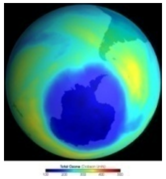
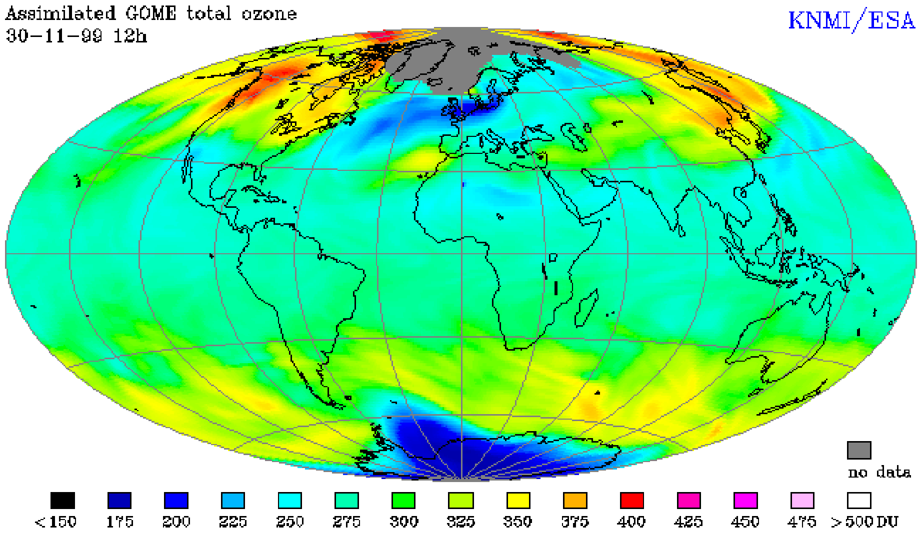


SECOND YEAR: 2604
REMOTE SENSING

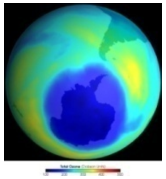
PASSIVE NADIR SOUNDING OF ATMOSPHERES

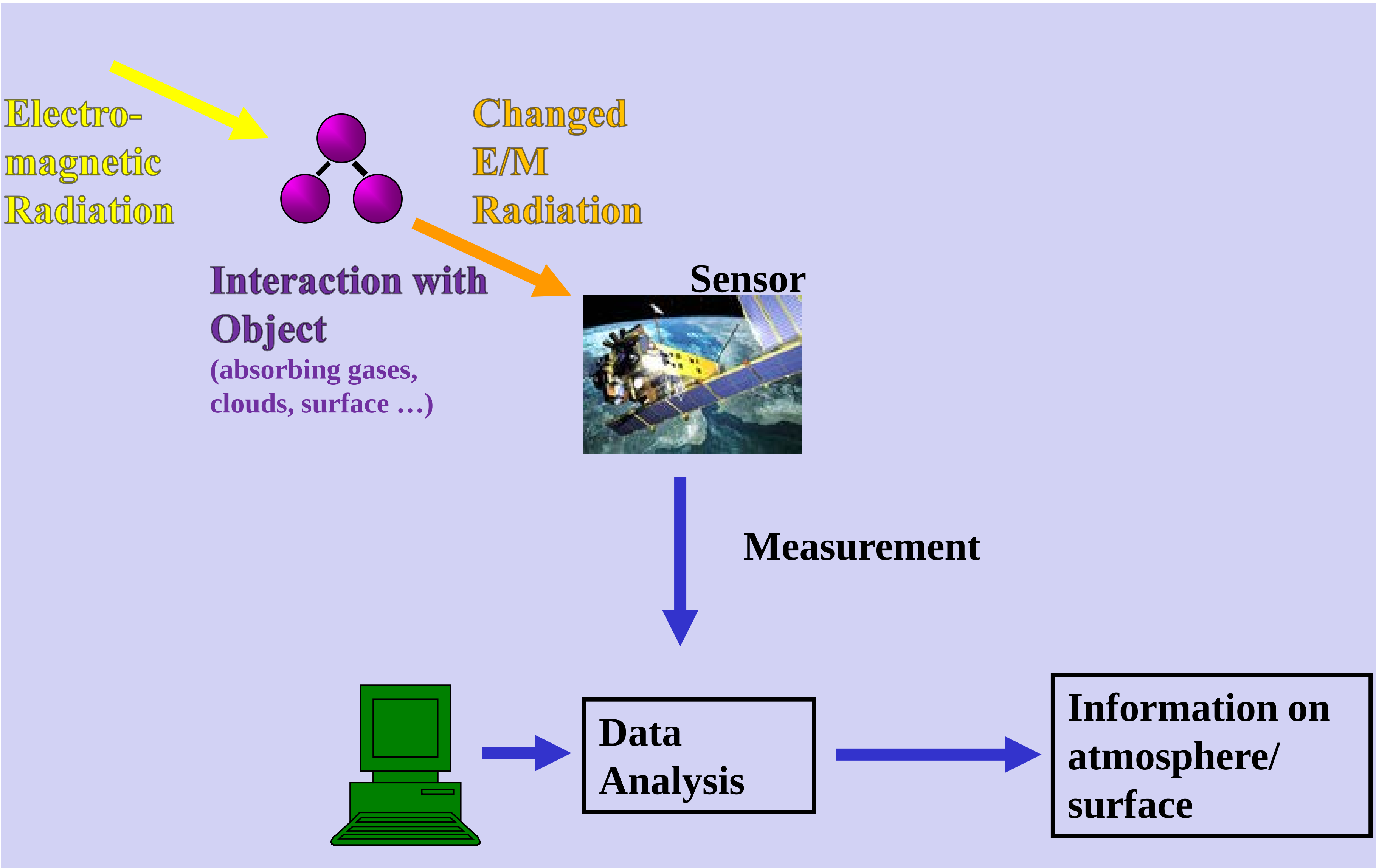
Prof. HARTMUT BOESCH

Earth Observation Group, Dept. of Physics and Astronomy, University of Leicester

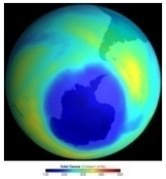


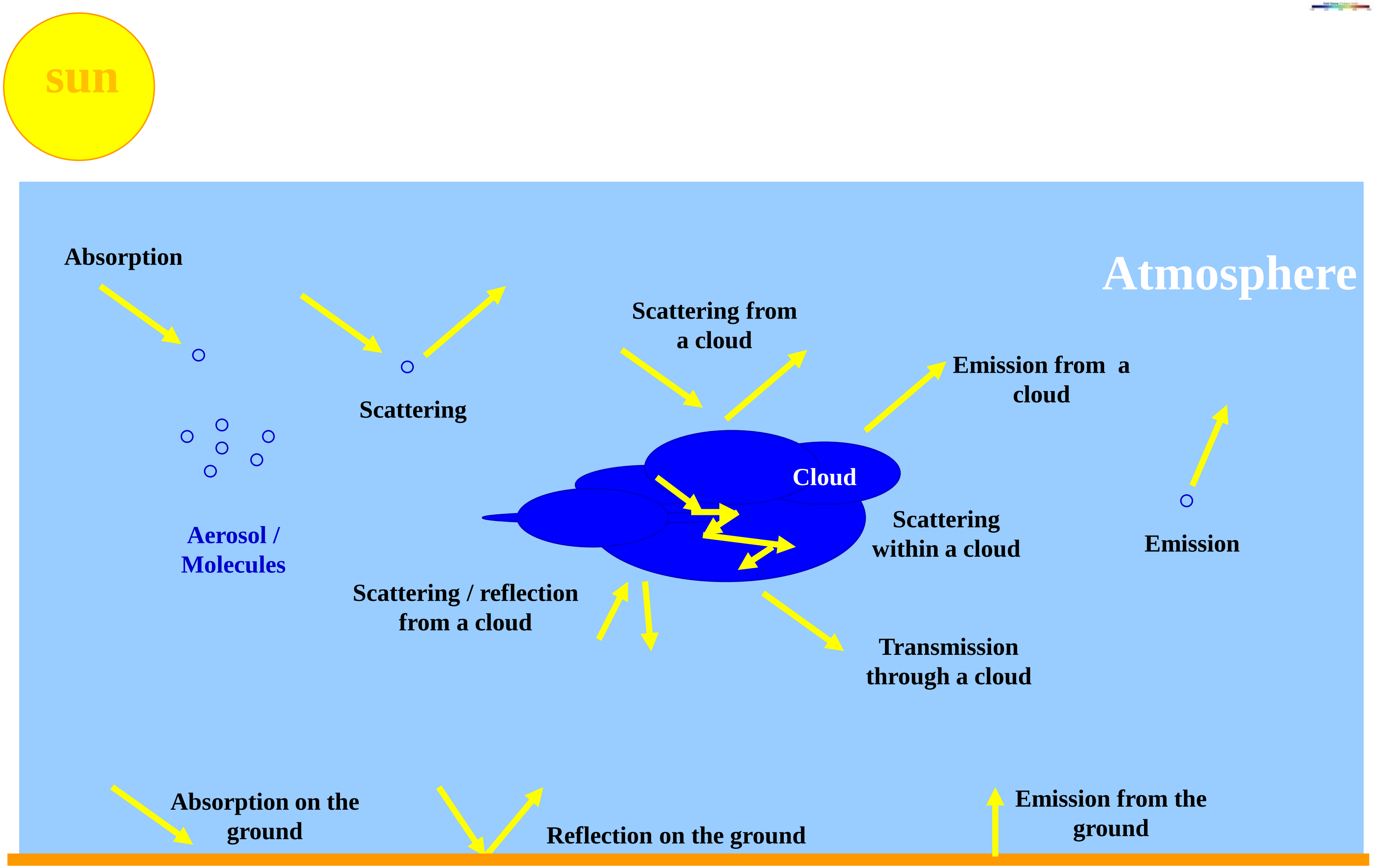
Recap: Principle of Remote Sensing Observations



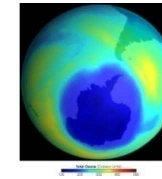


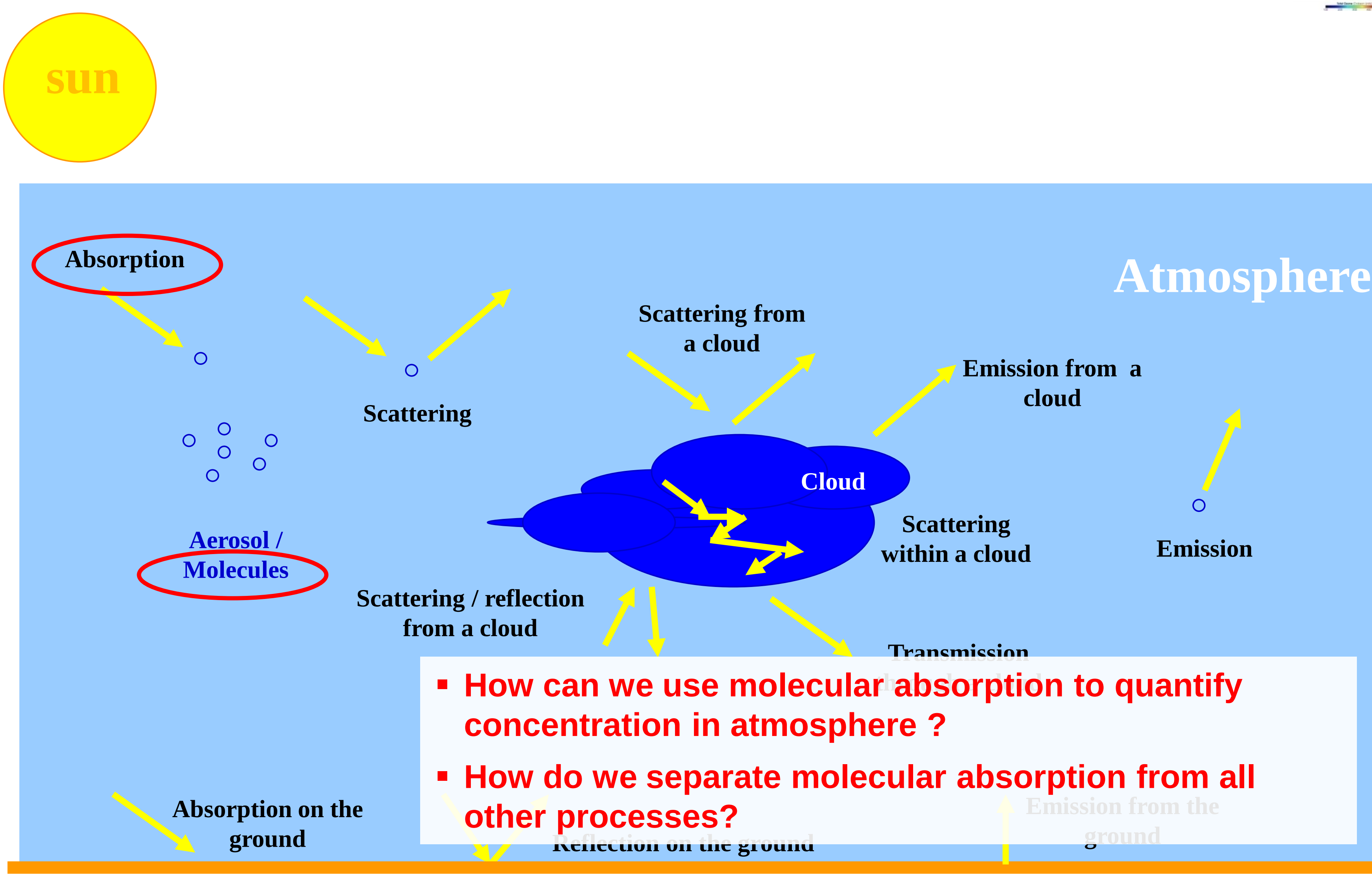
Recap: Interaction of EM radiation with atmosphere and surface





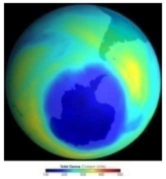
Recap: Interaction of EM radiation with atmosphere and surface





- How can we use molecular absorption to quantify concentration in atmosphere ?
- How do we separate molecular absorption from all other processes?

Radiative Transfer (RT) Equation



Change of intensity after a path element ds due to all loss and gain processes

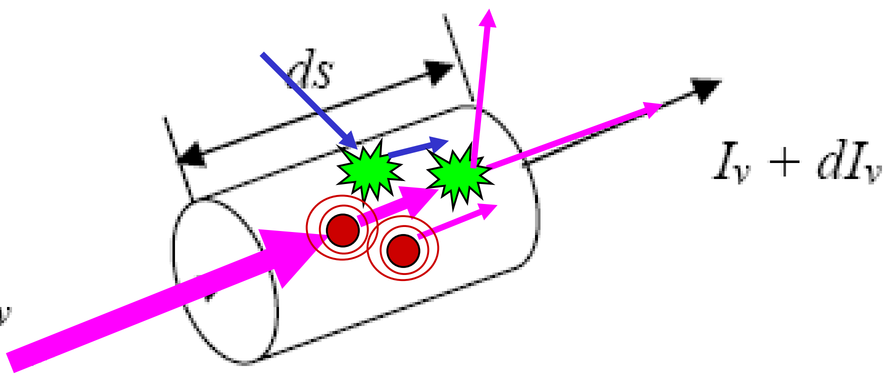
$$\frac{dI(\lambda)}{ds} = -k_s(\lambda)\,I(\lambda) - k_a(\lambda)\,I(\lambda) + k_e(\lambda)\,B(\lambda,T) + S_{MS}(\lambda)$$

loss by scattering

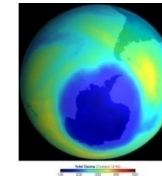
loss by absorption

gain by emission

gain by multiple scattering



Radiative Transfer (RT) Equation



Only for shortwave (UV-visible)

Only for longwave (IR)

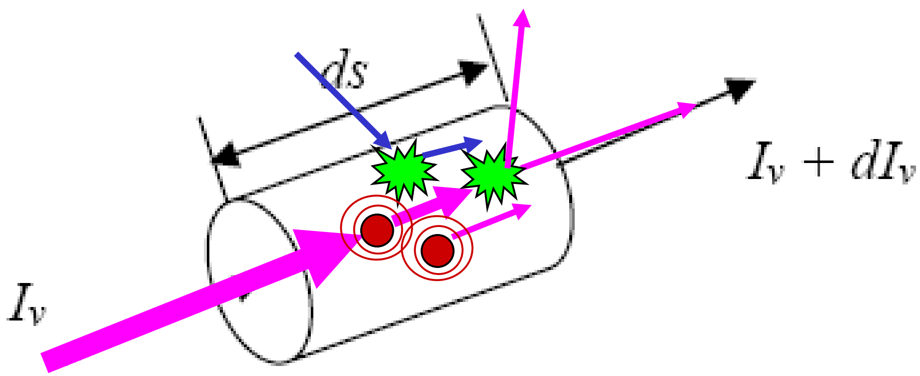
$$\frac{dI(\lambda)}{ds} = -k_s(\lambda)I(\lambda) - k_a(\lambda)I(\lambda) + k_e(\lambda)B(\lambda,T) + S_{MS}(\lambda)$$

loss by scattering

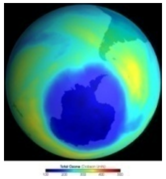
loss by absorption

gain by emission

gain by multiple scattering



Radiative Transfer (RT) Equation



Purely Absorbing Case

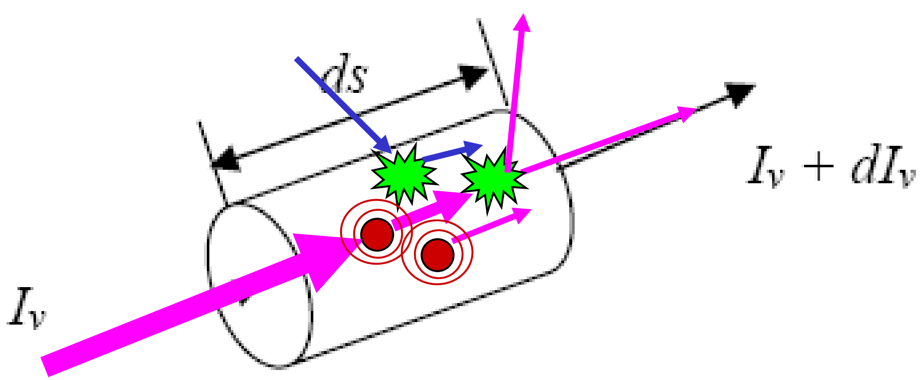
$$\frac{dI(\lambda)}{ds} = -k_s(\lambda)\,I(\lambda) - k_a(\lambda)\,I(\lambda) + k_e(\lambda)\,B(\lambda,T) + S_{MS}(\lambda)$$

loss by scattering

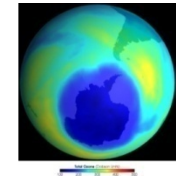
loss by absorption

gain by emission

gain by multiple scattering



TRANSMISSION (Purely Absorbing Case)



0 → L

$I_o(\lambda)$ → **GAS: $k_a(\lambda)$, c** → $I_\tau(\lambda)$

$$dI(\lambda) = -\ k_a(\lambda)\, dL$$

Lambert-Beer Law: $\mathcal{T}(\lambda) = \exp[-\sigma(\lambda)\, c\, L]$

with c = the density of molecules per unit volume.

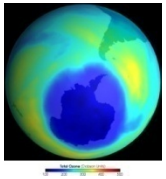
Three factors matter:

- **Spectroscopy: absorption cross section $\sigma(\lambda)$** [cm^2/molecule]
- **Composition/density: $c = \chi\, c_{air}$** [$molecules/cm^3$]
- **Photon pathlength: geometrical distance = L** [km]

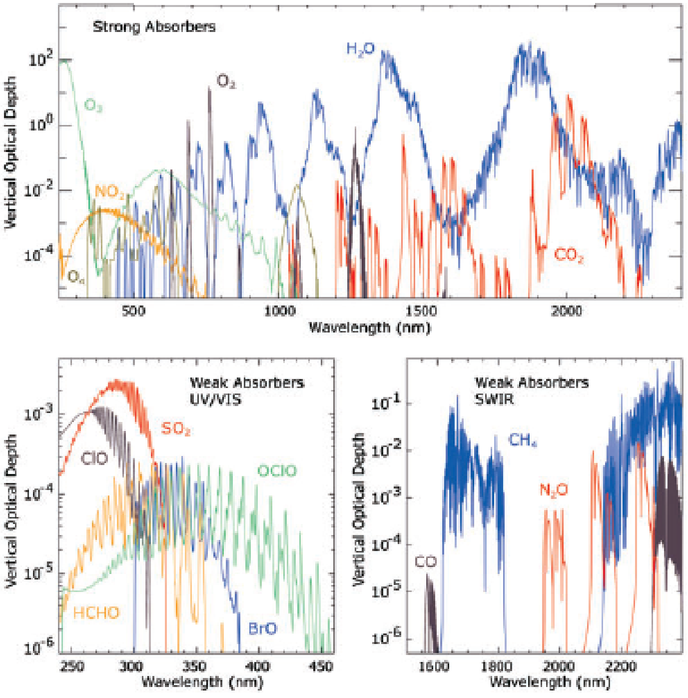
If we want to infer c (or χ), we need to know species-specific absorption cross section $\sigma(\lambda)$ and photon path L

Overview over Absorbers

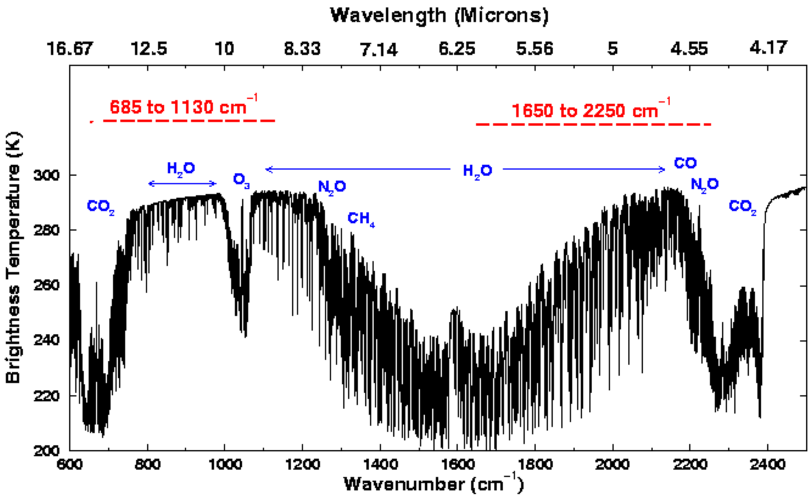
- Important gases in the
  - **ultra-violet**: O_3, SO_2, Halogenoxides
  - O_2, NO_2, O_3, IO
  - **shortwave IR (SWIR)**: CO_2, CH_4, CO, H_2O
- Some important bands in the **thermal infra-red**:
  - CO_2 - 15 μm, 4.3 μm
  - O_3 - 9.6 μm
  - N_2O - 7.7 μm
  - CH_4 - 7.6 μm
  - H_2O - 6.3 μm (but can be everywhere!)
  - CO - 4.6 μm
  - CFCs - have bands in the 8 and 12 μm windows
  - Also HNO_3, $ClONO_2$, HCl
- Gases in the **microwave**: O_3, H_2O, ClO, HNO_3



UV/vis /Near-IR Absorber



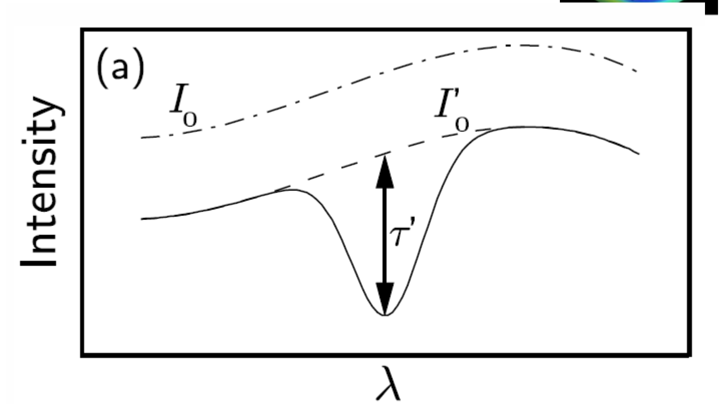
Thermal-IR Absorber



Absorption Spectroscopy

- Main assumption: no scattering
- Lambert Beer law:

$$I(L) = I_0 \exp\left(-\int_0^L \sigma(L')\, c(L')\, dL' \right)$$



and

$$\tau(L) = -\ln(I / I_0) \approx \sigma(\overline{T}, \overline{p}) \times SCD$$

with

$$SCD = \int_0^L c(L')dL'$$

Optical depth

absorption cross section for mean temperature and pressure

Slant column density gives the number of molecules per area along the path

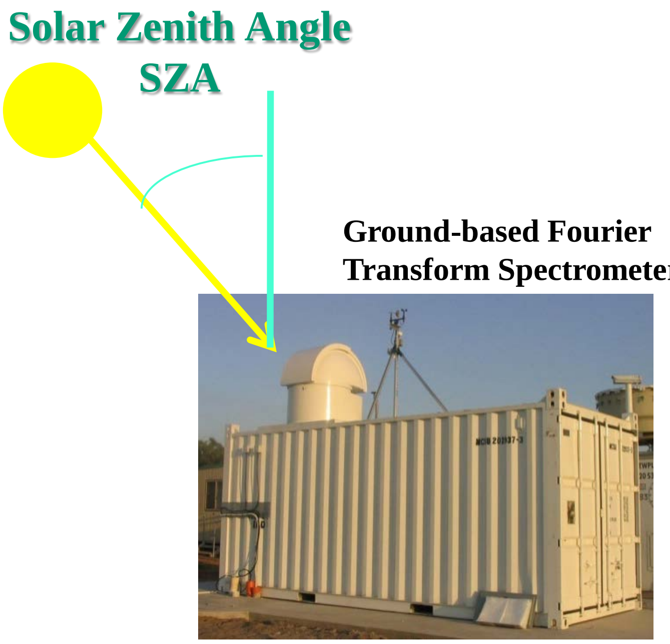
- A more useful quantity is the vertical column density *VCD:* number of molecules per area along the vertical direction for the whole atmosphere

$$VCD = \int_0^\infty c(L')dL'$$

How can you obtain VCD from SCD?

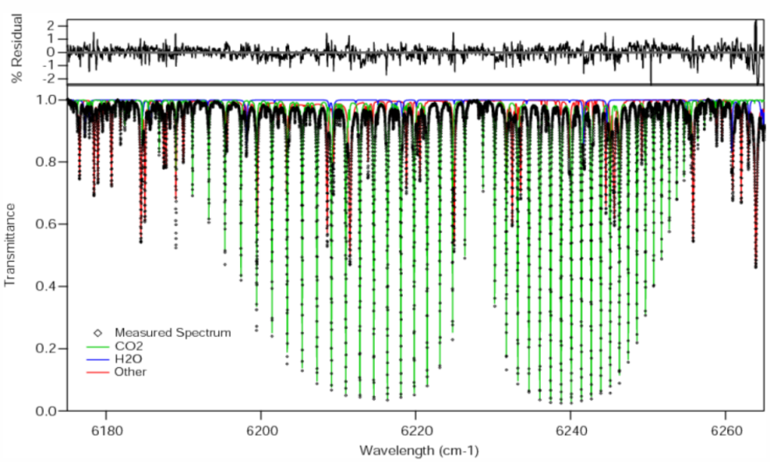
Example: Direct-Sunlight Observations

- The principal of absorption spectroscopy is valid for **direct-sunlight observations**:
  - No surface effects
  - High intensity and thus scattering into observer-direction is not important
  - Scattering will lead to broad reduction of total intensity but will not change optical depth

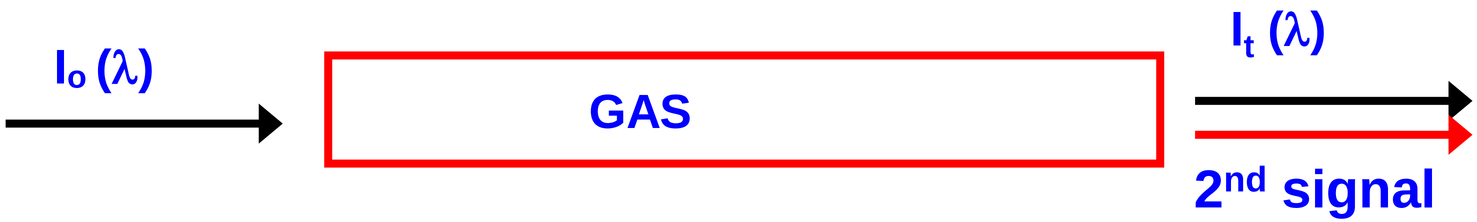


- Direct sunlight observations:
  - Relation between slant path and vertical path is given by geometric factor of **1/cos(SZA)**

Example of spectral fit to 6228 cm^{-1} CO_2 band



RECAP: Absorption and transmission in the IR



$\mathcal{T}(\lambda) + a(\lambda) + R(\lambda) = 1$ conservation of energy !!!

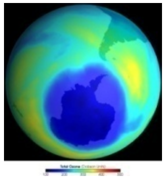
here $R(\lambda)$ includes both reflection and scattering

For a gas (atmosphere) in the infra-red: $a(\lambda) = \varepsilon(\lambda)$ (Kirchhoff Law) and $R(\lambda)=0$.

Hence $a(\lambda)= \varepsilon(\lambda) = 1- \mathcal{T}(\lambda)$ and there are 2 signals emerging:

1. Absorption by the gas in the cell: $(1- a(\lambda))\, I_o(\lambda) = \mathcal{T}(\lambda)\, I_o(\lambda)$
2. Emission by the gas in the cell: $\varepsilon(\lambda) \times B(\lambda,T) = a(\lambda) \times B(\lambda,T) = (1- \mathcal{T}(\lambda)) \times B(\lambda, T)$

RECAP: Absorption and transmission in the IR



Total Signal

$I_o(\lambda)$ → **GAS** $a(\lambda), \mathcal{T}(\lambda)$ → $I_\tau(\lambda)$

2nd signal

Total Signal, $I(\lambda)$ is given by

$$\Longrightarrow \quad I(\lambda) = \mathcal{T}(\lambda)\, I_o(\lambda) + (1 - \mathcal{T}(\lambda)) \times B(\lambda, T)$$

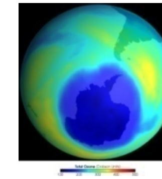
Transmissivity
$\mathcal{T} = \exp(-k_a L)$

Transmitted intensity

Emitted (and transmitted) intensity

Note: in IR, Scattering can usually be omitted

SINGLE LAYER GAS MODEL



Surface contribution — Atmosphere contribution

$$I(\lambda) = \varepsilon_s(\lambda) \times B(\lambda,T_s) \times \mathcal{T}_g(\lambda) + (1- \mathcal{T}_g(\lambda)) \times B(\lambda,T_g)$$

$I_T(\lambda)$ ↑ ↑ $\varepsilon_g(\lambda)\, B(\lambda, T_g)$

Atmosphere — GAS $\mathcal{T}_g(\lambda)$

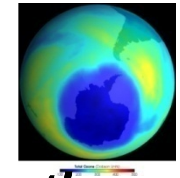
↑ $I_o(\lambda) = \varepsilon_s(\lambda) \times B(\lambda,T_s)$

Surface (T_s, ε_s)

Observed signal will depend on both $\mathcal{T}_g(\lambda, z)$ and $B(\lambda,T_g)$ (and surface term) and hence on both composition and temperature of atmosphere

More realistic description of atmosphere by combining multiple 'single layers'

Example: Thermal IR Radiative Transfer



A satellite radiometer measures the radiance from the surface in the nadir direction at 10 μm.

Assuming the atmosphere has 3 layers, write down an expression for the TOA radiance given transmissivity $\mathcal{T}_1 = 0.1, \mathcal{T}_2 = 0.2, \mathcal{T}_3 = 0.5$ for layers between the ground and space.

Single layer gas model:

$$I(\lambda) = \varepsilon_s(\lambda) \times B(\lambda, T_s) \times \mathcal{T}_g(\lambda) + (1 - \mathcal{T}_g(\lambda)) \times B(\lambda, T_g)$$

For 3 layers:

Surface term: $I_s = \varepsilon_s B(T_s, \lambda)\, \mathcal{T}_1(\lambda)\, \mathcal{T}_2(\lambda)\, \mathcal{T}_3(\lambda)$

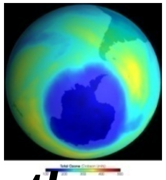
2nd term (1st atm layer): $I_1 = [1 - \mathcal{T}_1(\lambda)]\, B(\lambda, T_1)\, \mathcal{T}_2(\lambda)\, \mathcal{T}_3(\lambda)$

3rd term (2nd atm layer): : $I_2 = [1 - \mathcal{T}_2(\lambda)]\, B(\lambda, T_2)\, \mathcal{T}_3(\lambda)$

4th term (3nd atm layer): $I_3 = [1 - \mathcal{T}_3(\lambda)]\, B(\lambda, T_3)$

Total signal = sum of all 4 terms

Example: Thermal IR Radiative Transfer



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$$I_s = \varepsilon_s B(T_s, \lambda)\, \mathcal{T}_1(\lambda)\, \mathcal{T}_2(\lambda)\, \mathcal{T}_3(\lambda) = \varepsilon_s B(T_s, \lambda) \times 0.01$$

$$I_1 = [1 - \mathcal{T}_1(\lambda)]\, B(\lambda, T_1)\, \mathcal{T}_2(\lambda)\, \mathcal{T}_3(\lambda) = 0.9 \times B(\lambda, T_1) \times 0.1 = 0.09 \times B(\lambda, T_1)$$

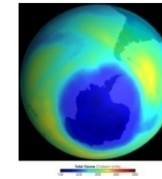
$$I_2 = [1 - \mathcal{T}_2(\lambda)]\, B(\lambda, T_2)\, \mathcal{T}_3(\lambda) = 0.8 \times B(\lambda, T_2) \times 0.5 = 0.4 \times B(\lambda, T_2)$$

$$I_3 = [1 - \mathcal{T}_3(\lambda)]\, B(\lambda, T_3) = 0.5 \times B(\lambda, T_3)$$

The transmissivity terms weight the contribution of each Planck function to the total signal. See weighting fns.

Note that temperature (in troposphere) decreases with altitude and value of Planck function B is much lower

INFRARED NADIR RADIATIVE TRANSFER



Schwarzschild's eqn:

$$I(\lambda) = \varepsilon_s B(\lambda,T_s)\,\mathcal{T}(\lambda,\infty) + \int B(\lambda,T_z)\, d\mathcal{T}(\lambda,z)/dz\, dz + R_s I_{Down}(atm)\,\mathcal{T}(\lambda,\infty)$$

- **1st term: Surface emission, $\varepsilon_s B(\lambda,T_s)$, modified by transmission of atmosphere between ground and space, $\mathcal{T}(\lambda,\infty)$**
- **2nd term: Emission from Planck fn. at each height in atmosphere, B (λ,T_z), modified by $d\mathcal{T}(\lambda,z)/dz$**
- **3rd term: Reflection, R_s, of radiation emitted from atmosphere back towards ground (often omitted)**

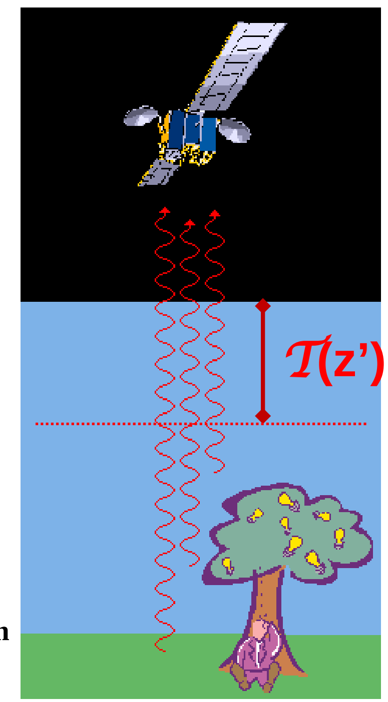
Transmissivity is now between altitude z and top of atmosphere

$$\mathcal{T}(\lambda,z) = \exp\left(-\int_z^{toa} k_a(z')dz'\right)$$

z=toa $\mathcal{T}$=1

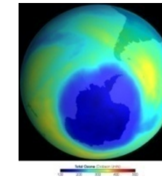
z=z' $\mathcal{T}$= $\mathcal{T}$'

z=0 $\mathcal{T}$= $\mathcal{T}_{min}$



Schwarzschild's eqn. is consistent with single layer gas model (Build up atmosphere as a series of single layers)

Derivation of Schwarzschild Equation (Homework)



RT Eq. $\dfrac{dI(\lambda)}{ds} = -k_s(\lambda)I(\lambda) - k_a(\lambda)I(\lambda) + k_e(\lambda)B(\lambda,T) + S_{MS}(\lambda)$

In IR $\dfrac{dI_\lambda}{ds} = -k_\lambda(I_\lambda - B_\lambda(T))$ $\quad$ k_a=k_e Kirchhoff law

Use $\dfrac{d}{ds}(I \cdot \mathcal{T}) = \dfrac{dI}{ds} \cdot \mathcal{T} + I \cdot \mathcal{T}k = kB \cdot \mathcal{T}$ $\quad$ $\dfrac{d\mathcal{T}}{ds} = \mathcal{T}k$ $\quad$ (note the definition of $\mathcal{T}$)

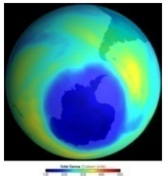
Thus $\int d(I \cdot \mathcal{T}) = \int kB \cdot \mathcal{T}\, ds$

and $I \cdot \mathcal{T}(toa) - I \cdot \mathcal{T}(surf) = \int_{surf}^{toa} kB \cdot \mathcal{T}\, ds$

Use $d\mathrm{T}/ds = k \bullet \mathrm{T}$, $I(surf) = \varepsilon_s B(T_s)$ **and** $\mathcal{T}(toa) = 1$

gives $I(toa) = \varepsilon_s B(T_s)\mathcal{T} + \int_{surf}^{toa} B \dfrac{d\mathcal{T}}{ds} ds$

CONTROLLING TRANSMISSION



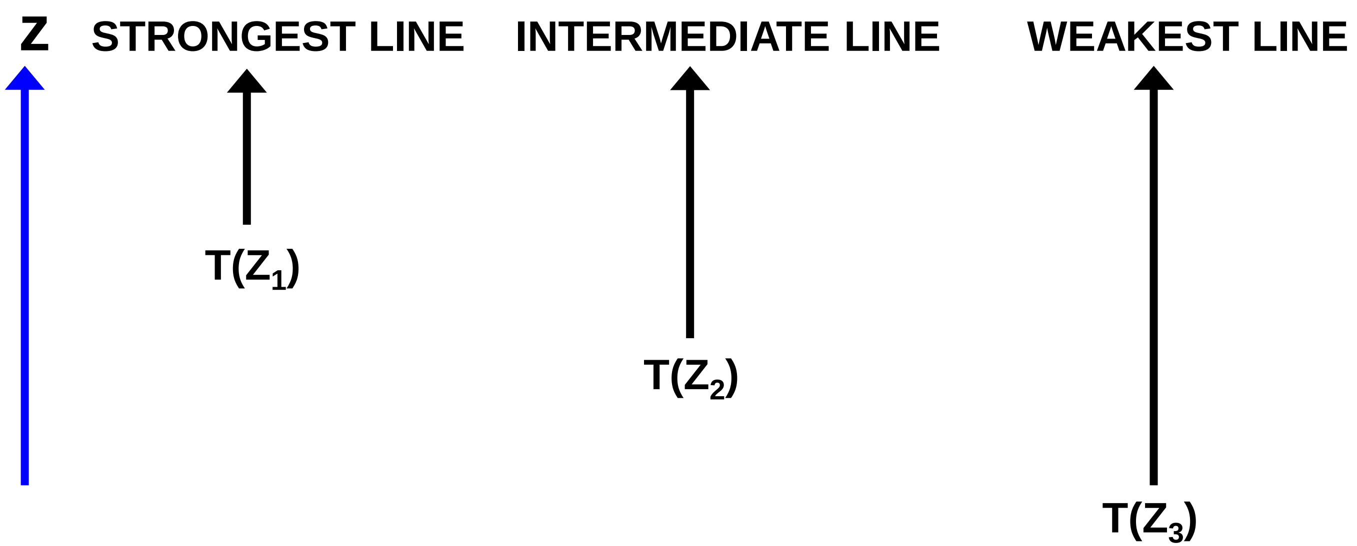
So how is $\mathcal{T}(\lambda)$ controlled?

Remember: $\mathcal{T}(\lambda, z) = \exp(-\int_{z}^{toa} k_a(z')dz')$

with k = σ*c with the abs. cross. section σ and concentration c

Imagine spacecraft looking down at surface at wavelengths where only 1 gas absorbs

- **-> for the strongest lines, $k(\lambda)$ is largest and $\mathcal{T}(\lambda)$ reaches zero at higher altitude z (or shorter path from TOA)**
- **-> We end up with (T=temperature):**



EXAMPLE ONE: NADIR IR RADIATIVE TRANSFER

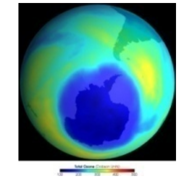
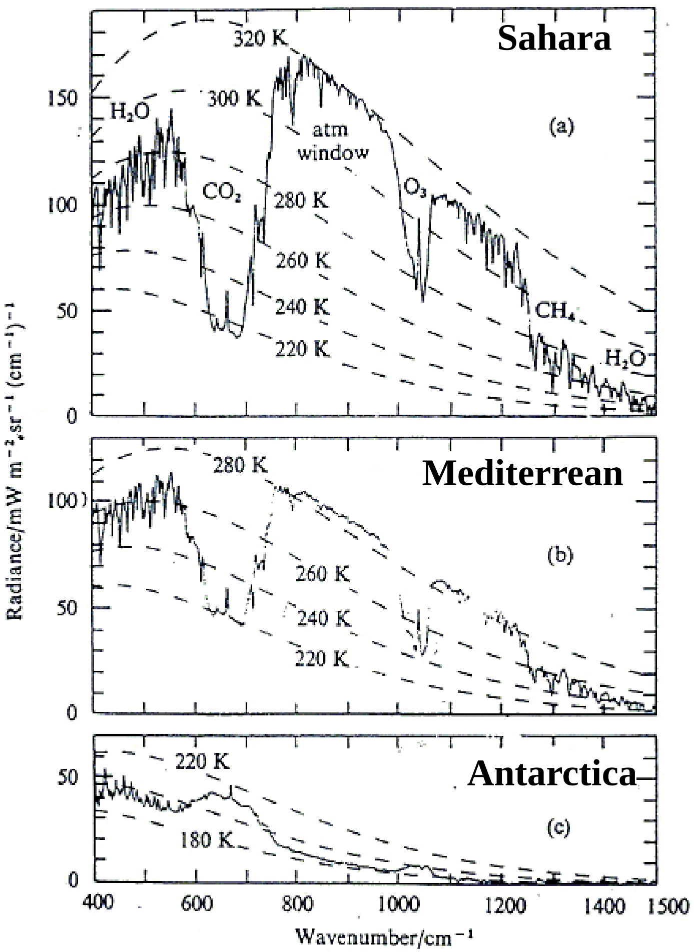


Fig. 12.6. Thermal emission from the earth plus atmosphere emitted vertically upwards and measured by the infrared interferometer spectrometer on Nimbus 4, (a) over Sahara, (b) over Mediterranean, (c) over Antarctica. The radiances of black bodies at various temperatures are superimposed. (From Hanel *et al.*, 1971)



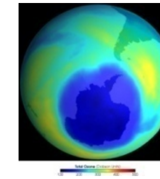
15 µm   10 µm   7 µm

In the presence of absorber, we see atmospheric temperatures of different heights (depending on k_a)

In each of diagrams:

- **Surface T is different (180 -320 K).**
- **Signal at centre of CO_2 band is always at 220K because $\mathcal{T}(\lambda)$ is zero at same height in atmosphere**
- **For very cold background, emission lines are observed**

WEIGHTING FUNCTIONS: NADIR SOUNDING I



- **The contribution of layer to Schwarzschild eqn. is given by 2nd term:**

$$I(\nu) = \varepsilon_S B(\lambda,T_s)\,\mathcal{T}(\lambda,\infty) + \boxed{\int B(\lambda,T_z)\,d\mathcal{T}(\lambda,\rho,T_z)/dz\,dz} + R_S I_{Down}(atm)\,\mathcal{T}(\lambda,\infty)$$

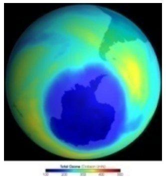
Surface contribution *Atmospheric contribution*

- **$W(z) = d\mathcal{T}(\lambda,\rho,T_z)/dz$ weights the Planck function at each height, z, by change of $\mathcal{T}(\lambda)$ at z**

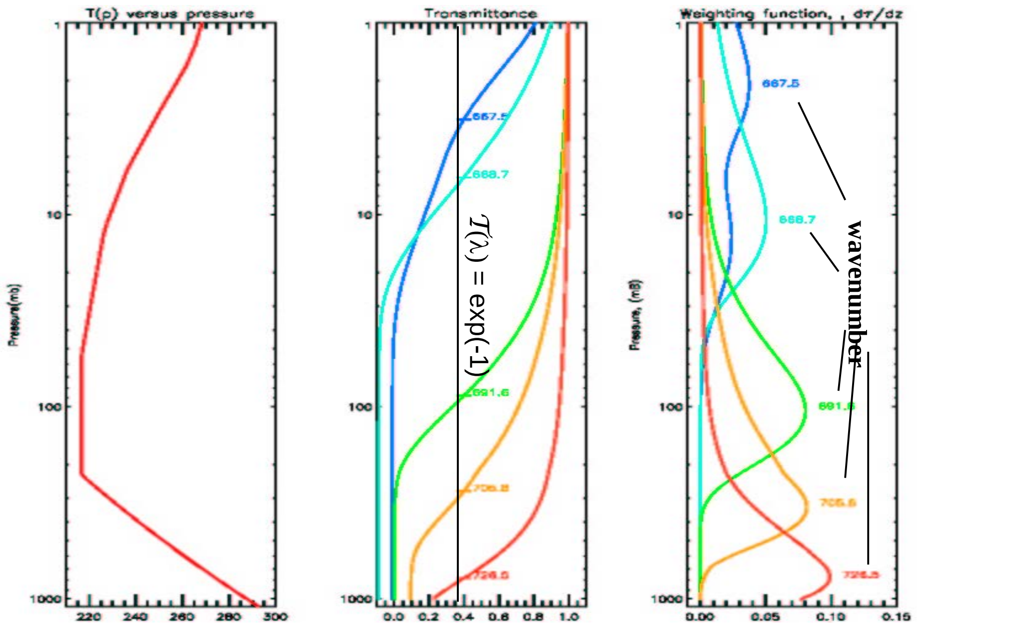
- **$W(z) = d\mathcal{T}(\lambda,\rho,T_z)/dz$ is known as a weighting function and its peak and width determine which part of the atmosphere is sensed**

- **Often, we are interested in the sensitivity of the radiance to changes in the gas concentration at each layer, not the contribution to the total radiance from each layer. Gas weighting functions are more complicated because they depend on the potentially variable gas concentration itself.**

WEIGHTING FUNCTIONS: NADIR SOUNDING II



- Weighting functions for *nadir sounding* are broad (8 - 15km) and bell-shaped for well mixed gases (constant mixing ratio):
  - Increase in transmissivity with height
  - Decrease in absorbing gas concentration with height
- Maximum of weighting function: $dW(z)/dz = 0 \rightarrow \mathcal{T}(\lambda) = \exp(-1)$
- Weighting functions for lines of different optical depth provide information from different height



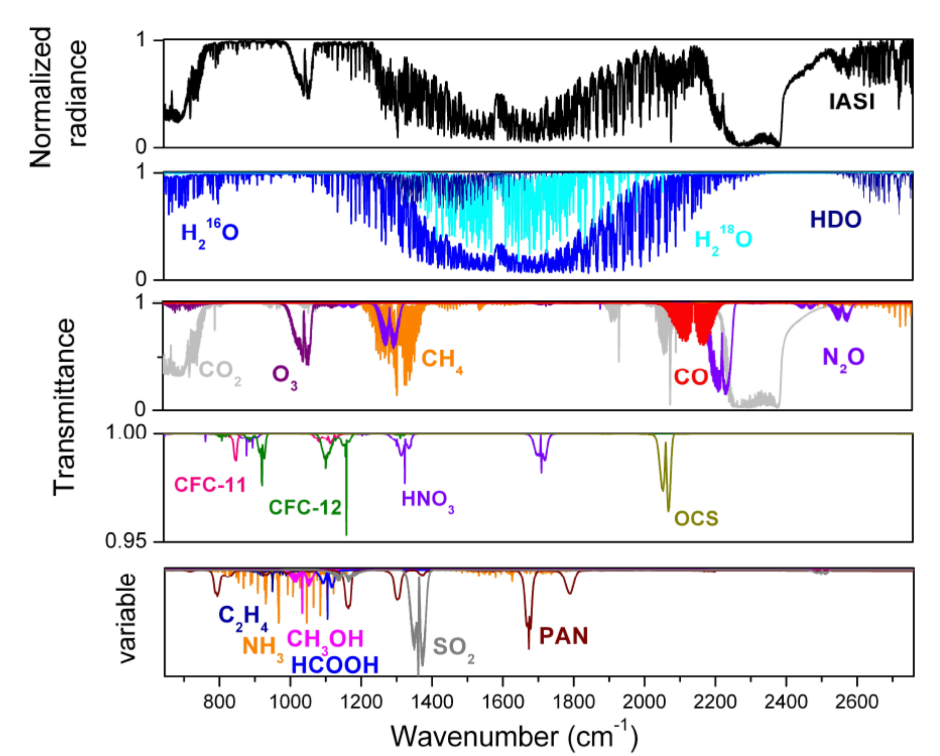
Temperature Transmissivity $\mathcal{T}$ Weighting Function $d\mathcal{T}/dz$

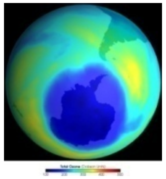
NADIR, MULTI-λ Each curve = different λ

Weaker (more transmitting lines) have peak weighting lower in atmosphere

Question: What happens for very weak lines where $\mathcal{T}(\lambda)$ is smaller than 0.36 ?

IASI ON METOP

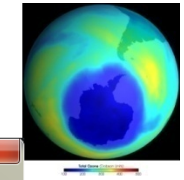


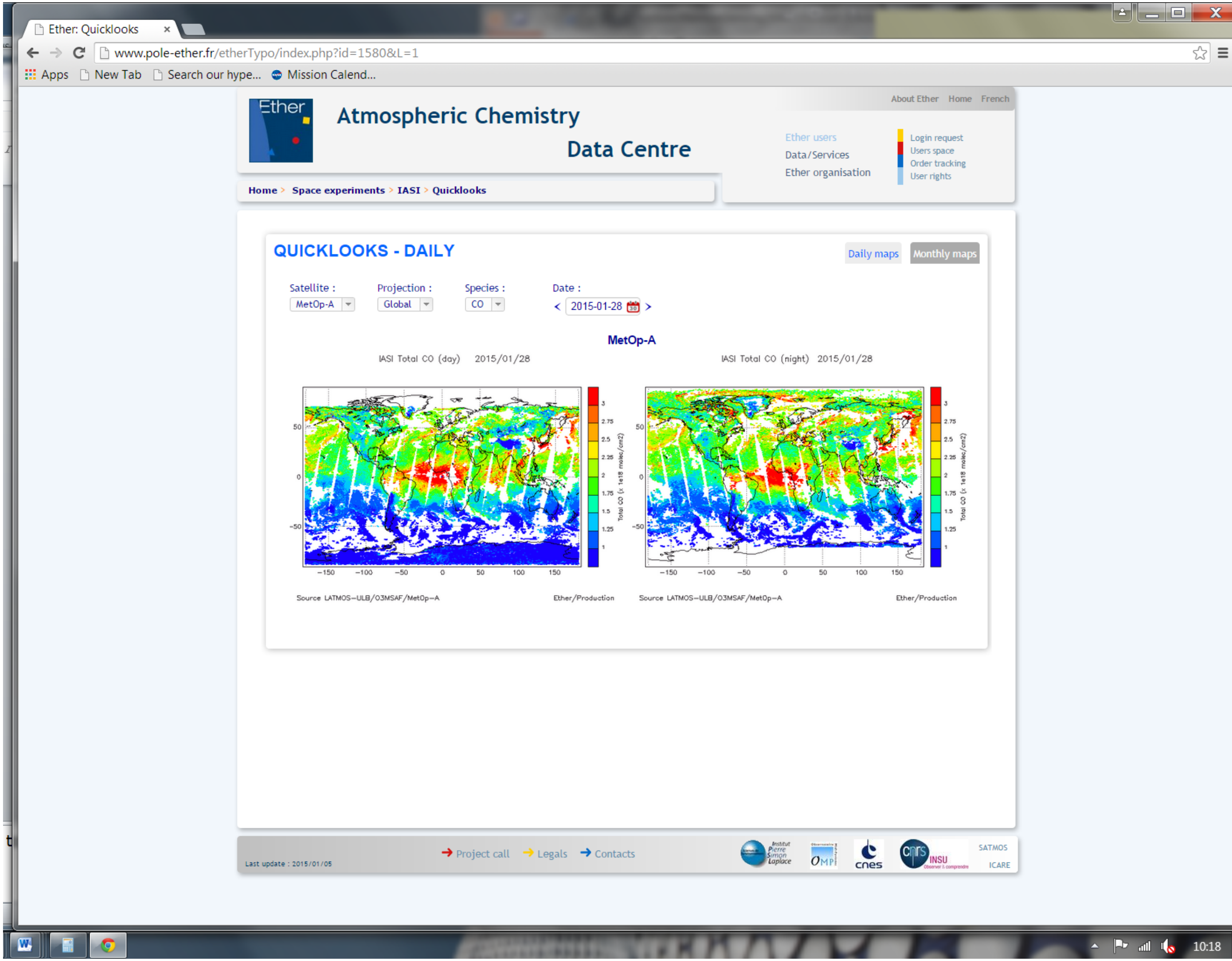


IASI on METOP launched Oct. 2006

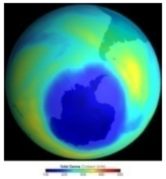
- **Michelson Interferometer imaging nadir sounder**
- **Coverage: 650-2700 cm^{-1} with 8461 channels**
- **Resolution: 0.5 cm^{-1}**
- **Field of view :12 km**
- **Twice daily global coverage**

Operational Datastreams from IASI





IR NADIR SOUNDING OF ATMOSPHERES



Targets:

Gases e.g. O_3, H_2O, CO_2, CO, CH_4,

(Aerosols and Clouds)

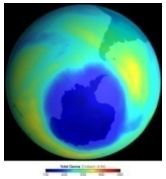
For gases, there are 3 important aspects:

1. **Measurements at one λ provide partial columns of gases [column= total number of molecules per unit area in a vertical path from the surface/or an atmospheric layer to space].**

$$\frac{d\mathcal{T}}{dz}(\lambda_1, target\ \ gas) \neq \frac{d\mathcal{T}}{dz}(\lambda_2, target\ \ gas)$$

2. **Multi-wavelength measurements allow some profile information to be measured provided that weighting functions for gas are different from wavelength to wavelength**
3. **Weighting functions for nadir sensing of gases are broad at each wavelength (typically 8 $\rightarrow$ 15km). This limits information on vertical profiles. Vertical resolution is of this order**

RT in the Shortwave (solar)



$$\frac{dI(\lambda)}{ds} = -k_s(\lambda)I(\lambda) - k_a(\lambda)I(\lambda) + \cancel{\varepsilon_e(\lambda)B(\lambda,T)} + S_{MS}(\lambda)$$

loss by scattering

loss by absorption

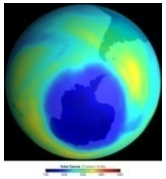
gain by emission

gain by multiple scattering

RT with scattering and absorption:

- **Emission term can be omitted**
- **Atmospheric scattering will have a strong effect on light path which we need to know**
- **In general: RT equation is system of coupled differential equations, ie. both, absorption and scattering at on altitude z will impact the intensity all other altitudes**

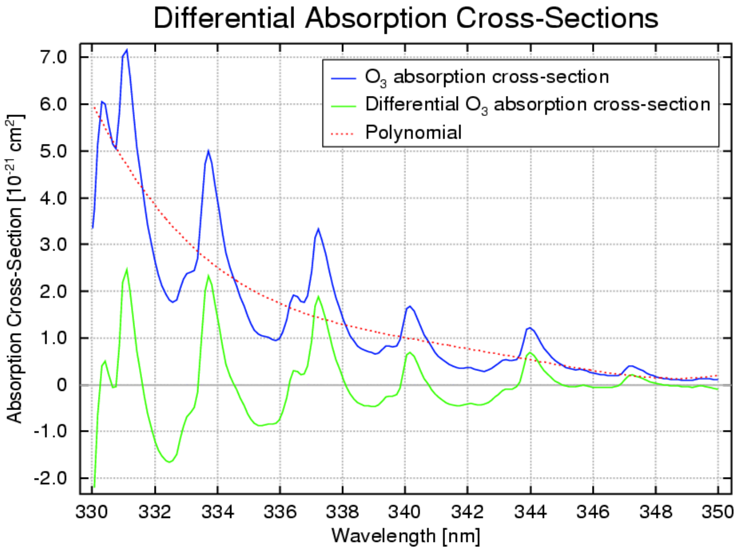
Differential Optical Absorption Spectroscopy (DOAS)



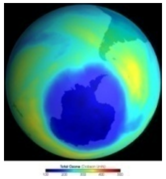
DOAS: Extension of absorption spectroscopy for situations with scattering

Main ideas:

- **For very weak absorbers we can assume that**
  - **Absorption and scattering are independent of each other and**
  - **Light path is determined by scattering properties**
  - **Absorption spectroscopy can be used to infer SCD along 'unknown' path**
- **Use only those parts of the spectra that vary rapidly with wavelength which are result of molecular absorption**
- **Use spectral filter to remove slowly varying effects without changing optical depth of absorption lines (Mie and Rayleigh scattering, surface reflectance, continuum or broad absorption of gases)**



DOAS DATA ANALYSIS



- Lambert Beer Law: Transmitted intensity (loss of light from absorption and scattering) after traveling path *L*

Sum over all absorbers

$$I(\lambda) = I_0(\lambda) \times \exp\left\{ -\int_L \left(\sum_i \sigma_i(\lambda, T, p)\, c_i - k_R(\lambda) - k_M(\lambda) \right) dl \right\}$$

Measured Spectrum

(Solar) Reference Spectrum

Molecular Absorption

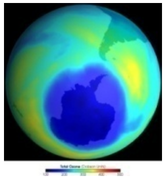
Rayleigh and Mie Scattering

Compare RTE:

$$\frac{dI(\lambda)}{ds} = -k_s(\lambda)\, I(\lambda) - k_a(\lambda)\, I(\lambda) + \cancel{\varepsilon_e(\lambda) B(\lambda, T)} + \cancel{S_{MS}(\lambda)}$$

We will have to deal with the last term separately

DOAS DATA ANALYSIS



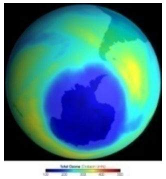
- Lambert Beer Law: Transmitted intensity (loss of light from absorption and scattering) after traveling path *L*

$$I(\lambda) = I_0(\lambda) \times \exp\left\{ -\int_L \left(\sum_i \sigma_i(\lambda, T, p)\, c_i - k_R(\lambda) - k_M(\lambda) \right) dl \right\}$$

Absorption with strongly-varying wavelength dependence

Broad (λ^{-1} - λ^{-4}) wavelength dependence – can be removed by spectral filter

DOAS DATA ANALYSIS



- Lambert Beer Law: Transmitted intensity (loss of light from absorption and scattering) after traveling path *L*

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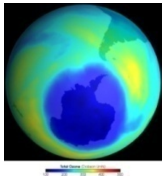
- Re-write logarithm of Lambert-Beer law

$$F(\lambda) = \ln I_0(\lambda) - \sum_i \overline{\sigma_i}(\lambda) SCD_i - \sum_p a_p \lambda^p$$

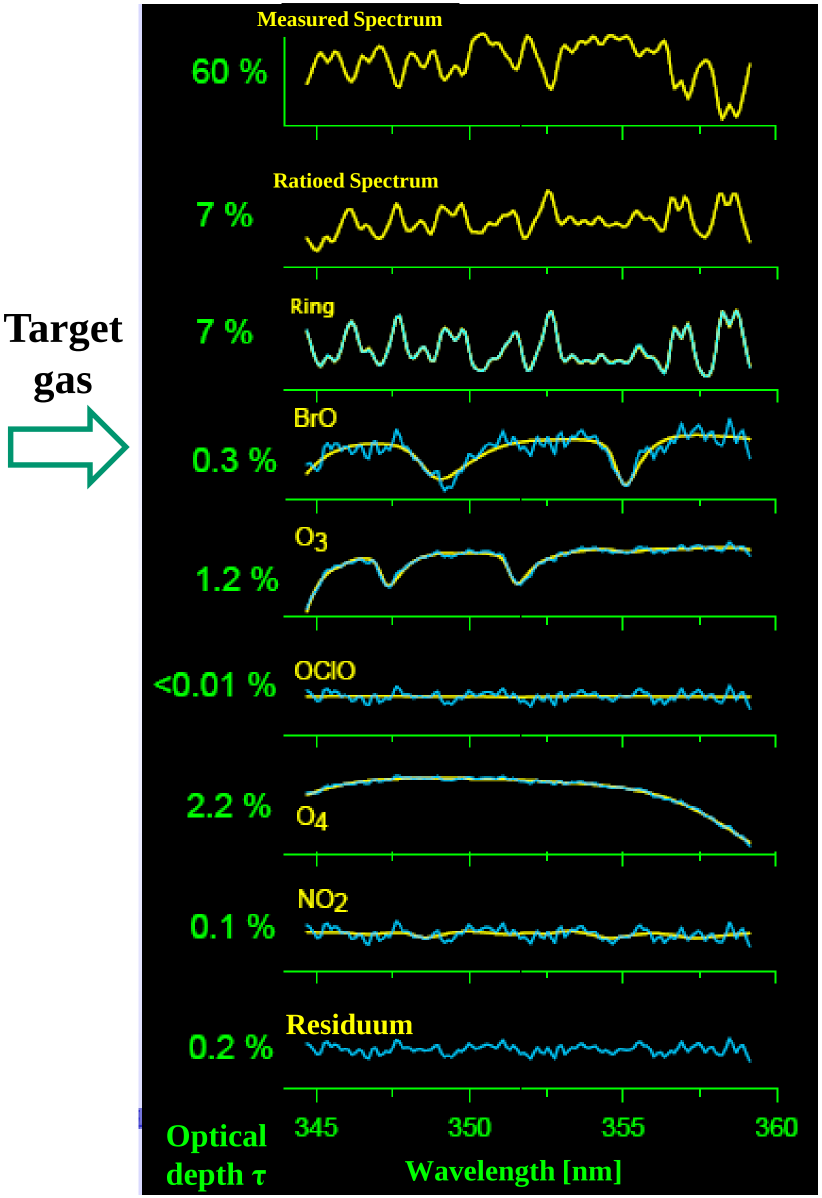
Polynomial used as a high-pass filter

- We determine Slant column densities SCD_i for each gas and coefficients of polynomial a_p

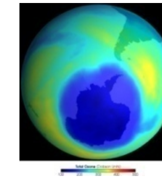
BrO DOAS Retrieval

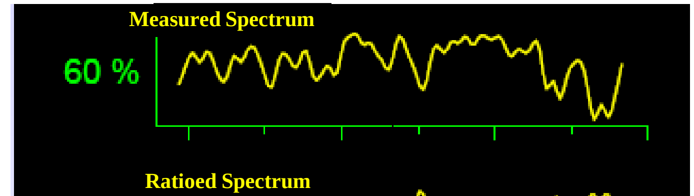


- Measured Spectrum is dominated by Fraunhofer lines
- Many different absorbers can be separated
- In UV/vis, inelastic Raman scattering (Ring effect) needs to be taken into account
- Very weak absorption can be measured with optical depth ~ 10^{-3} (= transmission of ~0.999)



BrO DOAS Retrieval



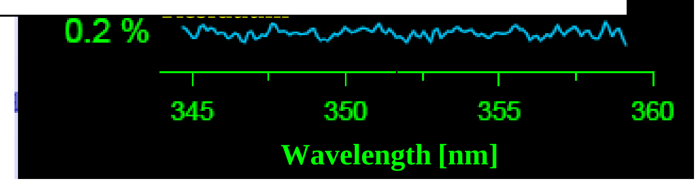


- Measured Spectrum is

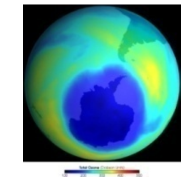
- Now, we can determine the **number of molecules along the 'unknown' path of the light** (the slant column density SCD) using the DOAS method

- However, in general, this is not a very useful quantity and we need to infer the 'path-independent' **vertical column density** (number of molecules from surface to top of atmosphere).

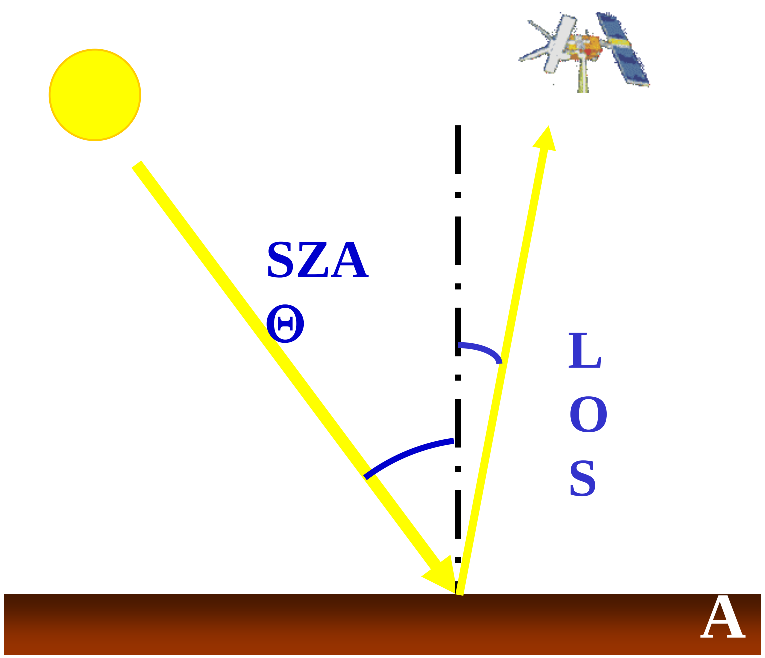
- This requires dealing with the last term in RTE (source from scattering)



Where is the light coming from for a satellite looking downward ?



A: Simplest situation: plane parallel, no extinction

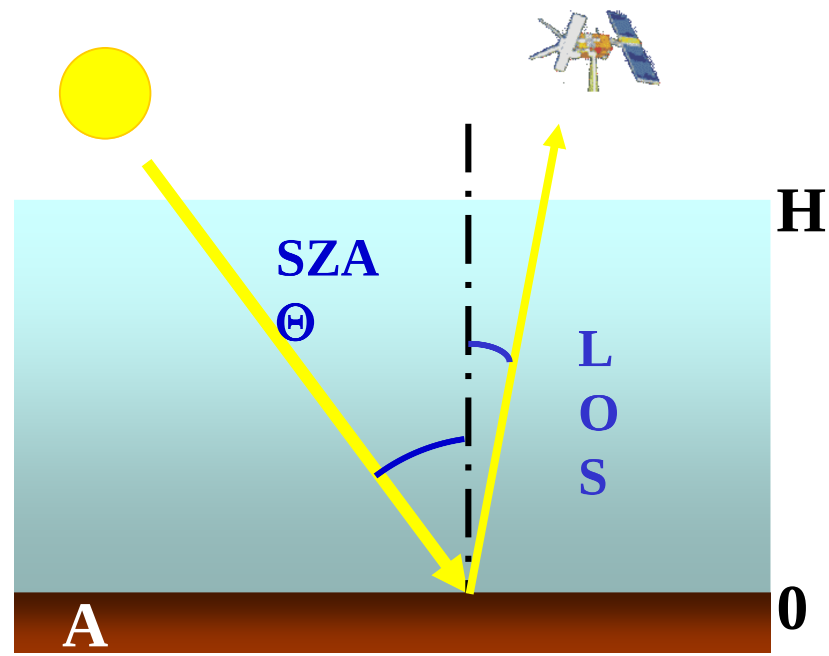


$$s = \frac{1}{\cos(\theta)} + \frac{1}{\cos(\varphi)}$$

$$I = I_0 A$$

=> Clearly wrong for low sun!

B: plane parallel, with absorption



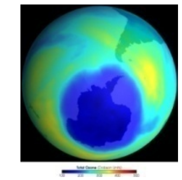
SZA and LOS independent of altitude!

Lambert-Beer Law:

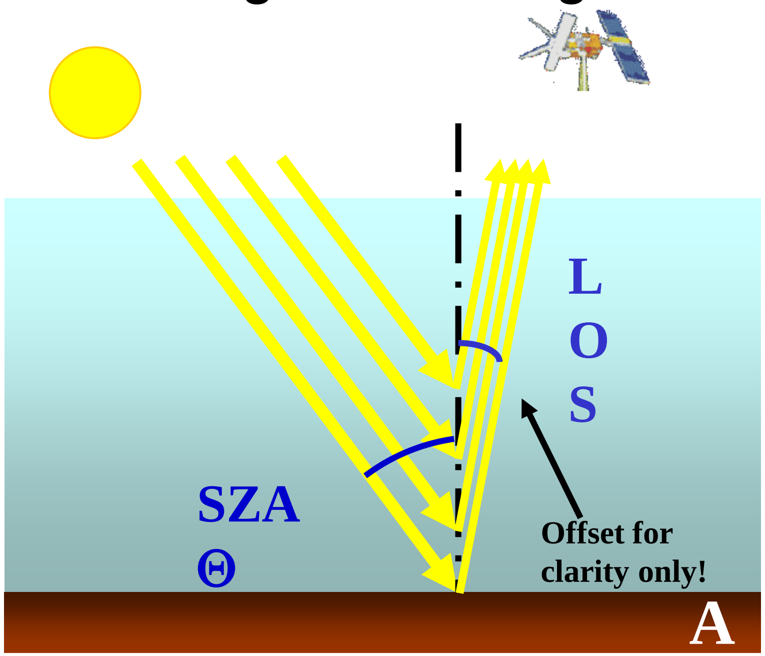
$$I = I_0 e^{\int_0^H -k_a(h)/\cos(\theta)\,dh} A e^{\int_0^H -k_a(h)/\cos(\varphi)\,dh}$$

$$= I_0 A e^{\int_0^H -(k_a(h)/\cos(\theta) + k_a(h)/\cos(\varphi))\,dh}$$

Where is the light coming from for a satellite looking downward ?



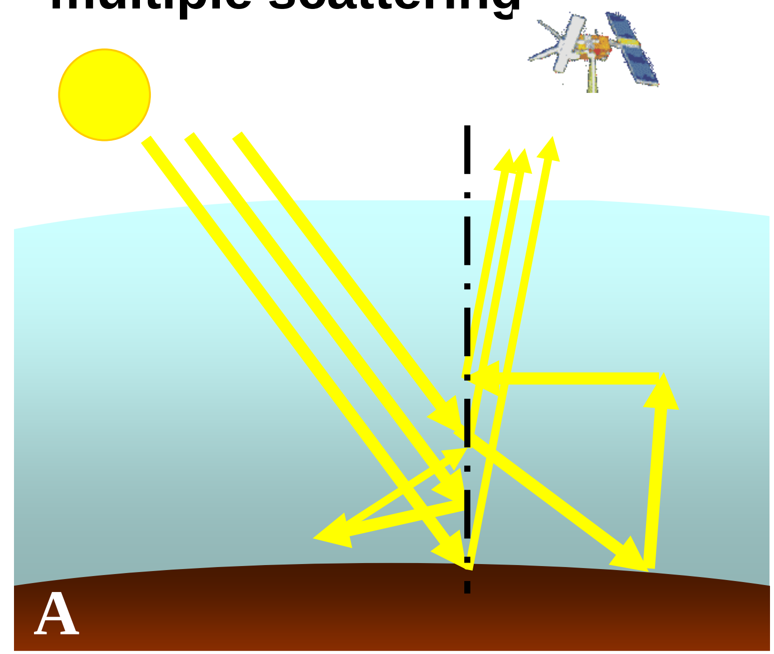
C: plane parallel, with absorption and single scattering



Intensity measured at top of atmosphere is sum of

- Light reflected from surface
- Scattered light from different altitudes
- Can still be written analytically as extension of Lambert Beer Law
- Valid for small angles and little scattering

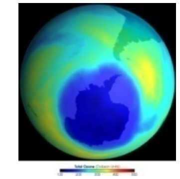
D: spherical, with absorption and multiple scattering



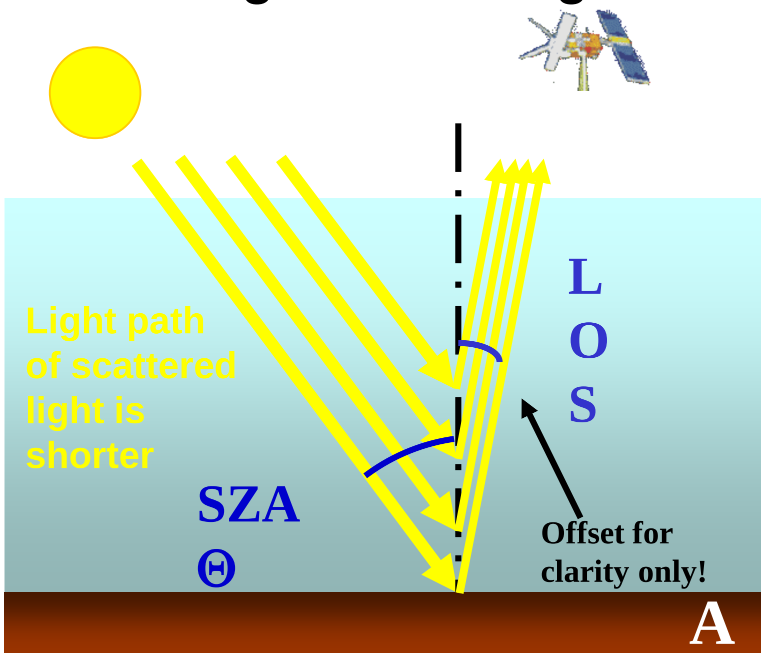
Reality is more complicate:

- Multiple scattering
- Spherical geometry
- RT equations needs to be solved

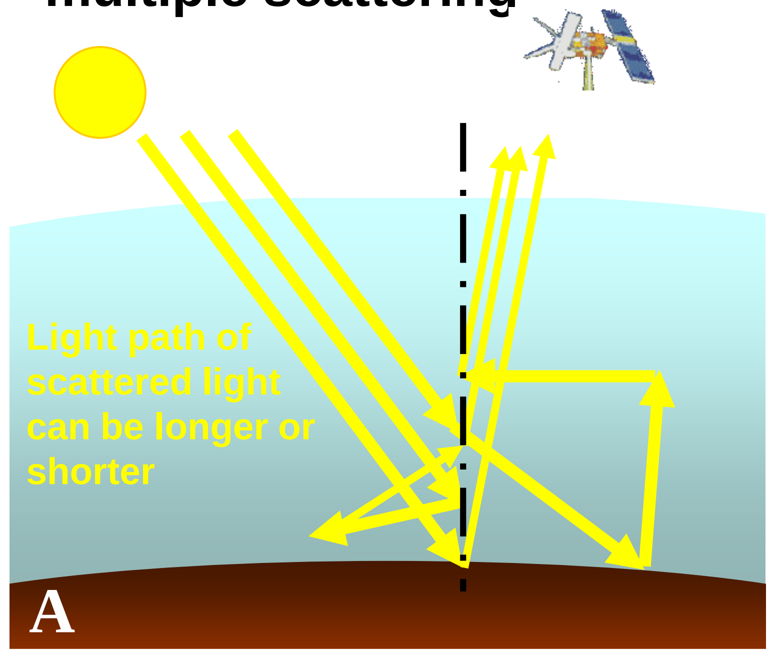
Where is the light coming from for a satellite looking downward ?



C: plane parallel, with absorption and single scattering



D: spherical, with absorption and multiple scattering



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- Light reflected from surface
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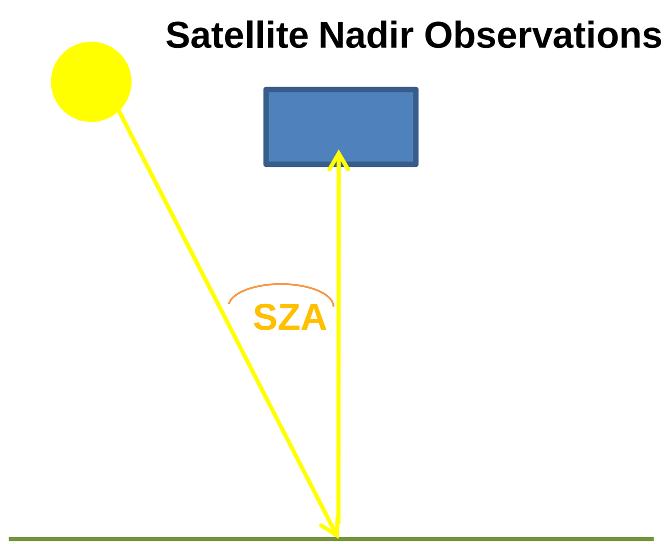
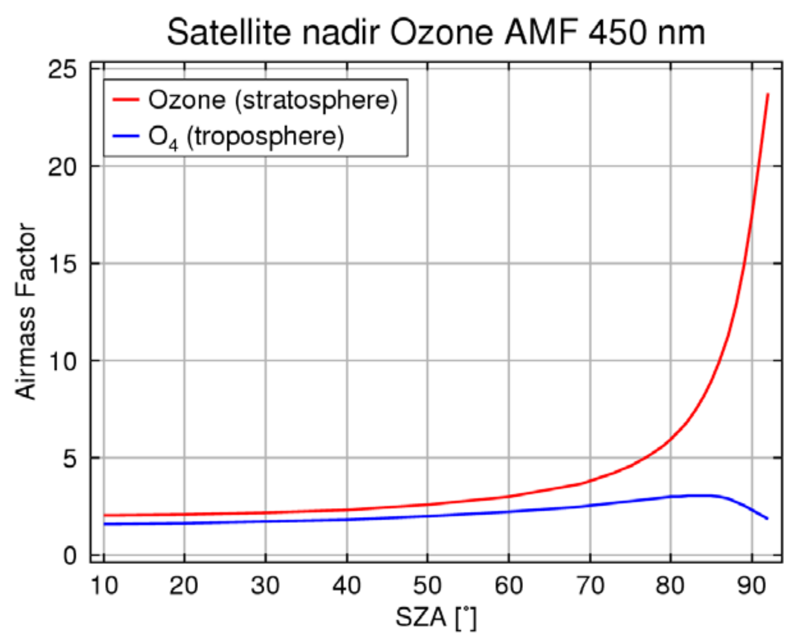
Reality is more complicate:

- Multiple scattering
- Spherical geometry
- RT equations needs to be solved

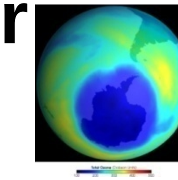
Airmass Factor

- Conversion factor from unknown slant column density SCD to well defined vertical column density VCD: $$AMF = \frac{SCD(\lambda, \Theta, \ldots)}{VCD}$$
- Direct sunlight from the ground: AMF ~ 1/cos(SZA)
- For satellite nadir geometry:
  - No/little scattering (e.g. stratospheric gases): AMF is given by ratio of direct light path to vertical height: AMF ~ 1 + 1/cos(SZA)
  - Tropospheric gases: AMF is low because photons are usually scattered before they 'see' the absorber

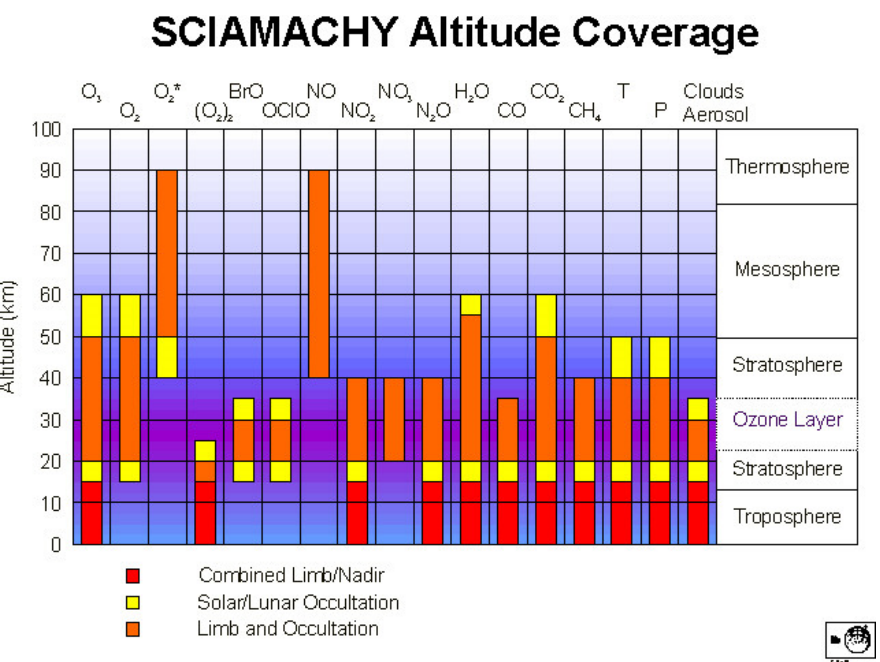


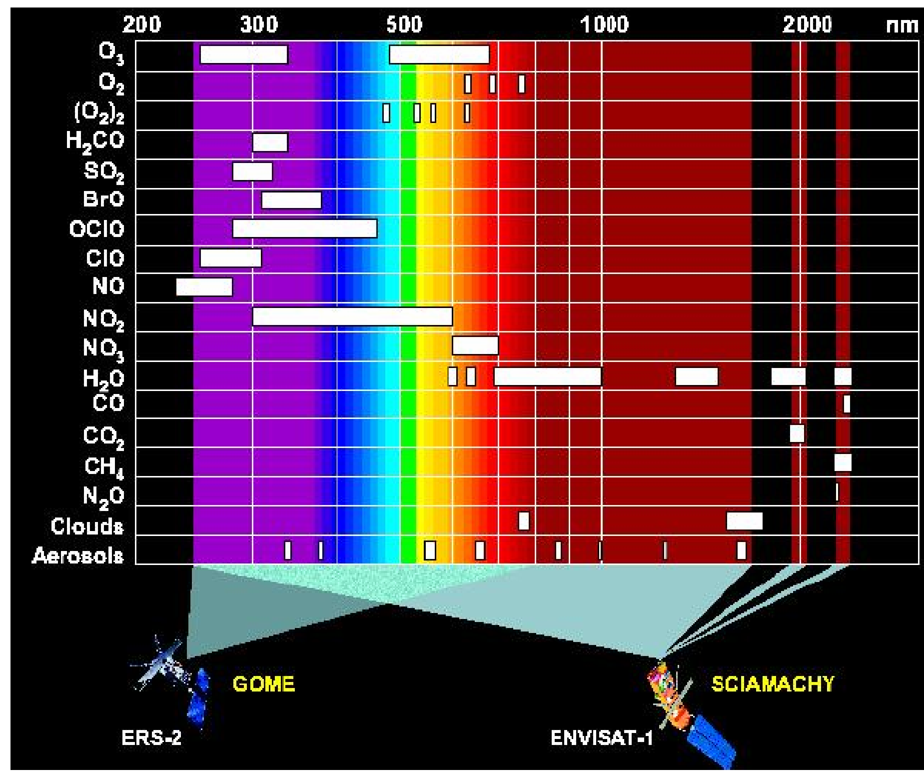


SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY)

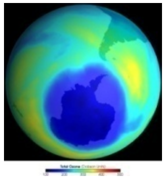


- Multi-channel grating spectrometer that covers spectral range from UV (~240 nm) to near-infrared (~2380 nm) with moderate spectral resolution between 0.2 - 1.5 nm
- Limb, nadir and occultation geometry
- Good spatial resolution (typically 30 x 60 km^2)
- Global coverage within 3-4 days
- Launched March 1st, 2003 on ENVISAT (ended 2012)
- Successor of GOME instrument launched April 1995

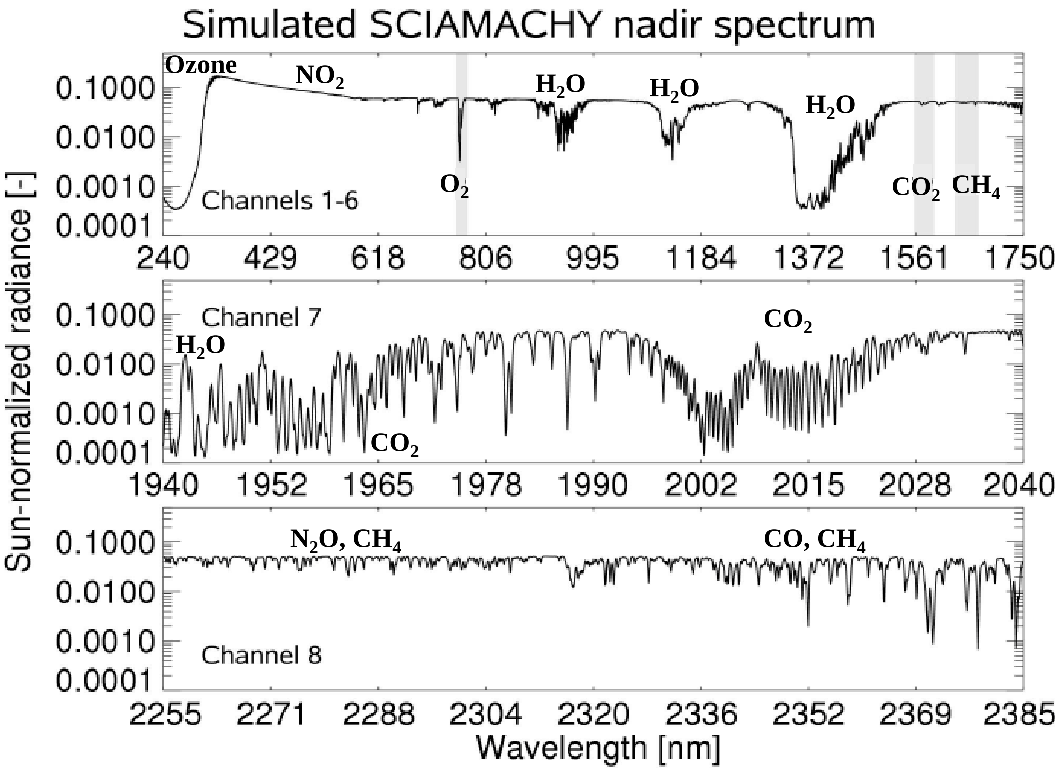




SCIAMACHY Spectrum



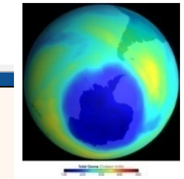
A large number of species as well as cloud and aerosol information can be retrieved from SCIAMACHY spectra



SCIAMACHY Channels

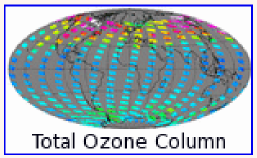
Channel	Range (nm)	Resolution (nm) / Resolving power
1	214-334	0.24 / ~1000
2	300-412	0.26 / ~1400
3	383-628	0.44 / ~1200
4	595-812	0.48 / ~1500
5	773-1063	0.54 / ~1700
6	971-1773	1.48 / ~1000
7	1934-2044	0.22 / ~9000
8	2259-2386	0.26 / ~9000

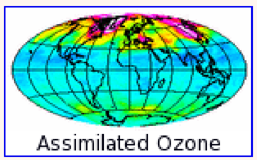
Similar instruments: GOME and GOME-2, OMI, Sentinel 5 precursor

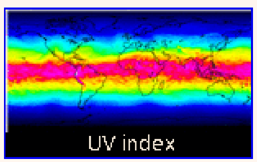


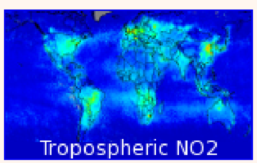
Tropospheric Emission Monitoring Internet Service

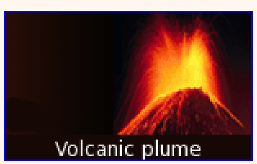
Near-real time data


Total Ozone Column


Assimilated Ozone


UV index


Tropospheric NO2


Volcanic plume

Air pollution monitoring

- Nitrogen Dioxide (NO_2)
- Formaldehyde (CH_2O)
- Carbon Monoxide (CO)

Ozone and related gases

- Total ozone columns
- Ozone hole statistics
- Assimilated total ozone
- Ozone profiles
- Bromine monoxide (BrO)

UV radiation

- Clear sky UV index
- UV daily dose

Climate Change

- Aerosol Optical Depth
- Aerosol Index
- Cloud information
- Methane (CH_4)
- Surface Solar Irradiance
- Carbon Dioxide (CO_2)

Monitoring volcanic plumes

- Volcanic SO_2 and ash

Surface products

- Albedo climatologies

Introduction
Utilities
Overview NRT images
Google Earth Maps
Air Quality Index Netherlands

Emission Estimates

Air Quality in China

Contact

Restricted access pages

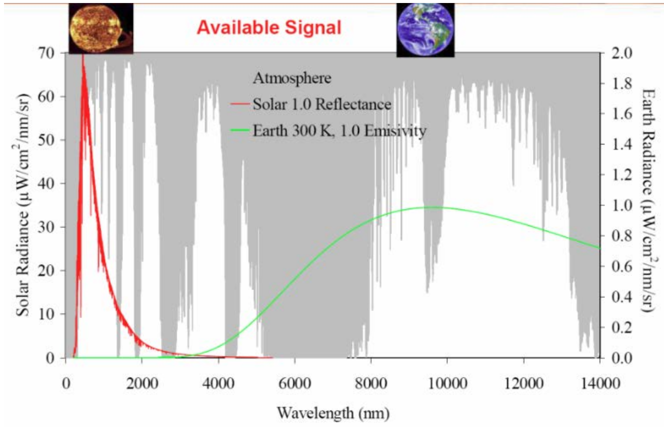
How can we infer information about tropospheric gases ?

We often want to measure tropospheric gases:

- Sources and sinks for most pollutants and greenhouse gases are near the surface
- Air that we breath ('air quality')

In general, best suited are nadir observations in Shortwave range (UV/vis/SWIR):

- High transparency of atmosphere

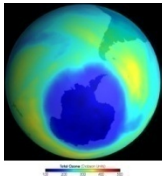


But DOAS retrieval only provides us only total atmospheric column (VCD)

-> we do not know if the gas is near the surface

How can we overcome this problem?

How can we infer information about tropospheric gases ?



1) **Absorber is present in troposphere only (e.g. HCHO): inferred column represent tropospheric column**

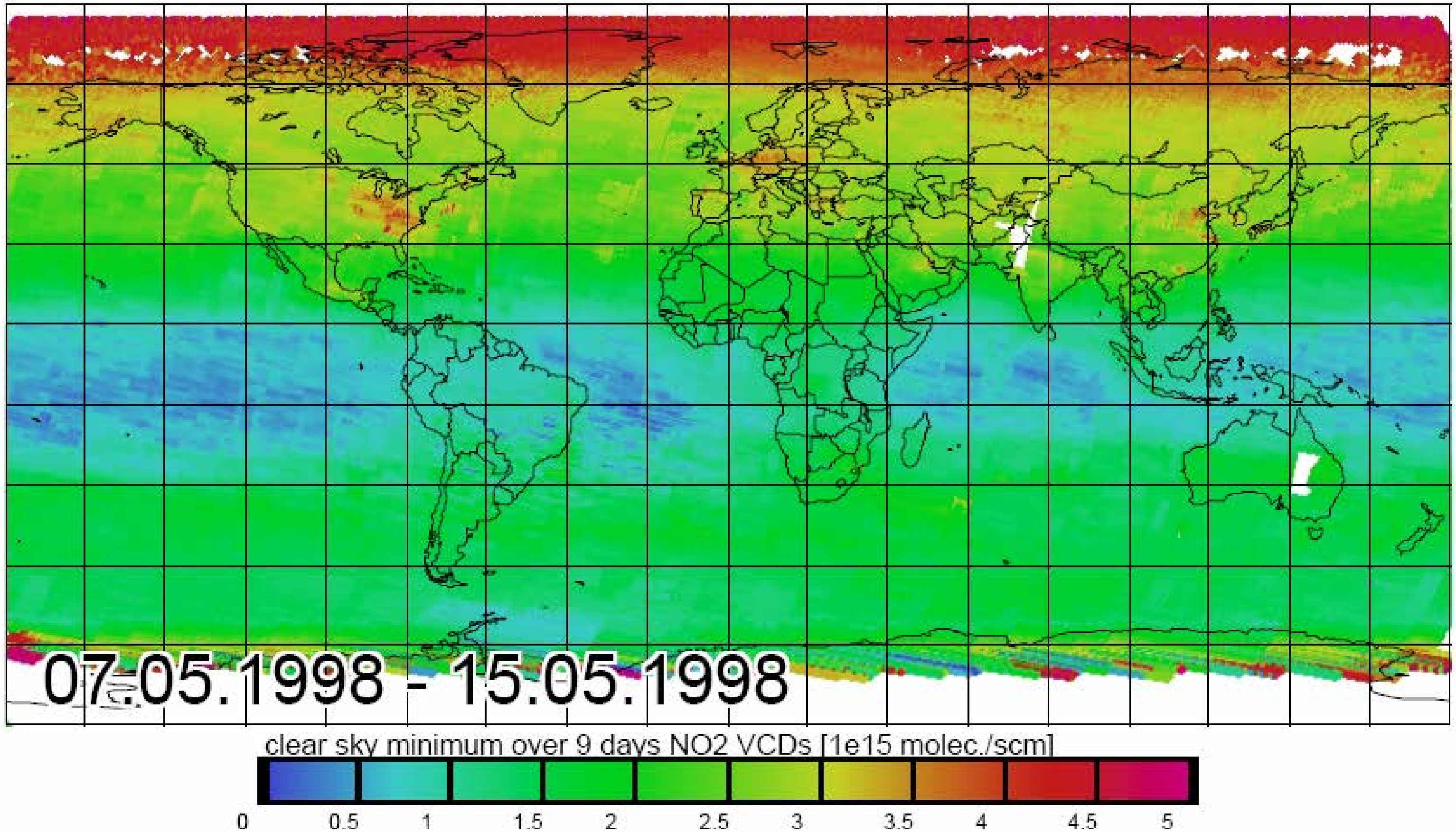
2) **Combine different observation modes: nadir with limb (point to horizon) sounding or with thermal-IR (sensitive to middle atmosphere) soundings**

3) **Use cloudy and cloud free observations to infer vertical information: cloud shield the lower atmosphere and thus cloudy scenes yield upper atmospheric columns**

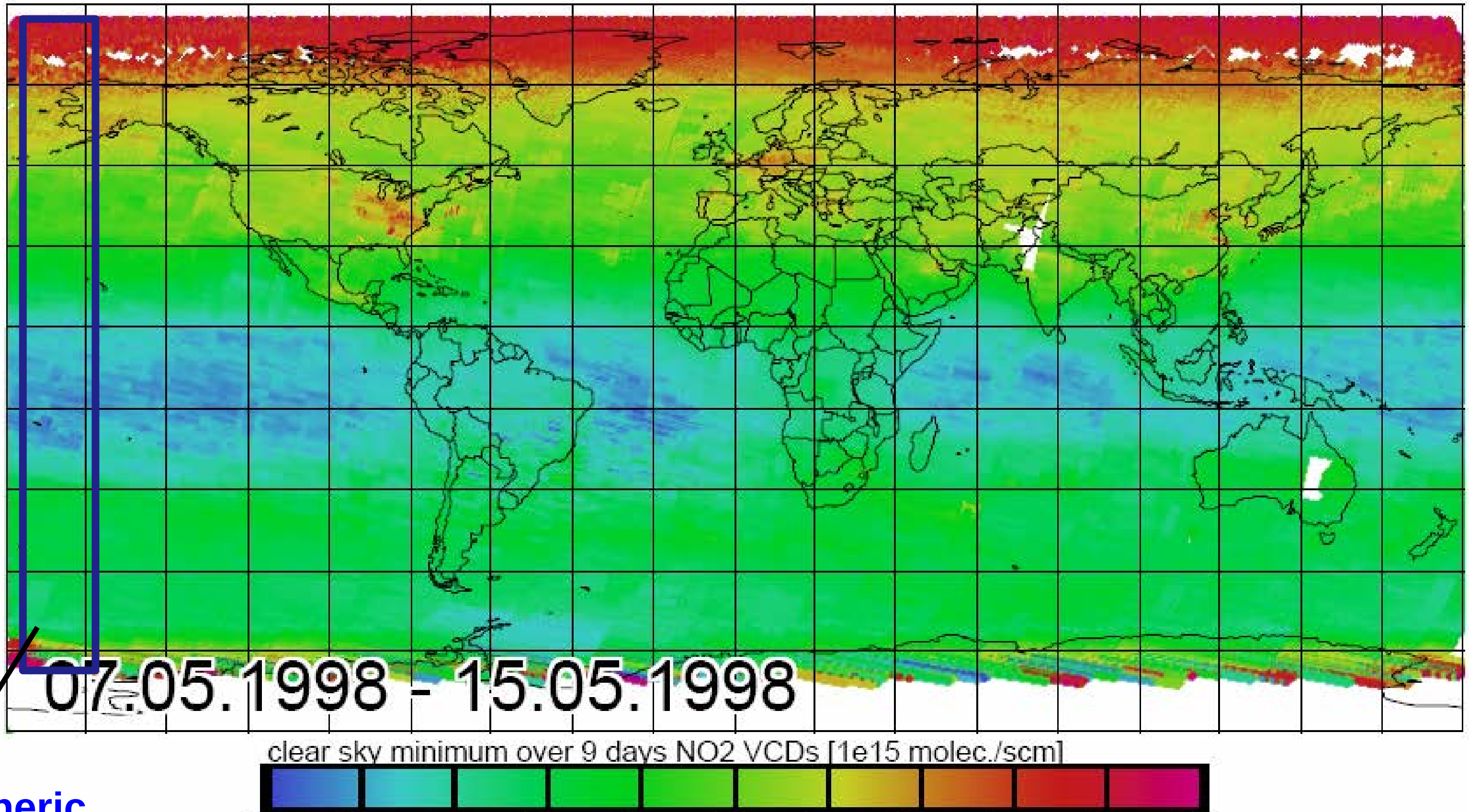
4) **Strong absorbers (O_3 or H_2O): light penetrates less deep into atmosphere for strong absorption lines thus combination of weak and strong lines yields vertical information**

5) **Subtract stratospheric background: For short-lived species such as NO_2 this can be inferred from areas without tropospheric sources assuming smoothly varying stratospheric amounts**

NO2 VCD 9 days minimum (cloud free pixel)

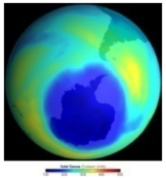


NO2 VCD 9 days minimum (cloud free pixel)

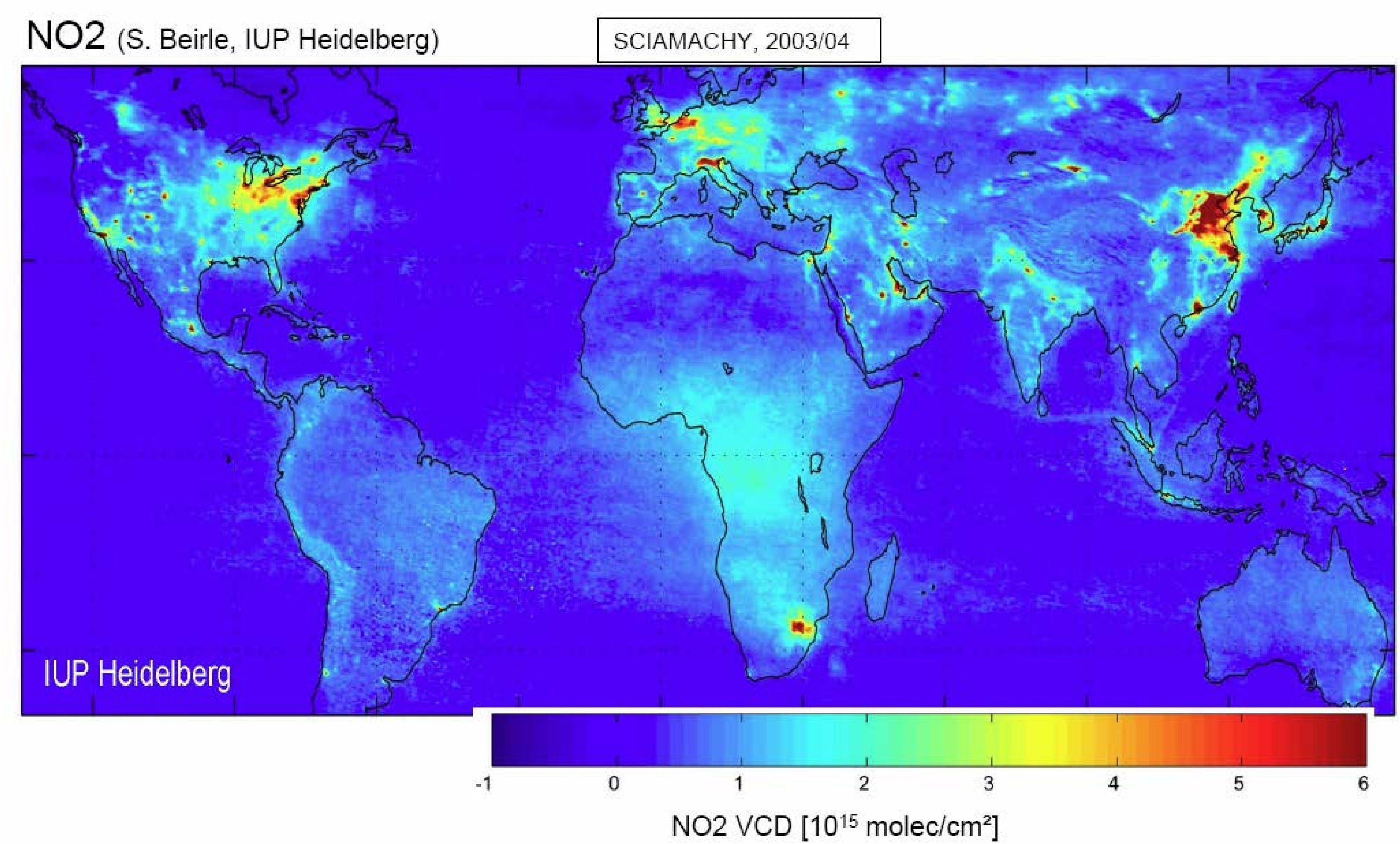


Stratospheric background (only depends on latitude and season)

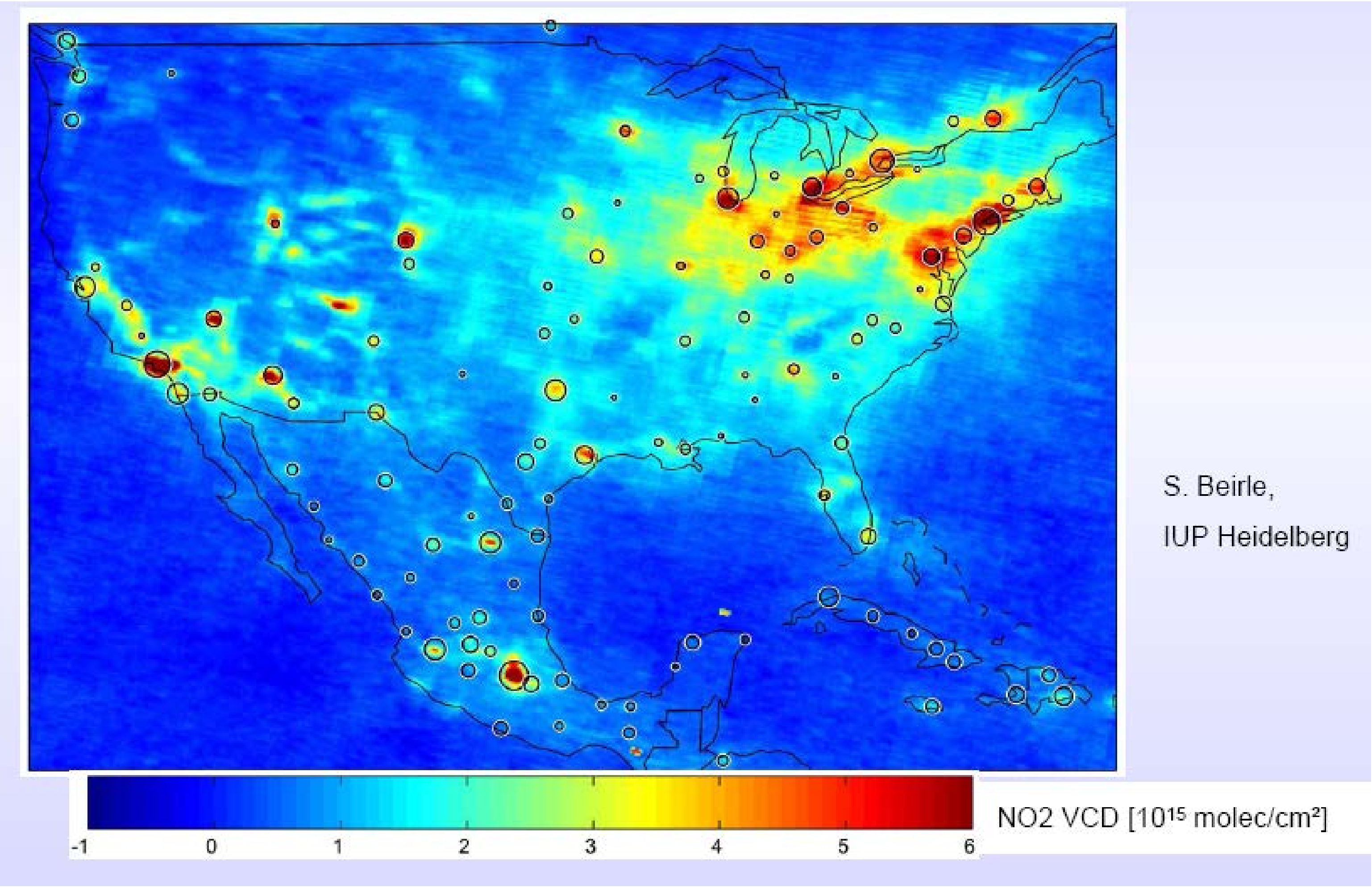
SCIAMACHY - TROPOSPHERIC NO_2



NO_2 is a major air pollutant (combustion of fossil fuels, biomass burning)



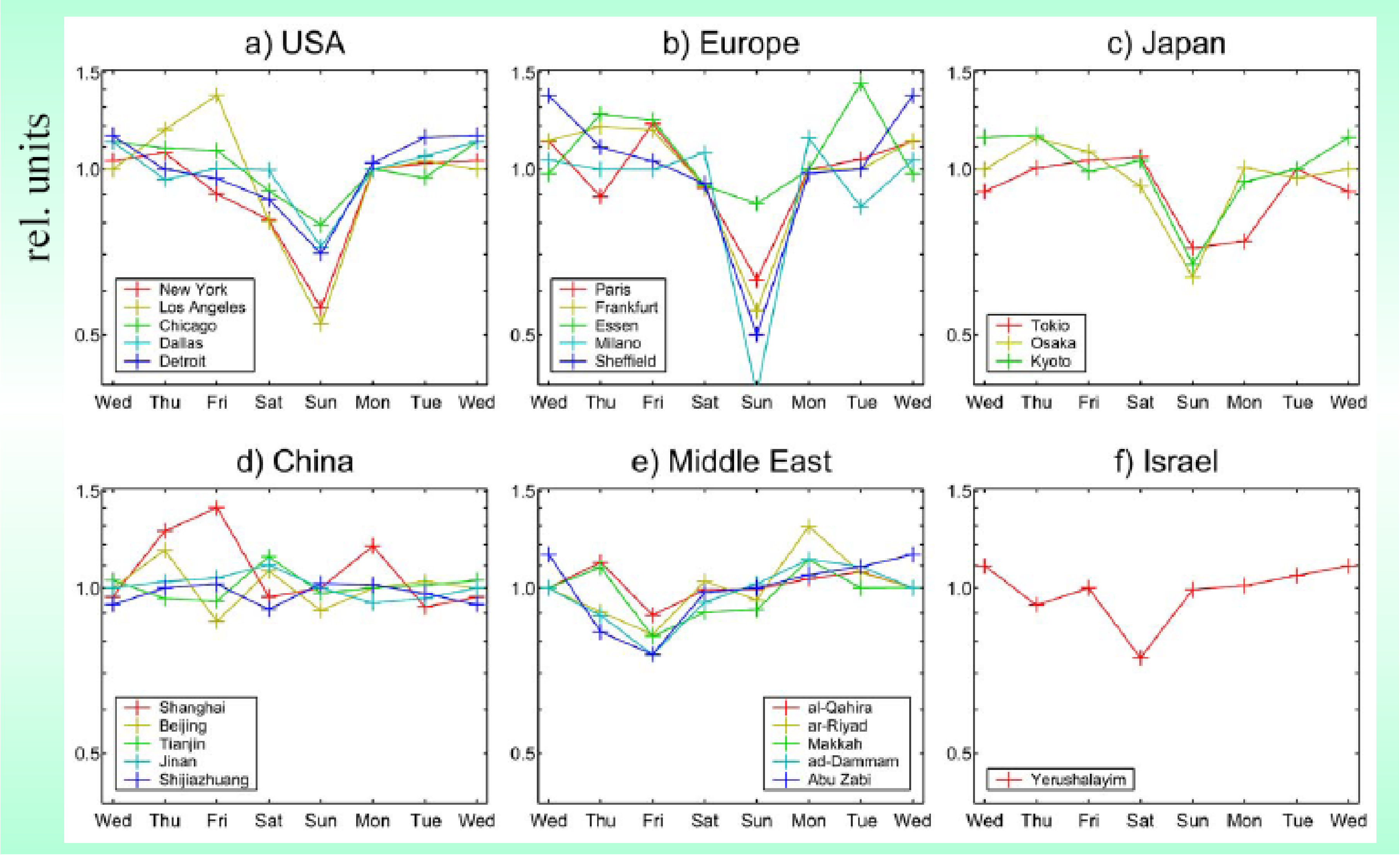
Tropospheric NO_2: USA



S. Beirle,

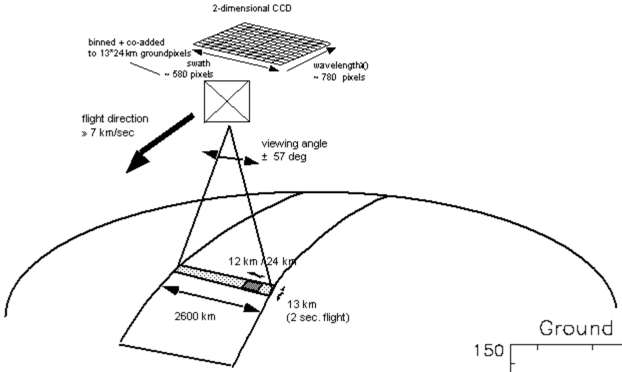
IUP Heidelberg

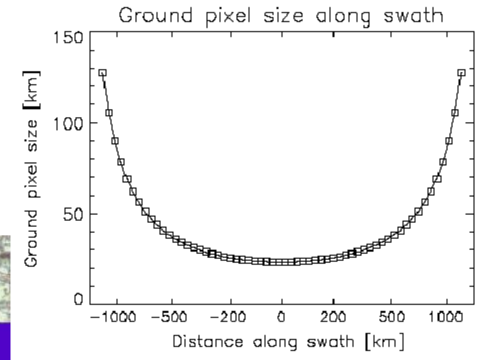
SCIAMACHY – WEEKLY CYCLE OF TROPOSPHERIC NO_2

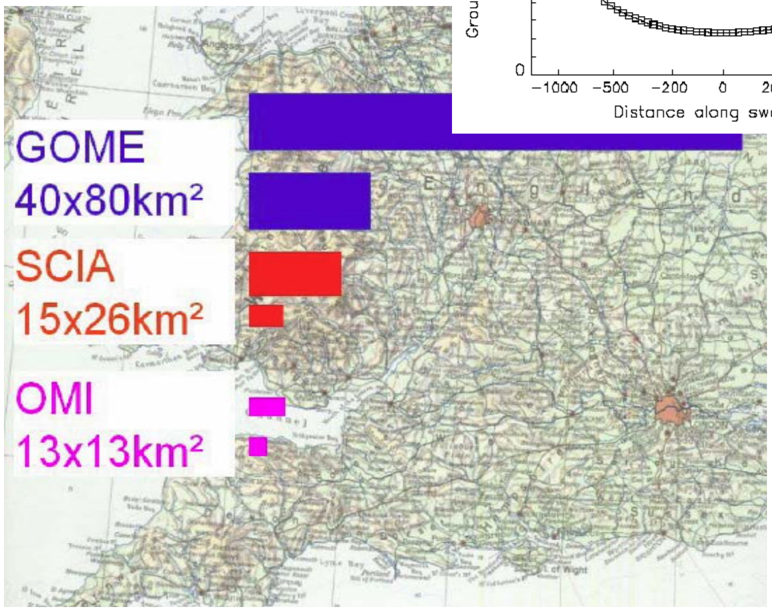


Ozone Monitoring Instrument

- **Idea:** **Wide swatch imaging UV/vis instrument**
- **Benefits:**
  - **global coverage in one day**
  - **high spatial resolution: 13 x 24 km²**
    (zoom mode 13 x 12 km²)
  => less cloud problems
  => better resolution of emissions
  - **multiple trace gases**
- **Specification:**
  - **Spectrum: 270 – 500 nm**
  - **FWHM: 0.4 – 0.6 nm**
  - **polarisation scrambler**
  - **frame transfer CCD**
  - **Launch: July 15, 2004 on Aura**



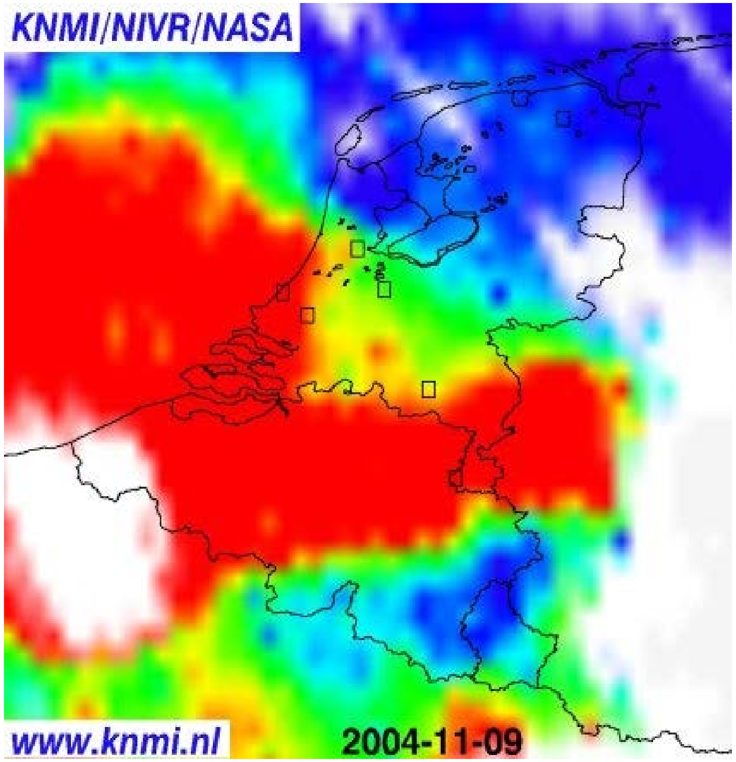




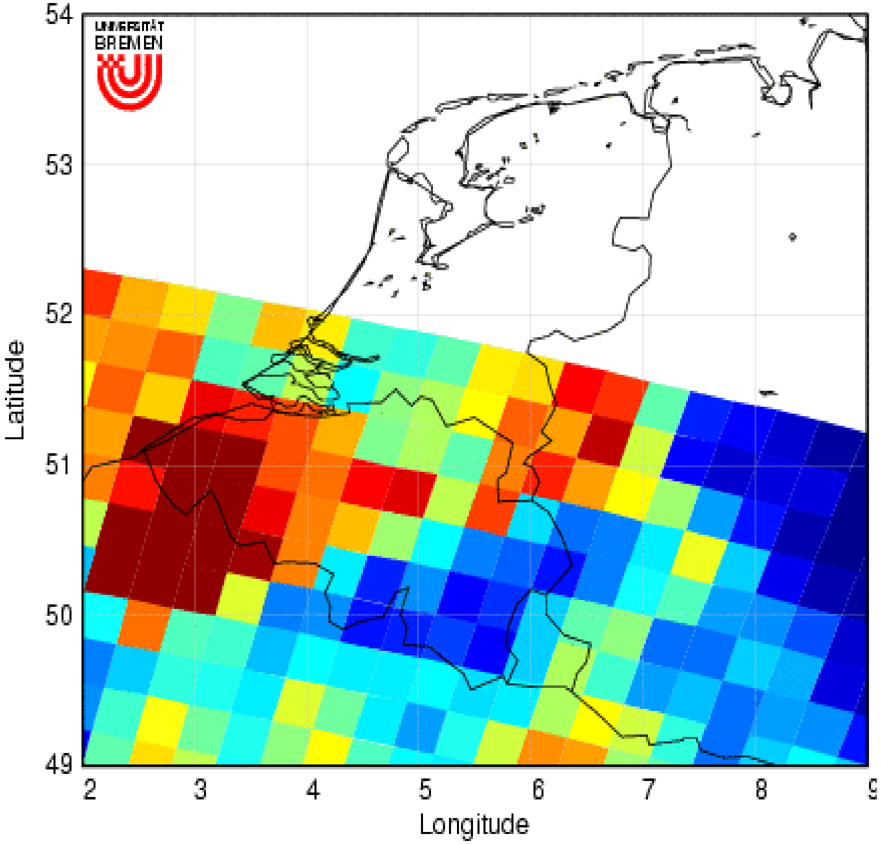
http://www.knmi.nl/omi/index_en.html

Improved Spatial Resolution: OMI

OMI NO_2: 2004-11-09



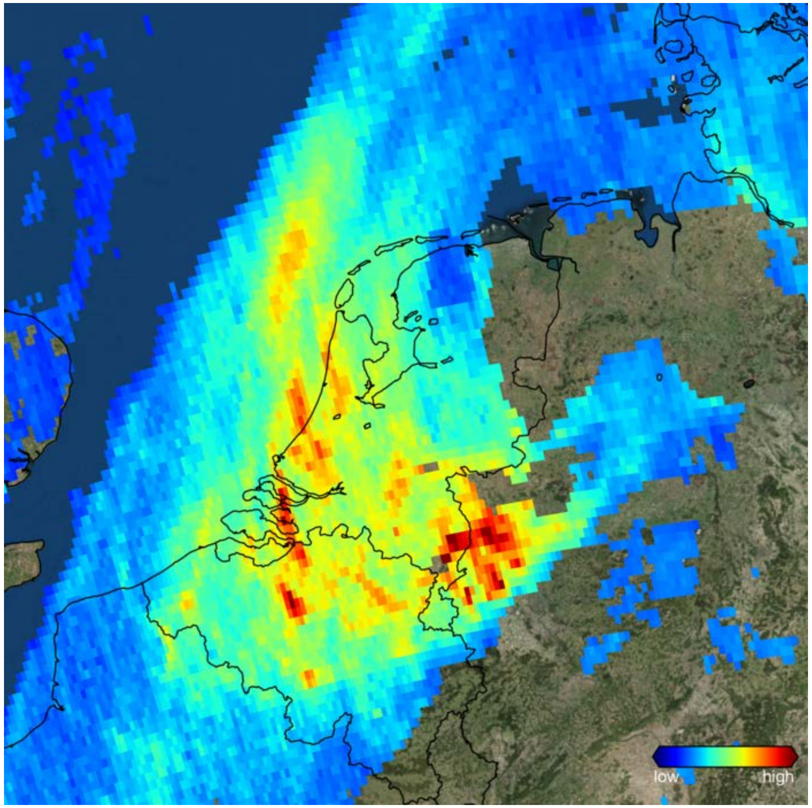
SCIAMACHY NO_2: 2004-11-09



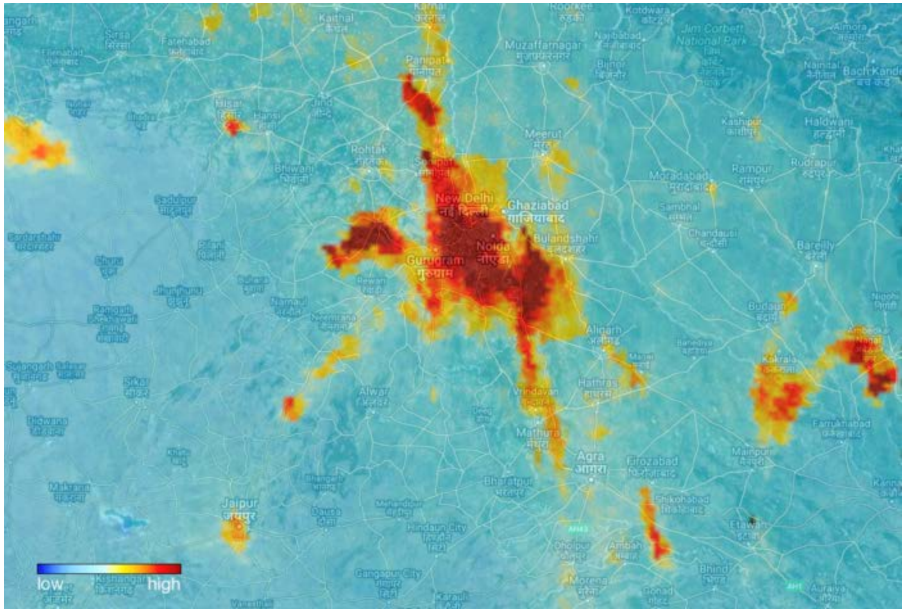
- Tropospheric gases often show large spatial gradients
- At SCIAMACHY/GOME spatial resolution details are lost
- large impact on local results!

And Even Better from Sentinel 5P

NO2 Pollution over Netherlands



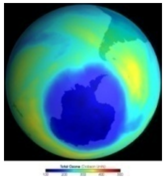
NO2 Pollution over India



S5P:

- Resolution as high as 7x3.5 km2
- Daily global coverage thanks to 2600 km-wide swath

What do you need to know?



- Typical absorber measured in the infrared and in the UV/visible
- Principals of Absorption spectroscopy and Differential optical absorption spectroscopy
- Simple light path approximations in the UV/vis
- Schwarzschild eqn. (nadir) – the atmosphere terms.
- Single gas layer model for nadir IR
- Weighting function – the use of several wavelengths to measure the vertical distribution in atmosphere
- Typical instruments and applications: IASI, SCIAMACHY ...