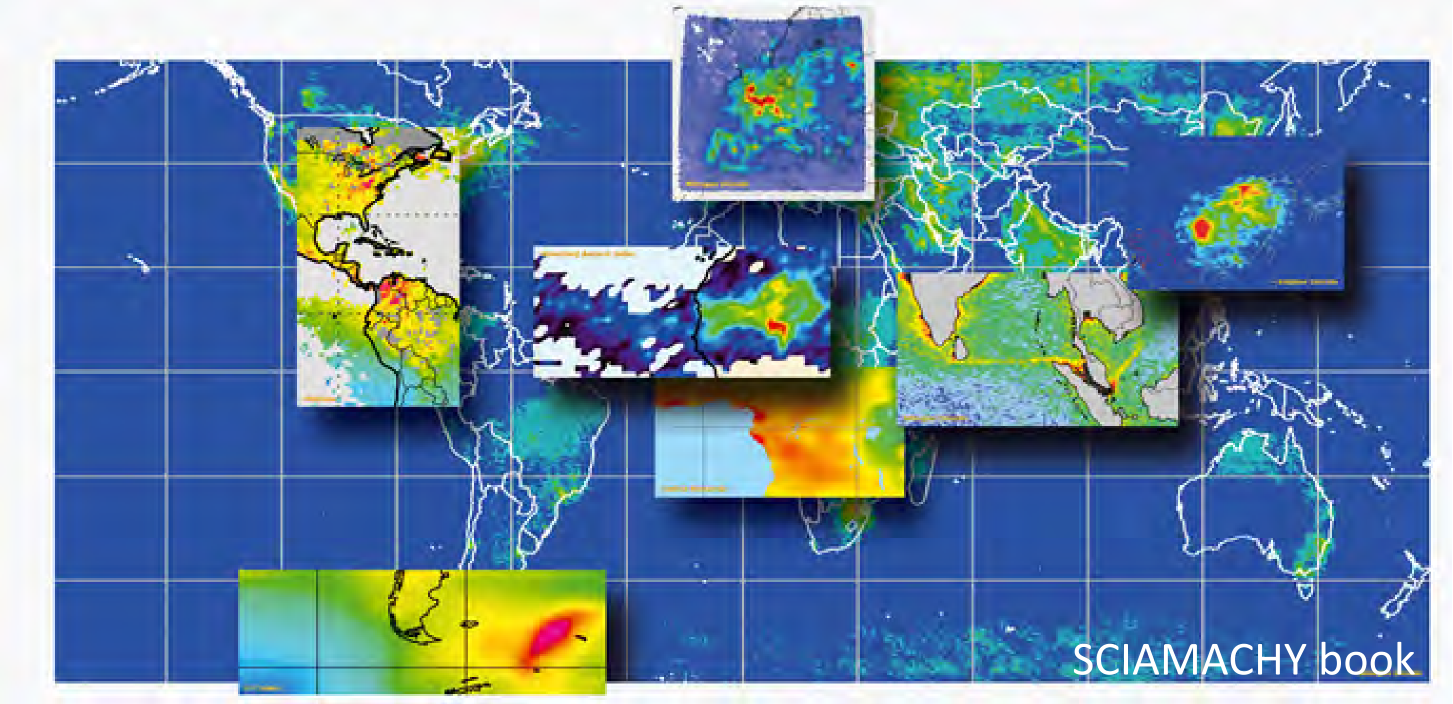


Remote sensing of atmospheric composition

(with a focus on tropospheric and stratospheric trace gases)

Michel Van Roozendael

Royal Belgian Institute for Space Aeronomy (BIRA-IASB)

Content

- Basics of remote-sensing of atmospheric gases
- Observations platforms
- Spectral ranges
- Radiative transport and retrieval methods
- Limb and occultation techniques
- Nadir sensing of the tropospheric composition using UV-Vis and TIR observations (GOME and IASI)
- Future missions

Basics of (atmospheric) remote sensing

- **Location of measurement is different from that of the instrument**

⇒ Information from atmosphere must be propagated to instrument by means of electromagnetic radiation

⇒ Remote sensing requires 'retrieval' = derivation from the atmospheric information from the radiation characteristics measured by the instrument

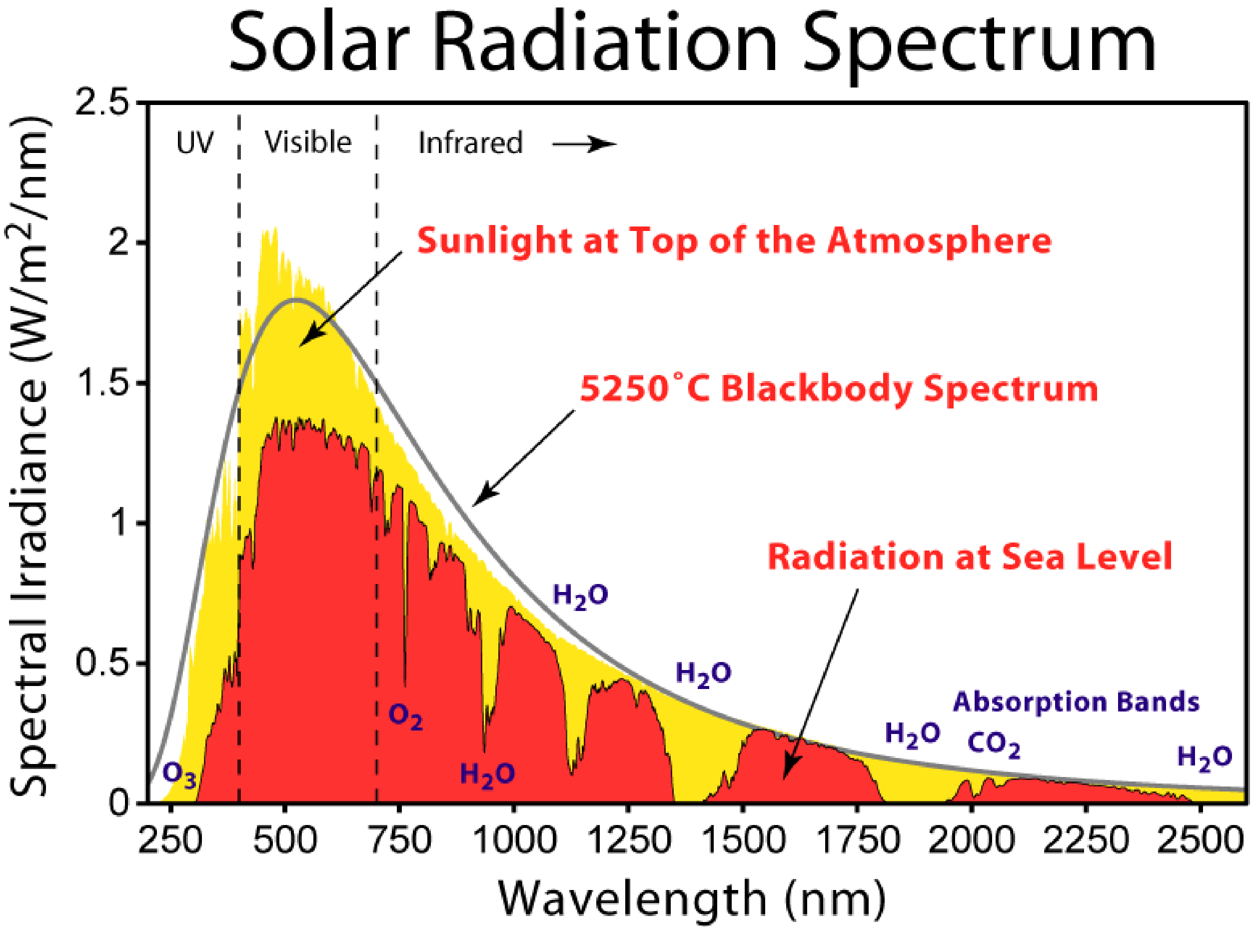
⇒ Most common instruments: spectrometers

- Radiation comes from a natural source (sun, moon, stars, earth/atmosphere emission, …) directly, after reflection, or scatttering ⇔ ***passive*** remote sensing

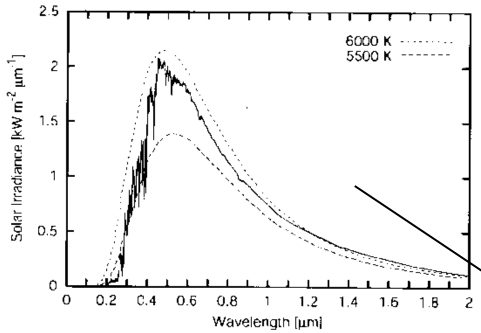
or

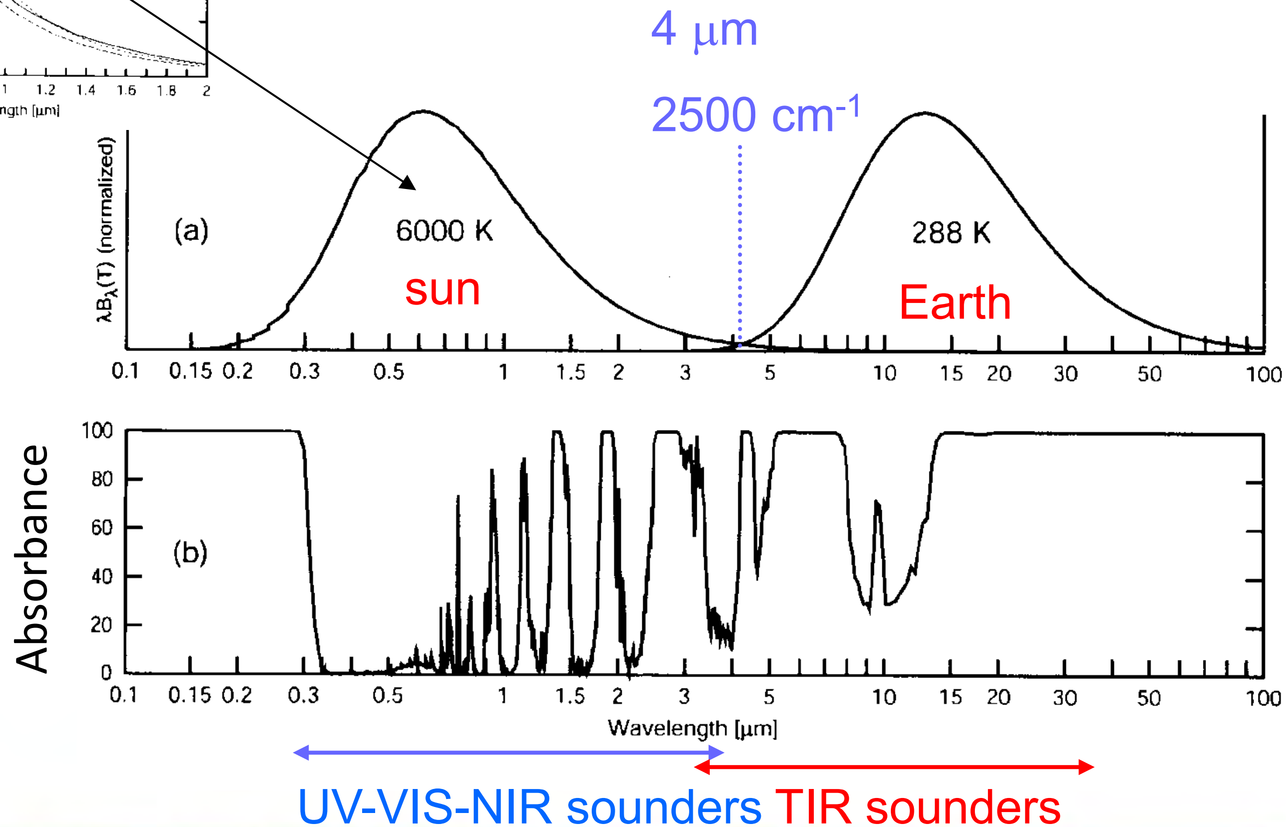
- Radiation comes from an artificial light source (lamp, laser, …) ⇔ ***active*** remote sensing

Basics of remote sensing (2)



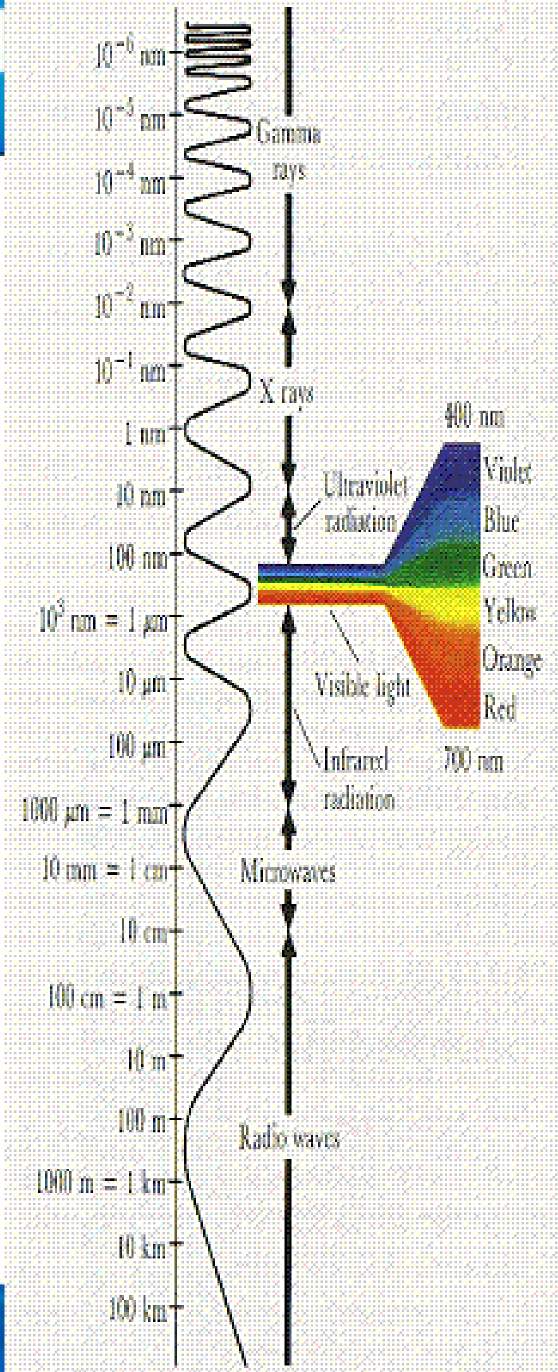
Basics of remote sensing (3)



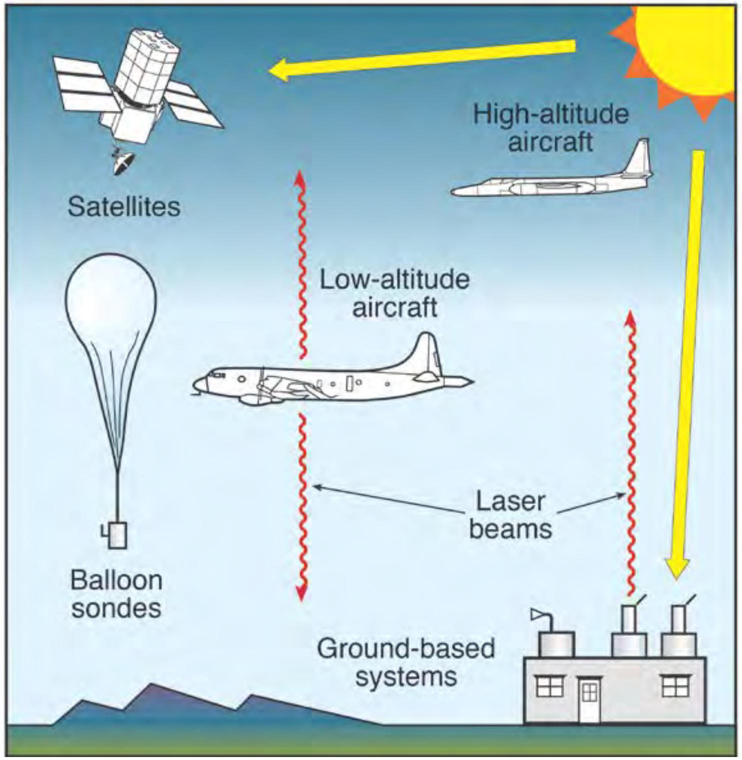


Wavelength ranges in remote sensing

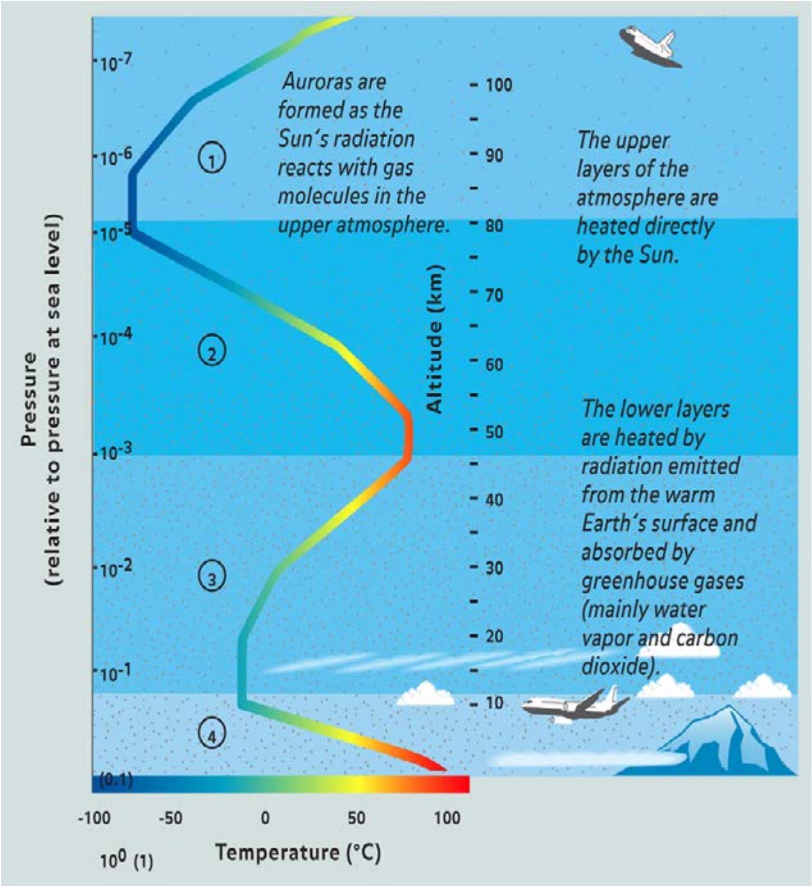
- **UV** some absorptions + profile information, aerosols
- **VIS** surface information (vegetation)
  some absorptions
  aerosol information
- **IR** temperature information
  cloud information
  water / ice distinction
  many absorptions / emissions
  + profile information
- **MW** clouds are transparent
  ice / water contrast
  surfaces



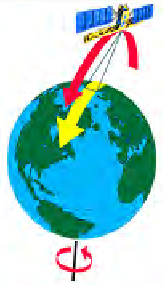
Remote-sensing platforms



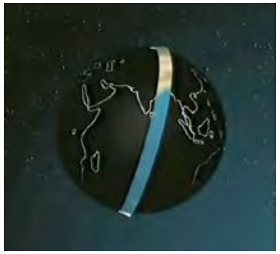
Ground, aircraft, balloon, rocket, satellite



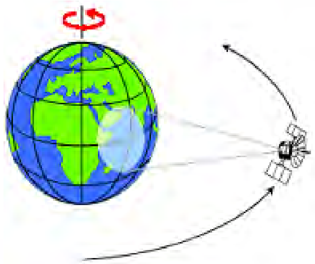
Satellite Orbits



- **(Near) Polar Orbit:**
  → orbits cross close to the pole
  → global measurements are possible
  → low earth orbit LEO (several 100 km)
  → ascending and descending branch



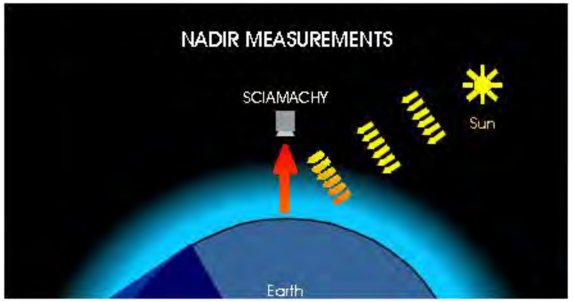
- Special case: **sun-synchronous orbit:**
  - overpass over given latitude always at the same local time, providing similar illumination
  - for sun-synchronous orbits: day and night branches

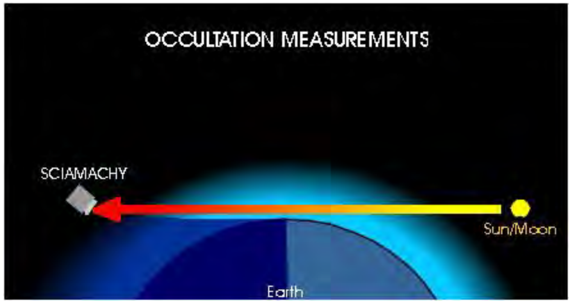


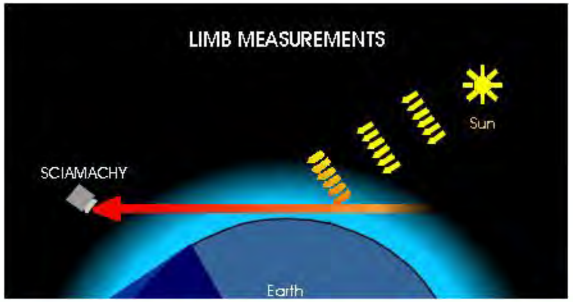
- **Geostationary Orbit:**
  → satellite has fixed position relative to the Earth
  → parallel measurements in a limited area from low to middle latitudes
  → 36 000 km flight altitude, equatorial orbit

http://marine.rutgers.edu/mrs/education/class/paul/orbits2.html

Satellite observation geometries







<u>Nadir:</u>

- Backscattered solar radiation and/or emission measurements (also nighttime)
- Good spatial coverage and resolution
- Low vertical resolution

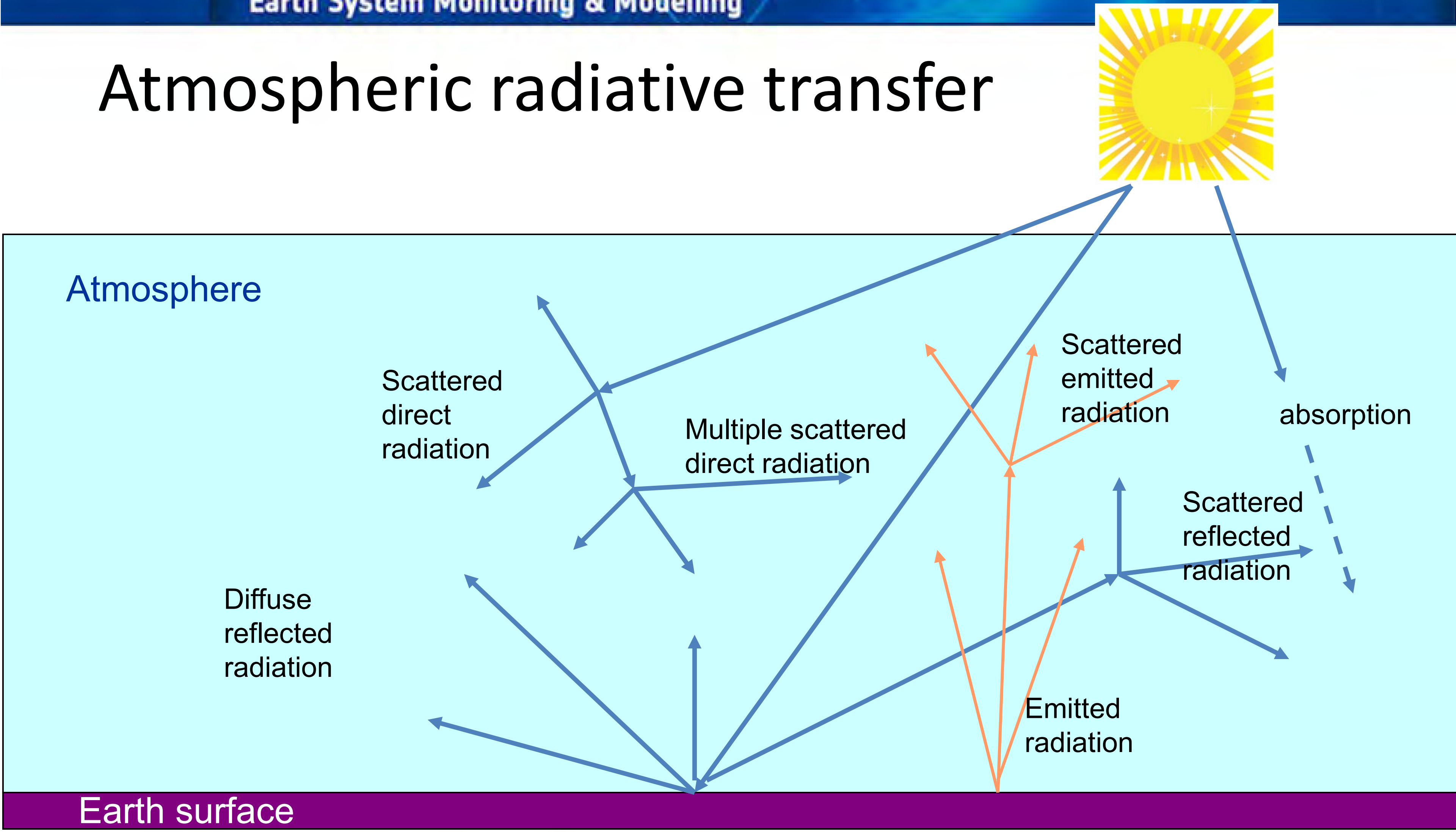
<u>Solar occultation:</u>

- Direct solar absorption
- High vertical resolution
- Low spatial resolution; low spatial coverage

<u>Limb:</u>

- Scattered light at the limb (UV-Vis)
- Limb emission (IR) $\Rightarrow$ also nighttime
- High vertical resolution
- Low spatial resolution; high spatial coverage

Atmospheric radiative transfer



Radiative transfer equation

Express the variation of the diffuse radiation in height *z* at one wavelength:

$$\mu \frac{d}{dz} I(z,\mu,\varphi) = -(\varepsilon(z)+\varsigma(z))I(z,\mu,\varphi)$$

loss by extinction

$$+\frac{\varsigma(z)}{4\pi}\int_0^{2\pi} d\varphi' \int_{-1}^{1} d\mu' P(z,\mu,\varphi,\mu',\varphi')I(z,\mu',\varphi')$$

gain by multiple scattering

$$+\frac{\varsigma(z)}{4\pi} P(z,\mu,\varphi,-\mu_0,\varphi_0) F_{sol} e^{-\tau(z)/\mu_0}$$

gain by single scattering of solar radiation

$$+\frac{\varsigma(z)}{4\pi} F_{sol} e^{-\tau_0/\mu_0} \int_0^{2\pi} d\varphi' \int_0^{1} d\mu' P(z,\mu,\varphi,\mu',\varphi') A e^{-(\tau_0-\tau(z))/\mu'}$$

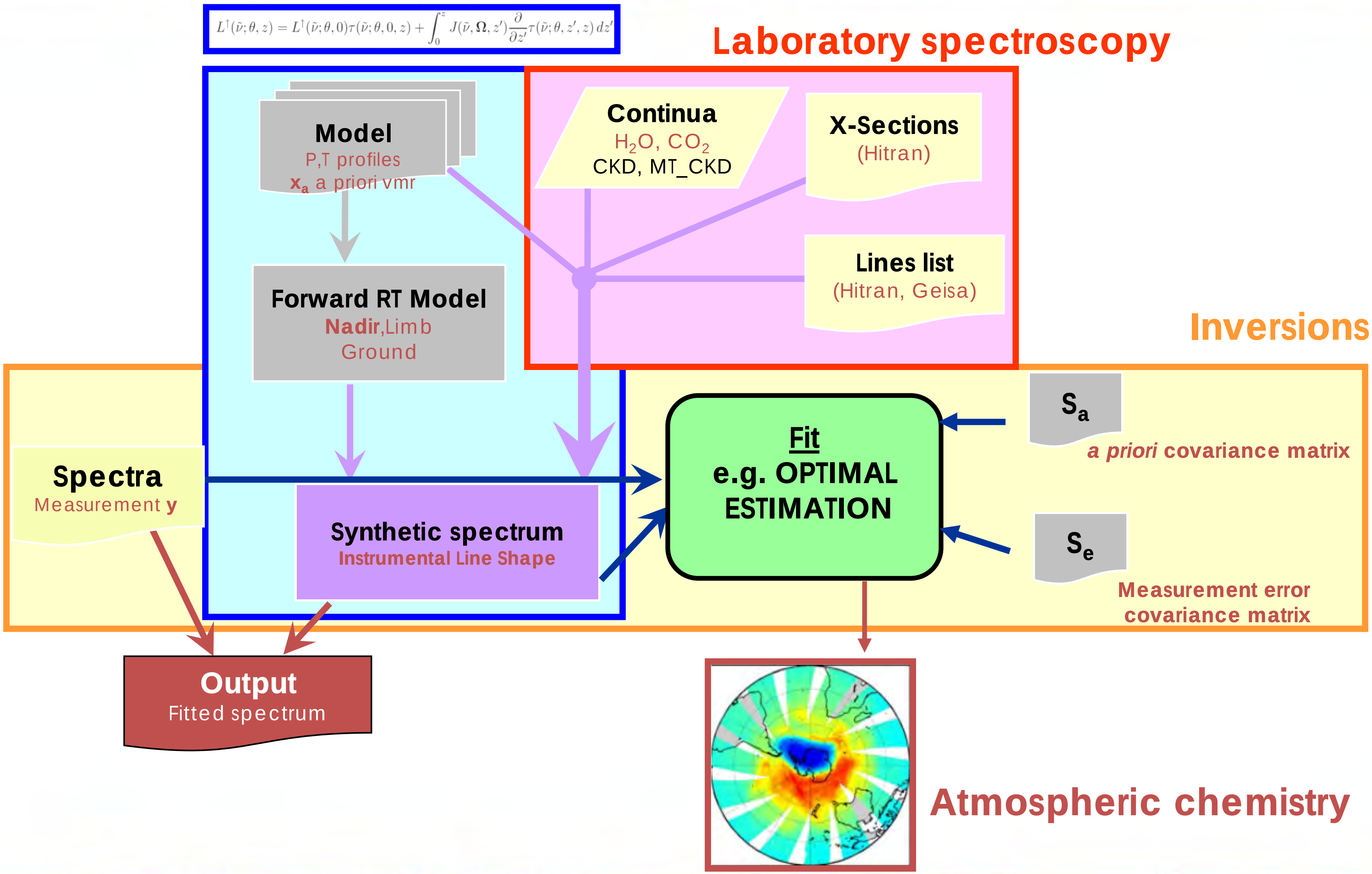
gain by reflection of light from the surface

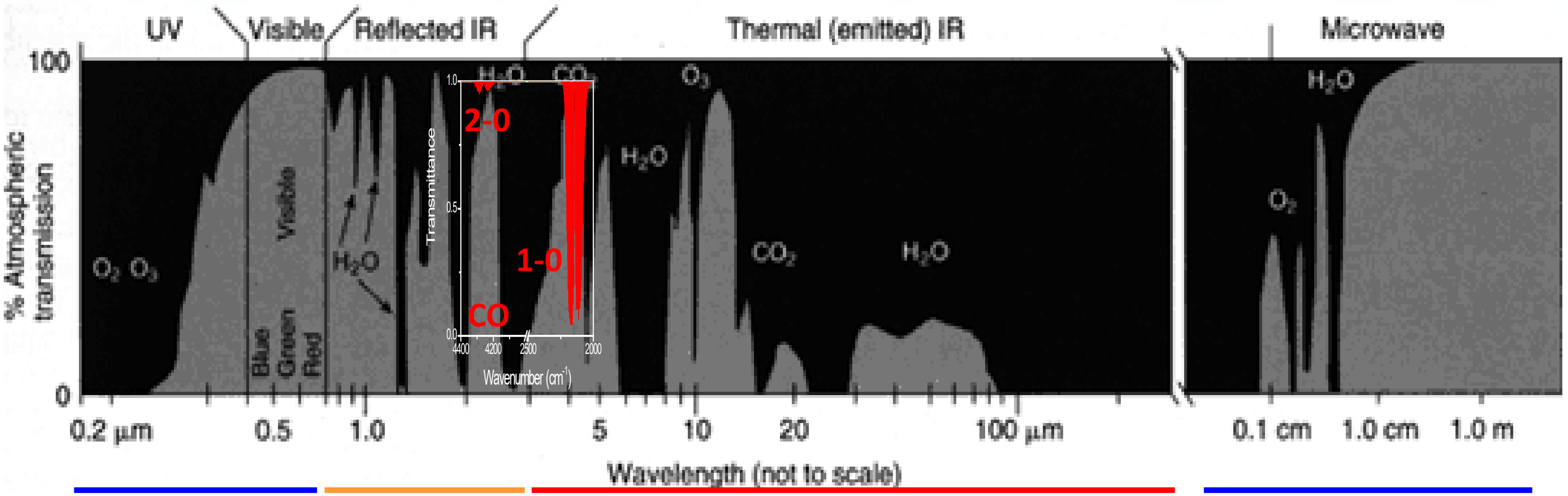
$$+\varepsilon(z)B(T)$$

gain by emission

Fsol	flux from the sun
P	weighted phase function for scattering
A	surface albedo
B	Planck radiation
τ	optical depth

Retrieval: principle





O_3
H_2O
NO_2
SO_2
H_2CO, $C_2H_2O_2$
IO
BrO

GOME, GOME-2, SCIAMACHY, OMI *at nadir*
SCIAMACHY, OSIRIS *at limb*

CO_2
CH_4
CO

SCIAMACHY, GOSAT, OCO *at nadir*

H_2O
CO_2
CH_4
N_2O
O_3
CO
HNO_3
NH_3
CFC11, CFC12, …
CH_3OH, HCOOH, C_2H_2, C_2H_6,…
+ isotopologues

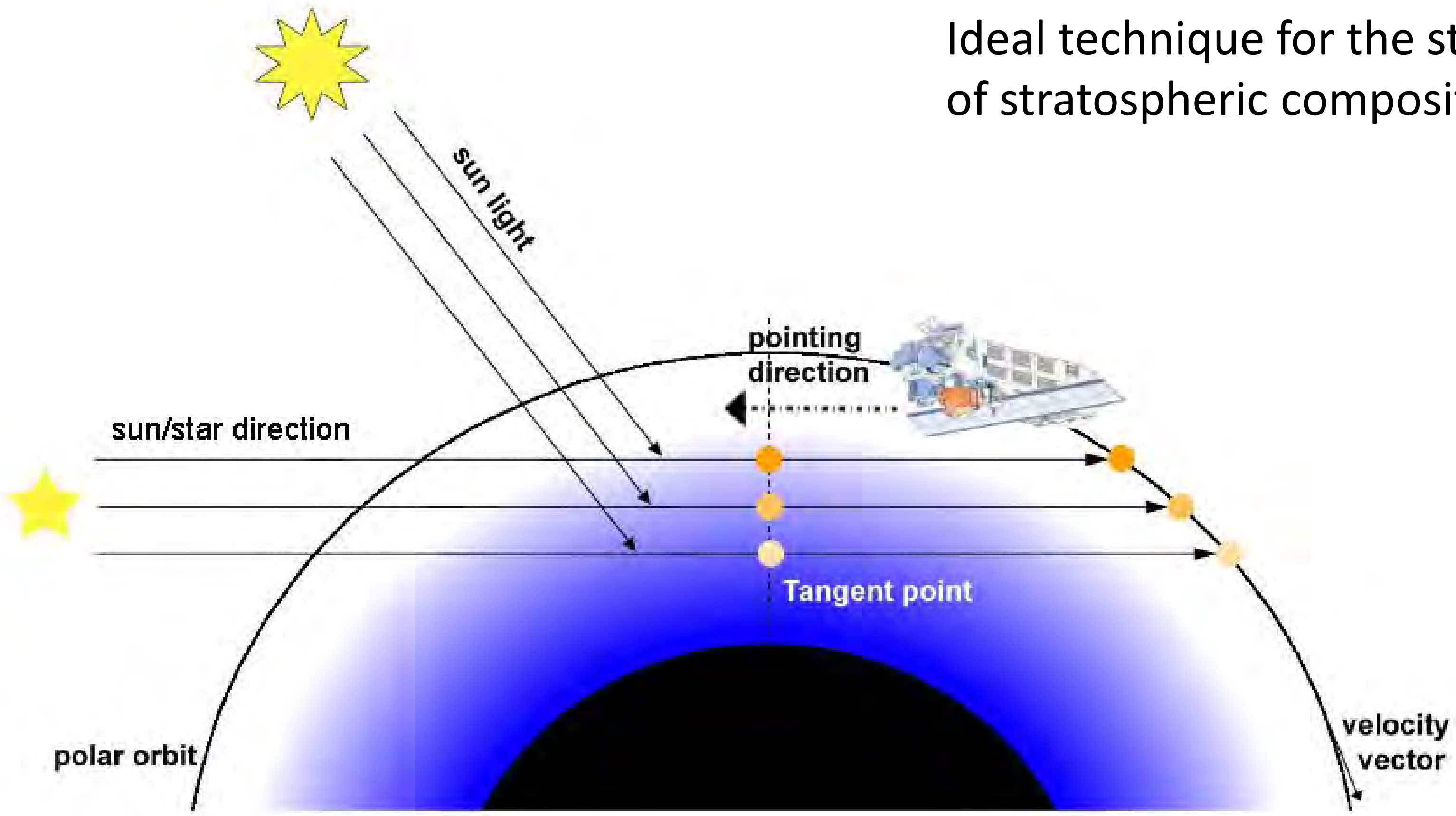
TES, AIRS, IASI, MOPITT *at nadir*
MIPAS, ACE *at limb*

O_2
H_2O, OH, HO_2
HNO_3
HCl, BrO, ClO, HOCl
O3
CO
HCN, CH_3CN

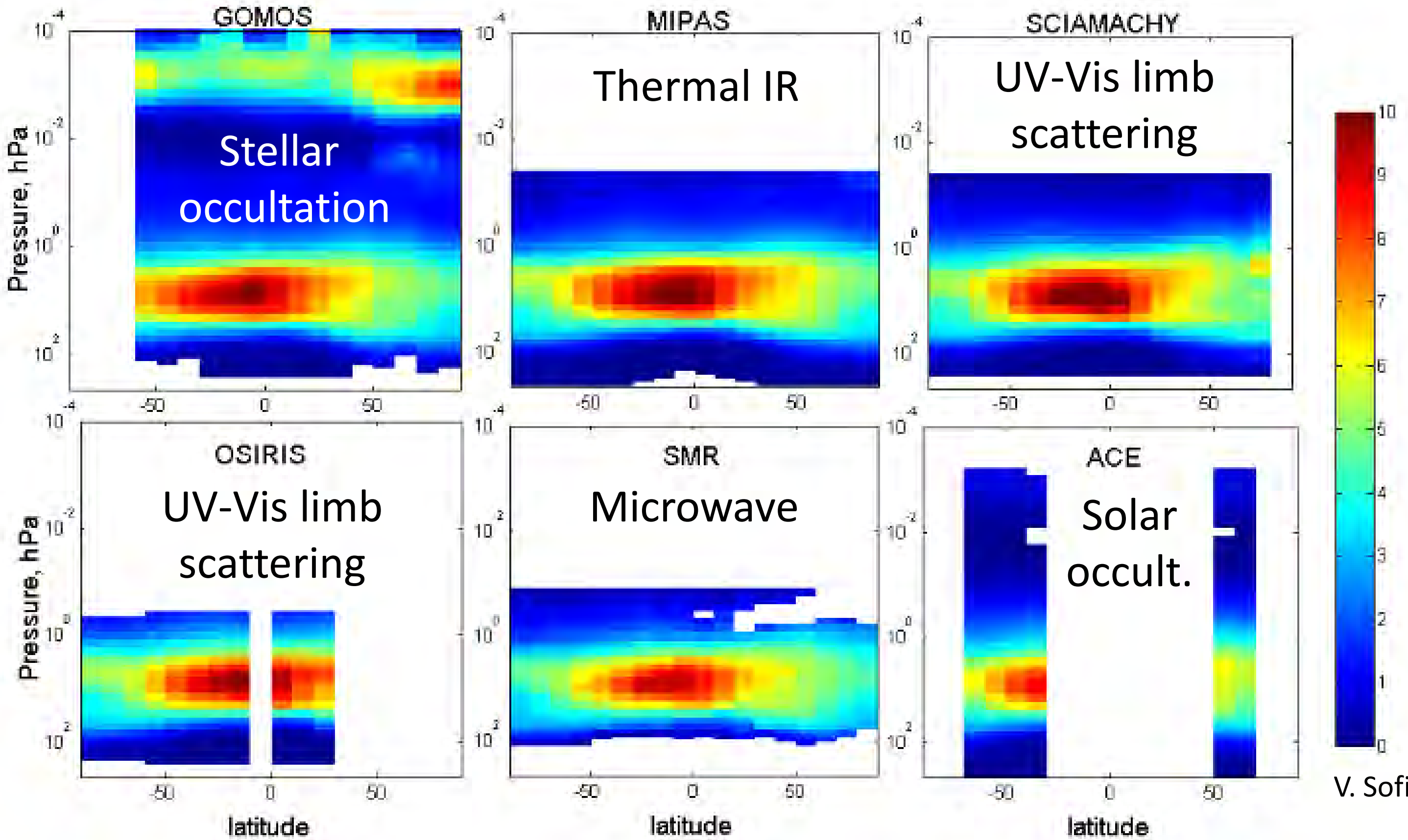
DMR, MLS *at limb*

Principle of limb/occultation profiling

Ideal technique for the study of stratospheric composition



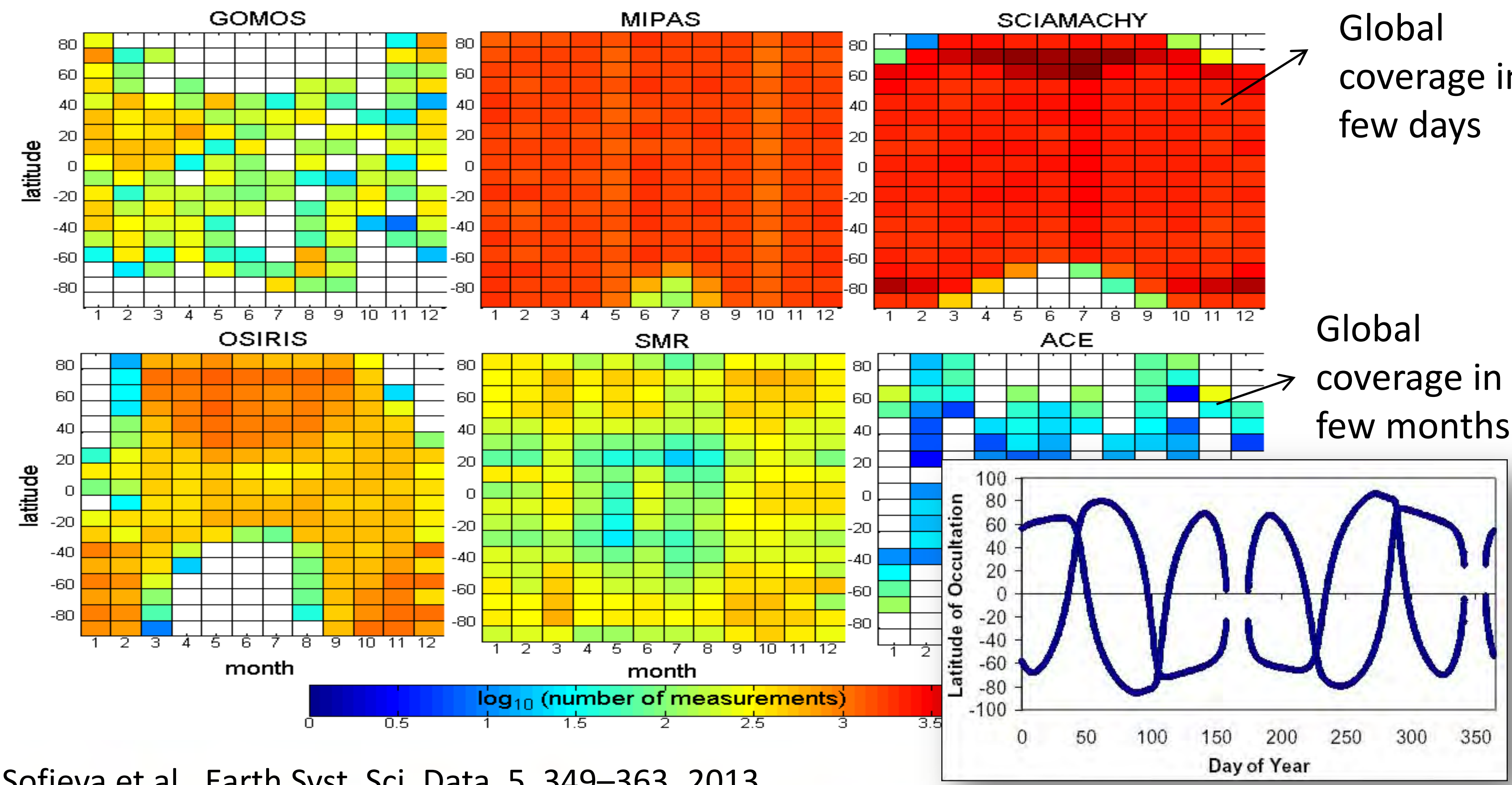
Ozone profiles from 6 limb sensors



V. Sofieva, FMI

Monthly zonal mean profiles of ozone mixing ratio (ppmv), for January 2008

Sampling of limb sensors

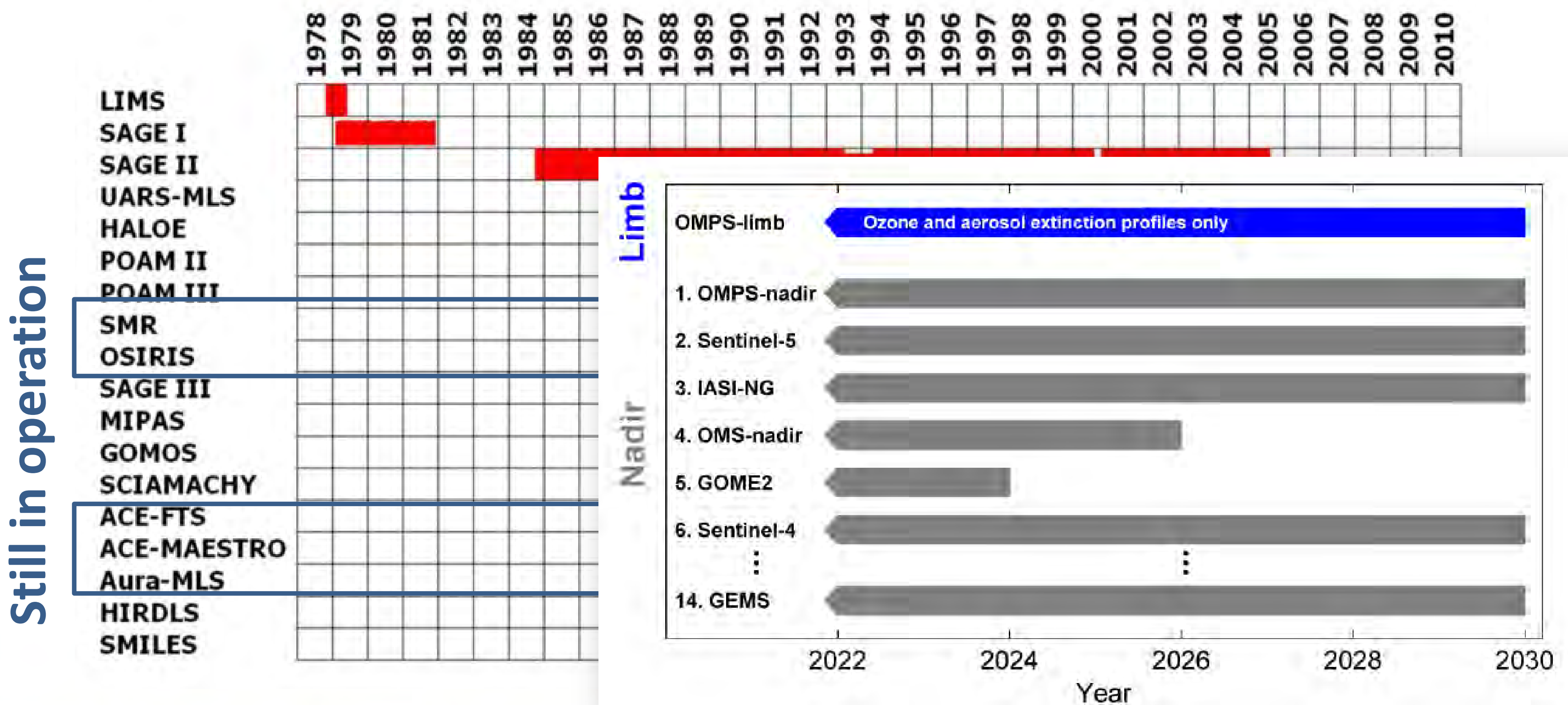


Global coverage in few days

Global coverage in few months

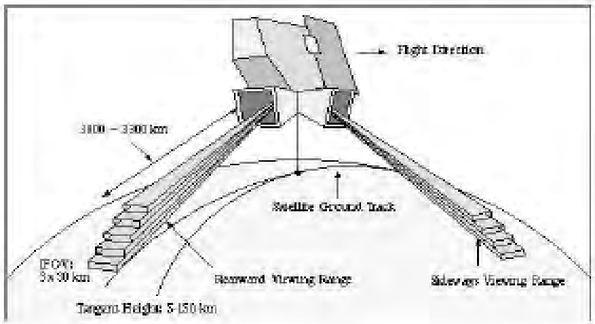
Sofieva et al., Earth Syst. Sci. Data, 5, 349–363, 2013

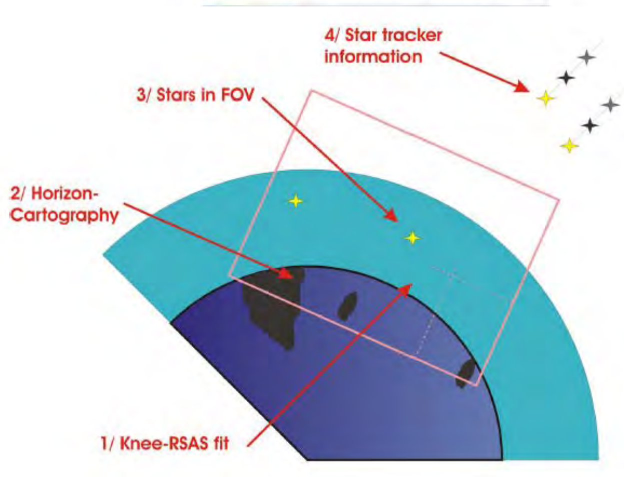
Data records from Limb-sounding satellite instruments between 1978 and 2010



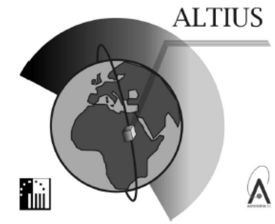
Altius: new limb imaging concept

Limb scanning





limb imaging



Recently approved as an ESA Earth Watch mission

Limb scan
Filter or grating spectrometers
No gradients

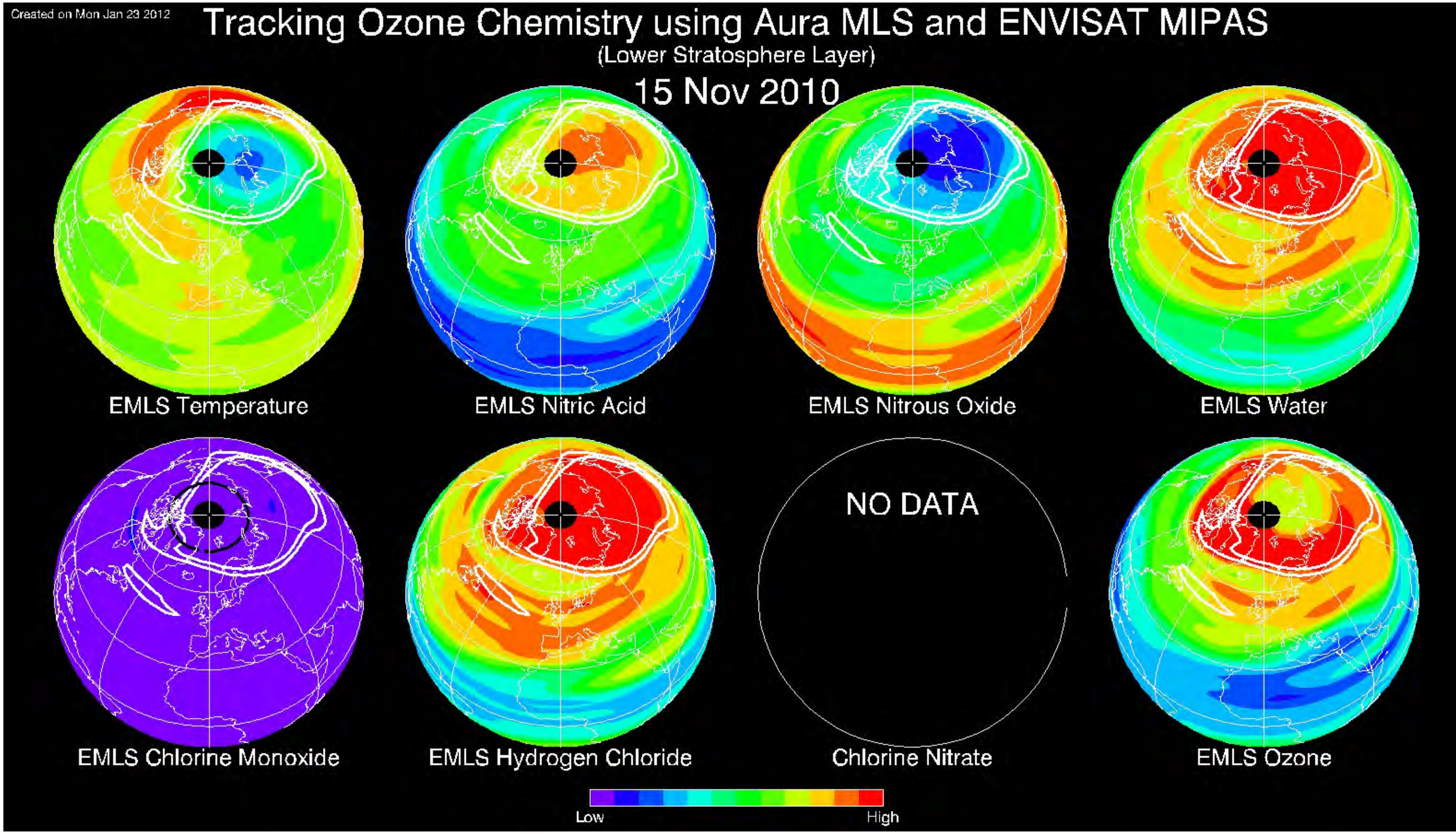
Full 2-D limb imaging
Acousto-optical and FP filters
Horizontal gradients

ALTIUS uses the simple concept of a spectral camera, i.e., a combination of an AOTF filter with a 2-D imager

HYPERSPECTRAL CUBE

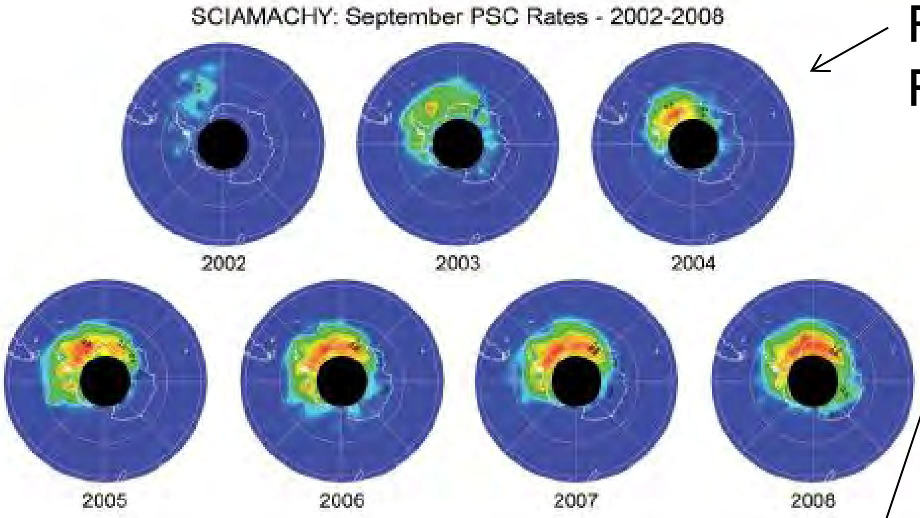
(wavelength x space) x space = wavelength x (space x space)

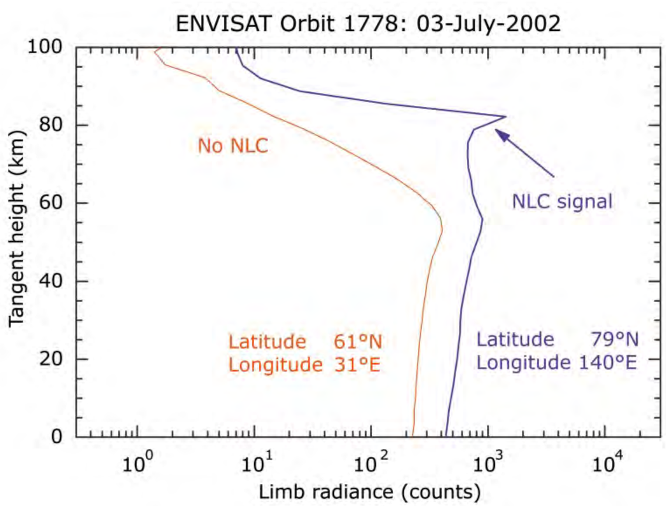
The very cold conditions in Arctic winter 2010/2011 led to the first Northern Hemisphere 'ozone hole'



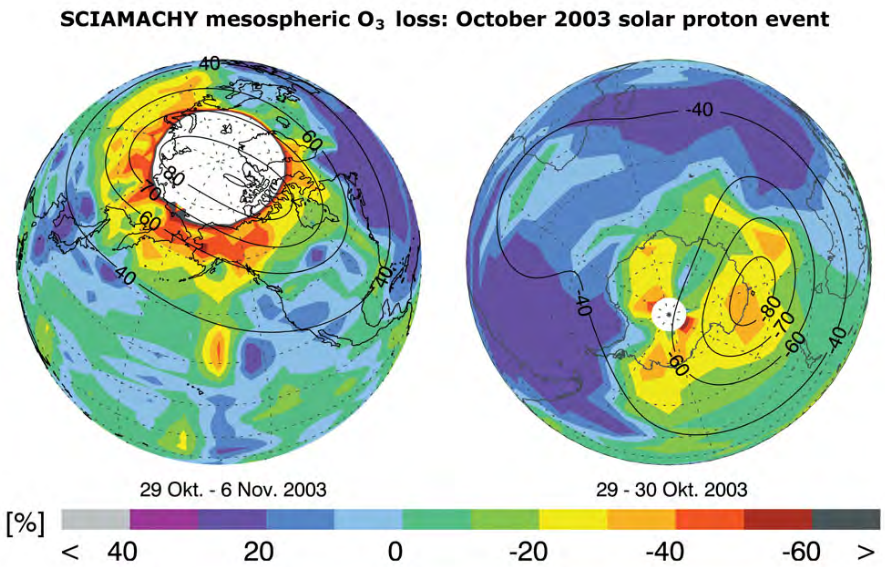
https://www.imk-asf.kit.edu/english/1189.php

Polar Stratospheric Clouds (PSC) and Polar Mesospheric Clouds (NLC)



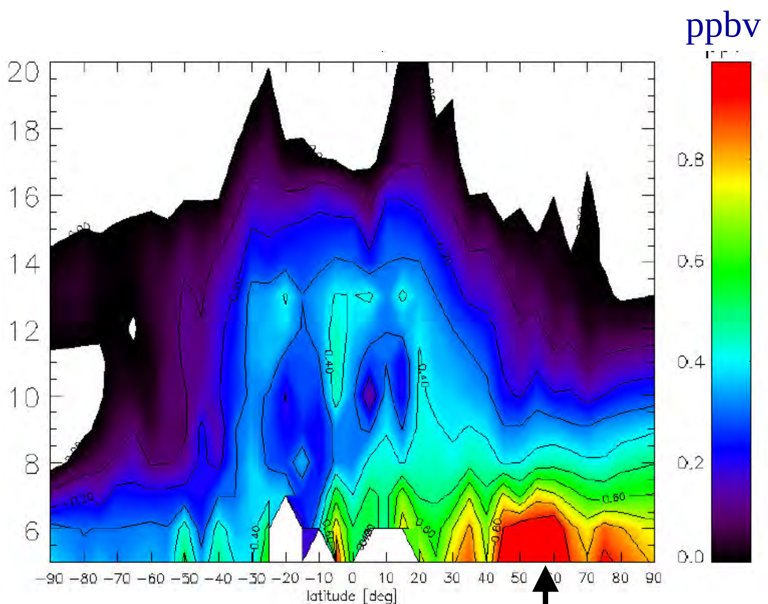


Mesospheric ozone loss due to solar proton event (Oct 2003)



Limb TIR UPPER-TROPOSPHERIC SOUNDINGS

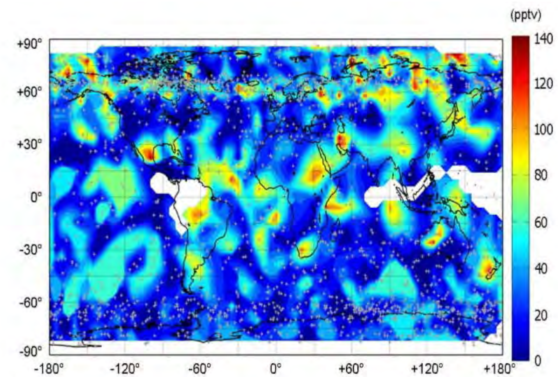
Ethane (C_2H_6) from MIPAS

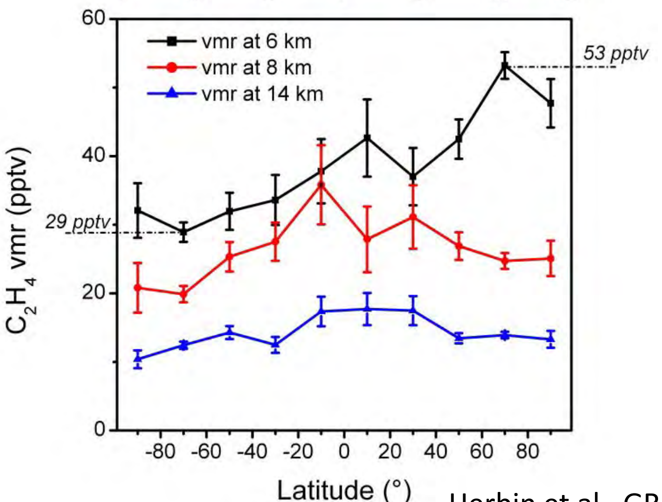


Anthropogenic emissions

Courtesy of G.Stiller, KIT

Ethene (C_2H_4) from ACE-FTS

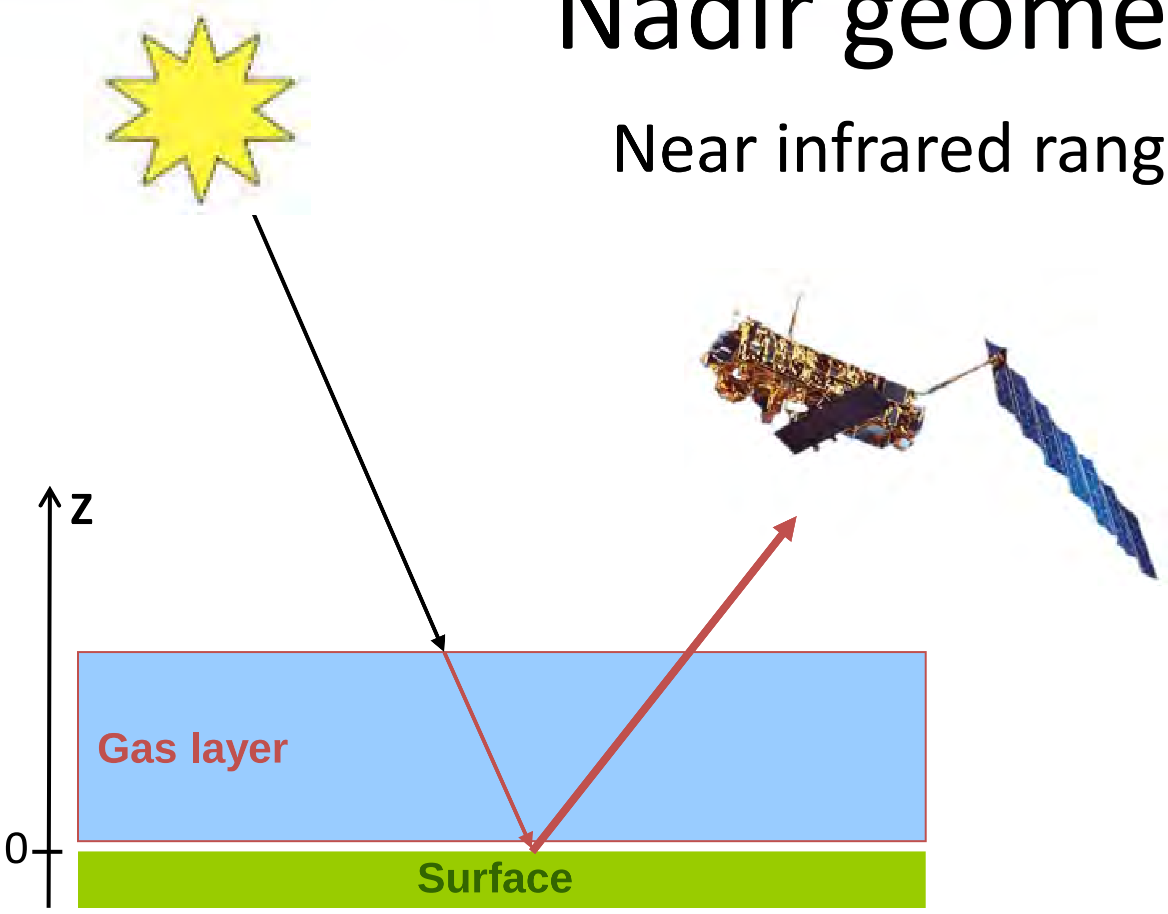


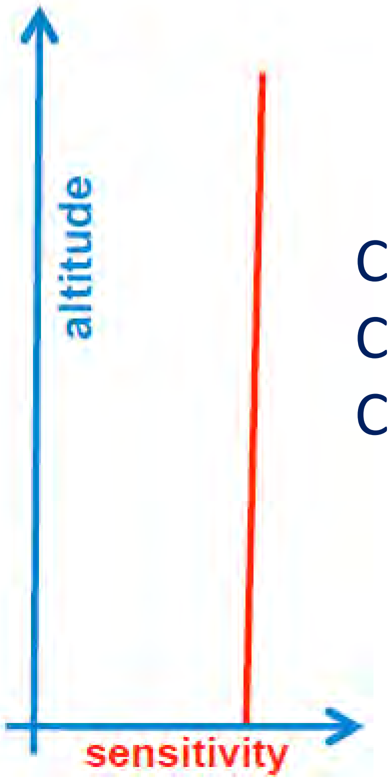


Herbin et al., GRL, 2009

Nadir geometry

Near infrared range

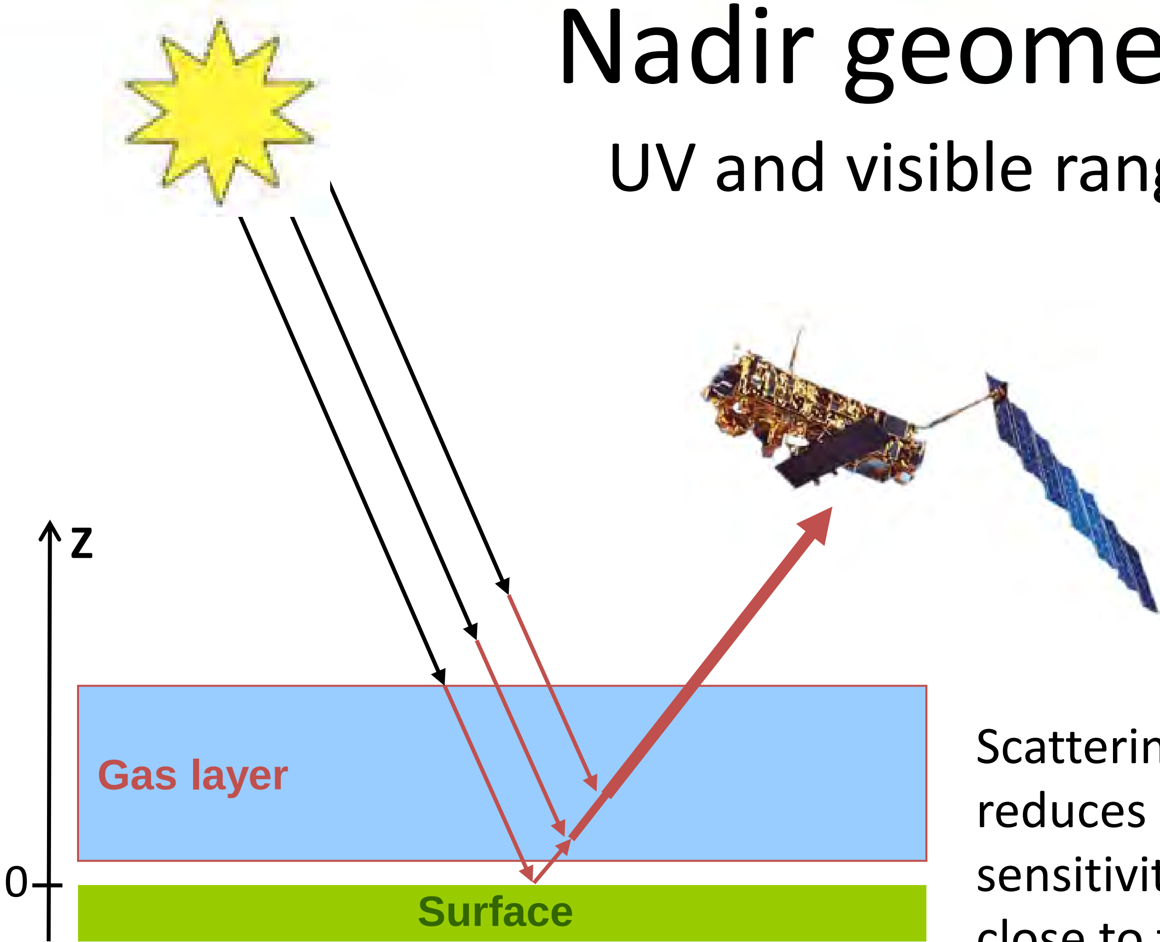




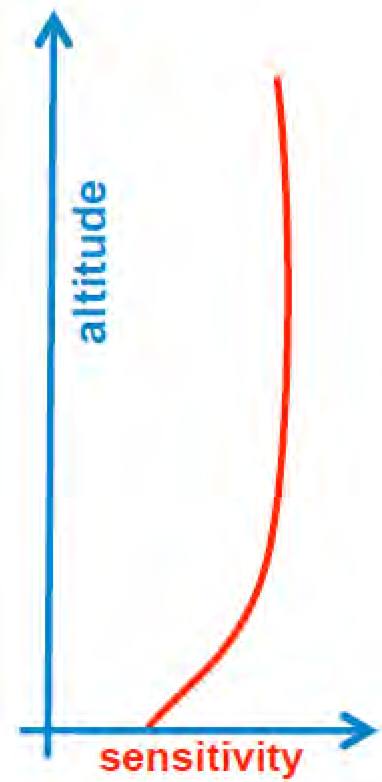
CO_2
CH_4
CO

Nadir geometry

UV and visible range



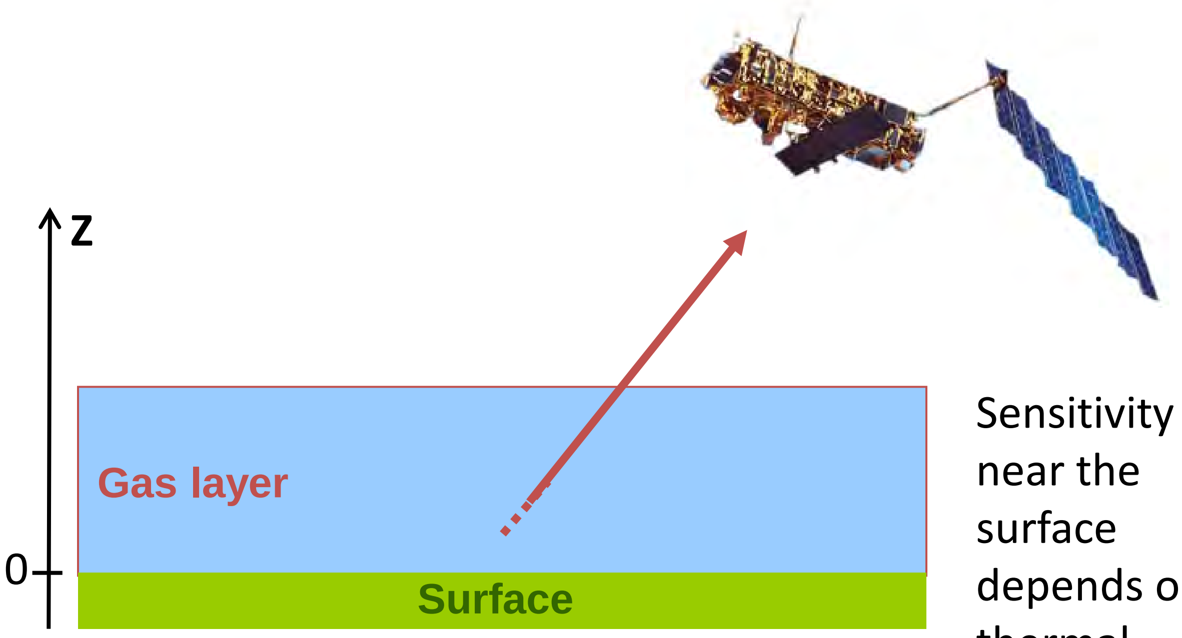
Scattering reduces sensitivity close to the surface



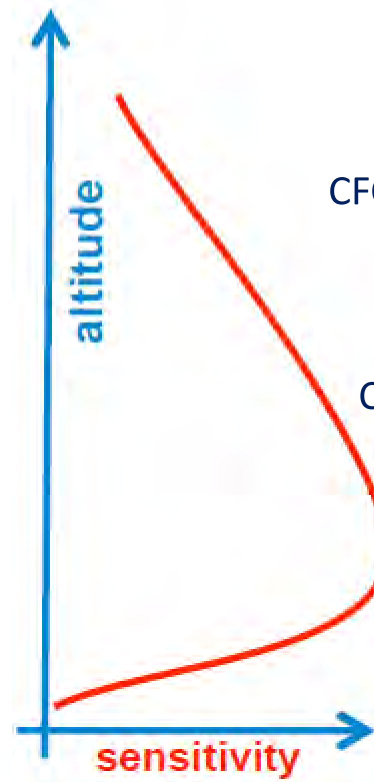
O_3
NO_2
SO_2
H_2CO
BrO
…

Nadir geometry

Thermal infrared range

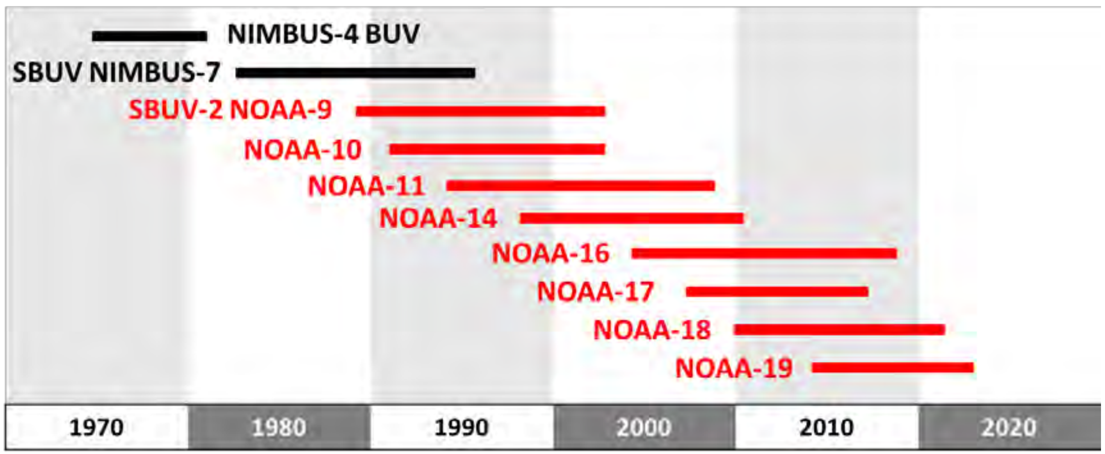


Sensitivity near the surface depends on thermal contrast



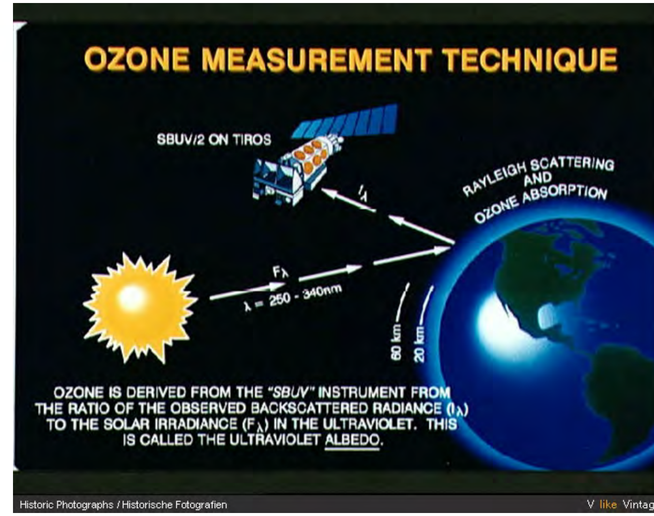
H_2O
N_2O
O_3
CO
HNO_3
NH_3
SO_2
CFC11, CFC12,
…
CH_3OH,
HCOOH,
C_2H_2, C_2H_6,…

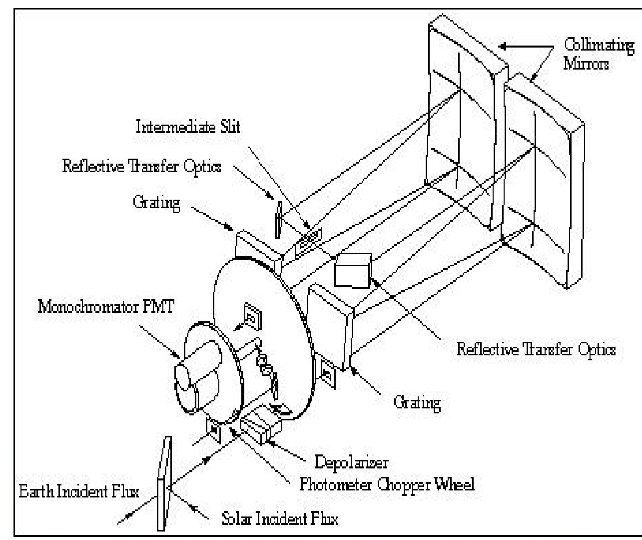
Solar Backscatter UV (SBUV)



- Retrieval of ozone profile information from measurements at several wavelengths

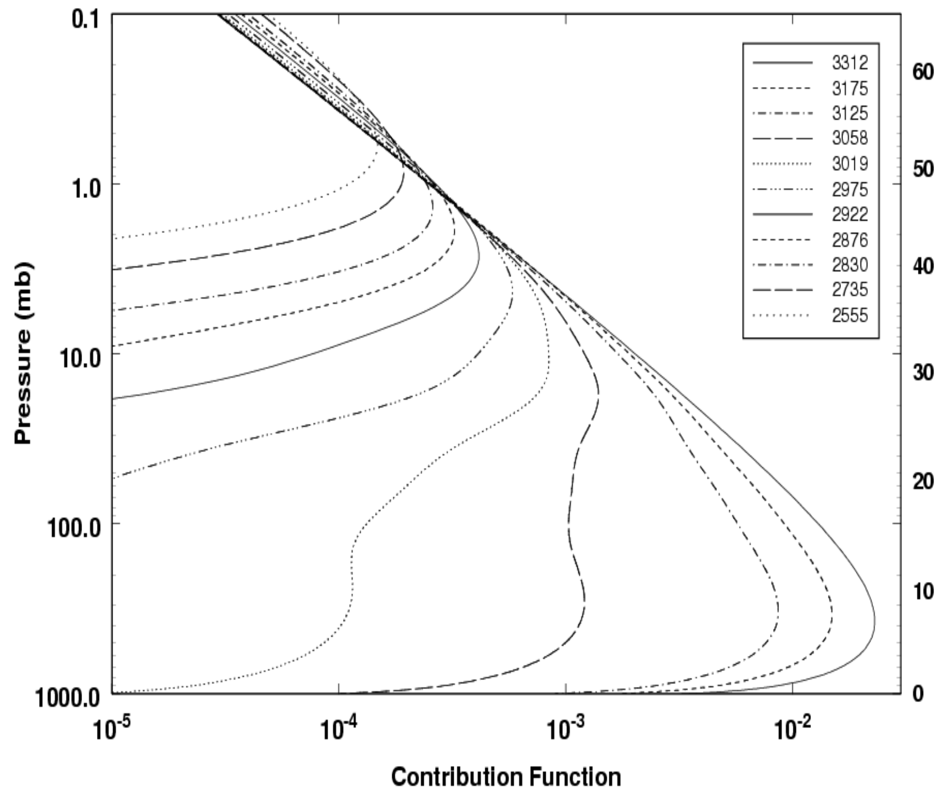
- 12 wavelengths (250 – 340 nm)
- spectral band with of the channels : 1.1 nm
- horizontal resolution : 200 x 200 km^2
- vertical resolution : approx. 8 km





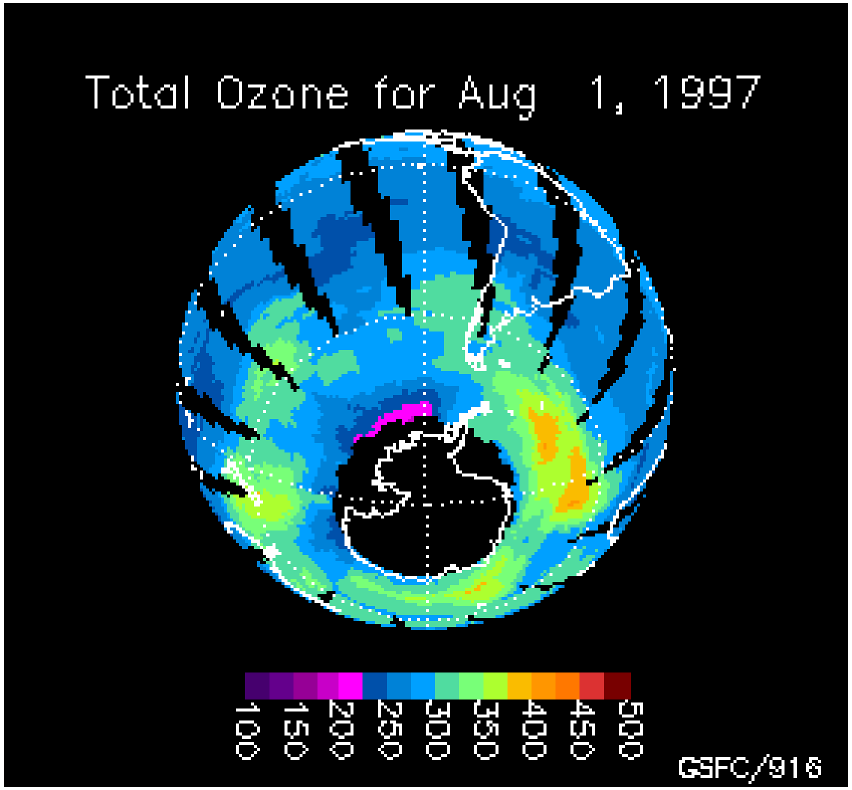
SBUV measurement principle

- Because of the large ozone absorption the penetration depth depends on the wavelength
- Comparison of measurements at different wavelengths provides profile information



Total Ozone Mapping Spectrometer (TOMS)

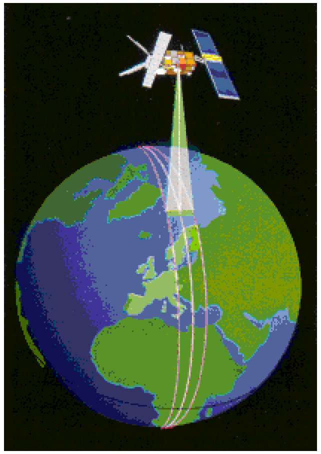
- Global total ozone mapper
- 6 wavelengths in the UV
- good spatial resolution (50x50 km^2)
- global coverage in 1 day
- Additional products (SO_2, aerosols)



The TOMS programme:

Satellite	Period
Nimbus 7	Oct 78 – May 93
Meteor3	Aug 91 – Dec 94
Adeos	Aug 96 – Jun 97
Earth Probe	Jul 96 – Dec 97
	Dec 97 – Dec 2006

Global Ozone Monitoring Experiment (GOME)



- First simultaneous measurements of complete spectrum from the UV to the near IR
- good spectral resolution (0.2 – 0.4 nm)
- use of DOAS to retrieve columns of a number of species (O_3, NO_2, OClO, BrO, HCHO, SO_2, H_2O)
- use of UV wavelengths to retrieve ozone profiles (BUV technique)
- global coverage in 3 days

Operation on ERS-2:

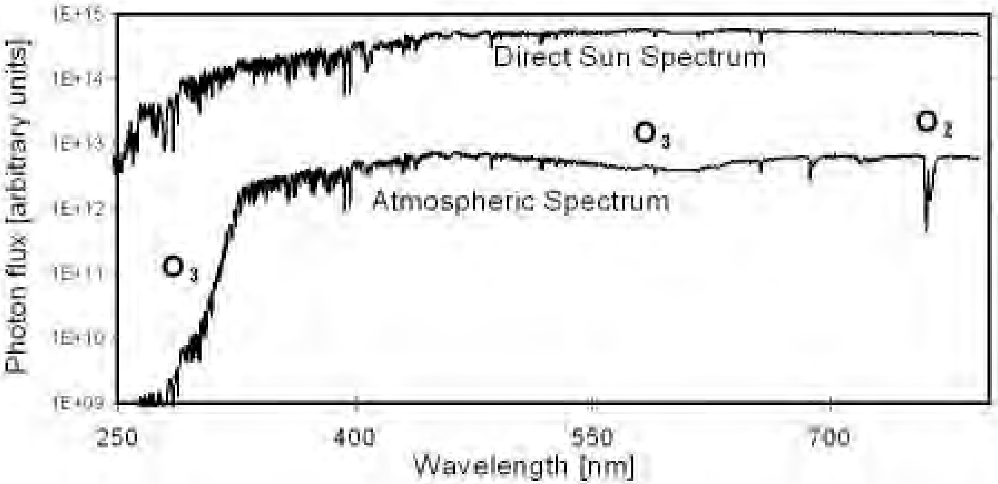
From April 1995 until July 2011

Successors:

SCIAMACHY ENVISAT (2002-2012)

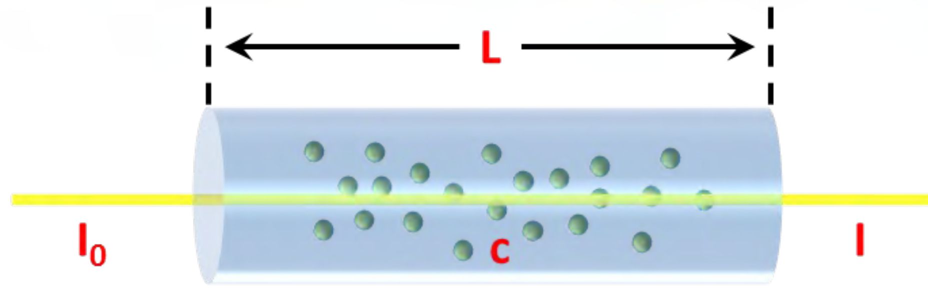
GOME-2 METOP (2006-now)

OMI AURA (2004-now) …



Differential Optical Absorption Spectroscopy

Beer-lambert law applied to light transmission through a slab in the atmosphere



$$I(\lambda) = I_0(\lambda) \cdot e^{-\left[\sum \sigma_i(\lambda) \cdot c_i \cdot L \,+\, \left(\varepsilon_{Ray}(\lambda) + \varepsilon_{Mie}(\lambda)\right) \cdot L\right]}$$

Trace gases

Rayleigh scattering ~ λ^{-4}

Mie Scattering ~ $\lambda^{-(1\ldots3)}$

DOAS → Frequency separation in the wavelength space

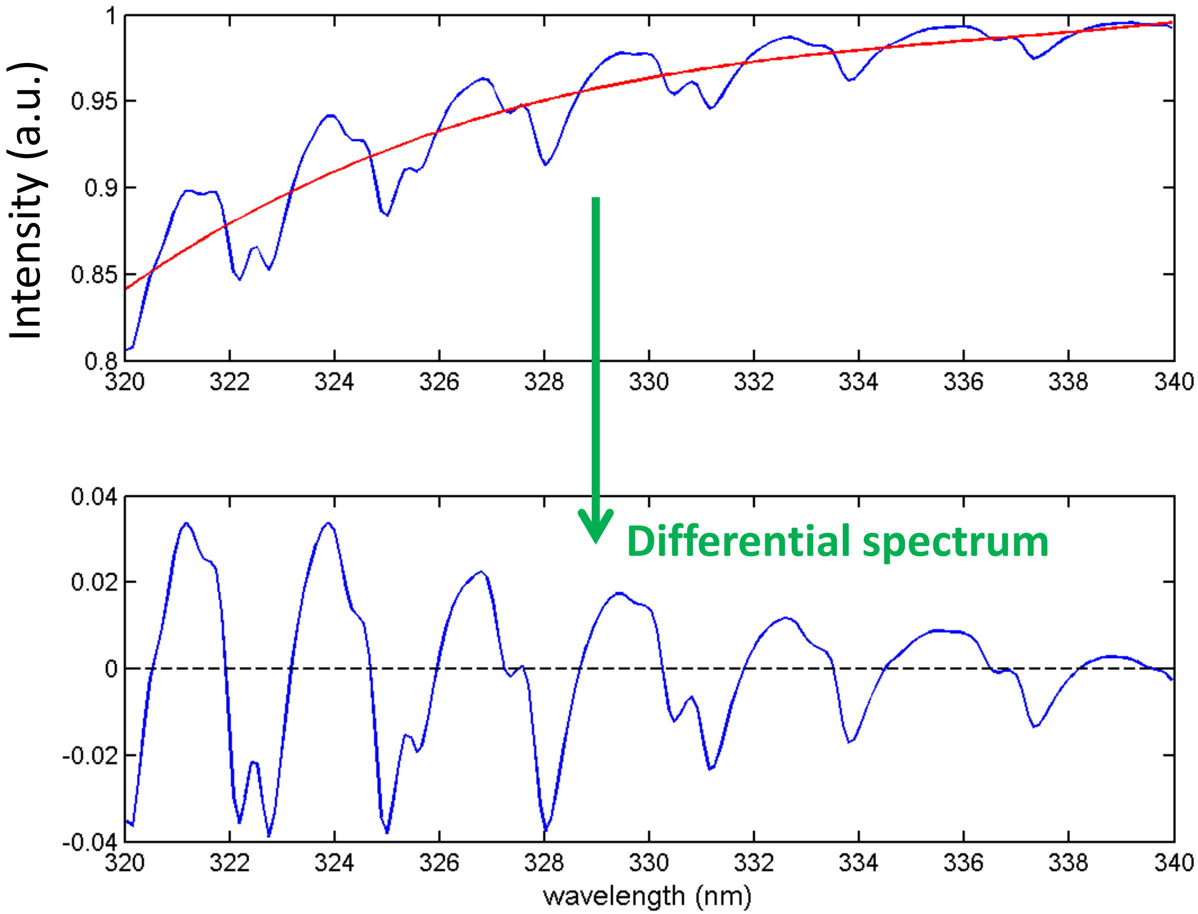
$$I(\lambda) = I_0(\lambda) \cdot e^{-\left[\underbrace{\sum \sigma'_i(\lambda) \cdot c_i \cdot L}_{\text{High frequency}} \,+\, \underbrace{\left(\sigma_{bi}(\lambda) + \varepsilon_{Ray}(\lambda) + \varepsilon_{Mie}(\lambda)\right) \cdot L}_{\text{Broadband band extinction}}\right]}$$

High frequency

Broadband band extinction

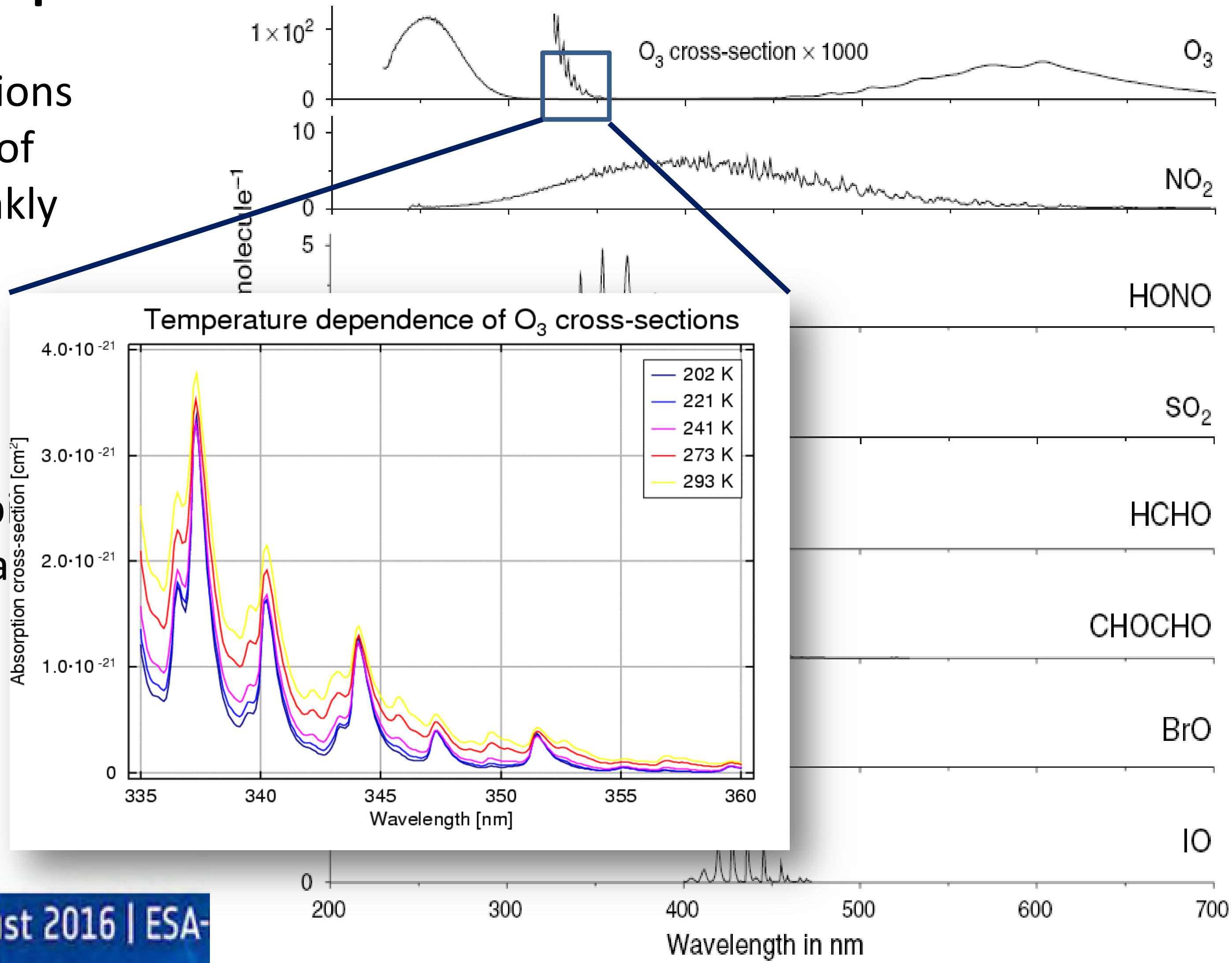
Remove by high-pass filtering

Exemple of frequency separation

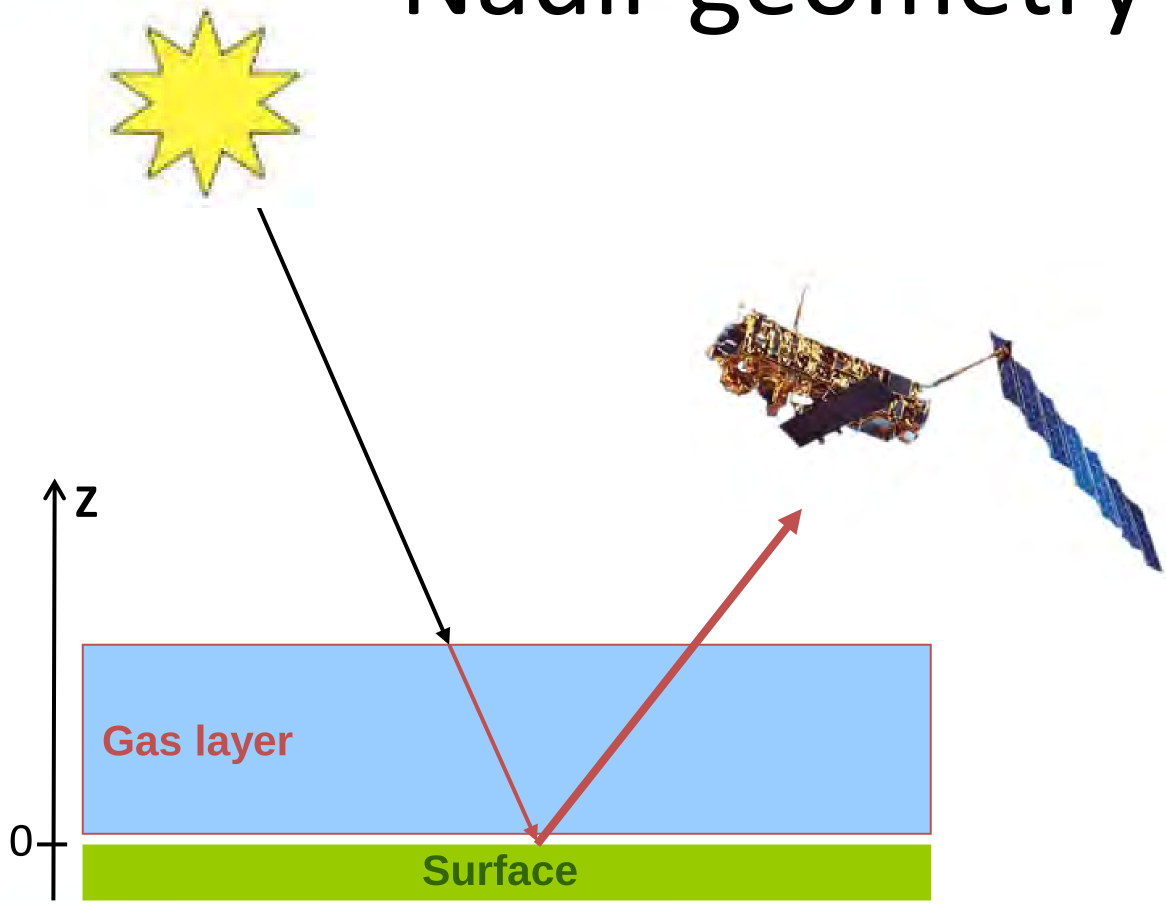


UV-Vis absorption cross-sections

- UV-Vis cross-sections are independent of pressure and weakly dependent on temperature (can linearised)
- Molecules absorbi UV-Vis are genera short-lived



Nadir geometry



Air Mass Factor (AMF)

The AMF is defined as the ratio of the trace gas slant optical density to the vertical one in the atmosphere:

$$AMF = \frac{\tau_s(\lambda, \Theta, \ldots)}{\tau_v}$$

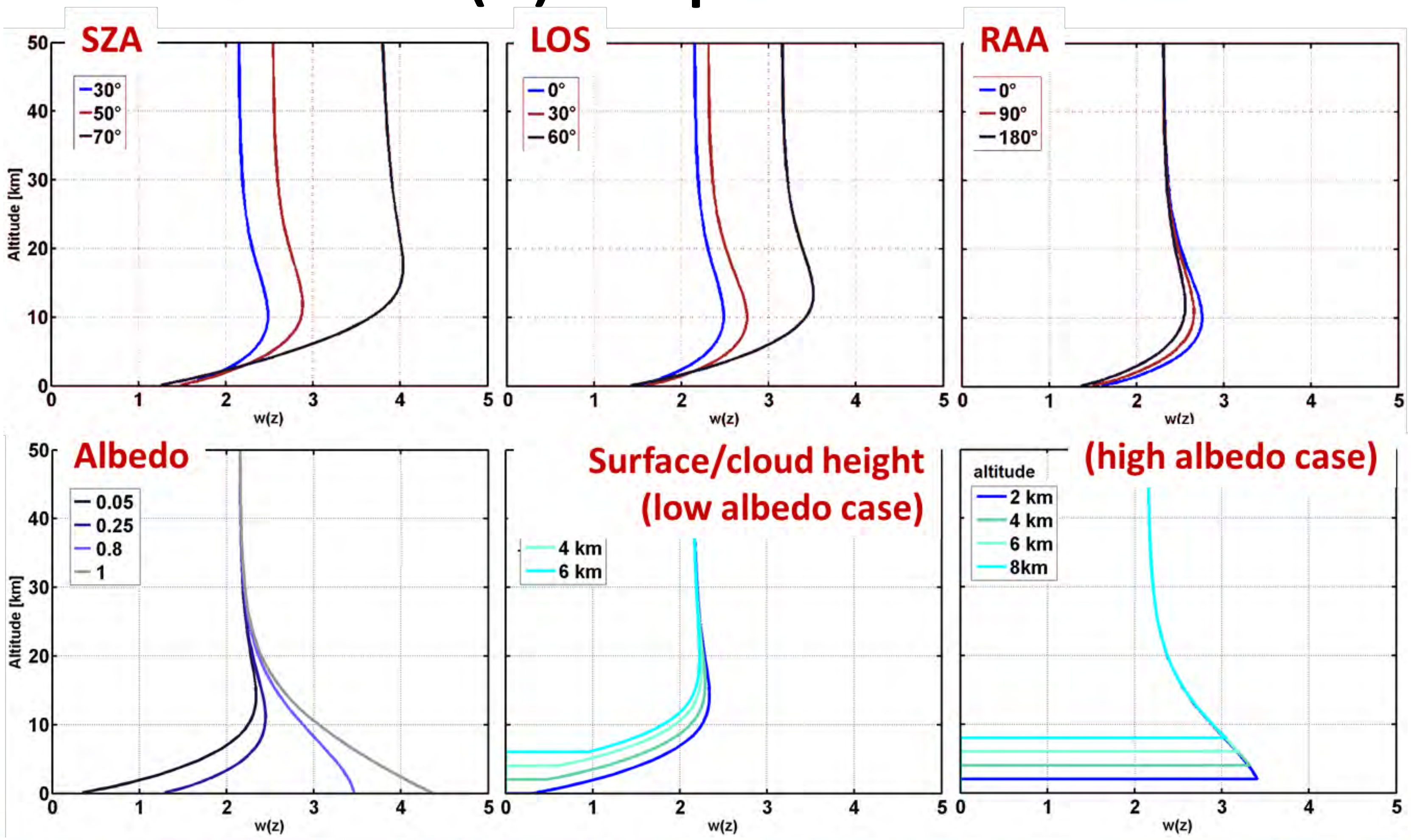
The AMF expresses the sensitivity of the measurement, and depends on a variety of parameters such as:

- wavelength
- geometry
- vertical distribution of the species
- clouds
- aerosol loading
- surface albedo

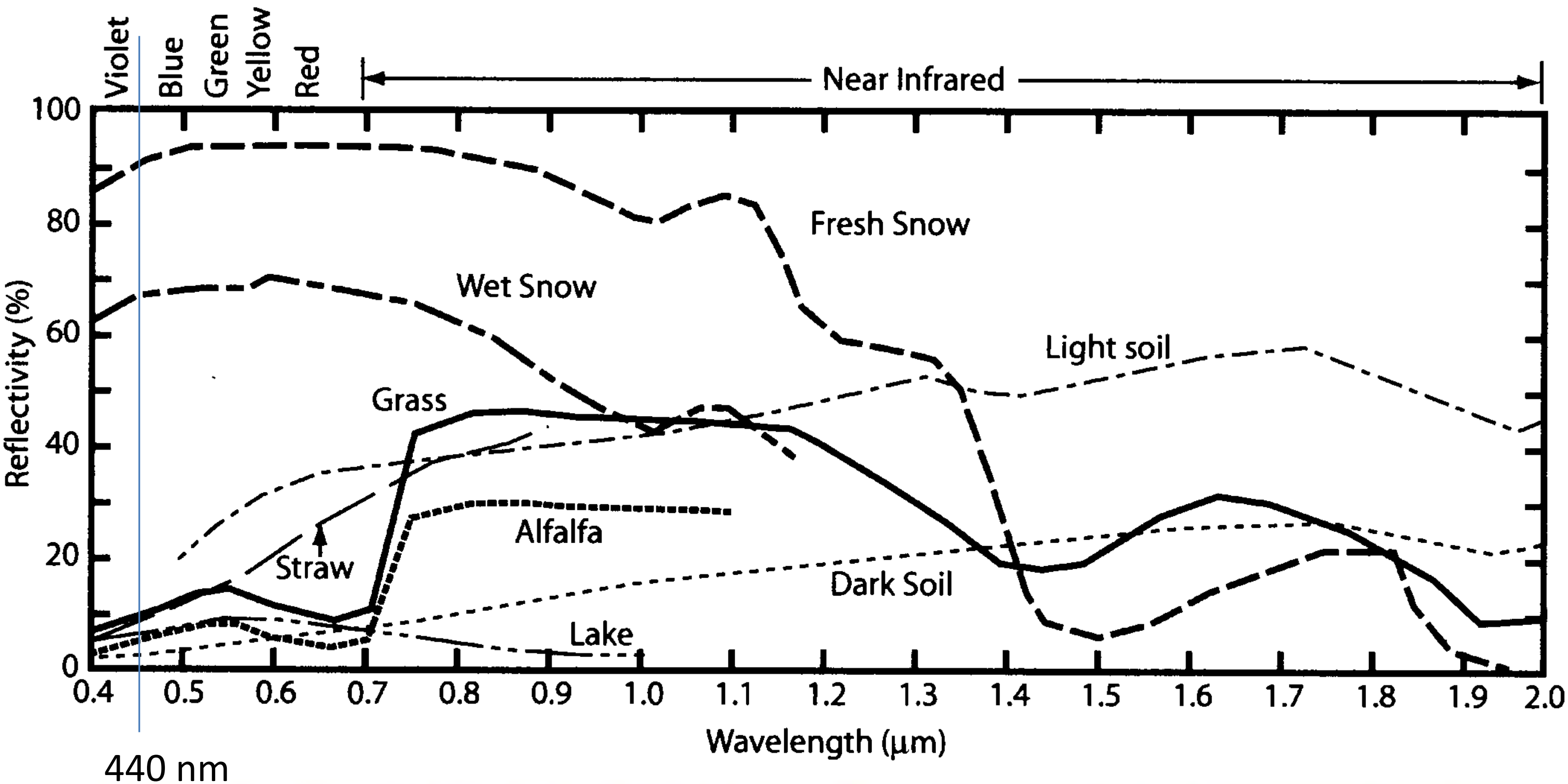
$$AMF(\lambda, \theta) = \frac{-\log\{ I^{-}(\lambda, \theta) / I^{+}(\lambda, \theta) \}}{\sigma(\lambda) \cdot VC}$$

Because of the optically thin approximation, the AMF depends weakly on the vertical column → the idea is that if all other dependences are known, the measured signal is proportional to the VC.

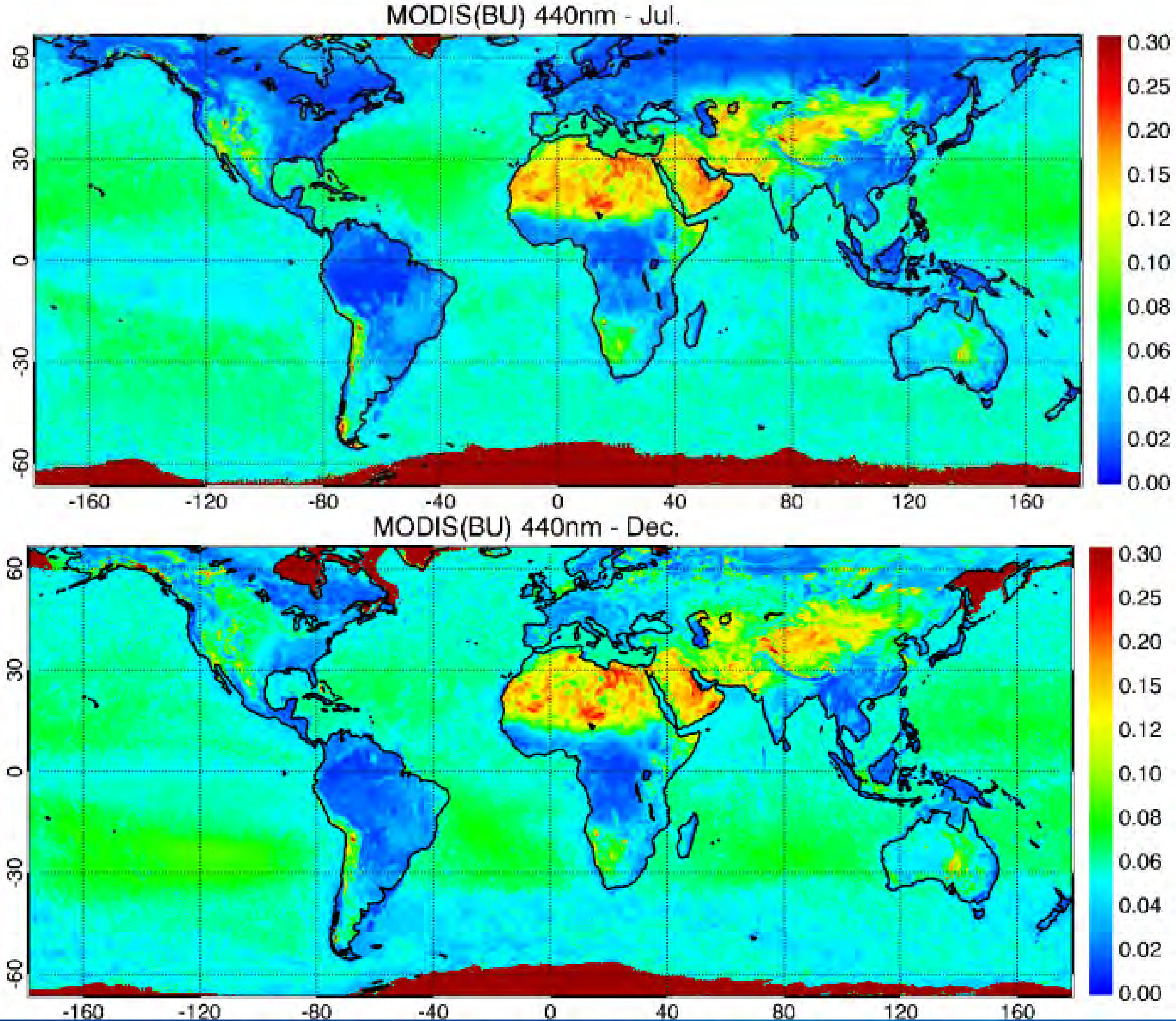
AMF(z) dependences



Surface albedo (or reflectivity)



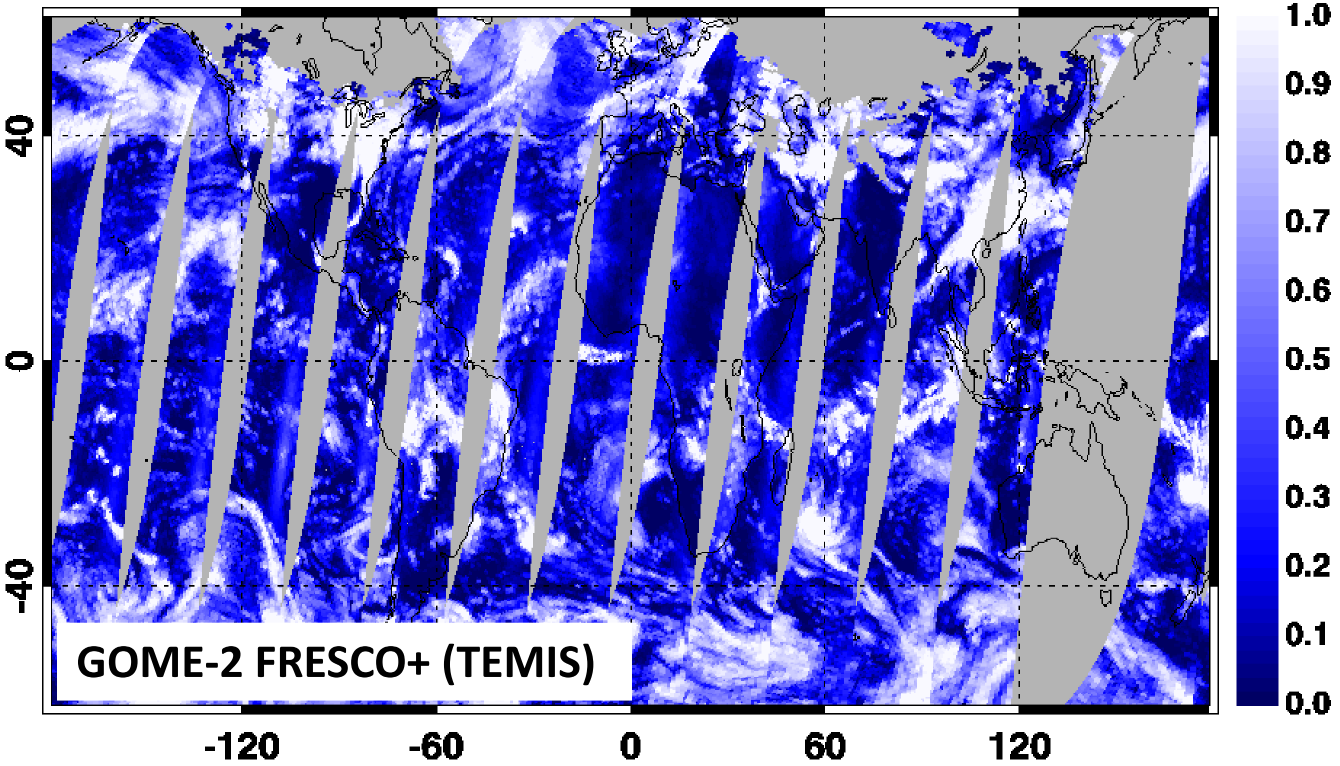
Surface albedo climatology (MODIS)



440 nm
July

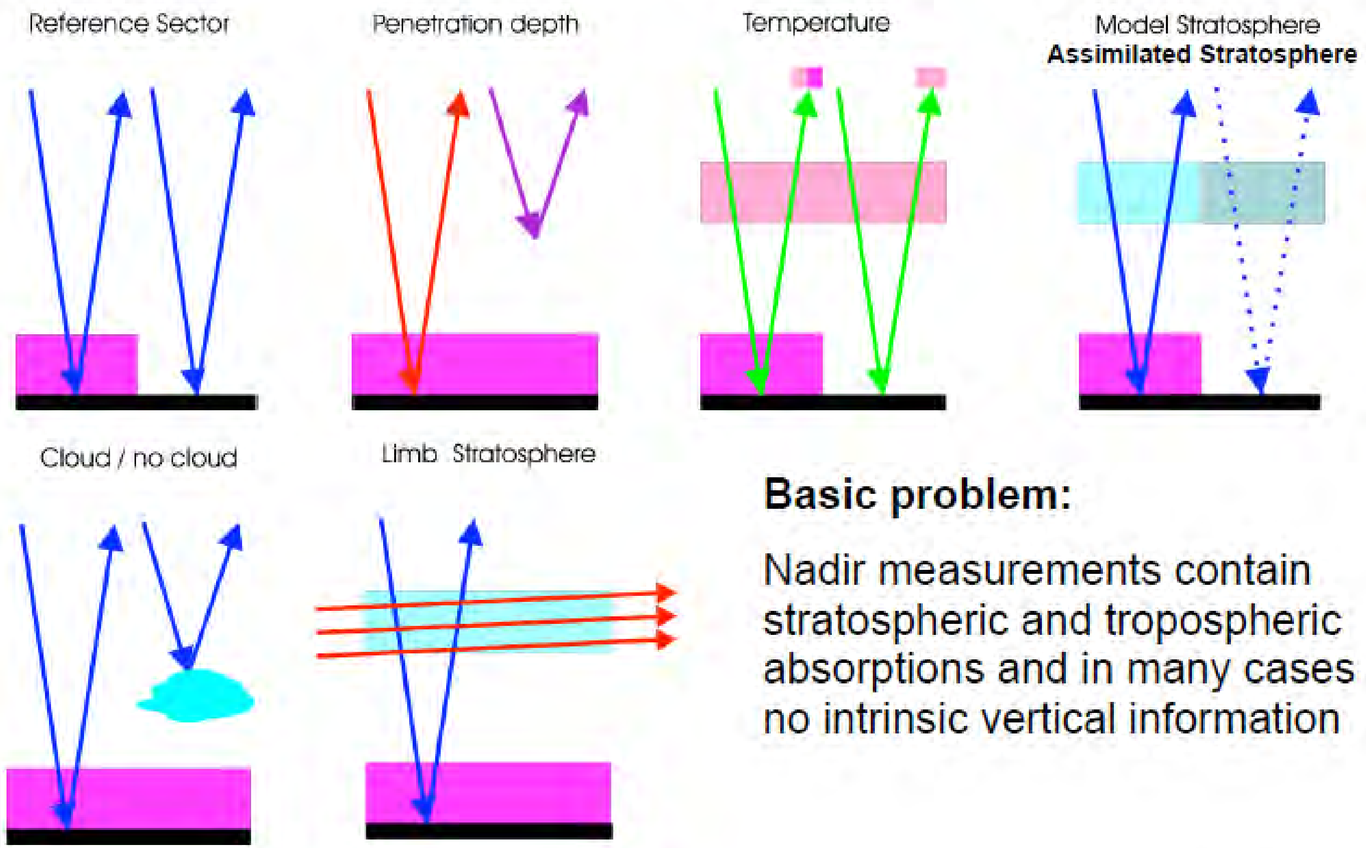
440 nm
Dec.

Cloud fractions



Clouds detected as bright targets above dark surfaces.
Their altitude can be derived from depth of O_2-A band absorption in the NIR.

How do we get vertical resolution in nadir UV/vis observations?

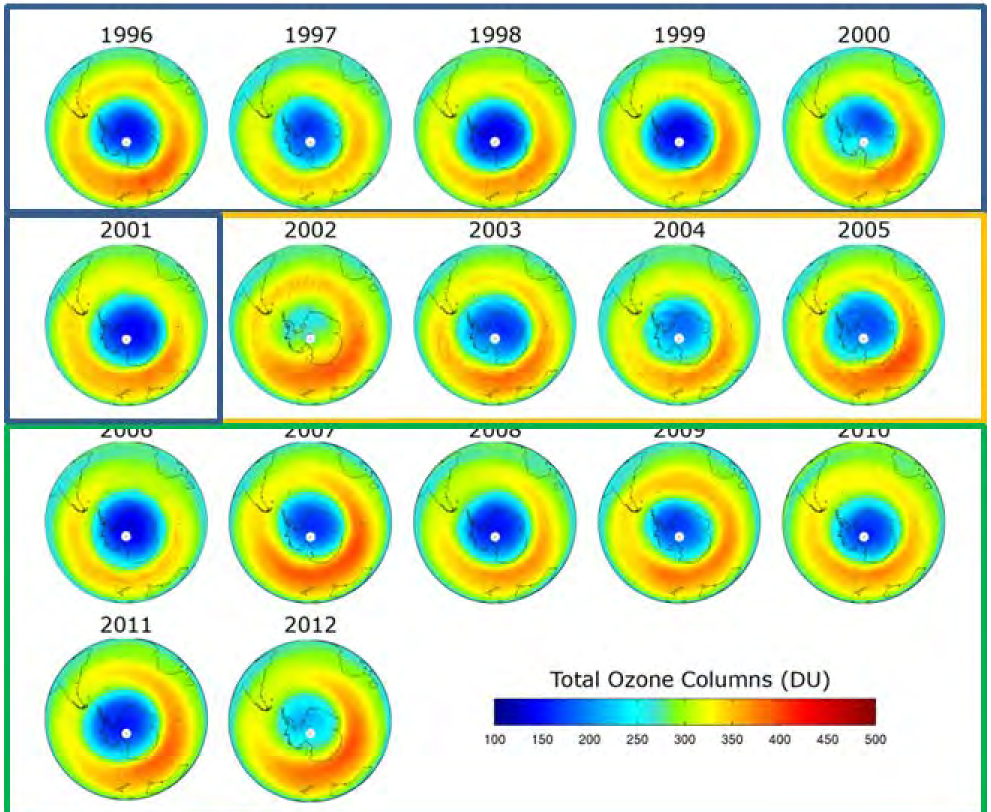


Basic problem:

Nadir measurements contain stratospheric and tropospheric absorptions and in many cases no intrinsic vertical information

A few highlights from GOME and successor missions

Long-term ozone monitoring



GOME

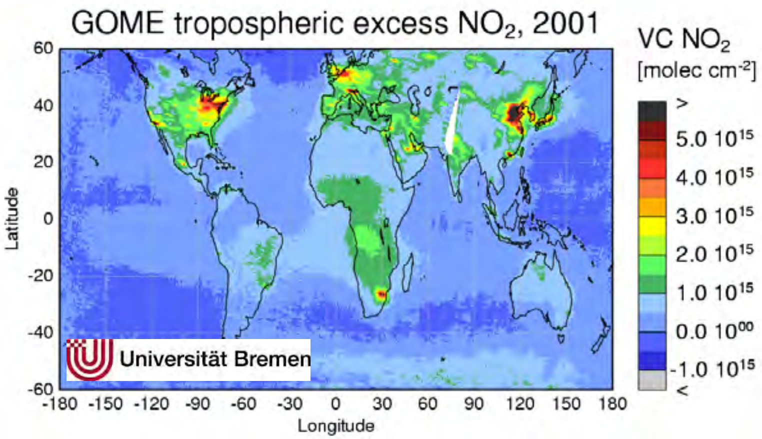
SCIAMACHY

GOME-2

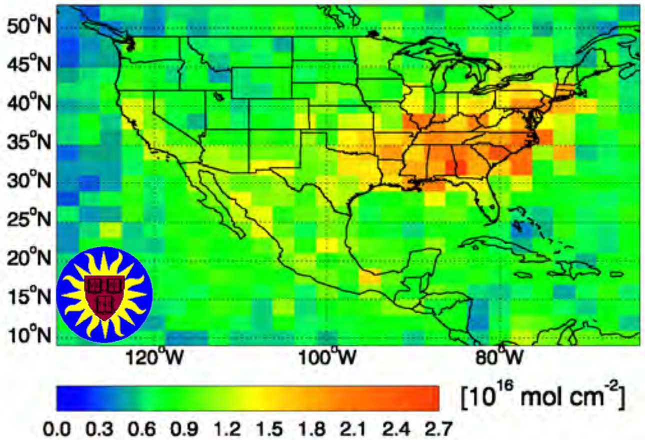
OMI

....

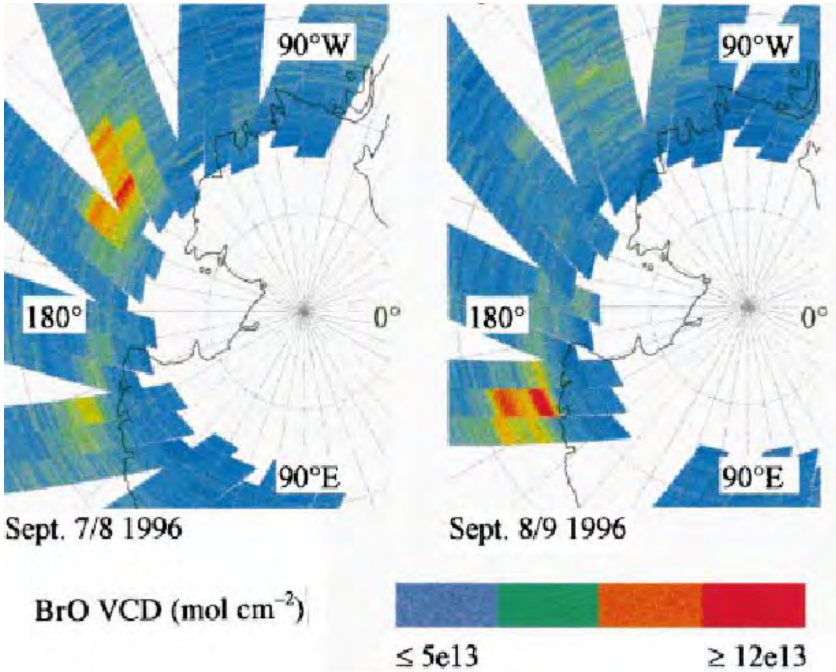
ESA CCI



GOME formaldehyde, July 1996

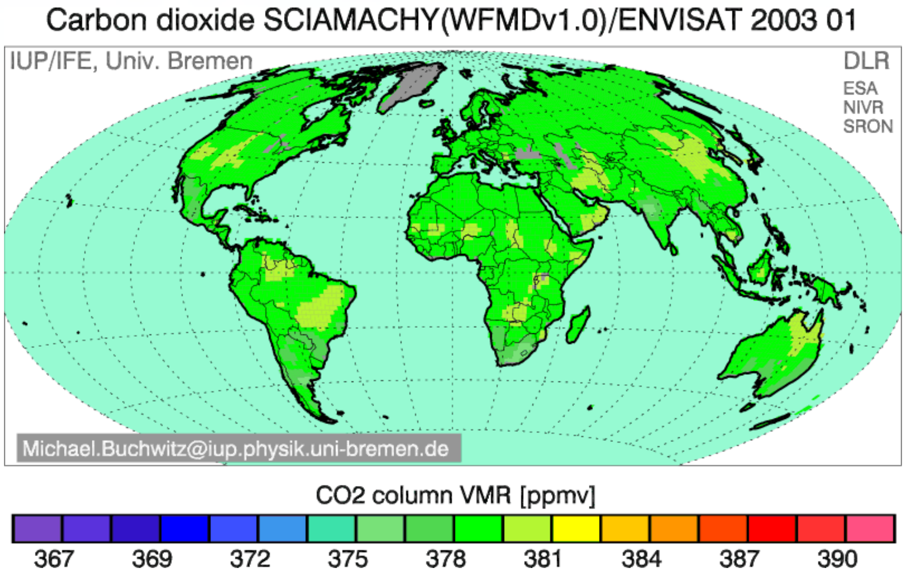


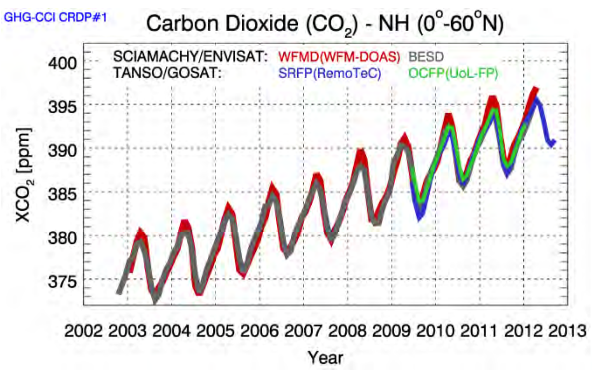
Polar BrO « explosion events »

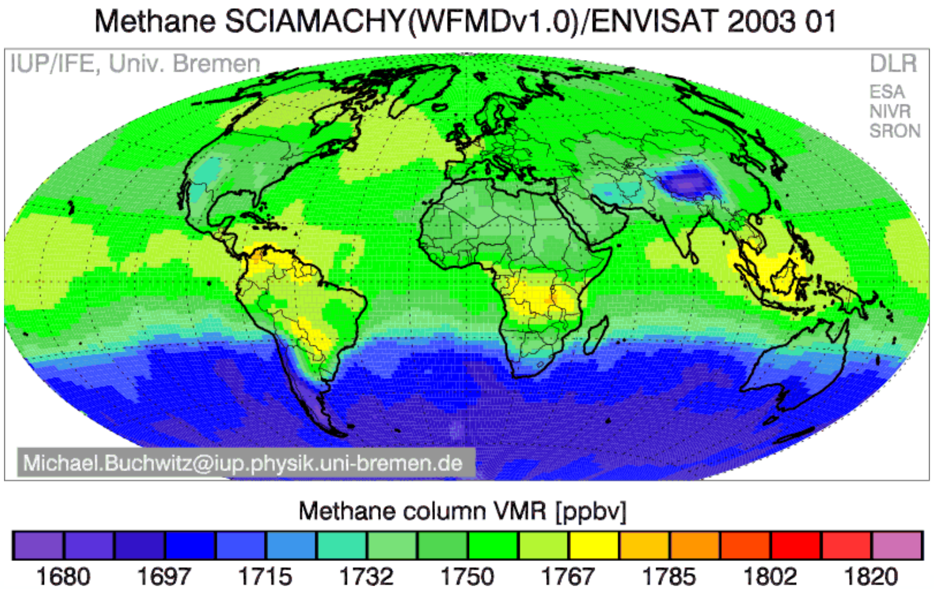


Wagner and Platt, Satellite mapping of enhanced BrO concentrations in the troposphere, *Nature*, **395**, 1999, 486-490

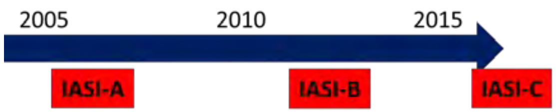
SCIAMACHY → mapping of carbon gases CO_2 and CH_4





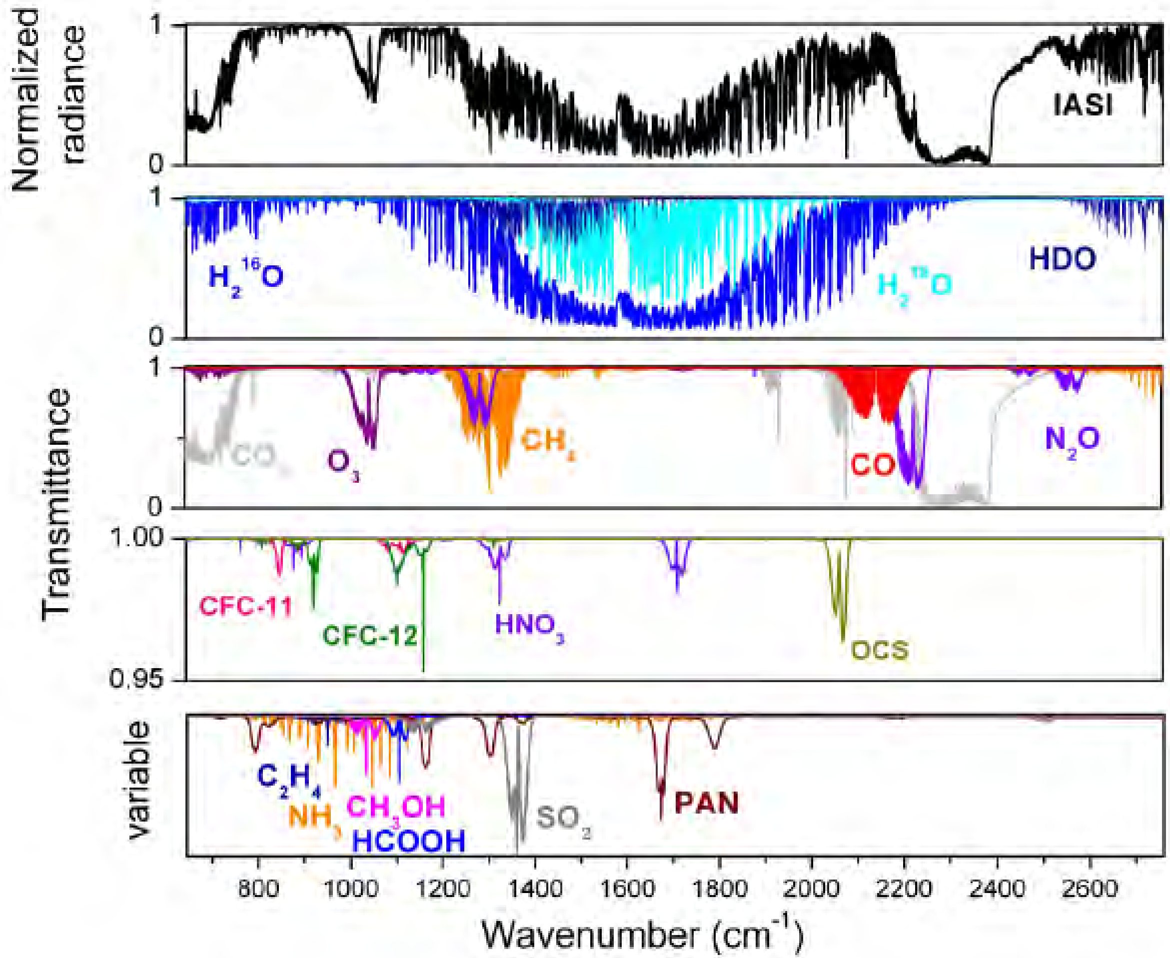


MetOp IASI



Infrared
Atmospheric
Sounding
Interferometer

- *advanced* thermal IR sounder.
- global measurements 2 times per day (at 9h30 and 21h30 local solar time)



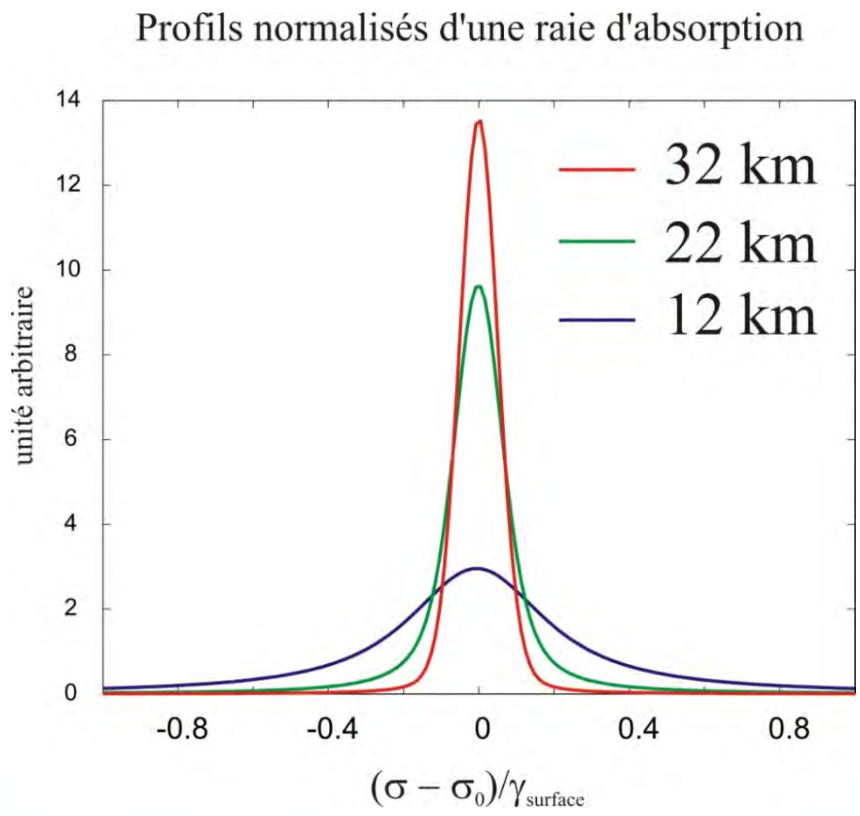
Vertical profile information from TIR

Altitude information can be derived from:

1. Pressure broadening of absorption lines
2. Temperature dependence of line strengths

Vertical profile information up to ~35 km max

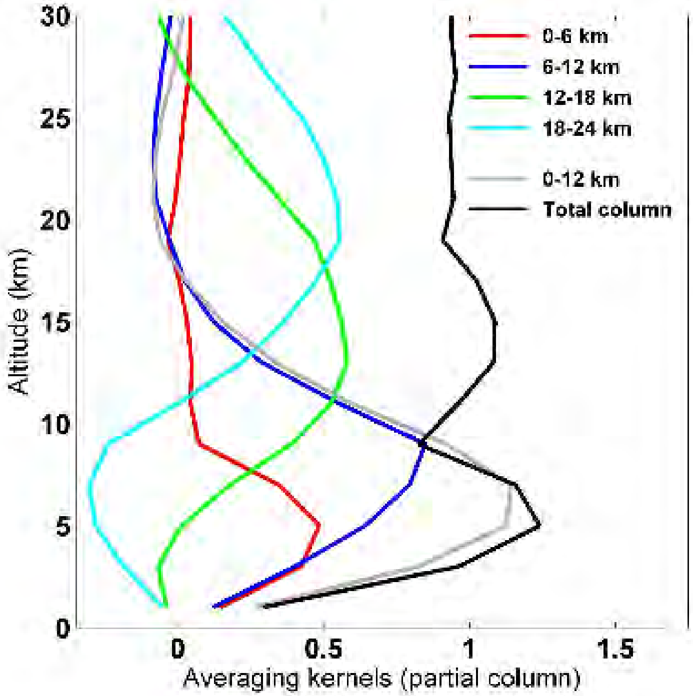
Details of retrievable profile information depend on molecule, S/N, spectral resolution of instrument…



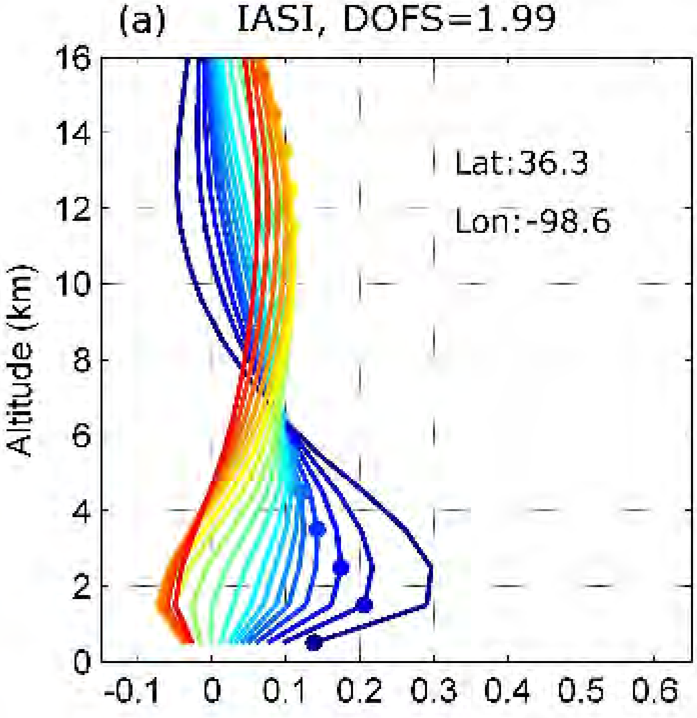
Examples of averaging kernels for ozone and CO

Ozone

IASI, DOFS=3.5



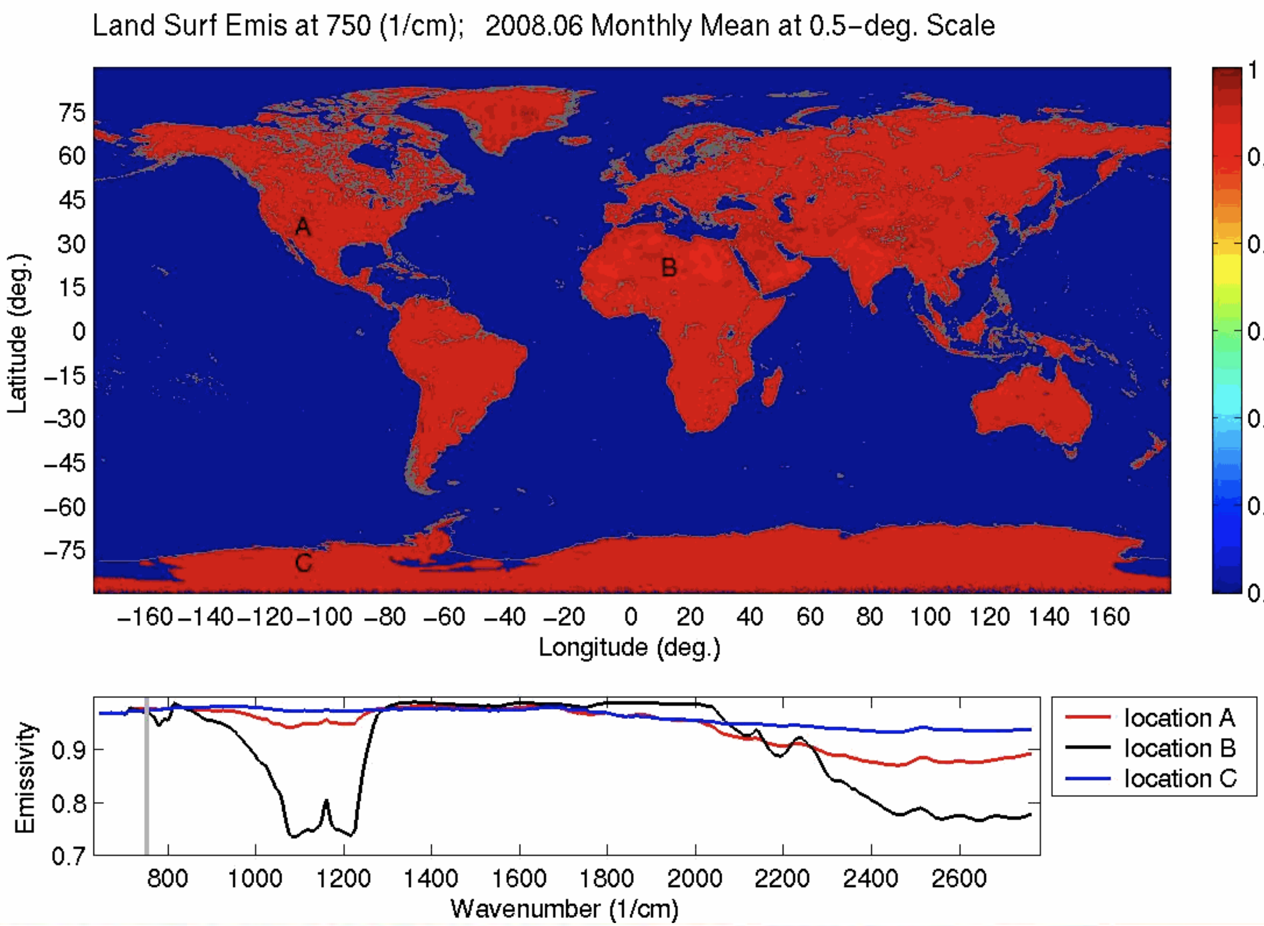
CO



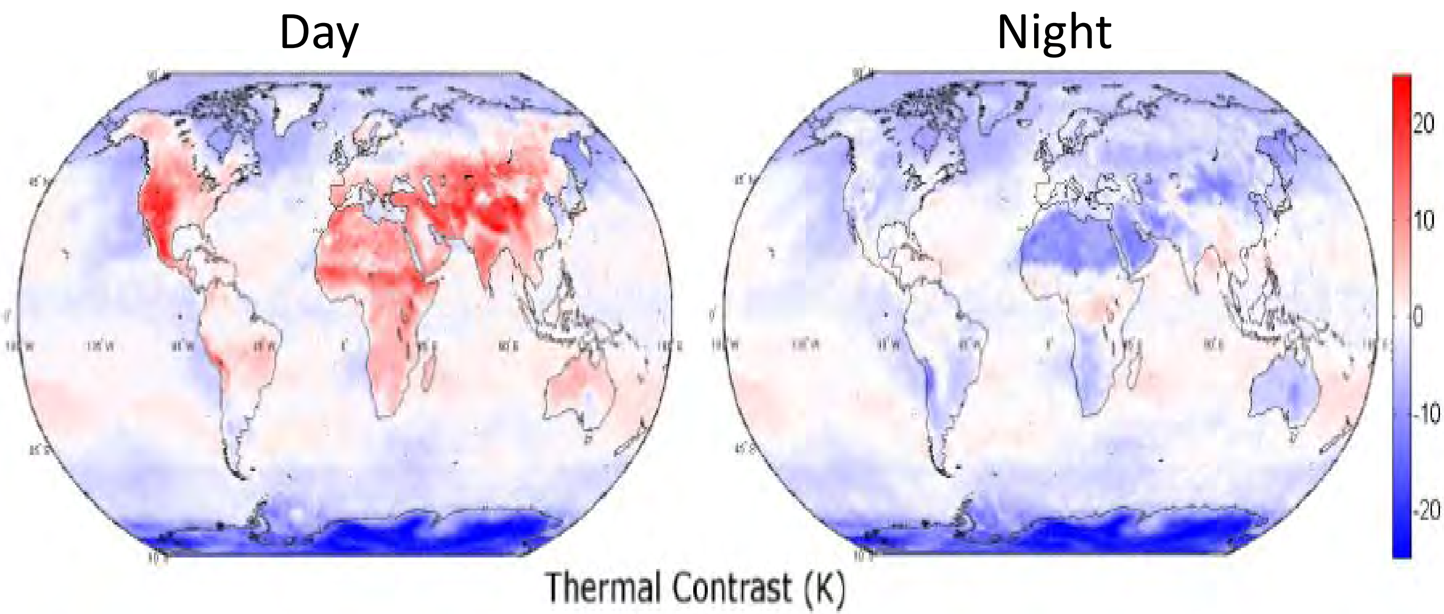
Averaging kernels

Surface emissivity

Emissivity retrieved from satellite hyperspectral imagers (IASI)



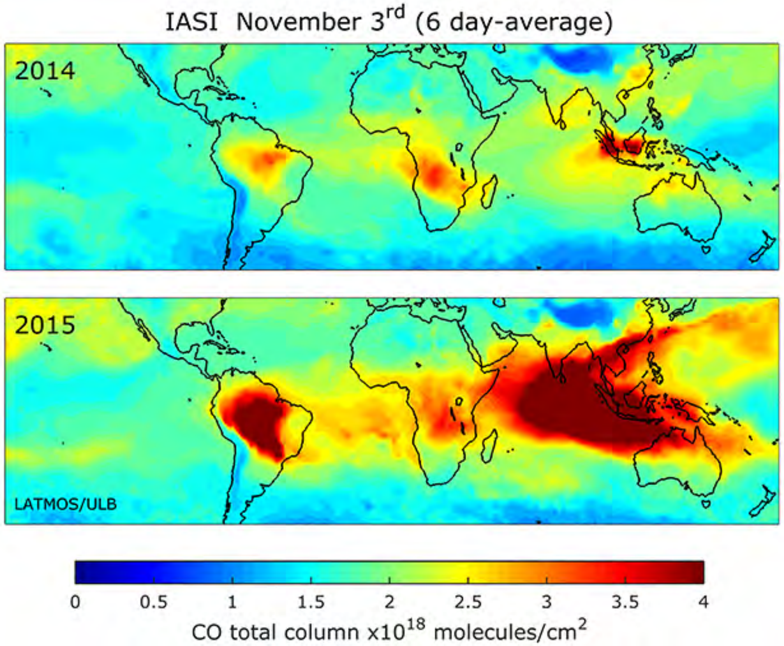
Thermal contrast (IASI)



Thermal contrast is highest in the morning over land surfaces

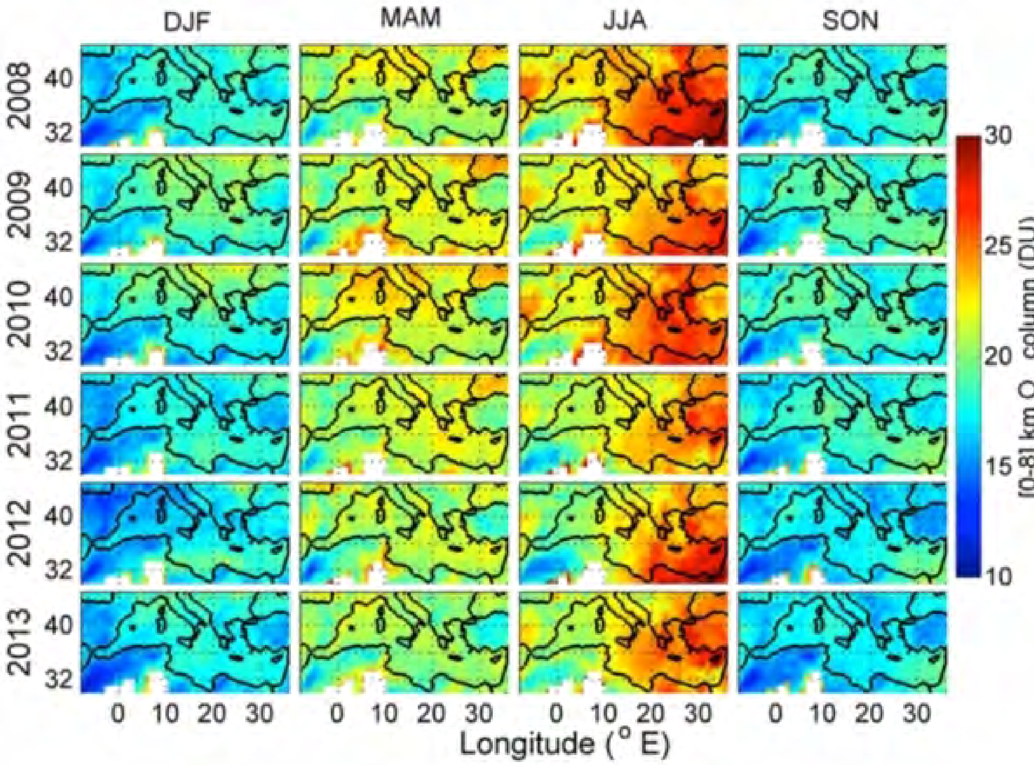
Clerbaux et al, Atmos. Chem. Phys., 9, 6041–6054, 2009

A few IASI highlights



CO concentrations due to fires observed last fall over Indonesia

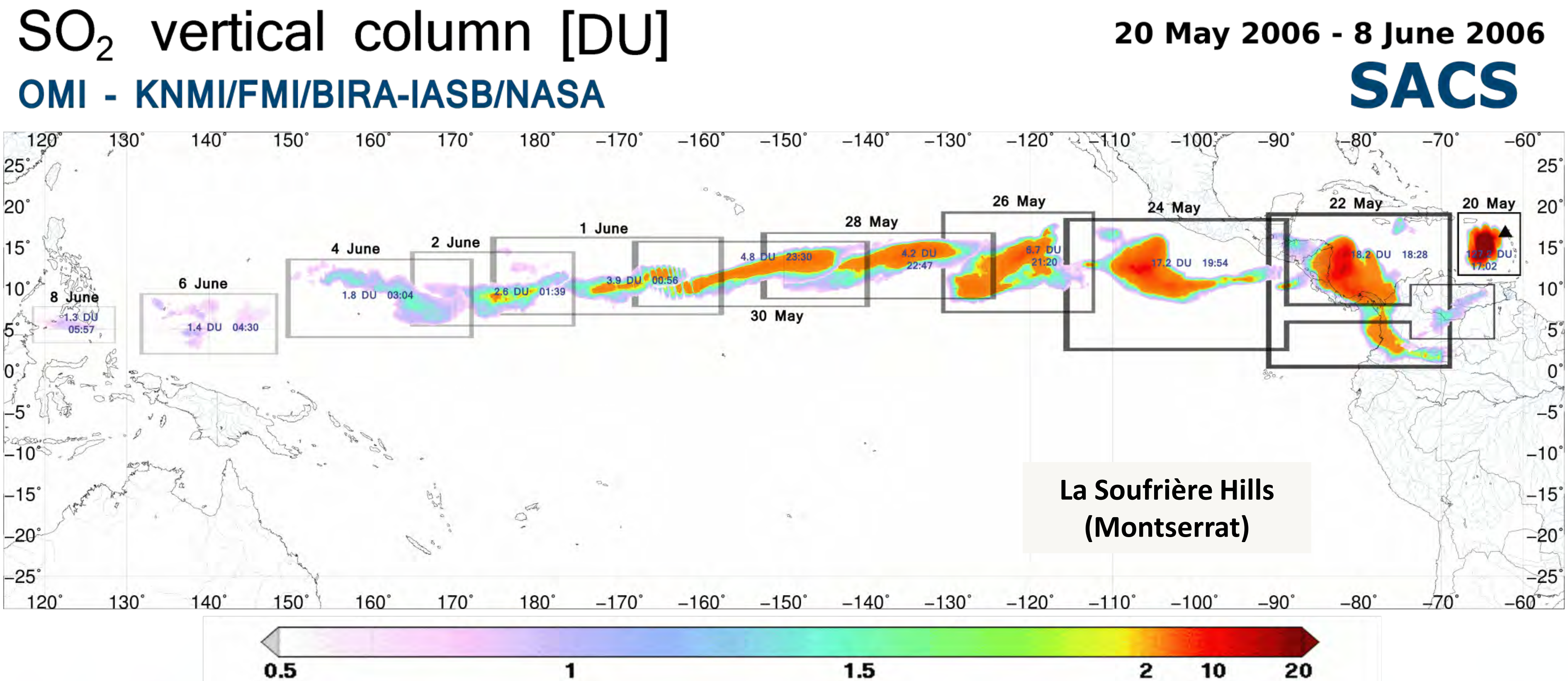
Courtesy M. George, LATMOS



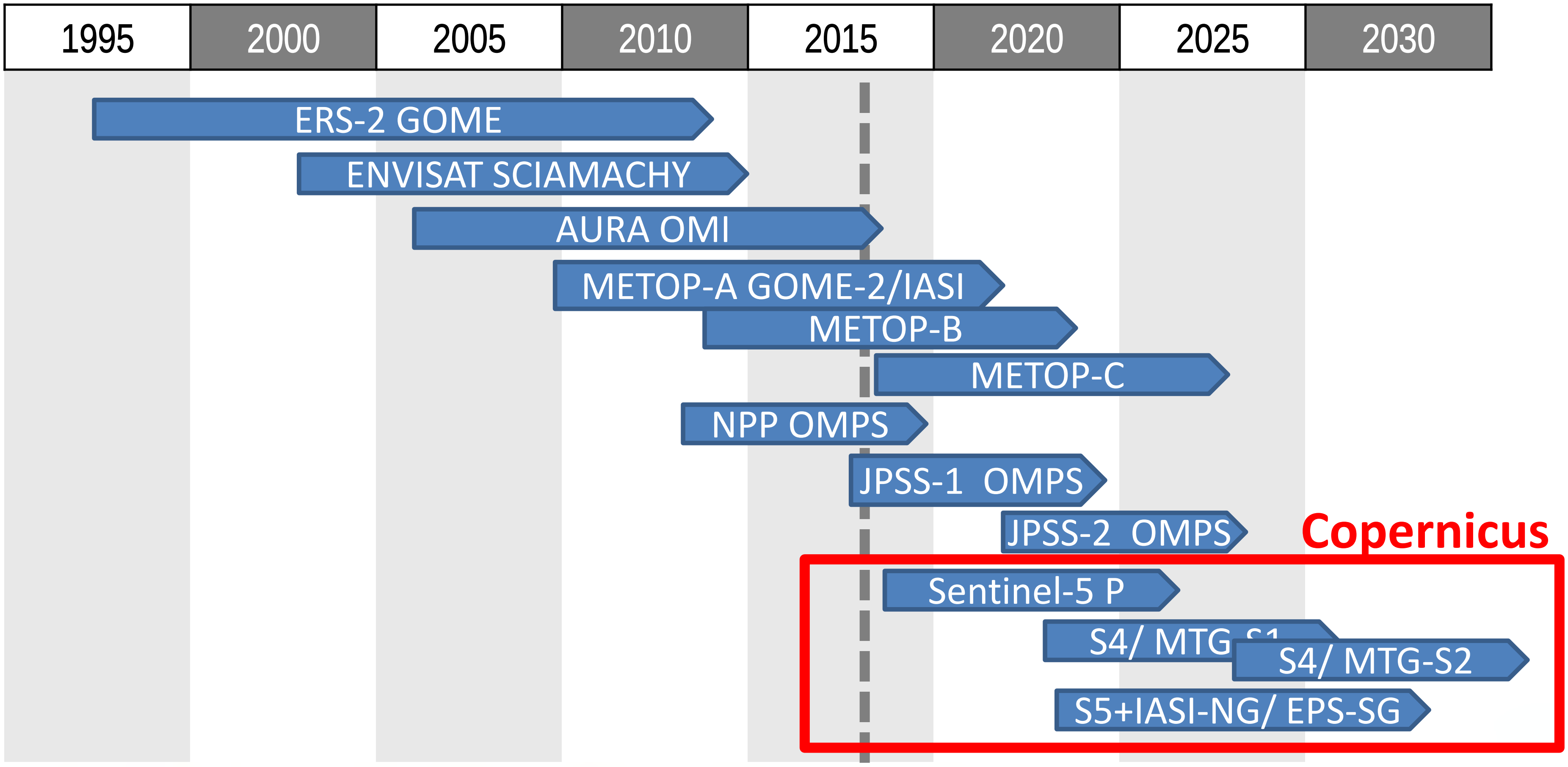
Mediterranean tropospheric ozone summer anomaly

Safieddine et al., ACP, 14, 10119-10131, 2014

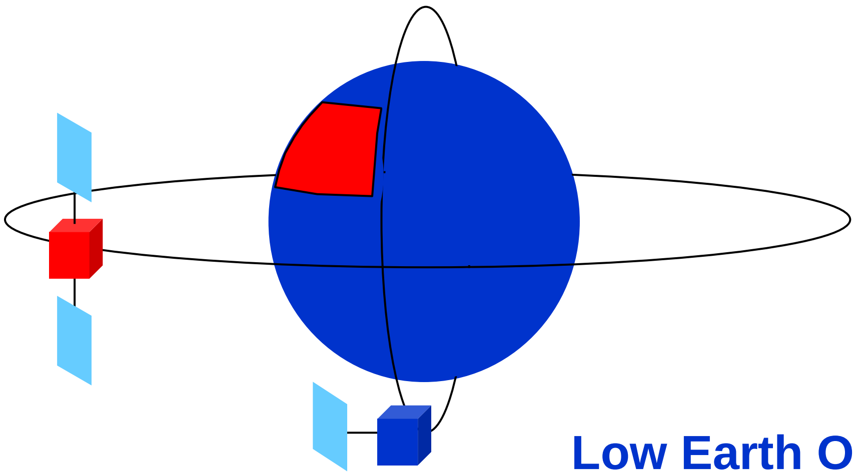
Volcanic SO_2 plume detection



Overview of current and future nadir missions



The Sentinel Missions for Copernicus Atmosphere Services

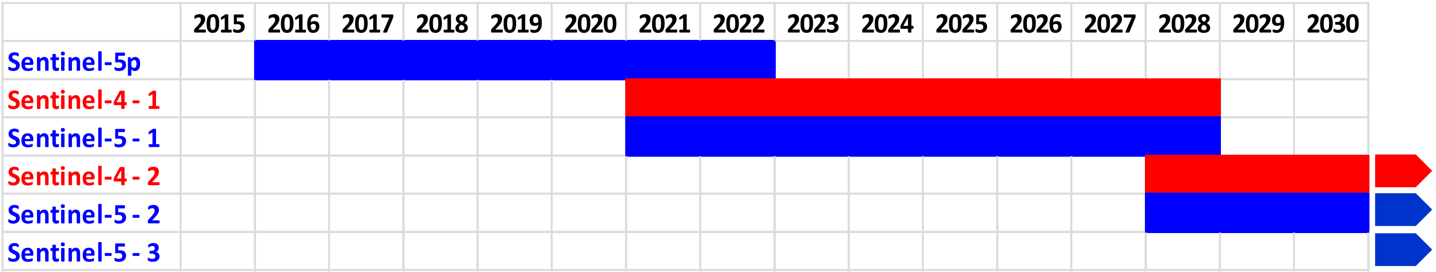


GEOstationary (GEO)

– Hourly revisit time over Europe
– Mainly air quality
– Diurnal cycle of tropospheric composition
→ **Sentinel-4 (on MTG-S)**

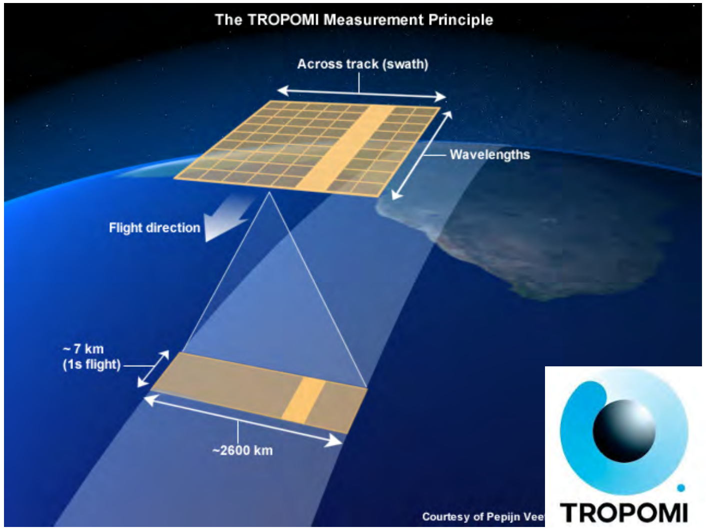
Low Earth Orbit (LEO)

– Daily revisit time global coverage
– Climate, air quality, ozone & UV
– Tropospheric & stratospheric composition
→ Sentinel-5 + IASI-NG (on MetOp-SG)
→ Sentinel-5 Precursor (dedicated platform)



Sentinel-5 Precursor - TROPOMI

- TROPOspheric Monitoring Instrument on ESA Sentinel-5 Precursor (TROPOMI)
- Pushbroom imager design similar to OMI, but with:
  - ➢ Improved spatial resolution (7x7 km^2)
  - ➢ Improved S/N ratio
  - ➢ More spectral channels covering UV-VIS-NIR-SWIR → Spectral bands: 270-500 nm, 675-775 nm, 2305-2385 nm



copernicus
The European Earth Observation Programme
sentinel-5p esa

Launch: November 2016

Summary / conclusion

- Satellite observations of atmospheric composition in the UV/vis, NIR and thermal IR provide consistent global datasets for many species distributed between the surface and the mesosphere
- The measurements are averaged horizontally and vertically which makes them difficult to interpret
- Remote sensing in an indirect method that necessitates use of a priori information in the data retrieval which has an impact on the results
- Visible and NIR measurements provide good sensitivity to the boundary layer, the thermal IR has intrinsic vertical information

- The future of nadir missions is bright, but we are facing a limb-sensor gap for the continued monitoring of the stratospheric composition

Thank you for your attention!

Questions?