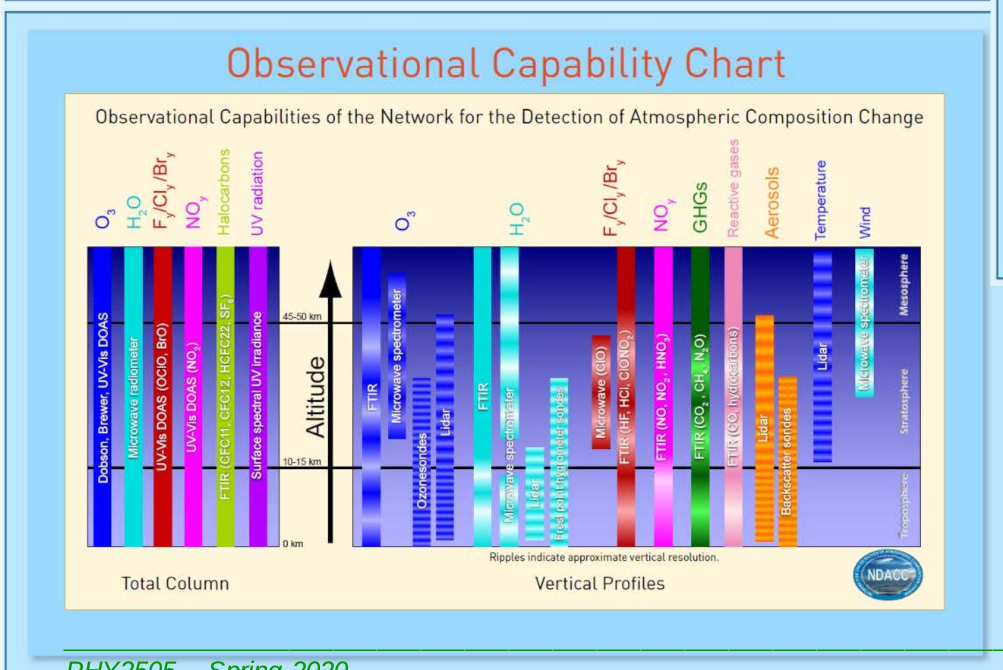
- *"formed to provide a consistent, standardised set of long-term measurements of atmospheric trace gases, particles, and physical parameters via a suite of globally distributed sites"*
- Ozone and key ozone-related chemical compounds and parameters are targeted for measurement.
- The NDACC is a major component of the international upper atmosphere research effort and has been endorsed by national and international scientific agencies, including the International Ozone Commission, the United Nations Environment Programme (UNEP), and the World Meteorological Organization (WMO).

http://www.ndacc.org

NDACC



http://www.ndaccdemo.org/about/poster



NDACC Primary Instruments and Measurements

- Ozone lidar
  - → vertical profiles of ozone from the tropopause to at least 40 km altitude; in some cases tropospheric ozone is also measured
- Temperature lidar
  - → vertical profiles of temperature from about 30 to 80 km
- Aerosol lidar
  - → vertical profiles of aerosol optical depth in the lower stratosphere
- Water vapour lidar
  - → vertical profiles of water vapor in the lower stratosphere
- Ozone microwave
  - → vertical profiles of stratospheric ozone from 20 to 70 km
- H_2O microwave
  - → vertical profiles water vapor from about 20 to 80 km
- ClO microwave
  - → vertical profiles of ClO from about 25 to 45 km, depending on latitude
- Ultraviolet/Visible spectrograph
  - → columns of ozone, NO_2, and, at some latitudes, OClO and BrO
- Fourier Transform Infrared spectrometer
  - → columns of many species including ozone, HCl, NO, NO_2, $ClONO_2$, HNO_3

Balloon-Based Measurements

Advantages:

- Carry a variety of instruments, payloads up to several tons
- Reach float altitudes of 40 km
- Provide height-resolved measurements
- Can be designed for special flights, e.g., long duration
- Inexpensive compared to rockets and satellites

Disadvantages:

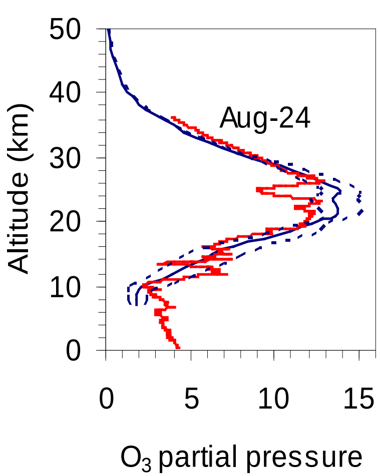
- Depend on meteorological conditions at launch and float
- Logistical factors
- Don’t provide global view or long time series
- More expensive than ground-based measurements

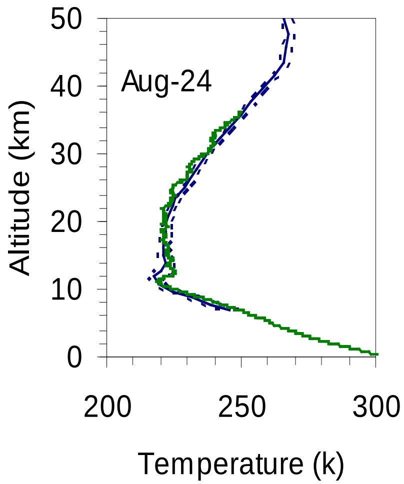
Ozonesondes (in situ – not remote)

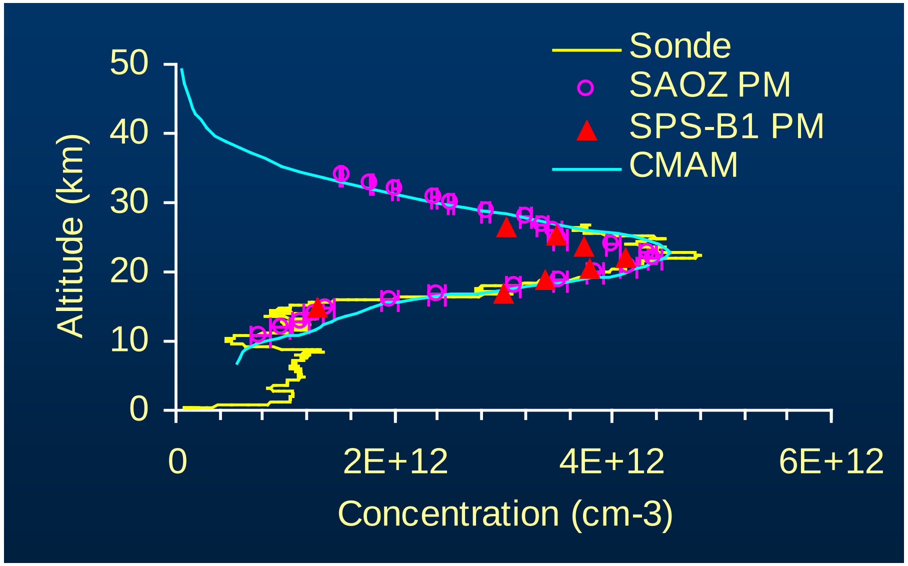
- Measure ozone concentration through the amount of electrons generated in an electro-chemical reaction of ozone in a KI solution (ECC sonde) - this is an *in situ* technique.
- The sonde is attached to a balloon, which reaches its maximum altitude at about 30-40 km. At this altitude the balloon bursts and the sonde falls down.
- Attached to the ozone sonde is a radio sonde, measuring pressure, temperature, and humidity.
- The vertical resolution of the profile is prescribed by the combination of the upward velocity (approximately 5 m/s) of the sonde and the time interval between the measurements (10 seconds), and is of the order of 100 m.
- The precision of the ozone concentrations is approximately 2%, and the accuracy is 5%.
- About 30 operational ozone sonde stations exist world-wide, the largest concentration of being in the Northern mid-latitudes.

Ozonesondes

O_3 and T from sondes compared with model







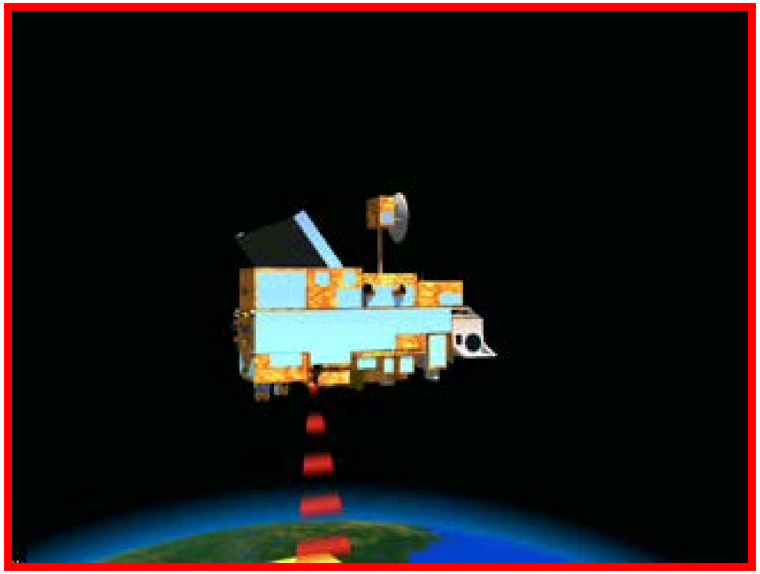
Space-Based Measurements

Advantages:

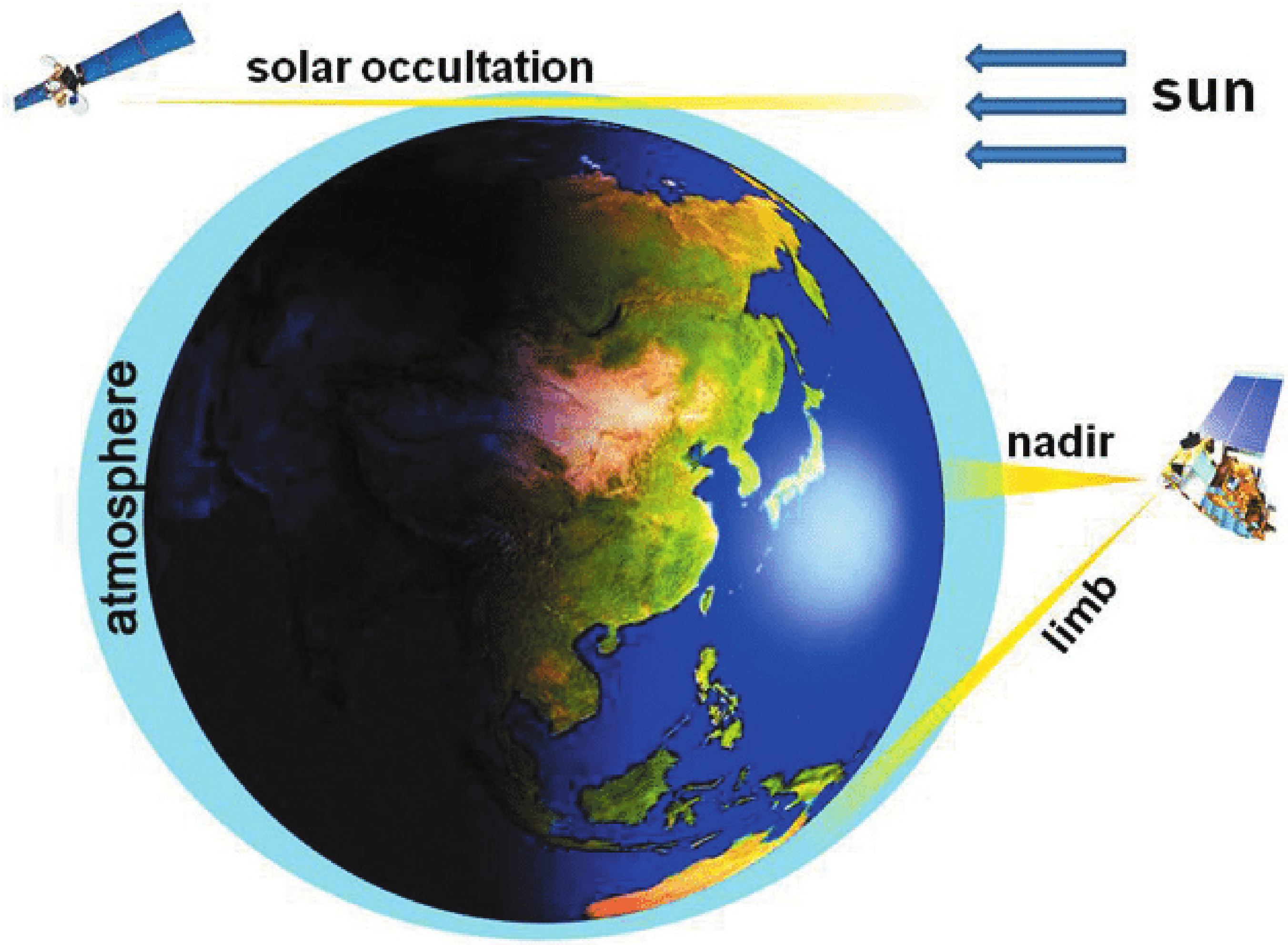
- Provide a unique global view
- Provide comprehensive coverage and sampling, so that all parts of the Earth can be observed regularly
- Can provide total column or height-resolved measurements
- Easier to study all but the lowest layers of the atmosphere looking down from above than looking up from below

Disadvantages:

- Expensive and high risk
- Require complex space-qualified instrumentation
- Can have limited lifetimes (~a few years)



Satellite Viewing Geometries

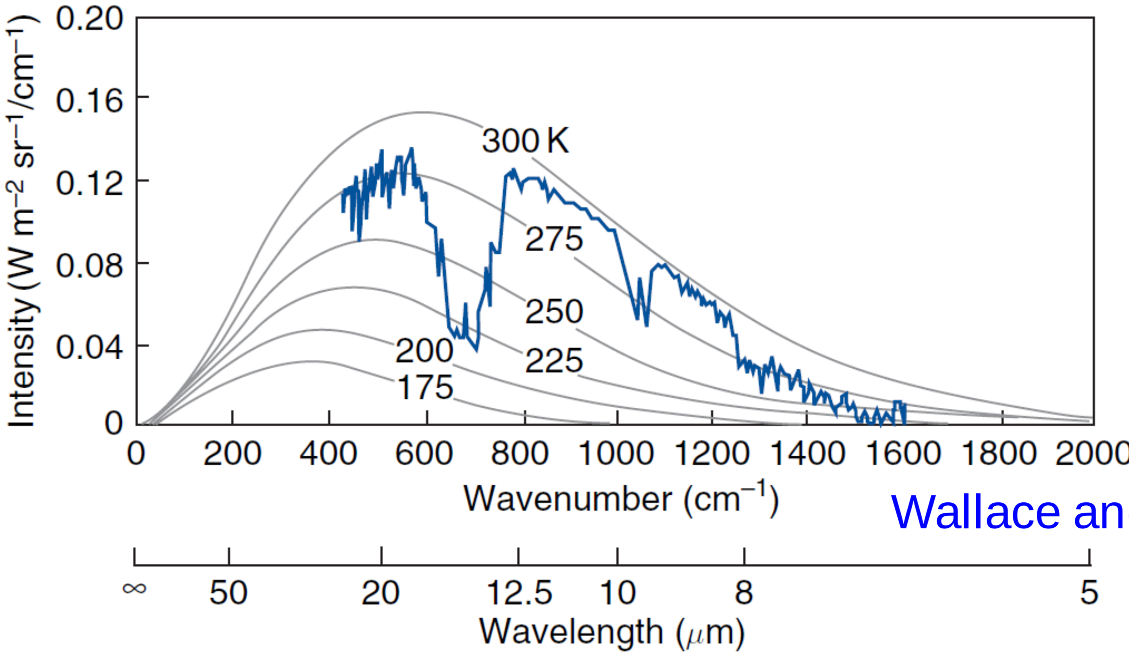


Lee et al. (2009)
https://www.researchgate.net/publication/233779970_Atmospheric_Aerosol_Monitoring_from_Satellite_Observations_A_History_of_Three_Decades

Satellite Remote Sounding of Temperature

Underlying principles:

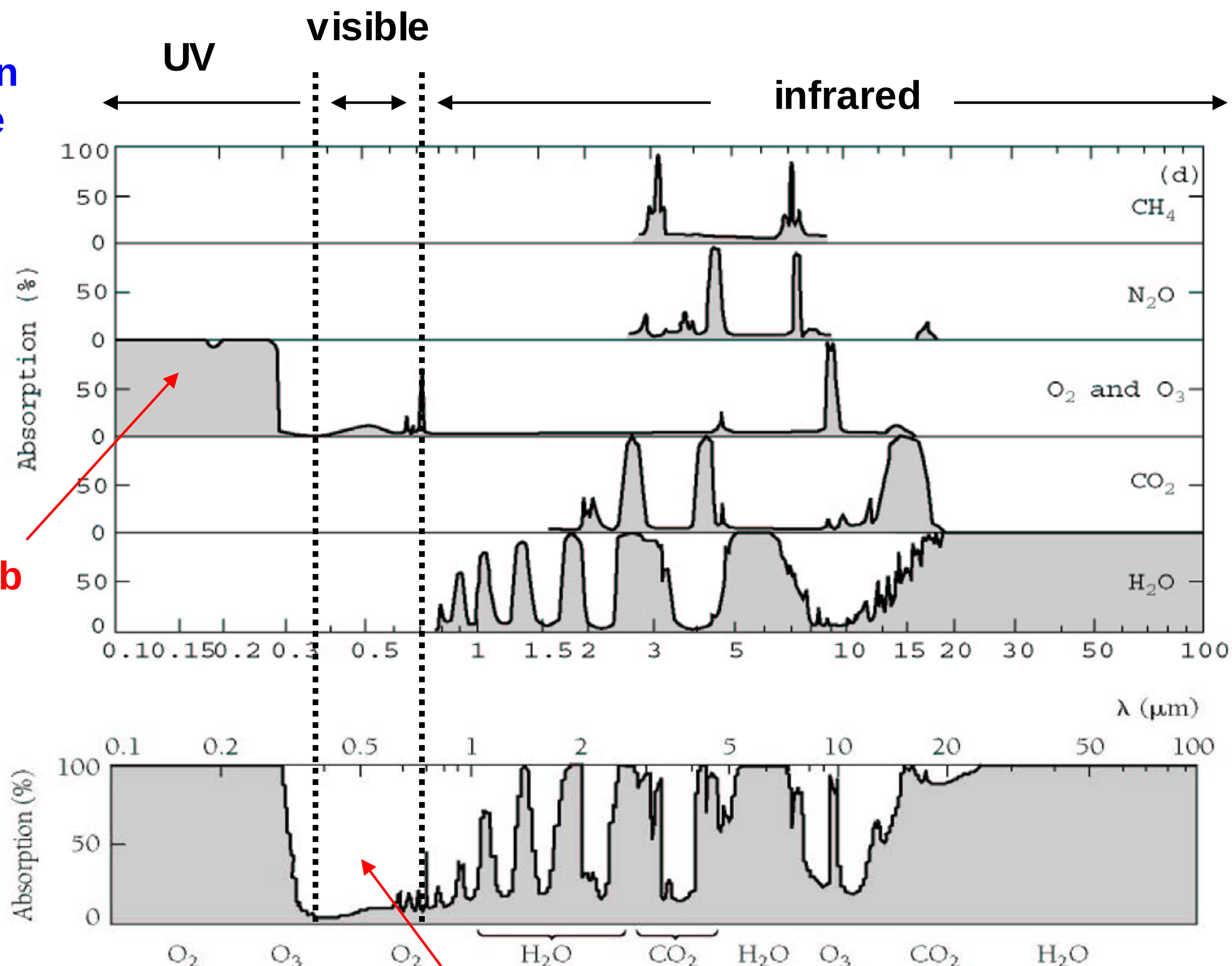
- Most of the radiation reaching a satellite in any spectral channel is emitted from near the level of unity optical depth for that channel.
- Spectral channels with higher absorptivities are associated with higher altitudes of unity optical depth (and vice versa).



Wallace and Hobbs, Figure 4.31

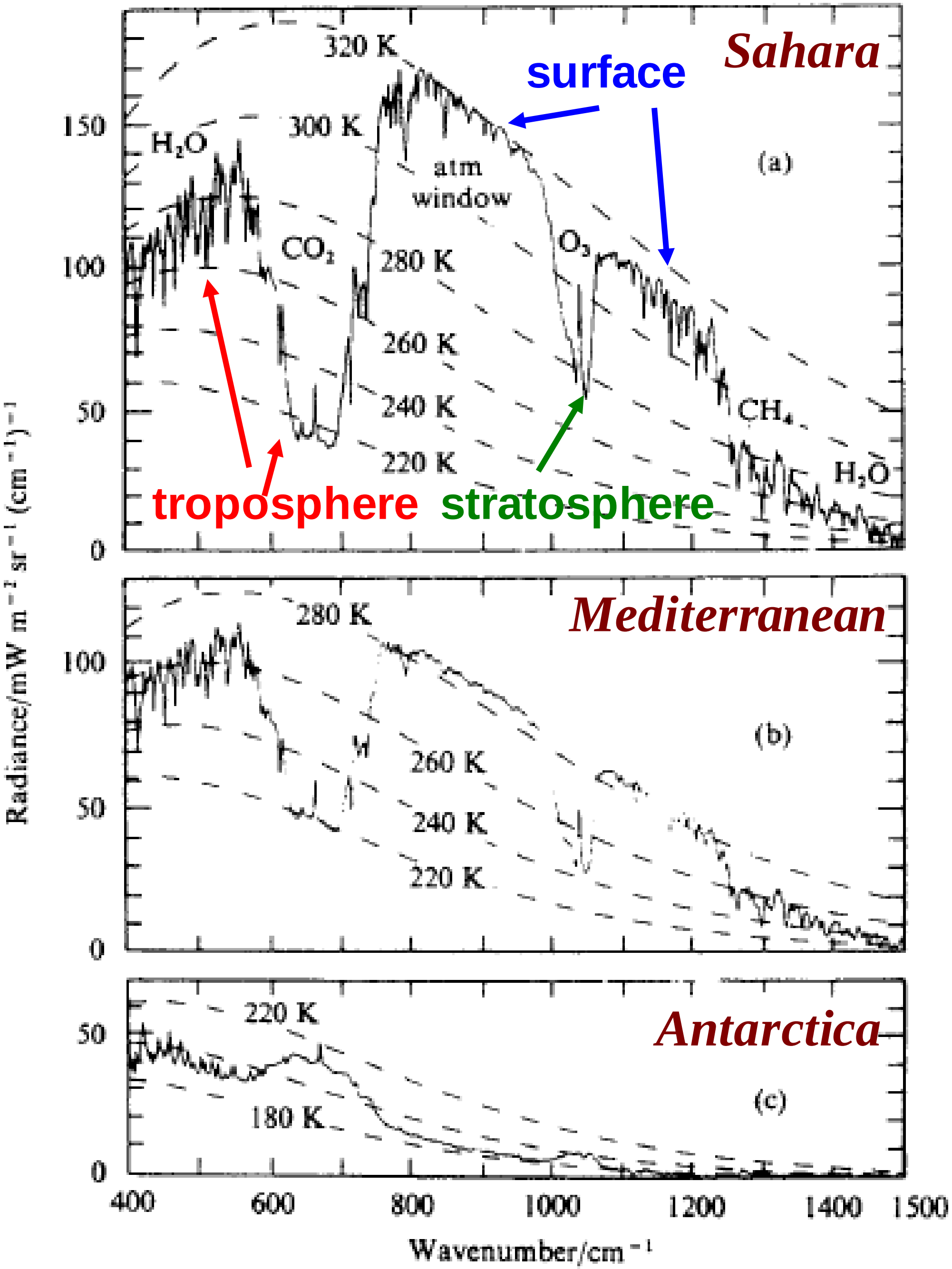
Greenhouse Gas Absorption

Absorption of radiation between the top of the atmosphere and the surface



O_2 and O_3 (in the stratosphere) absorb most of the harmful UV radiation

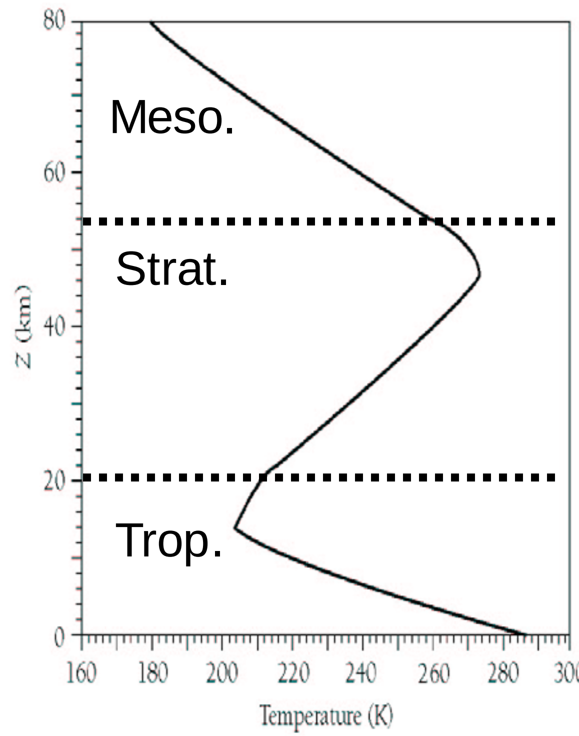
Most of the visible radiation from the sun passes through the atmosphere and reaches the surface



From J. Houghton, The Physics of Atmospheres, CUP, 2002.

T_e from Earth+atmosphere emitted vertically upwards and measured by the **InfraRed Interferometer Spectrometer** (IRIS) on the Nimbus 4 satellite.

Atmospheric T profile



Applying Schwarzchild's Equation

$$I_{\bar{\nu}}(X) = I_{\bar{\nu}}(0)e^{-k_{\bar{\nu}}\rho X} + \int_0^X k_{\bar{\nu}}\rho B_{\bar{\nu}}\, e^{-k_{\bar{\nu}}\rho x'}dx' = I_{\bar{\nu}}(0)\tau_{\bar{\nu}}(X) + \int_{\tau_{\bar{\nu}}(X)}^{1} B_{\bar{\nu}}\, d\tau$$

Surface emission *Atmospheric emission*

- This applies to a nadir-viewing (downward-looking) or vertical-sounding satellite instrument measuring radiance in the [near] local vertical, in a number of discrete infrared channels.
- The contribution of the surface emission term is reduced if transmission is small, i.e., if the observation is NOT in an atmospheric window.
- The atmospheric emission term includes information on the temperature through the blackbody function B(T), and on both the temperature and the concentration profile of the absorbing/emitting gas through the transmission and hence through the weighting function.

Applying Schwarzchild's Equation

- Channels on a real instrument each measure radiation from a range of altitudes, limiting the vertical resolution of the retrieved temperature profile.
- For temperature retrievals, we want to observe the intensity for an absorbing gas which:
  (1) is well mixed in the atmosphere (has a constant mixing ratio), and
  (2) has well known absorption lines.

Preferred regions (both gases are well mixed up to ~90 km):

(1) CO_2 near 15 μm

(2) O_2 near 60 GHz (5 mm)

Nadir Sounding of Temperature - 1

Schwarzchild's Equation (RTE for no scattering, valid in the IR):

$$I_\lambda(z_1) = I_\lambda(0)\tau_\lambda(0,z_1) + \int_{\text{surface}\to\tau_\lambda(0,z_1)}^{\text{satellite}\to\tau_\lambda(z_1,z_1)=1} B_\lambda(T)\,d\tau_\lambda$$

= surface radiance from surface to satellite

+ radiance emitted by each layer from that layer to satellite

See Houghton, Taylor, and Rodgers, Remote Sounding of Atmospheres, Chapter 5

where transmission from z to z_1 is:

$$\tau_\lambda(z,z_1) = \exp\left[-\int_z^{z_1} \frac{k_a \rho}{\mu} dz\right] = \exp\left[-\int_{u(z)}^{u(z_1)} k_a du\right]$$

Nadir Sounding of Temperature - 2

Now introduce an altitude-dependent variable y, which can be z, p, ln(p), or any function monotonic in z.

$$I_\lambda(z_1) = I_\lambda(0)\tau_\lambda(0,z_1) + \int_{\text{surface}}^{\text{satellite}} B_\lambda(T)\frac{d\tau_\lambda}{dy}dy$$

$$= I_\lambda(0)\tau_\lambda(0,z_1) + \int_{\text{surface}}^{\text{satellite}} B_\lambda(T)K_\lambda(y)dy$$

where $K_\lambda(y) = \frac{d\tau_\lambda}{dy}$ is called a <u>weighting function</u> (W in textbook).

Often, y = -ln(p) to make $K_\lambda(y)$ more independent of temperature.

A nadir-viewing instrument thus sees a surface term , and an atmospheric term which is the integral of the blackbody emission from each layer weighted by $K_\lambda(y)$.

Nadir Sounding of Temperature - 3

We can determine the form of $K_\lambda(y)$ by considering the lower atmosphere (< 40 km) where Lorentz broadening dominates and the absorption coefficient is thus:

$$k_a = \frac{S}{\pi}\frac{\alpha_L}{(\bar{\nu}-\bar{\nu}_o)^2+\alpha_L^2} = \frac{S}{\pi}\frac{\alpha_L' p}{(\bar{\nu}-\bar{\nu}_o)^2+(\alpha_L' p)^2}$$

where

$$\alpha_L(T,p) = \alpha_L^o(T_o,p_o)\frac{p}{p_o}\sqrt{\frac{T_o}{T}} \text{ and } \alpha_L' = \frac{\alpha_L(T,p)}{p} = \alpha_L^o(T_o,p_o)\frac{1}{p_o}\sqrt{\frac{T_o}{T}} .$$

Note: now working in space rather than space.

In the far wings of the Lorentz line, where $\bar{\nu}-\bar{\nu}_o >> \alpha_L' p$

$$k_a \approx \frac{S}{\pi}\frac{\alpha_L' p}{(\bar{\nu}-\bar{\nu}_o)^2}$$

Nadir Sounding of Temperature - 4

Thus, the transmission becomes:

$$\tau_{\bar{\nu}}(z,z_1) = \exp\left[-\int_{u(z)}^{u(z_1)} k_a du\right]$$

$$= \exp\left[-\int_{p(z)}^{p(z_1)} k_a \left(-\frac{Q}{\mu g}\right) dp\right]$$

$$= \exp\left[\frac{Q}{\mu g}\int_{p}^{p(z_1)=0} k_a dp\right]$$

$$= \exp\left[\frac{Q}{\mu g}\int_{p}^{0} \frac{S}{\pi}\frac{\alpha'_L p}{(\bar{\nu}-\bar{\nu}_o)^2} dp\right]$$

$$= \exp\left[\frac{QS\alpha'_L}{\pi\mu g(\bar{\nu}-\bar{\nu}_o)^2}\int_{p}^{0} p dp\right]$$

$$= \exp\left[-Ap^2\right]$$

where $A \equiv \dfrac{QS\alpha'_L}{2\pi\mu g(\bar{\nu}-\bar{\nu}_o)^2}$

and we have used the hydrostatic equation as follows:

$$du = \rho_{gas} ds = \rho_{gas}\frac{dz}{\mu}$$

$$= \frac{1}{\mu}\rho_{gas} dz = \frac{1}{\mu}\rho_{gas}\left(-\frac{dp}{\rho_{air} g}\right)$$

$$= \frac{1}{\mu}\left(-\frac{Q}{g} dp\right)$$

with mass mixing ratio $Q = \dfrac{\rho_{gas}}{\rho_{air}}$ assumed constant for a well-mixed gas

Nadir Sounding of Temperature - 5

Now the weighting function can be determined:

$$K_{\bar{\nu}}(y) = \frac{d\tau_{\bar{\nu}}}{dy} = -p\frac{d\tau_{\bar{\nu}}}{dp} = -p(-2Ap)\exp\left[-Ap^2\right] = 2Ap^2\exp\left[-Ap^2\right]$$

using y = -ln(p), dy = -dp/p.

Where (at what p_{max}) does the weighting function have a maximum?

$$\frac{dK_{\bar{\nu}}}{dy} = 0 = 2A\left\{2p_{max}\exp\left[-Ap_{max}^2\right] + p_{max}^2(-2Ap_{max})\exp\left[-Ap_{max}^2\right]\right\}$$

$$2p_{max} + p_{max}^2(-2Ap_{max}) = 0 \quad \Rightarrow \quad p_{max} = \frac{1}{\sqrt{A}}$$

Thus: $$K_{\bar{\nu}}(p) = 2\left(\frac{p}{p_{max}}\right)^2 \exp\left[-\left(\frac{p}{p_{max}}\right)^2\right]$$

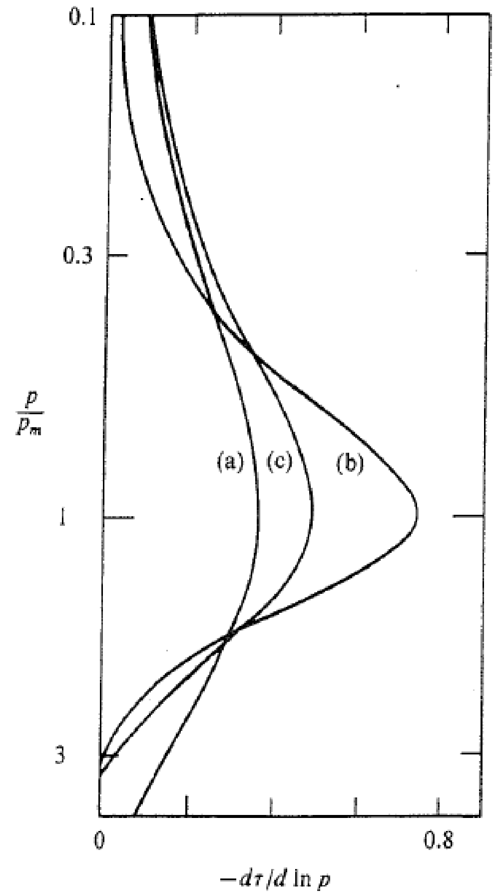
And we can plot $K_{\bar{\nu}}(p)$ vs. p/p_{max}

Nadir Sounding of Temperature

Comments:

- The value of p_{max}, i.e., the height of the maximum value $K_{\bar{\nu}}(p)$ of depends on $\bar{\nu}$.
- However, the half-width of the curve in units of ln(p) is independent of $\bar{\nu}$. If the atmosphere were isothermal, then this half-width would be ~10 km and would define the best possible vertical resolution.

Fig. 12.5. 'Weighting functions' appropriate to a radiometer sounding the atmosphere by observing radiation emitted vertically upwards from the atmosphere for (a) an atmosphere with uniform absorption coefficient, problem 12.3, (b) a frequency in the wing of a pressure broadened spectral line, problem 12.4, (c) an Elsasser band, problem 12.5. Note the greater vertical resolution of (b). p_m is the pressure at which the functions peak.



For derivations, see Houghton, Taylor, and Rodgers, Remote Sounding of Atmospheres, Chapter 5

Houghton, Figure 12.5

Nadir Sounding of Temperature

Now, how is the weighting function applied to obtain a vertical profile of temperature?

- Because k_a and K vary with $\overline{\nu}$, different $\overline{\nu}$ will possess weighting functions that peak at different heights. By measuring the intensities at a series of $\overline{\nu}$, a range of altitudes will be represented. Observations in the wings of a Lorentz line will see deeper into the atmosphere, while observations closer to line centre will see only the top layers of the atmosphere.

- In practice, most radiometers measure the intensity with a spectral bandwidth much broader than that of a single line, and so the weighting functions are effectively smeared out over several layers (e.g., curve 'c' in Figure 12.5 of Houghton).

15 μm CO_2 Absorption

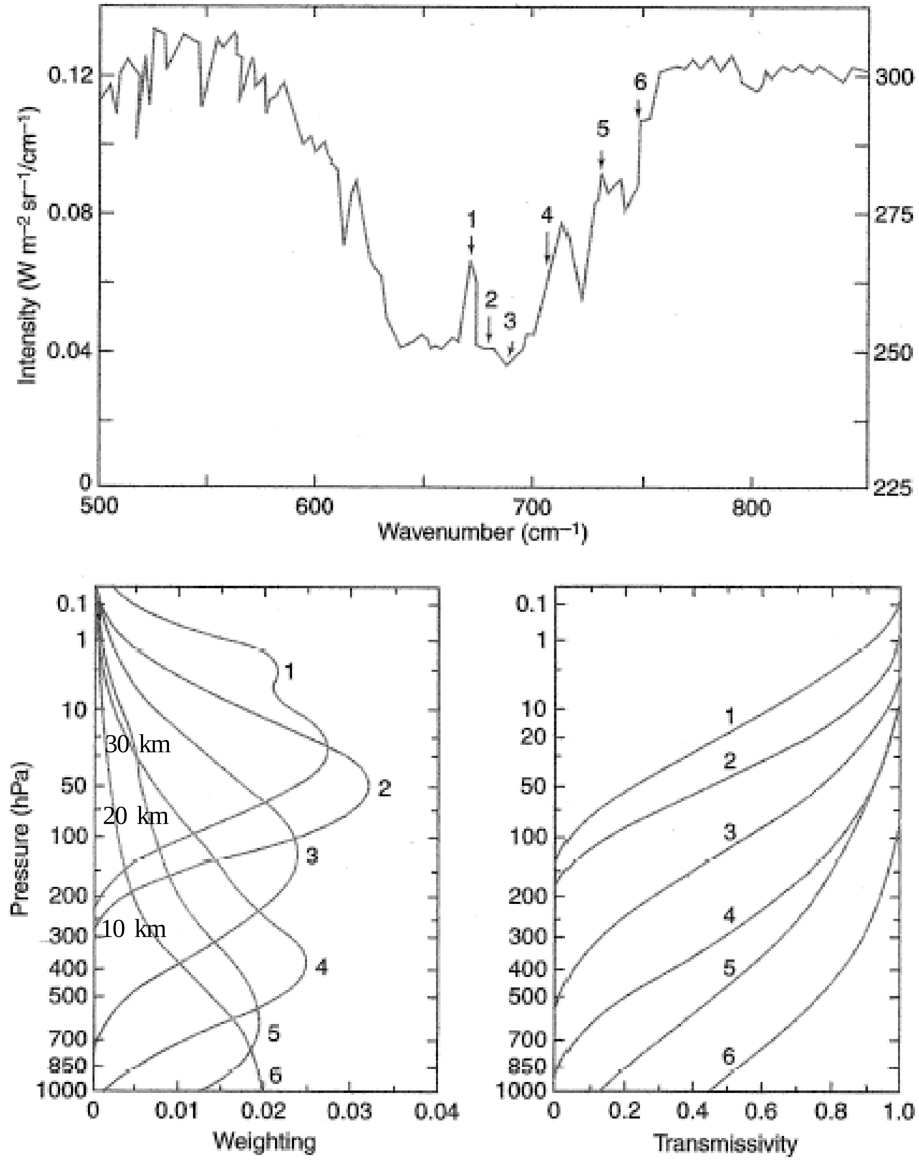
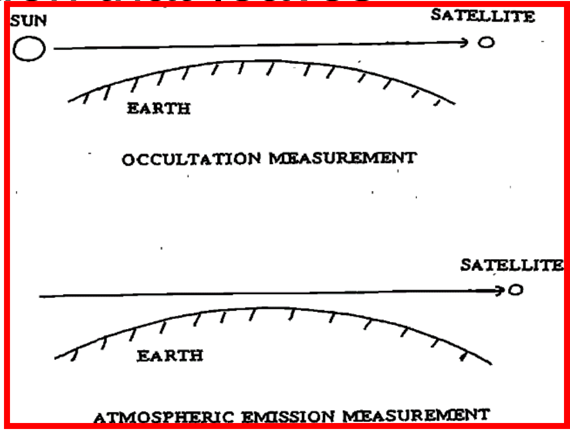


Fig. 4.33 (Top) Intensities or radiances (scale at left) and equivalent blackbody temperatures (scale at right) in the vicinity of 15-μm CO_2 absorption band, as observed from the satellite. Arrows denote the spectral bands or "channels" sampled by satellite-borne vertical temperature profiling radiometer (VTPR). The weighting functions and transmittances for each of the ch nels are shown below. [Adapted from K. N. Liou, *An Introduction to atmospheric radiation*, Academic Press, pp. 389–390, Copyri (2002), with permission from Elsevier.]

Wallace and Hobbs, Figure 4.33

Limb Sounding of Temperature - 1

Limb viewing or sounding - the satellite instrument looks towards the limb (horizon) of the atmosphere, measuring radiation that leaves the atmosphere nearly tangentially.



http://www.asp.ucar.edu/colloquium/1992/notes/part2/node7.html

The same RTE is used, but for different geometry:

- no longer have a surface term
- the intensity is integrated along the limb viewing line-of-sight

The appropriate RTE, again assuming a non-scattering case, is

$$I_{\bar{\nu}}(z_{tangent}) = \int_{-\infty}^{\infty} B_{\bar{\nu}}[T(x)] \frac{d\tau_{\bar{\nu}}(x, z_{tangent})}{dx} dx$$

where

- $z_{tangent}$ = tangent height, the height above the surface of the closest point to the Earth in the instrument's line-of-sight
- x = distance along line-of-sight with origin at the tangent point

Limb Sounding of Temperature - 2

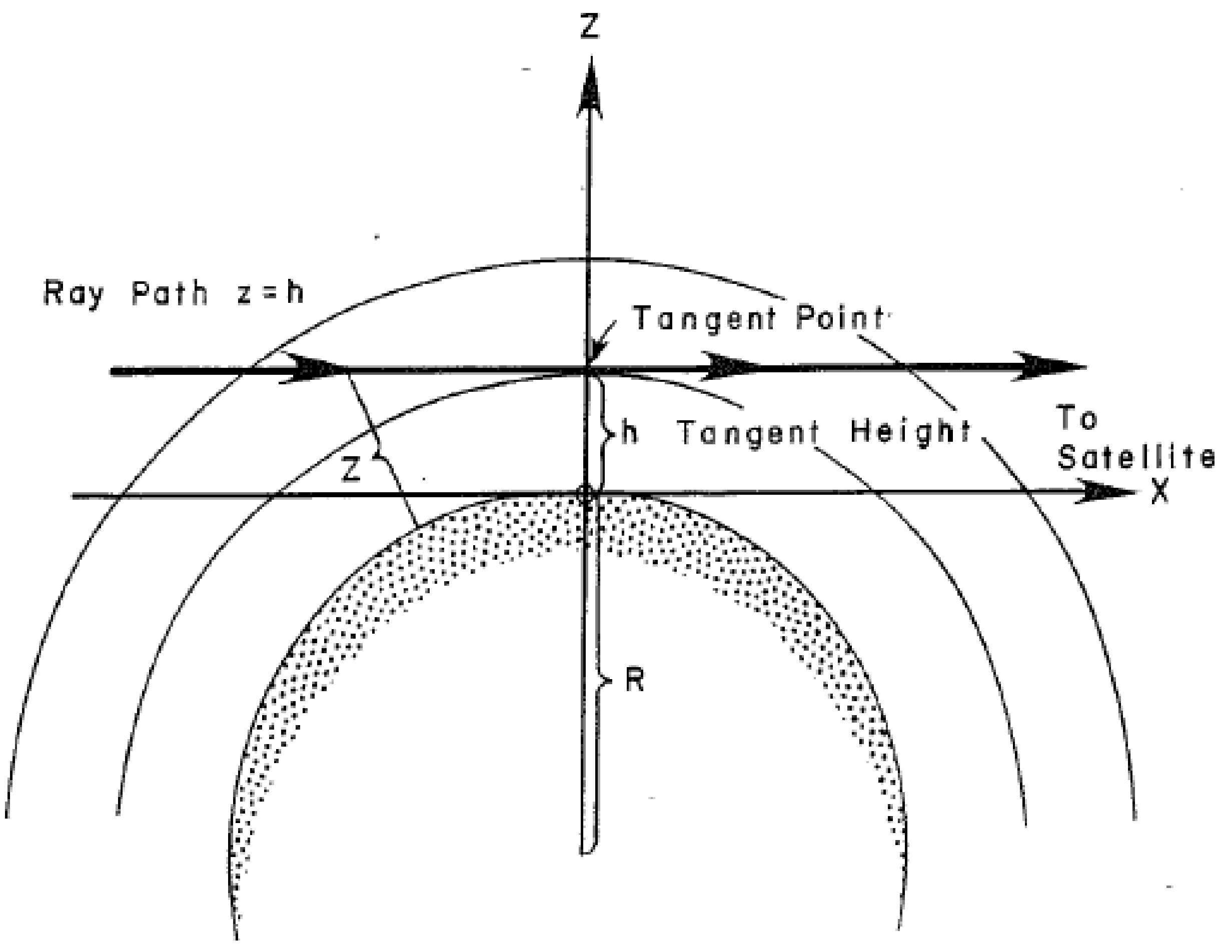


Fig. 7.8 The geometry of limb viewing.

Liou, Figure 7.8

Limb Sounding of Temperature - 3

Since the temperature profile is wanted as a function of z, not x, this equation is converted to a vertical integral

$$I_{\bar{\nu}}(z_{tangent}) = \int_{z_{tangent}}^{z_1=\infty} B_{\bar{\nu}}[T(z)] K_{\bar{\nu}}(z, z_{tangent}) dz$$

where $K_{\bar{\nu}}(z, z_{tangent}) = \left[\left(\frac{d\tau_{\bar{\nu}}(x, z_{tangent})}{dx} \right)_+ + \left(\frac{d\tau_{\bar{\nu}}(x, z_{tangent})}{dx} \right)_- \right] \left| \frac{dx}{dz} \right|$

and +/- indicate values along the +x and -x directions. (Liou Fig. 7.9)

Limb Sounding of Temperature - 4

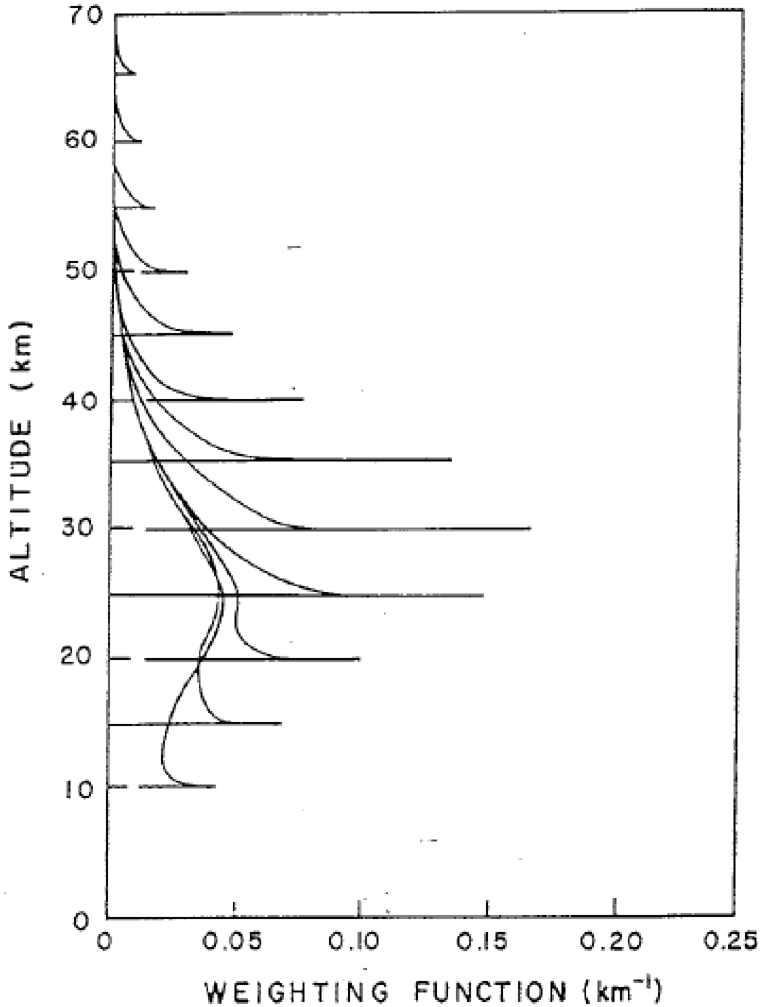


Fig. 7.9 Limb viewing weighting function for the ideal case of an instrument with an infinitesimal vertical field of view for the spectral band 585–705 cm^{-1} covering most of the 15 μm band of CO_2 (after Gille and House, 1971).

Note the sharp cut-off at the lower boundary because the atmosphere is not viewed below the tangent height.

Liou, Figure 7.9

Limb Sounding of Temperature - 5

Advantages of limb sounding:

(1) Good vertical resolution because the weighting functions peak sharply at the tangent height, with the instrument seeing nothing below $z_{tangent}$ while pressure and density decrease exponentially above $z_{tangent}$.

(2) The background is either the direct source (Sun) or space (which is cold and uniform) unlike the hot and variable surface of the Earth.

(3) There is as much as 60-75 more emitting/absorbing material in the limb path than along the nadir path, allowing measurements of temperature and composition to higher altitudes and measurements of gases having lower concentrations

Disadvantages of limb sounding:

(1) Observations are limited to the upper troposphere and above, due to clouds and the finite [~2 km] field-of-view of the instrument.

(2) The horizontal resolution is low.

(3) It requires precise information about the field-of-view and spacecraft attitude so that the spacecraft pointing can be accurately determined.

Measurements of Atmospheric Composition

The general principles for remote sounding of atmospheric composition are the same as those for remote sounding of temperature. Both use the fact that at any λ or $\bar{\nu}$, atmospheric transmission is a function of the temperature and of the mixing ratio of any gas that absorbs radiation at that λ or $\bar{\nu}$.

Two approaches:

(1) For a well-mixed gas (e.g., CO_2, O_2):

- $\rightarrow$ mixing ratio is known and constant with height
- $\rightarrow$ can retrieve temperature from measurements of $I(\lambda)$ at λ where the gas absorbs

(2) For a gas whose mixing ratio varies with altitude (e.g., O_3, H_2O):

- $\rightarrow$ assume a temperature profile
- $\rightarrow$ can retrieve mixing ratio from measurements of $I(\lambda)$ at λ where the gas absorbs

Measurements of Ozone from Satellites

- Many different techniques and instruments are used to measure atmospheric composition. We will concentrate on measurements of ozone.
- Ozone has absorption features in all regions of the EM spectrum and so can be detected using several techniques.
  - → e.g., 21 satellite experiments to measure ozone before 1980; many more since 1980
- Four common techniques:
  - → limb or nadir emission (IR or microwave)
  - → backscatter ultraviolet (BUV)
  - → solar occultation (UV-visible or IR)
  - → limb scattering (UV-visible)

(1) Ozone Measurements Using Emission

- usually measure longwave radiation thermally emitted by the atmosphere along the line of sight of the instrument
- infrared (9.6 μm ozone band) or microwave wavelengths
- limb sounding or nadir sounding viewing geometries
- used to retrieve ozone profiles and total columns

General principle:

$$I_\lambda(z_1) = I_\lambda(0)\tau_\lambda(0, z_1) + \int_{\text{surface} \to \tau_\lambda(0,z_1)}^{\text{satellite} \to \tau_\lambda(z_1,z_1)=1} B_\lambda(T)d\tau_\lambda = I_\lambda(0)\tau_\lambda(0, z_1) + \int_{\text{surface}}^{\text{satellite}} B_\lambda(T)\frac{d\tau_\lambda}{dy}dy$$

for no scattering in IR and a satellite at $z = z_1$.
In this case, T is known so B(T) can be determined. The $d\tau/dy$ term can be derived and used to calculate the unknown mixing ratio or the optical mass of ozone.

Examples:

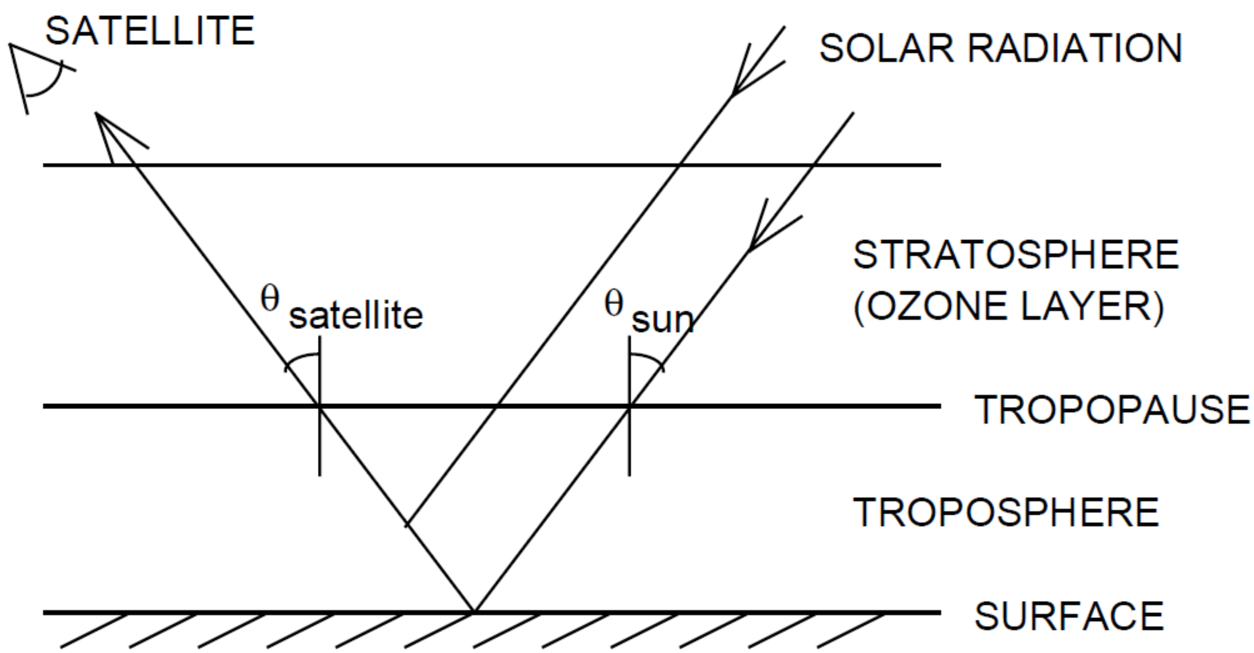
- Nadir: IRIS, TES, IASI
- Limb: LIMS, MLS, MIPAS

(2) Ozone Measurements Using UV Backscatter - 1

- probably the best-known method for the retrieval of ozone from satellites
- measure solar UV radiation reflected from the surface and backscattered by the atmosphere or clouds is absorbed by ozone in the Hartley-Huggins bands (< 350 nm)

See figure below. Note:

- most ozone lies in the stratosphere
- most of the backscattered UV radiation comes from the troposphere
- little absorption by ozone occurs in the troposphere
- little scattering occurs in the stratosphere
- radiation reaching the satellite passes through the ozone layer twice



(2) Ozone Measurements Using UV Backscatter - 2

Derivation of the total ozone vertical column:

The satellite measures radiance

$$I(\lambda) = E_{sun}(\lambda)\left[\tau_{ozone}(\lambda)\right]^{x} R(\theta_{sun}, \theta_{satellite}, R_{surface}, R_{air})$$

where

$E_{sun}(\lambda)$ = solar irradiance at the top of the atmosphere

$\left[\tau_{ozone}(\lambda)\right]^{x}$ = atmospheric transmission in the ozone band along the slant path, with

$\tau_{ozone}(\lambda)$ = vertical path transmission

$x = \sec\theta_{sun} + \sec\theta_{satellite}$

$R(\theta_{sun}, \theta_{satellite}, R_{surface}, R_{air})$ = combined surface-troposphere reflectance which depends on zenith angles, reflection from the surface ($R_{surface}$), and scattering from the air (R_{air})

Recall

$$\tau_{slant} = \exp\left[-\int \rho k_a ds\right] = \exp\left[-\int \rho k_a \frac{dz}{\cos\theta}\right] = \left\{\exp\left[-\int \rho k_a dz\right]\right\}^{1/\cos\theta} = \left\{\tau_{vertical}\right\}^{\sec\theta}$$

Note: this is a "no emission" form of the RTE, which is applicable at UV-VIS λ, where neither the surface nor the atmosphere emits significant radiation.

(2) Ozone Measurements Using UV Backscatter - 3

Want to solve this equation for the vertical path transmission $\tau_{ozone}(\lambda)$, where

$$\tau_{ozone}(\lambda) = \exp\left[-\int \rho k_a(\lambda) dz\right] = \exp\left[-\int k_a(\lambda) du\right] = \exp\left[-k_a(\lambda) U\right]$$

with

$k_a(\lambda)$ = mass absorption coefficient

U = total column ozone (molecules/cm^2)

T and P dependence of $k_a(\lambda)$ has been ignored (more valid in UV-VIS than in IR)

Thus, if $\tau_{ozone}(\lambda)$ can be found, then the total ozone column U can be calculated. The difficulty is determining the reflectance term R.

Several satellite instruments measure incoming solar irradiance $E_{sun}(\lambda)$ and backscattered radiance I(λ) at two UV wavelengths, one where ozone absorption is strong ($k_a(\lambda)$ is large) and one where ozone absorption is weak ($k_a(\lambda)$ is small).

Generate arbitrary quantities (account for logarithmic attenuation)

$$N_1 \equiv -100 \log_{10}\left[\frac{I(\lambda_1)}{E_{sun}(\lambda_1)}\right] = -100 \log_{10}\left[R(\lambda_1) \exp\{-k_a(\lambda_1) U x\}\right]$$

$$N_2 \equiv -100 \log_{10}\left[\frac{I(\lambda_2)}{E_{sun}(\lambda_2)}\right] = -100 \log_{10}\left[R(\lambda_2) \exp\{-k_a(\lambda_2) U x\}\right]$$

So $$N_1 - N_2 = -100 \log_{10}\left[\frac{R(\lambda_1)}{R(\lambda_2)} \exp\{-[k_a(\lambda_1) - k_a(\lambda_2)]\, U x\}\right].$$

(2) Ozone Measurements Using UV Backscatter - 4

If R can be considered constant between the two wavelengths, i.e., $R(\lambda_1) = R(\lambda_2)$, then

$$N_1 - N_2 = -100 \log_{10}\left[\exp\left\{-\left[k_a(\lambda_1) - k_a(\lambda_2)\right] U x\right\}\right]$$

$$\underbrace{N_1 - N_2}_{\text{measure}} = \underbrace{100 \log_{10}(e)}_{\text{constant}} \underbrace{\left[k_a(\lambda_1) - k_a(\lambda_2)\right]}_{\text{known}} \underbrace{U}_{\text{retrieve}} \underbrace{x}_{\text{known}}$$

However, the backscattered component, R_{air}, has λ^{-4} dependence, so $R(\lambda_1) \neq R(\lambda_2)$.

Generally, a third observation at λ_3, outside the ozone band, is used to determine the surface term $R_{surface}(\lambda_1) \approx R_{surface}(\lambda_2)$, calculate the Rayleigh scattering term $R_{air}(\lambda)$, and thus determine $R(\lambda_1)$ and $R(\lambda_2)$.

Vertical profiles of ozone can also be derived using the "BUV profiling technique". This relies on the fact that the longer the wavelength of the incoming UV irradiance, the weaker the ozone absorption and so the lower (in z) the penetration of the UV light into the atmosphere. The absorption increases with decreasing wavelength, such that radiation at progressively shorter wavelengths is significantly absorbed at progressively higher altitudes. So the backscattered radiation at specific UV wavelengths can only be scattered from above a particular height. Below this level, all the radiation is absorbed and there is no backscattered radiance. Measurements at certain UV wavelengths are sensitive to specific portions of the ozone vertical profile, and the full profile can be obtained by measuring radiation at a series of wavelengths and using a retrieval algorithm that converts each radiance measurement to and atmospheric quantity.

Examples: SBUV, TOMS, OMI, GOME, TROPOMI

(3) Ozone Measurements Using Occultation - 1

- probably the simplest method for the retrieval of ozone profiles from satellites
- atmospheric extinction at a UV-visible or infrared λ sensitive to ozone absorption is measured from a satellite as the Sun, Moon, or a star rises or sets
- the extinction though the limb of the atmosphere is measured as a function of tangent height, allowing the optical mass to be determined
- vertical resolution is typically 1-2 km, which is better than the BUV profiling technique

Define

I_λ^o = intensity at the highest altitude where ozone extinction is zero

$I_\lambda(z_i)$ = intensity measured at the i-th tangent height z_i

The ratio of $I_\lambda(z_i)$ to I_λ^o is a measure of the transmittance

$$\tau_\lambda(z_i) = \frac{I_\lambda(z_i)}{I_\lambda^o} = \exp\left(-\int_{-\infty}^{\infty}\sigma_{ext,\lambda}(s)ds\right)$$

where

$\sigma_{ext,\lambda}(s)$ = volume extinction coefficient at point s along the line-of-sight

Typically, $\sigma_{ext,\lambda}(s) = \sigma_\lambda^{Rayleigh}(s) + \sigma_\lambda^{ozone}(s) + \sigma_\lambda^{aerosol}(s) + \sigma_\lambda^{other\ gases}(s)$.

For a simplified case, ignoring scattering and other sources of extinction:

$$\sigma_{ext,\lambda}(s) = k_a^{ozone}(\lambda)\rho^{ozone}(s)$$

(3) Ozone Measurements Using Occultation - 2

Thus, $\tau_\lambda(z_i) = \exp\left(-\int_{-\infty}^{\infty} k_a^{ozone}(\lambda)\rho^{ozone}(s)ds\right) = \exp\left[-k_a^{ozone}(\lambda)U^{ozone}(z_i)\right]$,

ignoring T and p dependence of $k_a^{ozone}(\lambda)$.

By measuring $\tau_\lambda(z_i)$ for a series of tangent heights, a set of columns $U(z_i)$ can be calculated and then inverted to get the ozone vertical profile.

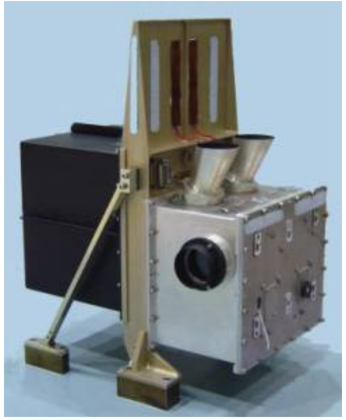
Note that the same instrument is used to measure the attenuated and unattenuated radiation, so any long-term instrument changes disappear when the ratio is calculated. This is why occultation instruments are often called self-calibrating.

Main disadvantage: Observations are made as the source (usually the Sun) rises or sets relative to the satellite. For a satellite in LEO, this means that there are typically 15 sunset and 15 sunrise measurements per day (maximum = 24 of each). Also, the concentration of some gases changes rapidly during twilight, which can make it difficult to interpret measurements over the long horizontal limb path.

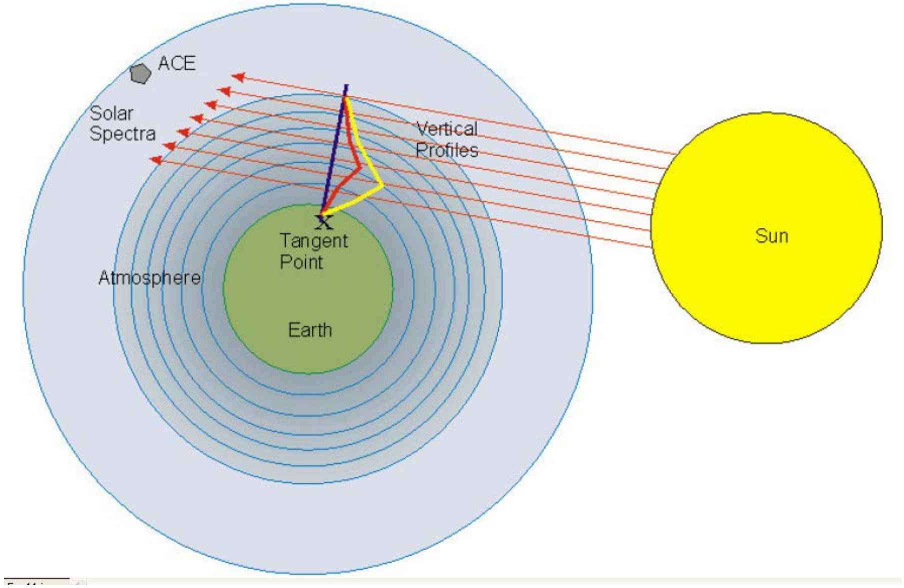
Examples: SAGE, ATMOS, HALOE, POAM, GOMOS, ACE

Solar Occultation: ACE

Atmospheric Chemistry Experiment (ACE)
on the Canadian Space Agency's SCISAT

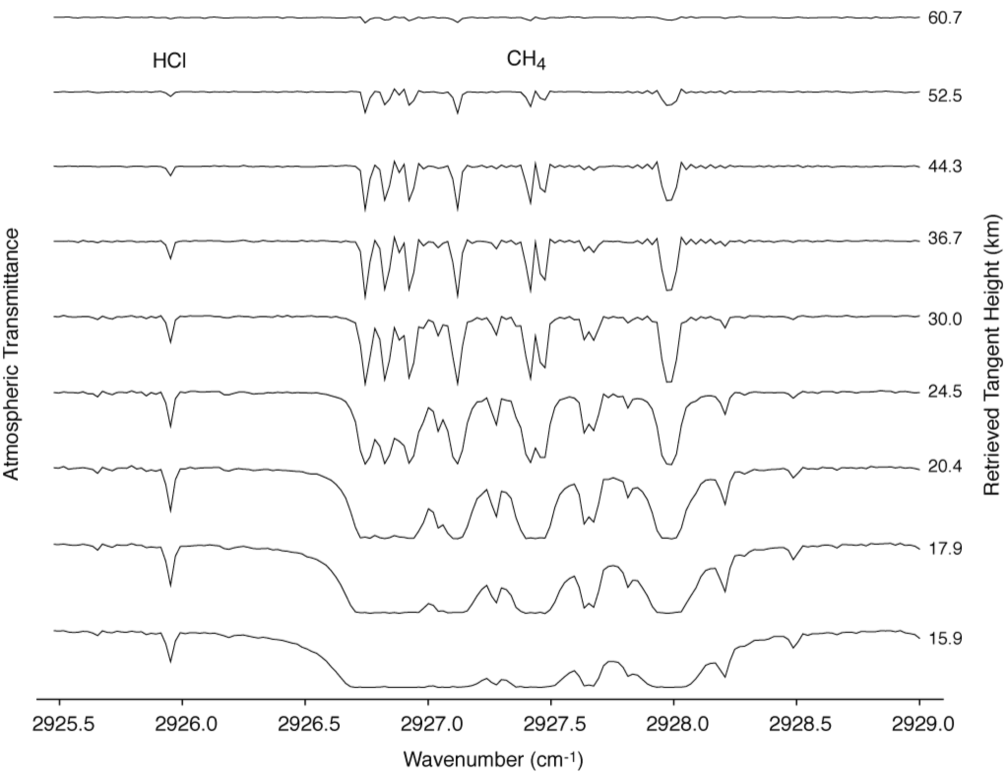


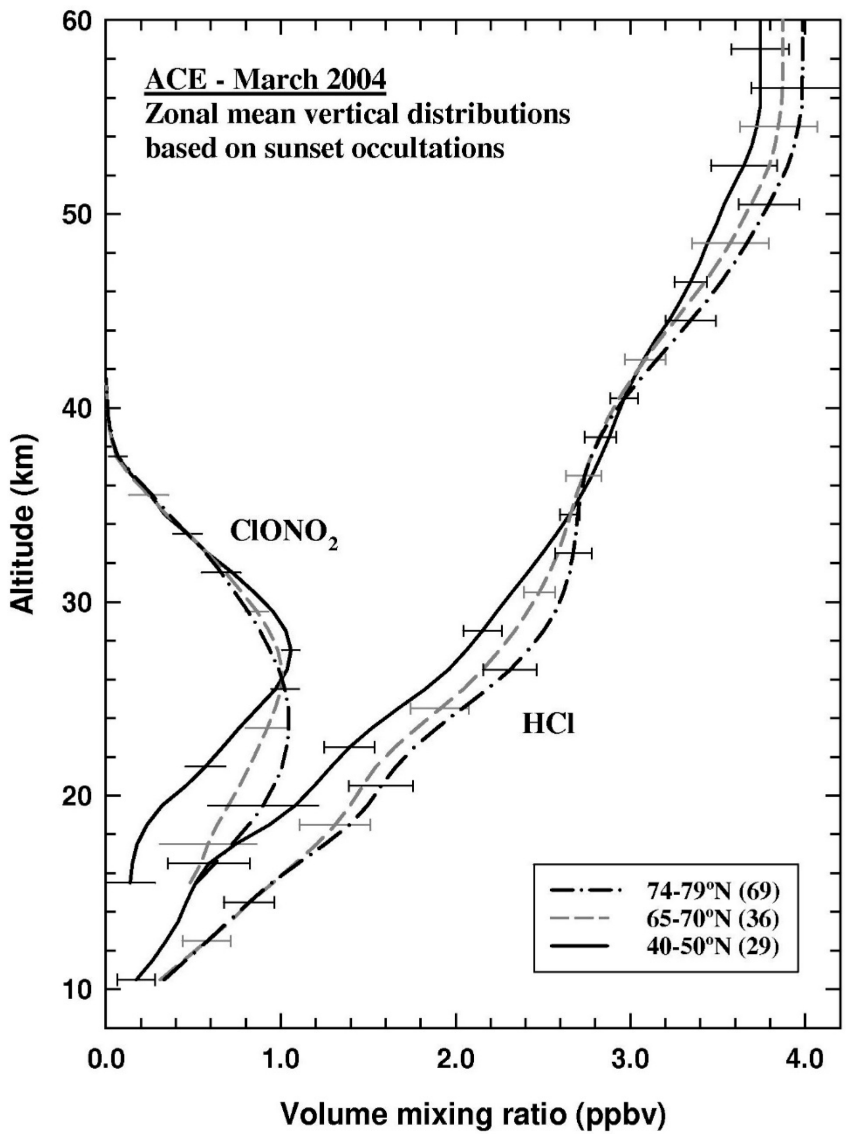
- Carries two instruments to measure gases and aerosols using solar occultation
  - → Points at Sun
- Large signal
- Long atmospheric path
- Very sensitive
- Measures many gases



ACE-FTS Measurements

An Occultation Sequence



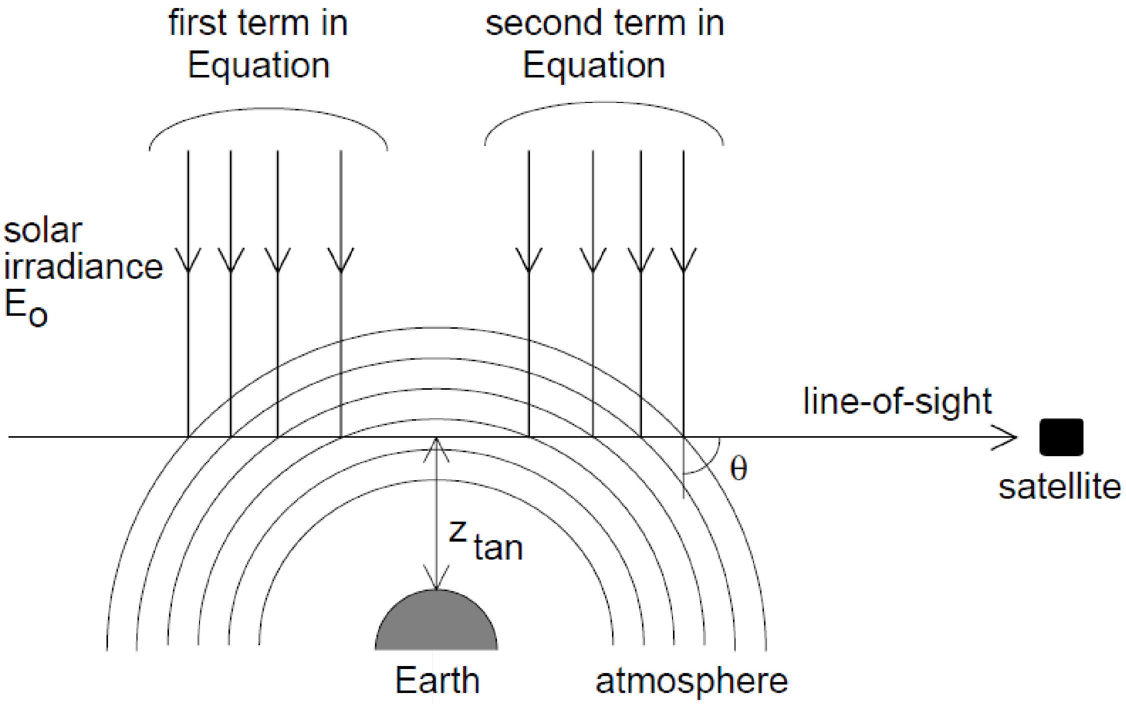


Stratospheric Chlorine Species

Courtesy: R. Zander and co-workers

(4) Ozone Measurements Using Limb Scattering - 1

- viewing geometry is similar to that of both limb emission and occultation, which provides good vertical resolution
- measures scattered solar radiation in a manner similar to BUV, but the light source is in Earth's limb
- provides coverage through the atmosphere, and hence good column measurements



Examples: SME, OSIRIS, SCIAMACHY

(4) Ozone Measurements Using Limb Scattering - 2

General equation for limb radiance I, at wavelength λ and tangent height z_{tan}, is:

$$I(\lambda, z_{tan}) = E_o(\lambda) \int_{line-of-sight} \tau_{in}(\lambda, \infty : z) S(\lambda, z, \theta) \tau_{out}(\lambda, z : \infty) dz$$

$$= E_o(\lambda) \int_{\infty}^{z_{tan}} \tau_{in}(\lambda, \infty : z) S(\lambda, z, \theta) \tau_{out}(\lambda, z : \infty) dz$$

$$+ E_o(\lambda) \int_{z_{tan}}^{\infty} \tau_{in}(\lambda, \infty : z) S(\lambda, z, \theta) \tau_{out}(\lambda, z : \infty) dz$$

where

$E_o(\lambda)$ is the solar irradiance incident on the top of the atmosphere (photons cm^{-2} s^{-1} $Å^{-1}$)

θ is the forward scattering angle

$\tau_{in}(\lambda, \infty : z)$ is the atmospheric transmission in from the top of the atmosphere to the scattering point at altitude z along the OSIRIS line-of-sight

$S(\lambda, z, \theta)$ is a scattering term describing the proportion of solar irradiance singly scattered into the instrument line-of-sight

$\tau_{out}(\lambda, z : \infty)$ is the atmospheric transmission back out from the scattering point at altitude z along the OSIRIS line-of-sight to the top of the atmosphere

The integral along the line-of-sight is broken down into two terms, corresponding to solar irradiance incident on the atmosphere beyond the tangent point and between the tangent point and the satellite, as illustrated below for a scattering angle of 90°.

Vertical profiles of concentration can be retrieved from UV-visible limb radiance spectra by using a radiative transfer model to simulate the measurements and derive a set of weighting functions. These can then be incorporated into an inversion scheme, such as optimal estimation to derive the trace gas profiles.

Advantages and Disadvantages of These Four Measurement Techniques

TECHNIQUE	ADVANTAGES	DISADVANTAGES
Emission	• doesn't require sunlight • long time series • simple retrieval technique • provide global maps twice a day (good spatial coverage)	• slightly less accurate than backscatter UV • long horizontal path for limb obs.
Backscatter UV	• accurate • long time series • good horizontal resolution due to nadir viewing	• requires sunlight, so can't be used at night or over winter poles • poor vertical resolution below the ozone peak (~30 km) due to the effects of multiple scattering and reduced sensitivity to the profile shape
Occultation	• simple equipment • simple retrieval technique • good vertical resolution • self-calibrating	• can only be made at satellite sunrise and sunset, which limits number and location of meas. • long horizontal path
Limb Scattering	• excellent spatial coverage • good vertical resolution • data can be taken nearly continuously	• complex viewing geometry • poor horizontal resolution