Satellite Measurements of Greenhouse Gases

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Overview of this Afternoon

1. **Basic Concepts of Remote Sensing**
2. **Remote Sensing of CO_2**
3. **Computer-based Activity**

<u>Relevant Literature:</u>

G. Petty - A first course in Atmospheric Radiation

G. Stephens – Remote Sensing of the Lower Atmosphere

W.G. Rees – physical Principles of Remote Sensing

R.M. Goody and Y.L. Yung – Atmospheric Radiation

K.N. Liou - An Introduction to Atmospheric Radiation

Section 1:

Basic Concepts of Remote Sensing

What is Remote Sensing ?

"Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation"

(*Lillesand and Kiefer 1987*)

"Remote sensing is the acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that is not in physical or intimate contact with the object"

(*Wikipedia*)

In practice, remote sensing is the utilization at a distance (as from aircraft, spacecraft, satellite, or ship) of any device for gathering information about the environment, e.g. an aircraft taking photographs, earth observation and weather satellites

What is Remote Sensing ?

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Remote Sensing: A New Technology?
Some early remote sensing methods
are still in use today.

An Example from the Early Days

So what do we see ?

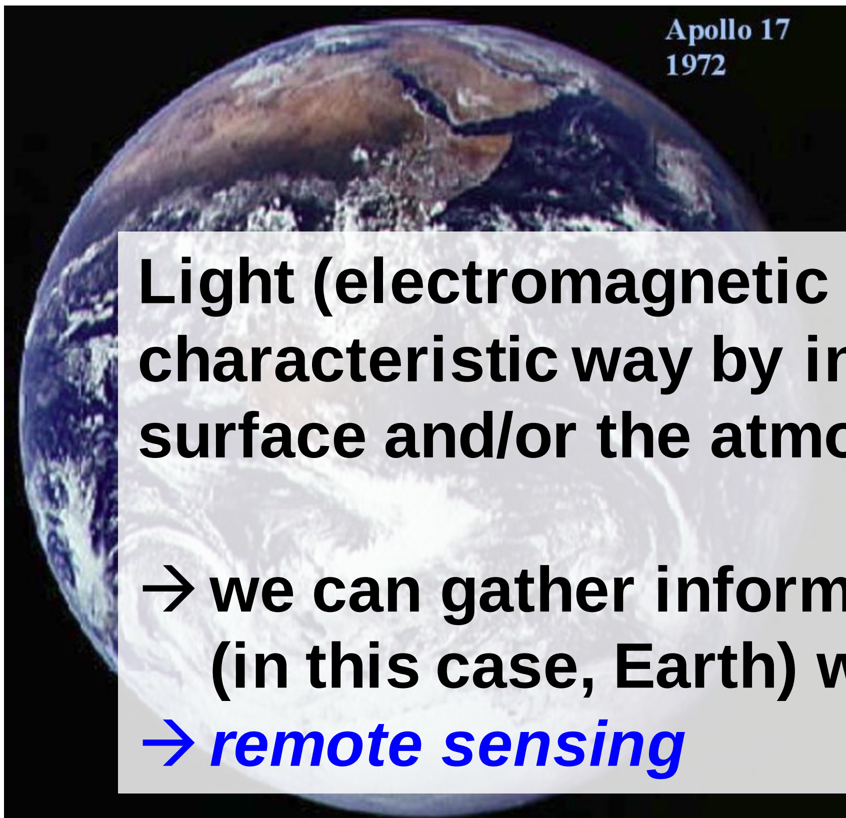
Nadir view

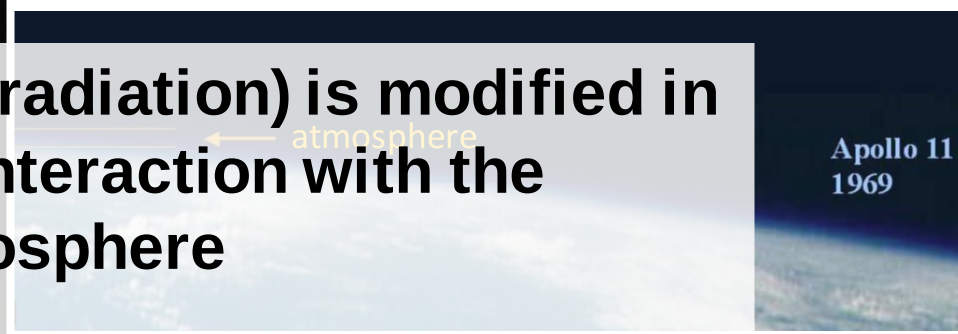
View towards the limb

An Example from the Early Days

So what do we see ?

- *Clouds, different surfaces, light scattered from the atmosphere …*





View towards the limb

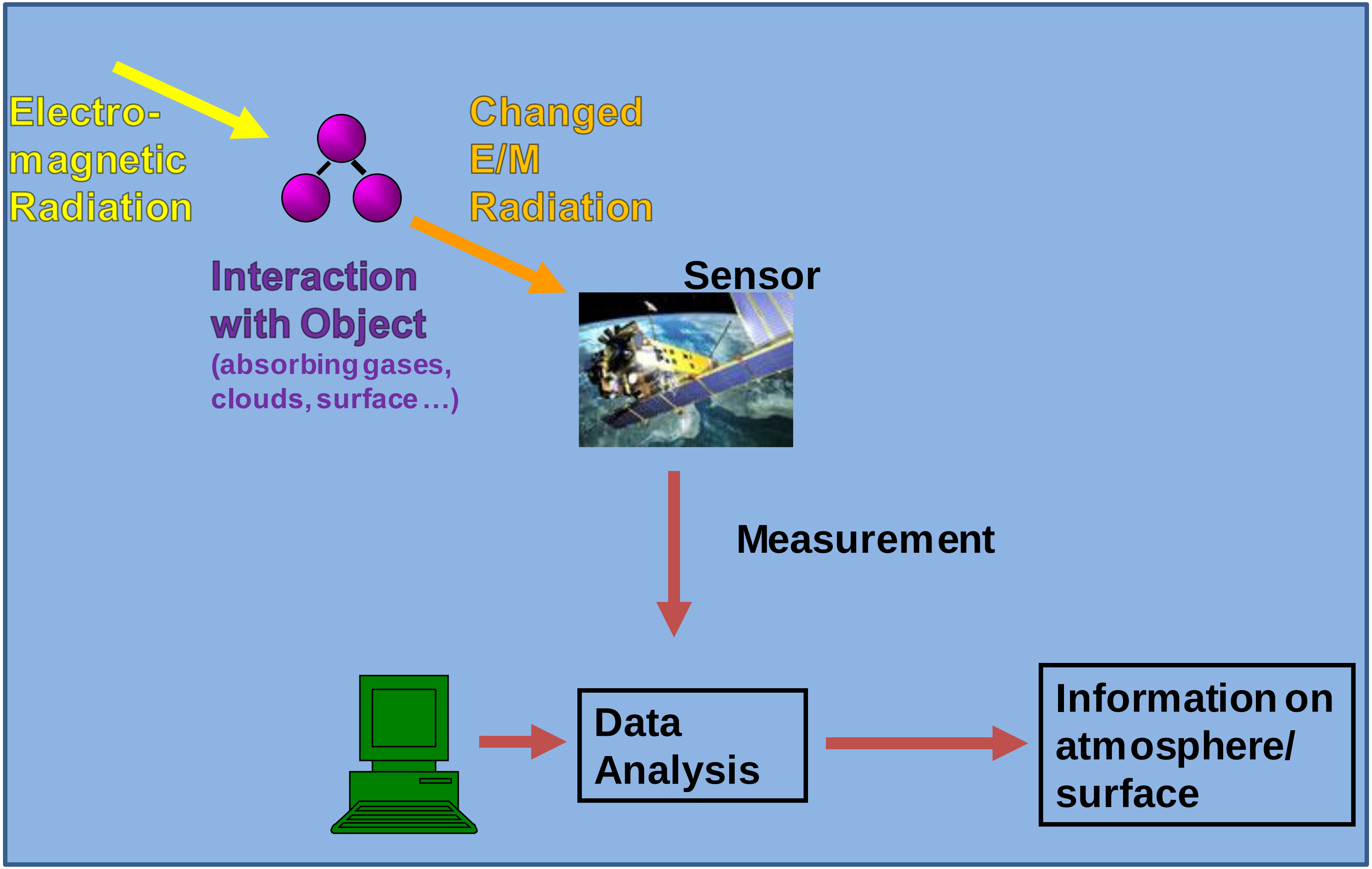
Light (electromagnetic radiation) is modified in characteristic way by interaction with the surface and/or the atmosphere

→ we can gather information about a system (in this case, Earth) without physical contact

→ *remote sensing*

Nadir view

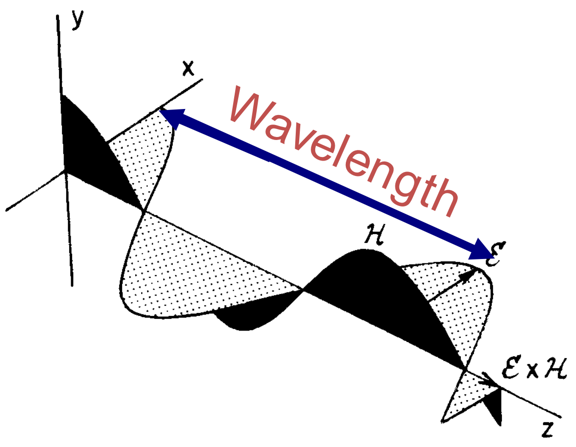
Principle of Remote Sensing Observations



Electro-Magnetic Radiation: Basic Properties

- **EM radiation is created via mutual oscillations of electric fields *E* and magnetic fields *H***
- **Direction of propagation of an EM wave is orthogonal to direction of oscillations (E, H, k form orthogonal system)**
- **EM waves travel at the speed of light: $c = c_0/n$, where n is refractive index of medium**

- **Oscillations can be described in terms of:**
  - **wavelength (λ): distance between individual peaks in the oscillation**
  - **frequency ($\nu = c/\lambda$): number of oscillations per second**
  - **wavenumber (= $1/\lambda$): number of wave crests (or troughs) per length**
  - ***Wavelength, (frequency) and wavenumber are often used interchangeably***



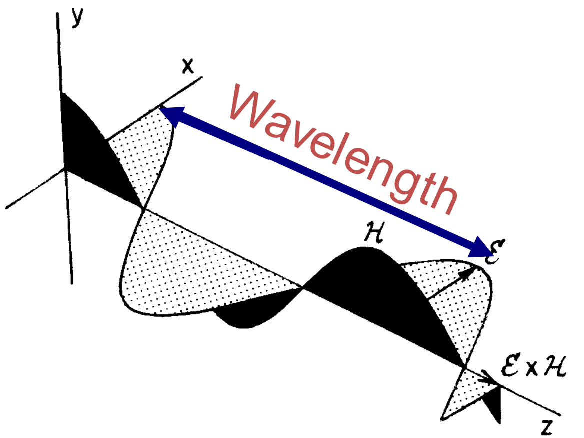
$$\mathbf{E}=\mathbf{E}_o \exp\{-j\,(wt-\mathbf{kr})\}$$
$$\mathbf{H}=\mathbf{H}_o \exp\{-j\,(wt-\mathbf{kr})\}$$

$$k=\omega/c=2\pi/\lambda$$

Electro-Magnetic Radiation: Basic Properties

Three basic properties describe EM radiation:

- ***Frequency*** **determines how radiation interacts with matter**
  - ***Rule of thumb: high frequency oscillations (e.g. UV wavelengths) interact with smallest matter (e.g. electrons), whilst low frequency oscillations (IR and microwave) interact with larger matter (e.g. molecules, water droplets, particles)***
- ***Amplitude*** **E_o directly defines the amount of energy carried by an EM wave (Poynting vector): proportional to $|E_o|^2$**
- ***Polarization*** **defines orientation of oscillation – which can affect way radiation interacts with matter (e.g. Fresnel laws)**



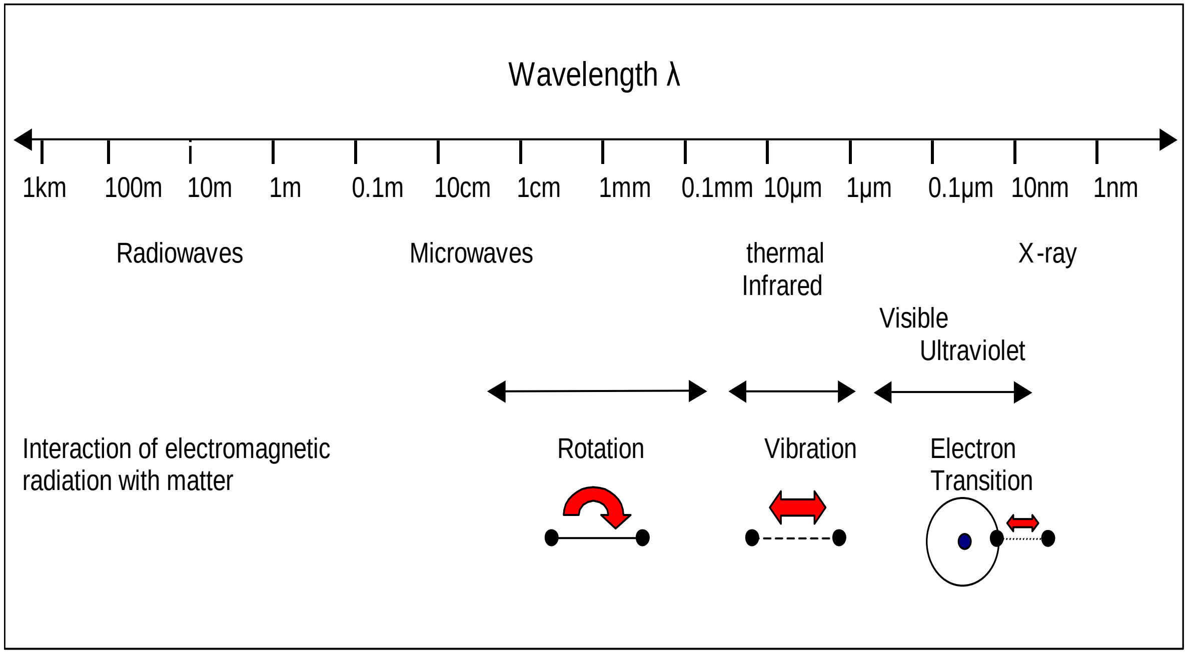
$$\mathbf{E}=\mathbf{E}_o \exp\{-j\,(wt - \mathbf{kr})\}$$
$$\mathbf{H}=\mathbf{H}_o \exp\{-j\,(wt - \mathbf{kr})\}$$

$$k=\omega/c=2\pi/\lambda$$

For the purposes of this course, we are interested primarily in energy carried by EM radiation, how it is affected by interactions with matter, and how those interactions vary spectrally (as a function of wavelength)

Electromagnetic spectrum

Highest Energy



Lowest Energy

The energy of a photon is determined by frequency ν:

$$E = h\nu = h\frac{c}{\lambda}$$

c: speed of light

h: Planck constant

- **UV/Vis and near-IR:** **Electronic and vibrational transitions**
- **Thermal IR:** **Vibrational transitions**
- **Microwaves:** **Rotational transitions**

- **Usually a combination of the different transition types occur**

Black Body Radiation

A black body is a body or gas volume that

- has constant temperature
- absorbs all incoming radiation completely
- has the maximum possible emission in all directions (isotropic) and at all wavelengths

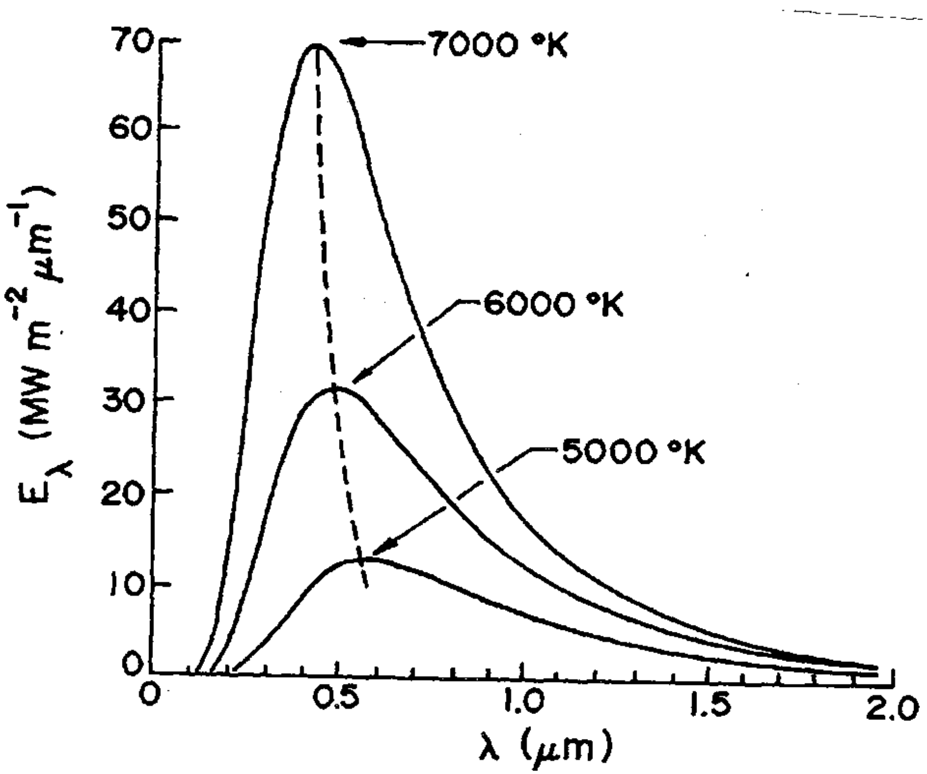
The Planck function describes the energy flux, B(λ,T), emitted by a black body

B(λ,T), is characterised by:

- Large dependence on λ
- Total emitted power increases strongly with temperature (~T^4) - ***Stefan Boltzmann Law***
- Well defined maximum for given T that is at smaller λ for larger T (***Wien law***)
- Emission from real object is given by:

  $I(\lambda) = \varepsilon(\lambda)\, B(\lambda,T)$

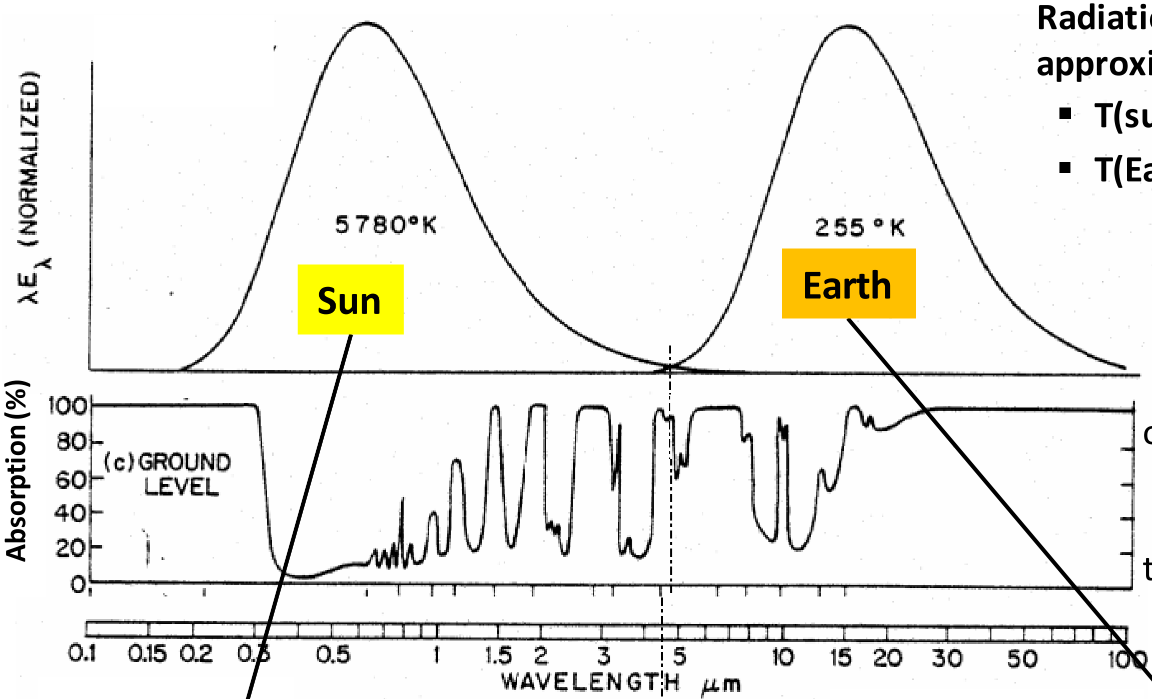
  with spectral emissivity ε(λ)



Two Main Sources for E/M Radiation

Radiation from Sun and Earth can be approximated by Black Body (Planck Functions):

- T(sun) ≈ 5780 K (peaks at ~0.6 µm = visible)
- T(Earth) ≈ 255K (peaks at ~10 µm = IR)



opaque

Atmosphere

transparent

Shortwave Range:

- Sun as a Light Source:
- High Intensity
- High transparency of atmosphere allows to see to the surface

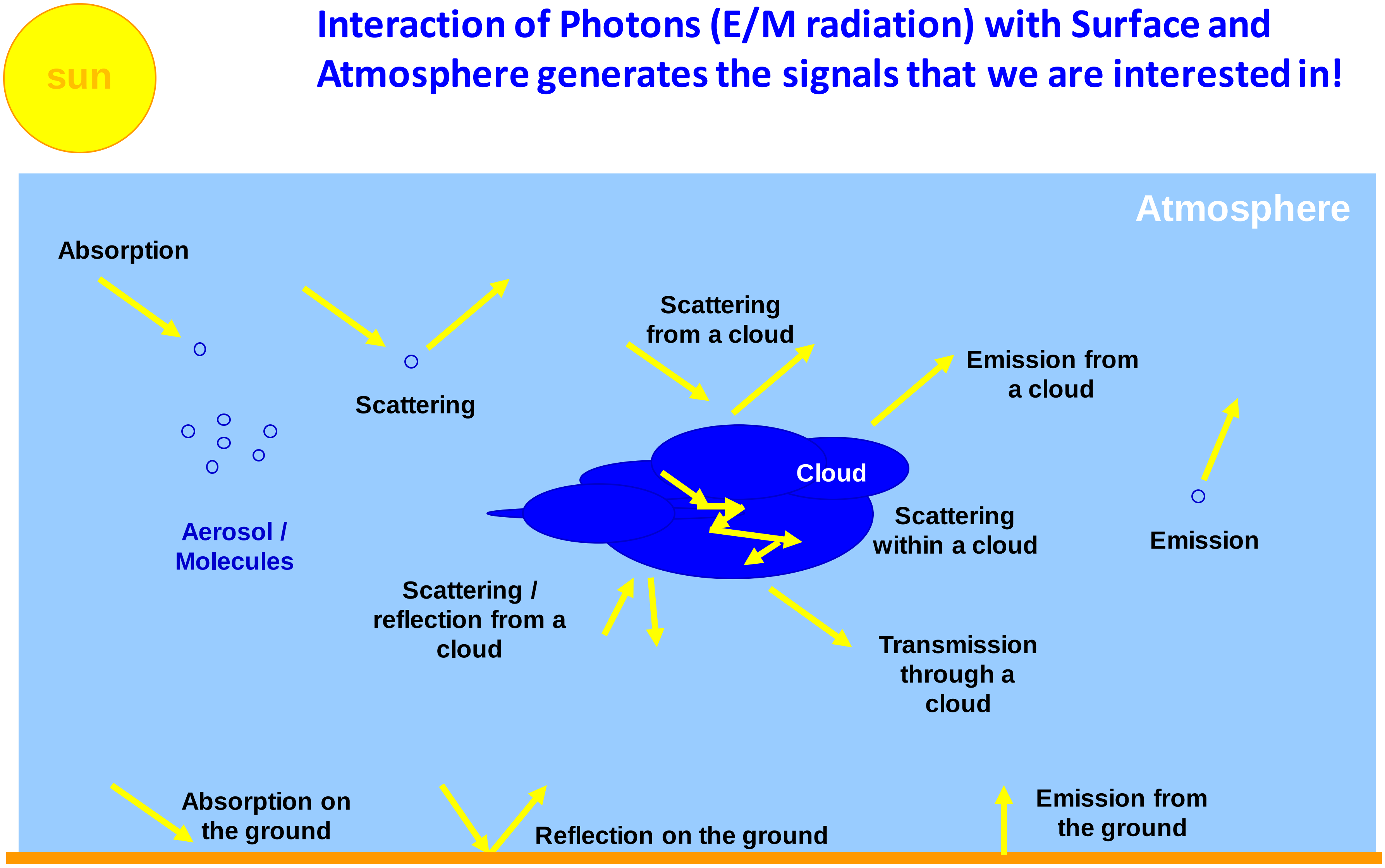
- Shortwave and longwave range are well separated
- Thermal emission can be (usually) neglected in the solar spectral range and vice versa

Long wave Range:

- Thermal IR radiation:
- Available night and day
- Many more absorbers/emitters

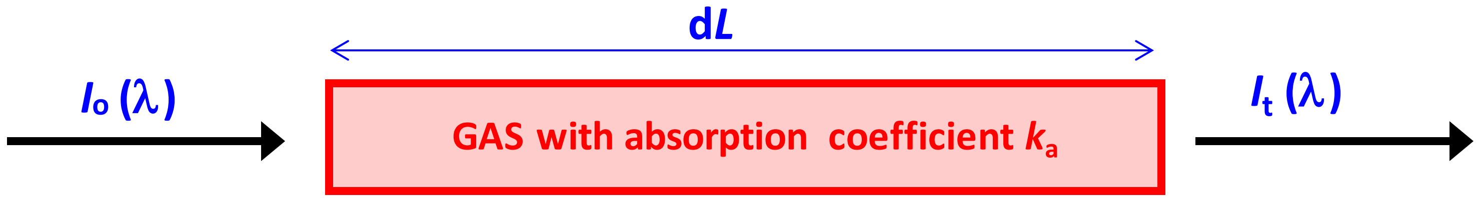
Overview of Radiative Transfer Processes

Interaction of Photons (E/M radiation) with Surface and Atmosphere generates the signals that we are interested in!



Beer-Lambert Law: The Conventional Case

The **Beer-Lambert (-Bouget) Law**: if a signal of intensity I(λ) passes a distance, dL, through a homogenous medium with absorption coefficient, k_a (per unit distance):



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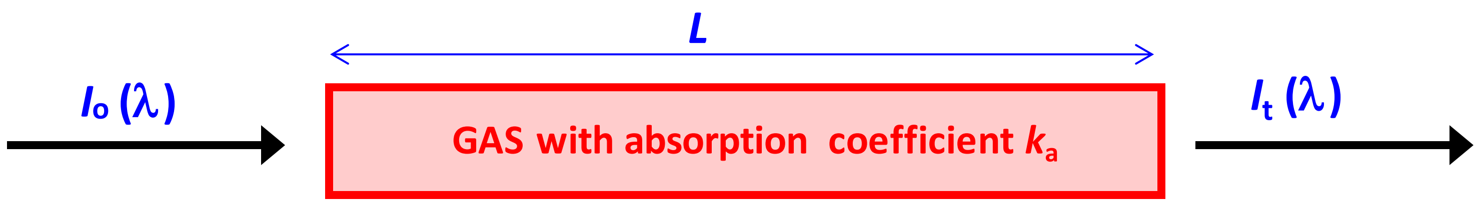


For a short path d*L*: $dI(\lambda) = - k_a(\lambda)\, I\, dL$

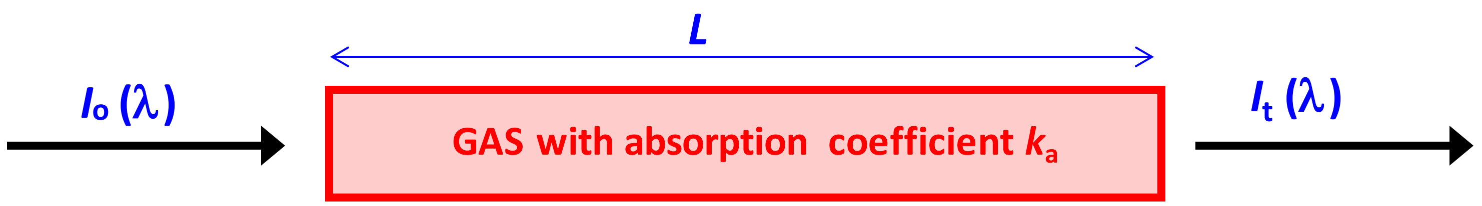
Then $I_t(\lambda) = I_0(\lambda) \exp\{- k_a(\lambda) L\}$ assuming k_a = constant

And transmissivity: $T(\lambda) = I_t(\lambda) / I_0(\lambda) = \exp\{- k_a(\lambda) L\}$

or $T(\lambda) = \exp\{- \sigma(\lambda)\, c\, L\} = \exp\{-\tau\}$

σ(λ): the absorption coefficient per molecule
c : density of molecules per unit volume
τ : optical depth

Transmissivity: The Purely Absorbing Case



And transmissivity: $T(\lambda) = I_t(\lambda) / I_0(\lambda) = \exp\{-k_a(\lambda) L\}$

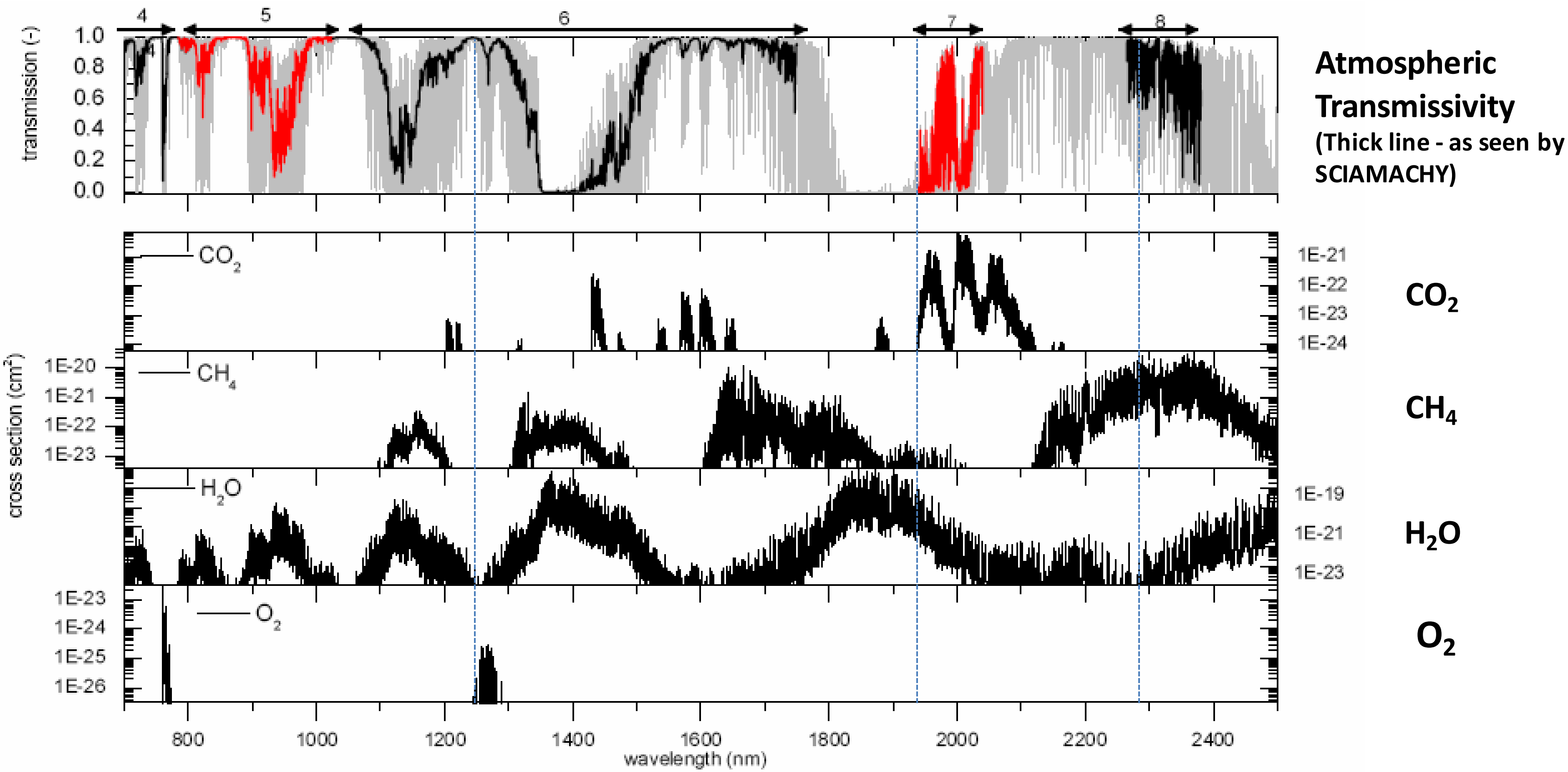
or $T(\lambda) = \exp\{-\sigma(\lambda)\, c\, L\} = \exp\{-\tau\}$

$\sigma(\lambda)$: the absorption coefficient per molecule
c : density of molecules per unit volume
τ : optical depth

→ Three factors matter:

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

Gas Transmissivity and Absorption Cross Section: Near-Infrared



- **100 % Absorption, 0% Transmissivity = Gases absorb all radiation**
- **Absorption depends on strength of absorption cross section (per molecule) and total number of molecules along path**

Example:

Calculate the transmissivity of well mixed gases CO_2, CH_4 and O_2 in the near-infrared…

Use: $$T(\lambda) = \exp - \{\sigma(\lambda)\, c\, L\}$$

Or more accurate: $$T(\lambda) = \exp - \int_L \sigma(\lambda, p(L), T(L)) \times c(L)\, dL$$

Which we approximate by: $$T(\lambda) = \exp - \{\sigma(\lambda, \overline{p}, \overline{T}) \times \chi \times VCD_{air}\}$$

Given mixing ratio χ for each gas, and vertical column density VCD of air = 2.14×10^{25} molec/cm^2 …

- **CO_2: χ = 380 ppm and σ(λ = 1.95 μm) = 1×10^{-21} cm^2 → T = exp{-8.1} = 3×10^{-3}**
- **CH_4: χ = 1800 ppb and σ(λ = 2.3 μm) = 4×10^{-21} cm^2 → T = exp{-0.15} = 0.86**
- **O_2: χ = 0.2 and σ(λ = 1.27 μm) = 1×10^{-25} cm^2 → T = exp{-0.43} = 0.65**

The Infrared Case

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

$$= (1 - \mathcal{T}(\lambda)) \times B(\lambda, T)$$

The Infrared Case

Hence, the total signal $I(\lambda)$ is given by:

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

Surface contribution — Atmosphere contribution

Limiting cases:

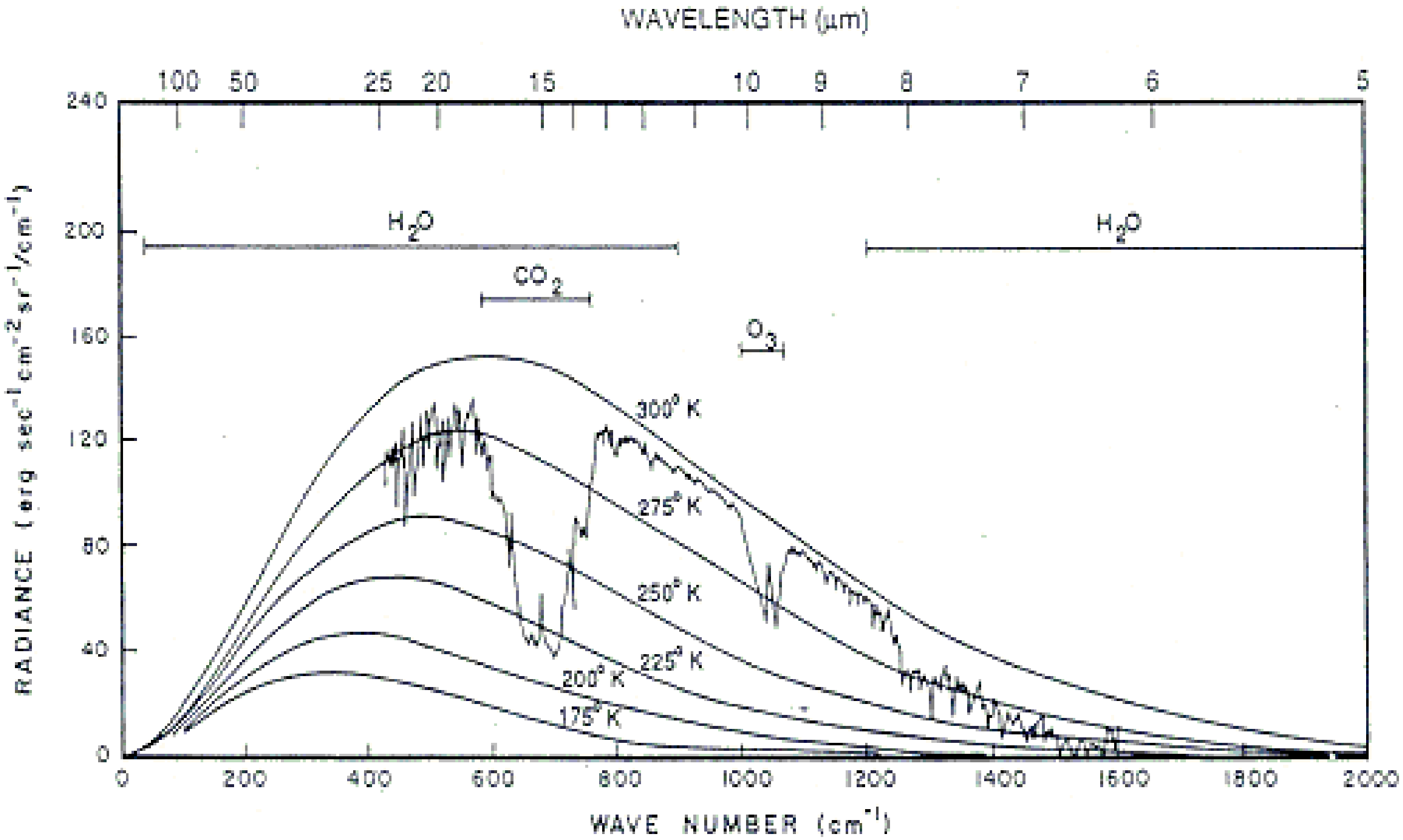
1. $\mathcal{T}(\lambda) \rightarrow 1 : I(\lambda) = \mathcal{T}(\lambda)\, I_o(\lambda)$ **[Known as a *spectral window* – also N.B.]**
2. $\mathcal{T}(\lambda) \rightarrow 0 : I(\lambda) = (1 - \mathcal{T}(\lambda)) \times B(\lambda, T)$ **[100% absorption, known as *saturation*]**

N.B. : If: a) term 1 >> term 2 or b) if $T_{gas} \approx 0$ K (!)

then case 1) would be true and conventional use of $\mathcal{T}(\lambda)$ alone is fine,

e.g. UV-visible wavelengths on Earth, or hot source relative to cold gas.

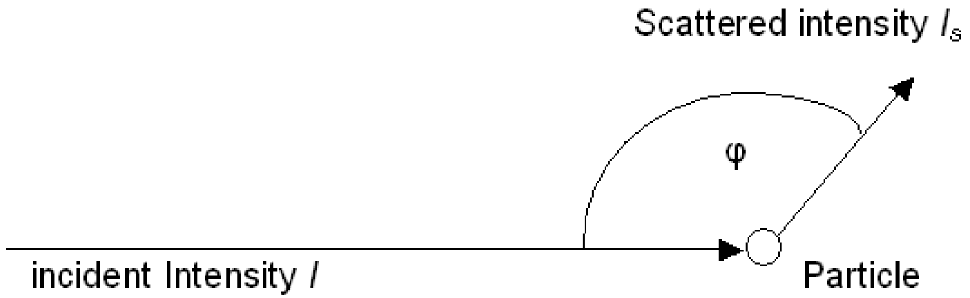
Emission spectrum of the Earth



- Earth surface emits radiation with *T*~280 K
- Gases (H_2O, CO_2, O_3 etc) in atmosphere absorb and re-emit with emissivity equal to the absorptivity (Kirchoff's Law).
- Gas is at a colder temperature and hence emits with a lower Planck function

Scattering Processes in the Atmosphere

- **Basic Considerations:**
  - **Scattering removes fraction of radiation along one direction and directs it into other directions**
  - **Photons passing through a medium may encounter only one particle (single scattering) or many particles (multiple scattering)**
  - **Scattering in the atmosphere occurs from molecules (Rayleigh scattering) and aerosol/cloud particles (Mie scattering)**



Main Parameters:

- **Scattering cross section σ_s(effective area for scattering)**
- **Scattering phase function p(ϕ) (direction)**

Scattering by Molecules (Rayleigh Scattering)

- **Scattering by molecules can be described as radiation from a oscillating dipole (Hertz Dipole)**
- **Rayleigh scattering cross section:**
  - $\sigma_s^{Rayleigh}(\lambda) \sim \lambda^{-4}$
- **Rayleigh scattering is very efficient for short wavelength**
  - **Sky appears blue**
  - **UV radiation is usually scattered before reaching the surface**
- **Rayleigh scattering polarises light**
  - **skylight is polarised**
  - **the maximum of polarisation is reached at 90° scattering angle**

Photography: Polarization filters can be used to remove polarized skylight

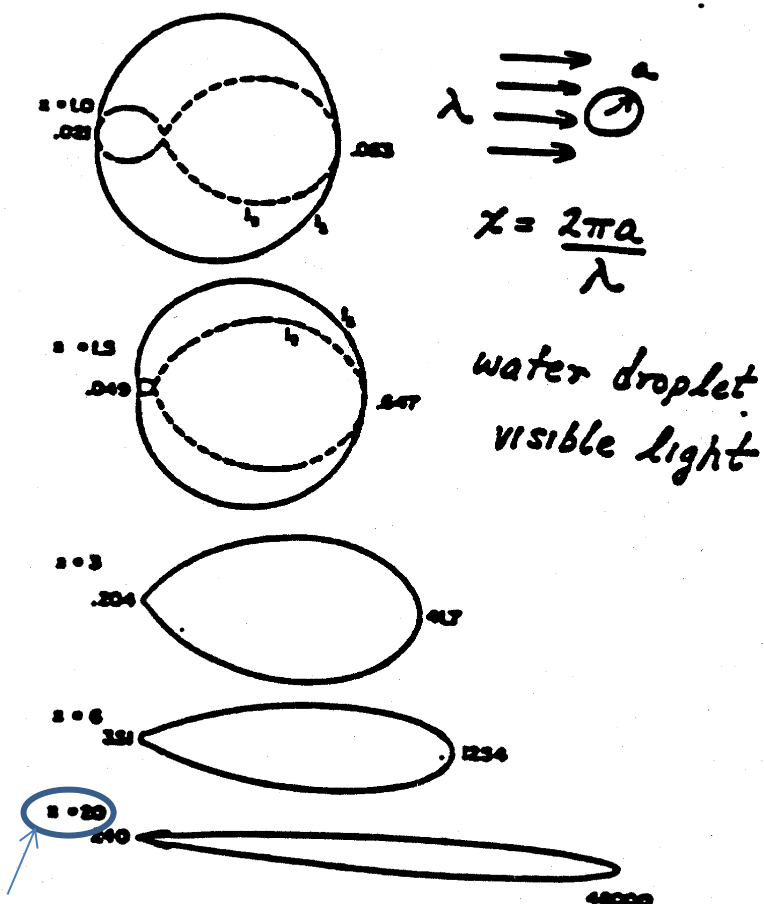
Scattering on Particles (Mie Scattering)

- **Explained by coherent scattering from many individual particles (dipoles)**
- **Mie scattering can be computed using Maxwell equations for spherical particles (Mie theory)**
- **Scattering/absorption properties are complex functions of chemical composition, size and shape of particles (sea salt, dust, sulphate …)**
- **The larger the particles, the stronger the forward peak**
- **Scattering cross section:**

$$\sigma_s^{Mie}(\lambda) \sim \lambda^{-1} \ldots \lambda^{-1.5}$$

  - ***Scattered light by aerosols/clouds is white-ish***
  - ***Mie scattering is the dominant scattering term for larger λ***

Scattering phase function



Size parameter

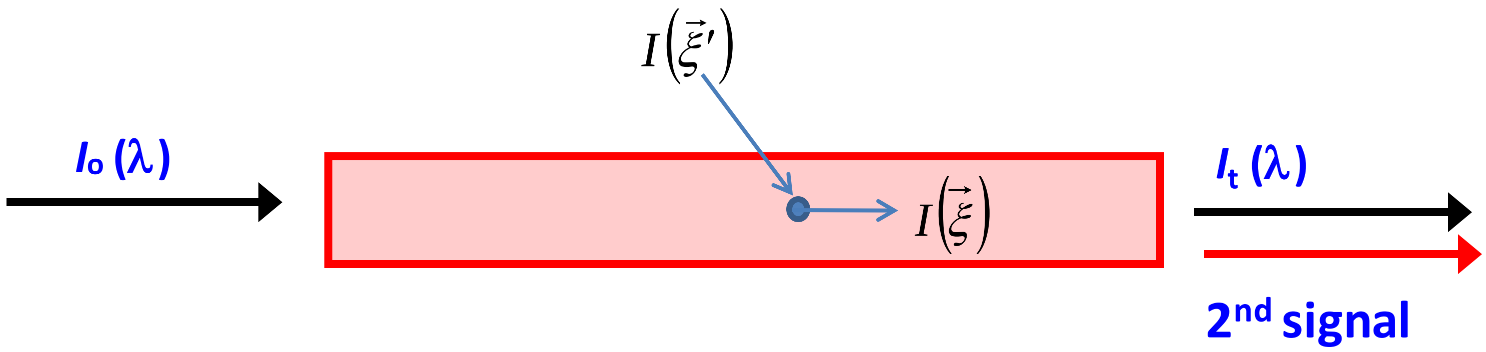
Scattering example:

- **Compare probability for Rayleigh and Mie Scattering between ultra-violet (λ = 300 nm) and visible red (λ = 1 micron):**

- **Rayleigh scattering ~ λ^{-4} → $(300/1000)^{-4} \approx$ 120**
- **Mie scattering ~ $\lambda^{-1.5}$ → $(300/1000)^{-1.5} \approx 6$**

→ *Rayleigh scattering* will dominate in *ultra-violet* and *Mie scattering* in *infrared*

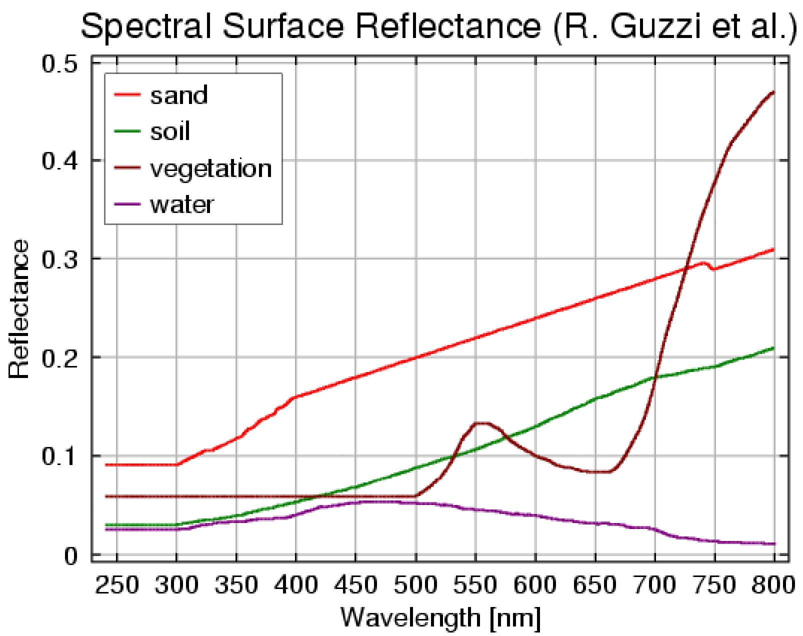
One more scattering effect…



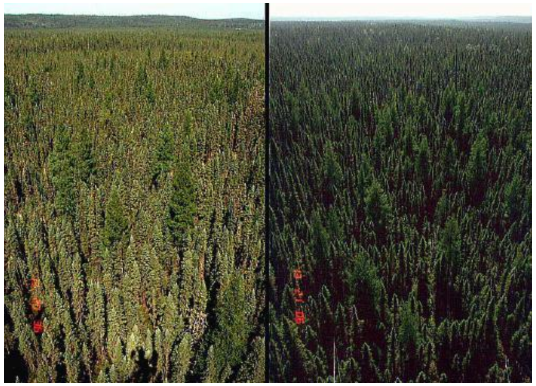
- Light can also be scattered from outside the volume into the viewing direction
- This term is difficult to calculate and leads to a second signal (an additional source) similar to the emission term
- This additional source term is a major difficulty for finding a solution to a radiative transfer problem (and in general the problem requires a dedicated RT solver)

Surface Reflection of E/M Radiation

- **Photons can be absorbed and/or reflected by the Earth surface**
- **The surface albedo is fraction of incoming solar radiation reflected by surface, integrated over all viewing directions**
- **Usually assume a Lambertian surface, where reflected intensity does not depend on viewing angle**
- **The wavelength-dependence of the albedo depends on surface characteristics (and provides information about surface)**



***In reality*: Surface reflectance is a function of direction and is characterised by the BRDF (bidirectional reflection distribution function).**

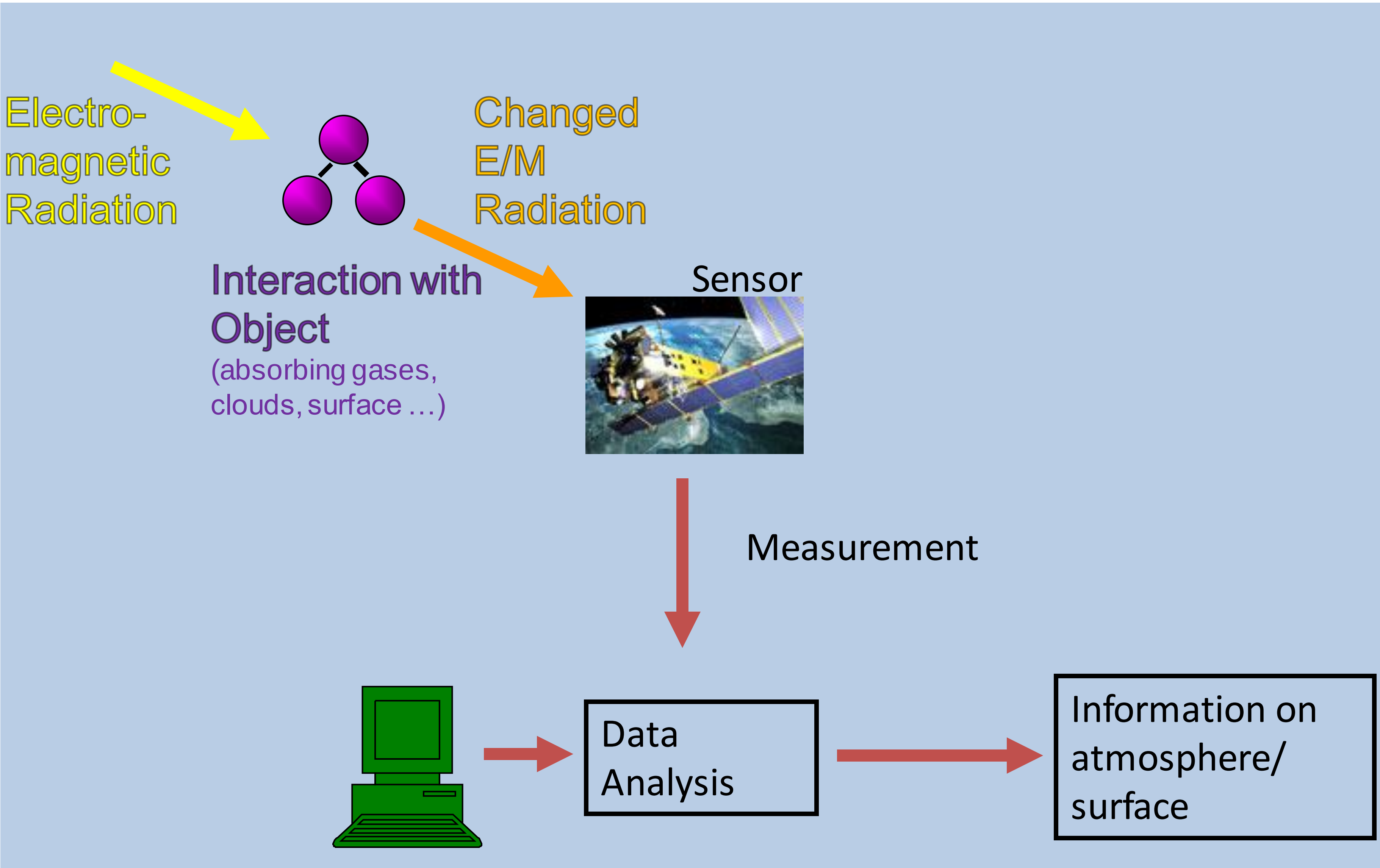


http://geography.bu.edu/brdf/brdfexpl.html

Section 2:

Remote Sensing of CO_2 in the shortwave-infrared spectral range

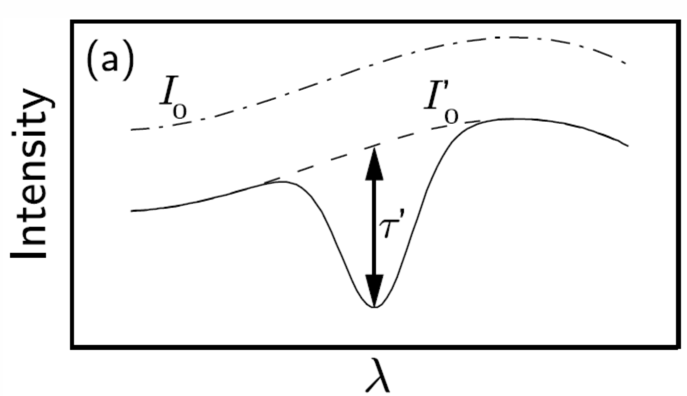
Principle of Remote Sensing Observations



Absorption Spectroscopy Allows Measurement of Gases

- Main assumption: no scattering
- Beer-Lambert law:

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



and thus:

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

Optical depth

Absorption cross section for mean temperature and pressure

Slant column density gives the number of molecules per area along the path → $SCD = \int_0^L c(L')dL'$

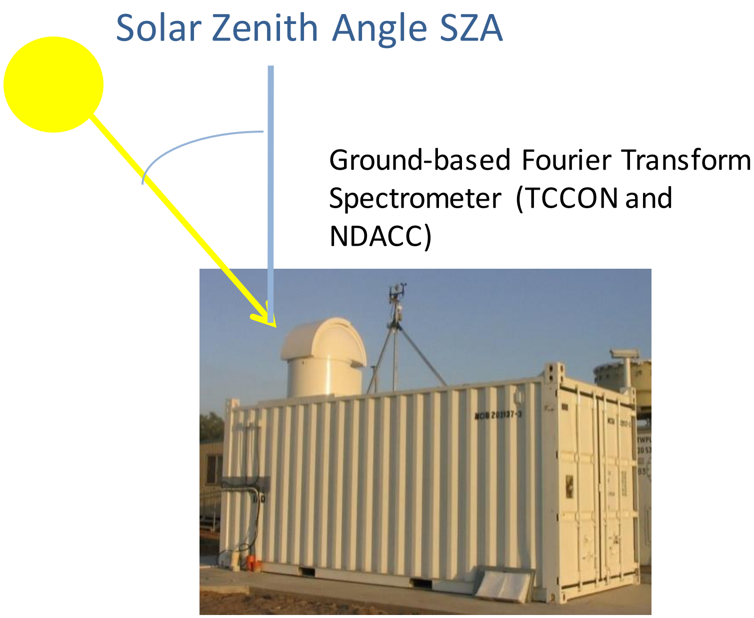
- For atmospheric measurements, a more useful quantity is the vertical column density *VCD:* number of molecules per area along the vertical direction for the whole atmosphere

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

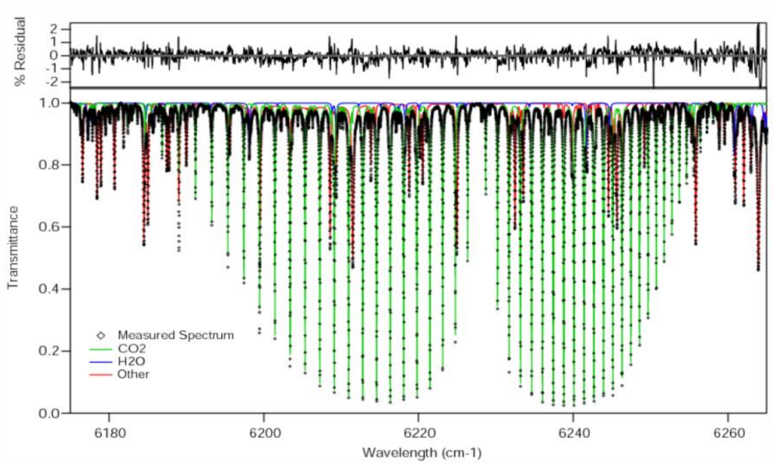
- How can you obtain VCD from SCD?

Example: Direct-Sunlight Observations from the Ground

- The principal of absorption spectroscopy is valid for **direct- sunlight observations**:
  - No surface effects
  - High intensity source, so scattering into observer-direction is not important
  - Scattering leads to broad reduction of total intensity but will not change the optical depth due to gaseous absorption
- Direct sunlight observations:
  - Relation between slant path and vertical path is given by geometric factor of **1/cos(SZA)**

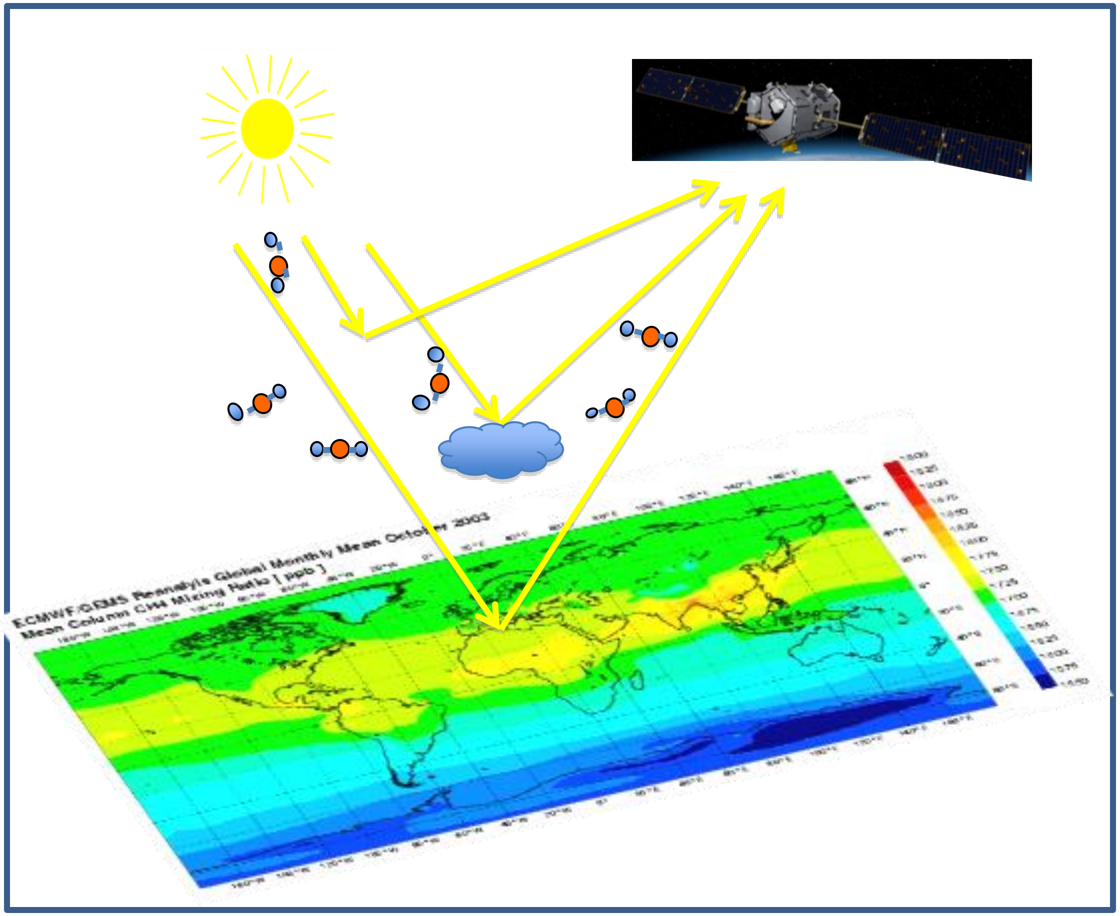


Example of spectral fit to 6228 cm^{-1} CO_2 band



http://www.tccon.caltech.edu/

The Retrieval Problem for Satellite Observations



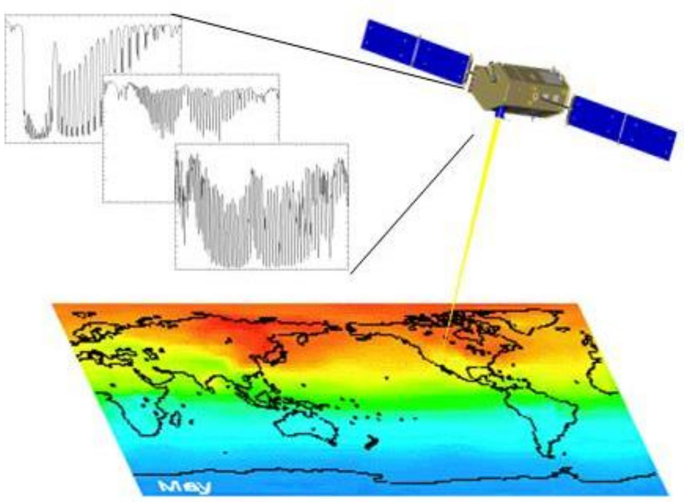
For accurate retrievals of CO_2 we need to be able to deal with:

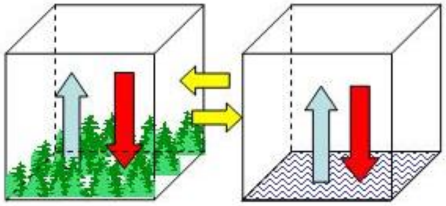
- Multiple-scattering
- Aerosols and thin clouds
- Polarization
- Surface properties
- Gas absorption (spectroscopy)
- Topography
- Atmospheric state (T, H_2O, p)
- …

The Approach for CO_2 Column Observations from Space

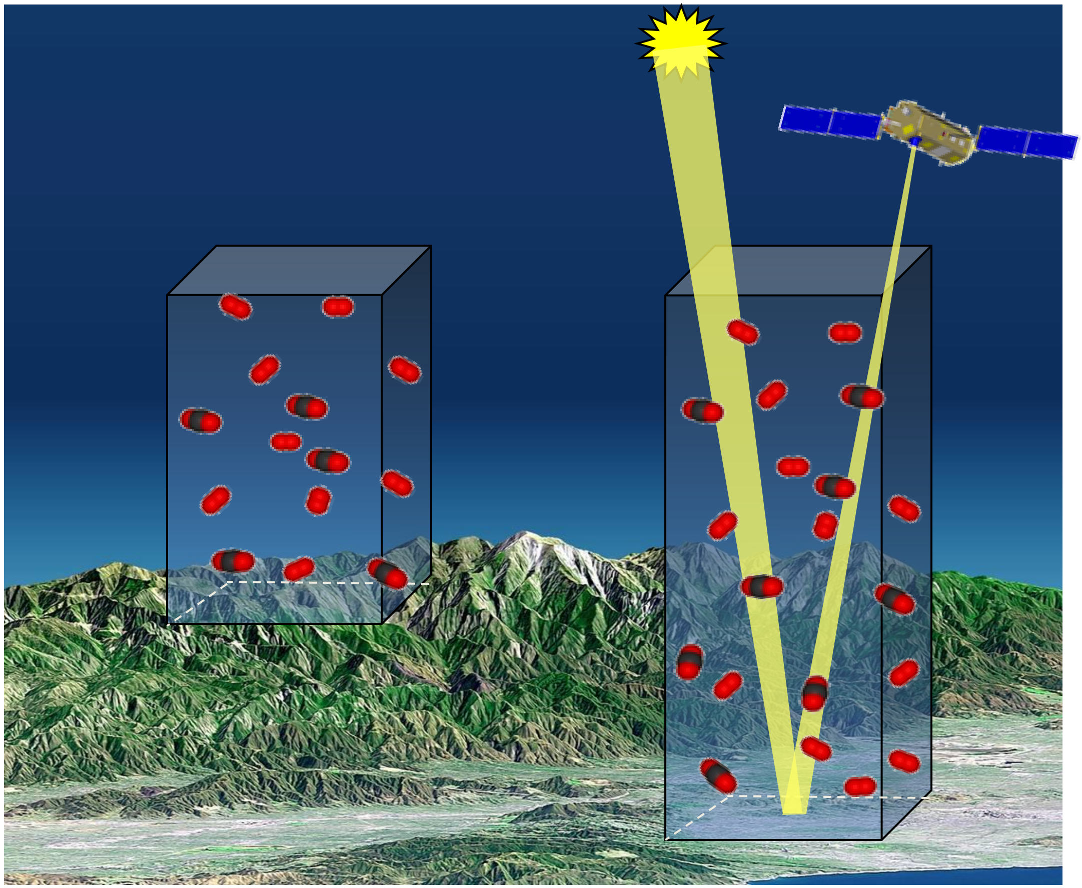
Approach:

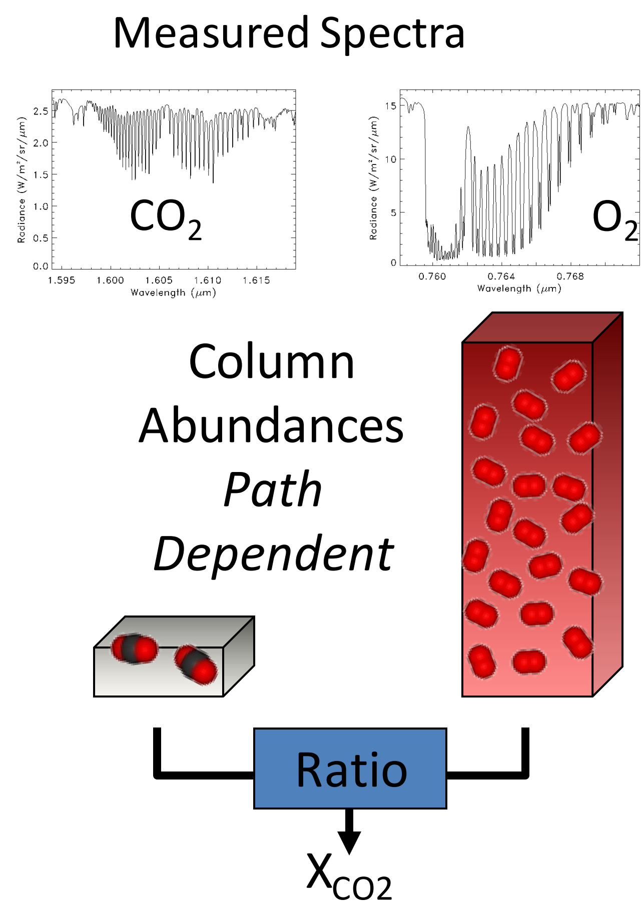
- **Collect spectra of CO_2 and O_2 absorption in reflected sunlight in the shortwave-infrared region**
- **Use these data to resolve variations in the *column averaged CO_2 dry air mole fraction*, X_{CO2} over the sunlit hemisphere**
- **Validate measurements to ensure X_{CO2} accuracies of 1 - 2 ppm (0.3 - 0.5%) on regional scales at monthly intervals ('tie data to WMO standard')**





What is column averaged CO_2 dry air mole fraction X_{CO2}?



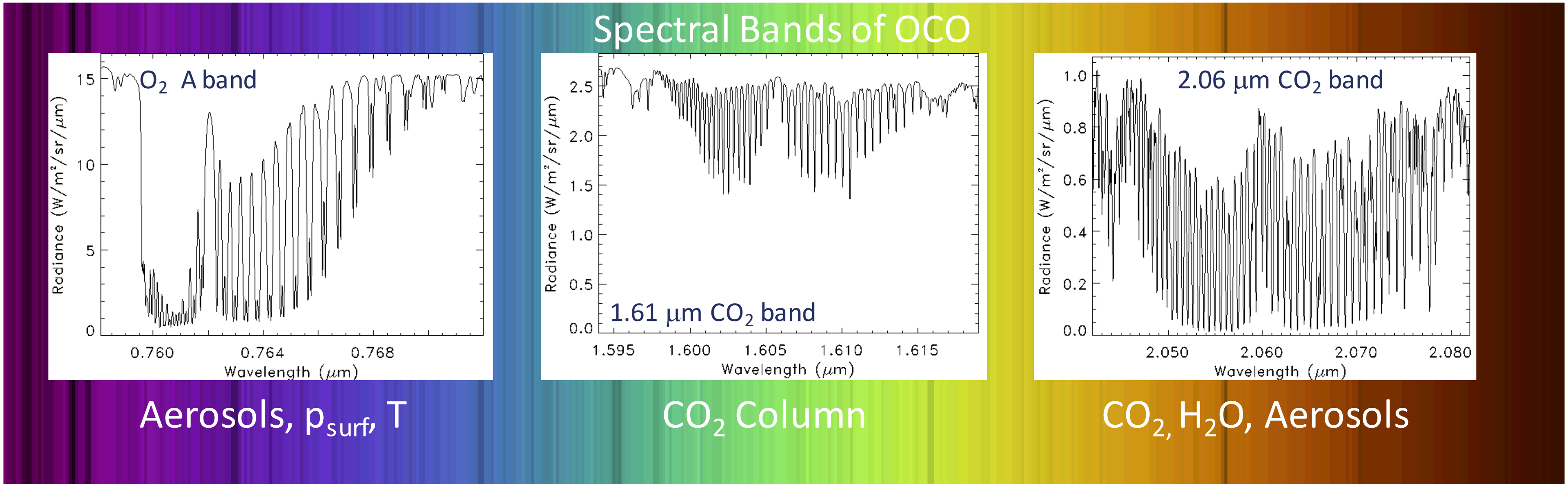


Normalization removes effects of varying surface pressure & topography

→ *26-meter change in surface elevation equals 0.3% (1 ppm) change in X_{CO2}*

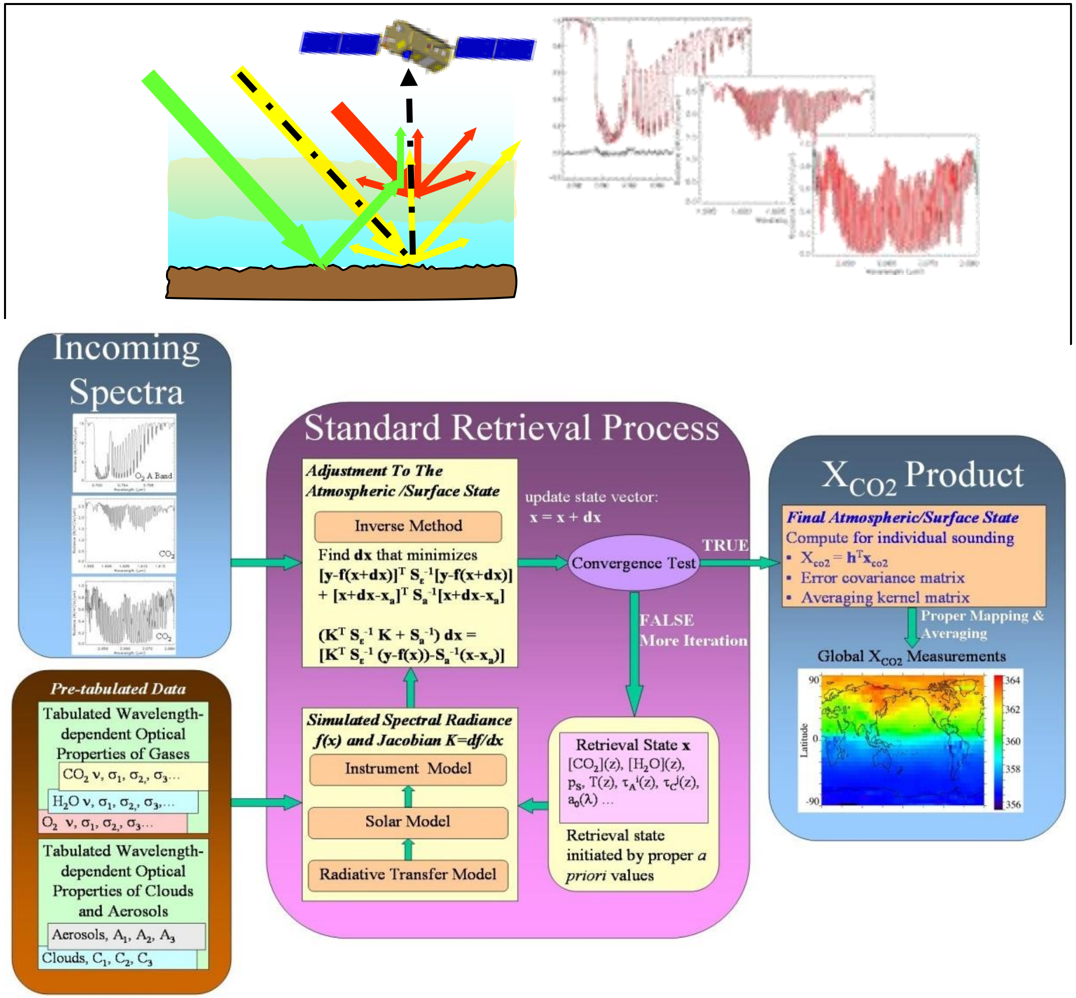
Measurement Approach

- Measurement of SWIR CO_2 and O_2 bands to retrieve information on scattering (aerosol/clouds) together with CO_2:
  - 1.61 μm CO_2 band: Column CO_2
  - 2.06 μm CO_2 band: Column CO_2, clouds/aerosols, H_2O, Temperature
  - 0.76 μm O_2 A-band: Surface pressure, clouds/aerosols, Temperature
- Instruments are specifically designed for CO_2 column observations:
  - High spectral resolution
  - Large number of key parameters can be retrieved independently
  - Enhanced sensitivity and minimized biases due to interferences



'Full-Physics' Retrieval Algorithm

- Accurately retrieving CO_2 (and CH_4) is extremely difficult and time-consuming:
  - Retrieved CH_4 and CO_2 will depend on assumptions of retrieval algorithm (retrieval biases)
- Forward Model needs to describe accurately physics of measurement:
  - Multiple-scattering RT
  - Polarization Correction
  - Spherical Geometry
  - Surface (polarized) BRDF
  - Instrument Model
  - Solar Model
- Inverse Method estimates state:
  - Rodgers' optimal estimation technique (based on Bayes' theorem)



(Boesch et al., 2006, 2011, O'Dell et al., 2011)

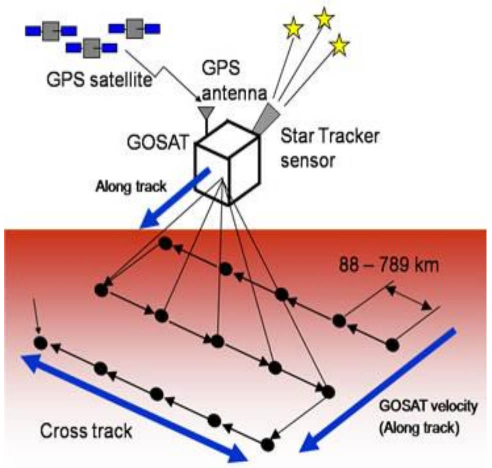
Greenhouse gases Observing SATellite (GOSAT) launched January 23rd 2009

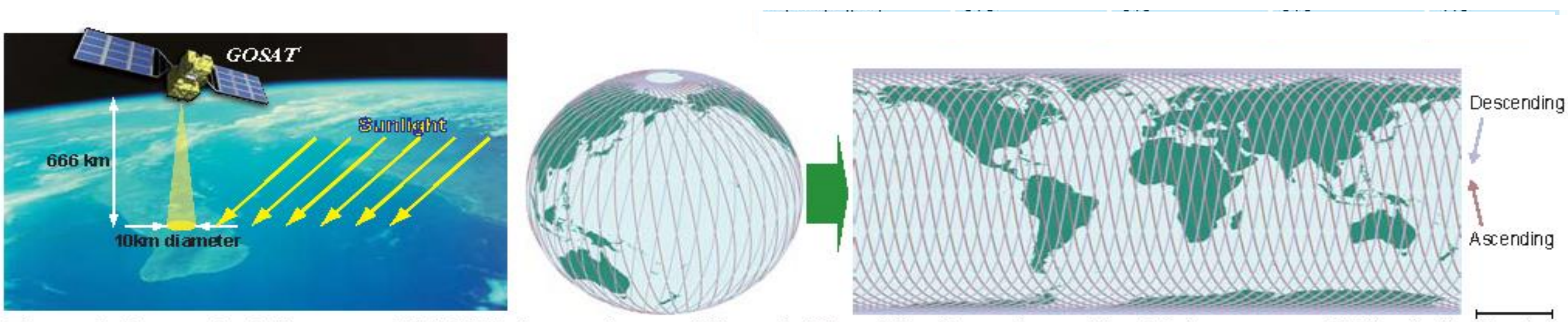
Mission objectives:

1) To monitor the density of greenhouse gases precisely and frequently worldwide.

2) To study the absorption and emission levels of greenhouse gases per continent or large country over a certain period of time.

3) To develop and establish advanced technologies that are essential for precise greenhouse-gas observations.





Conceptual diagram of GOSAT observation and the satellite orbits (three days, 44 orbits)

The GOSAT Payload

TANSO - FTS

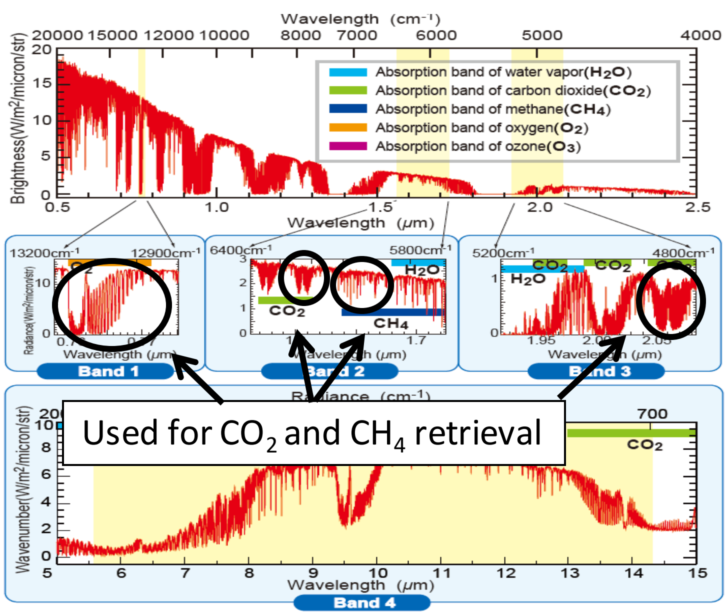
Provides spectrally-resolved radiances for 4 shortwave-IR (polarized) and thermal-IR bands

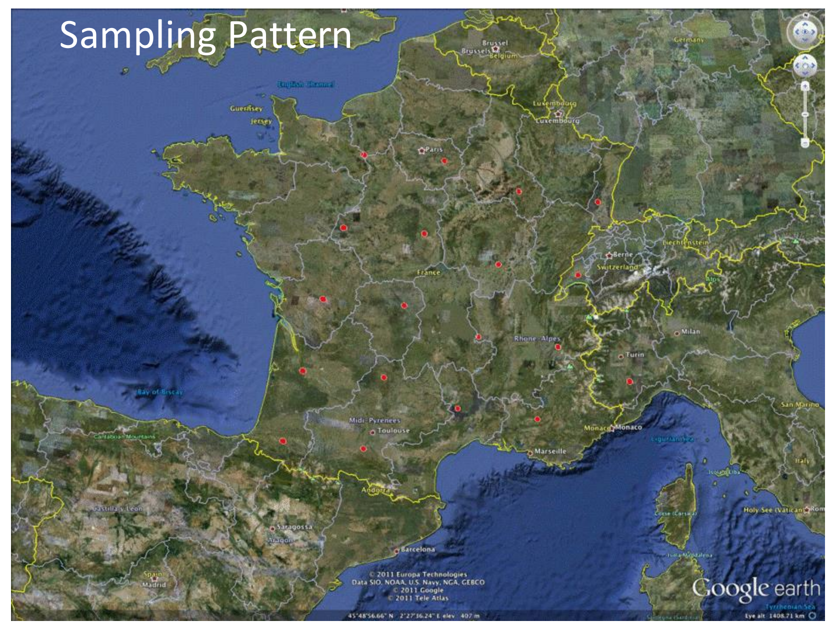
Covers several absorption bands of CO_2, CH_4, O_3 and H_2O (and others) and O_2

TANSO - CAI

4 broadband channels from UV to SWIR with high spatial resolution

Provides aerosol and cloud information required for the greenhouse gas retrieval

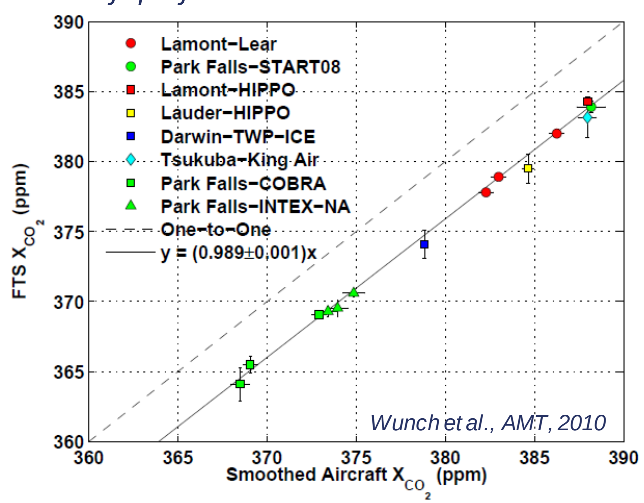




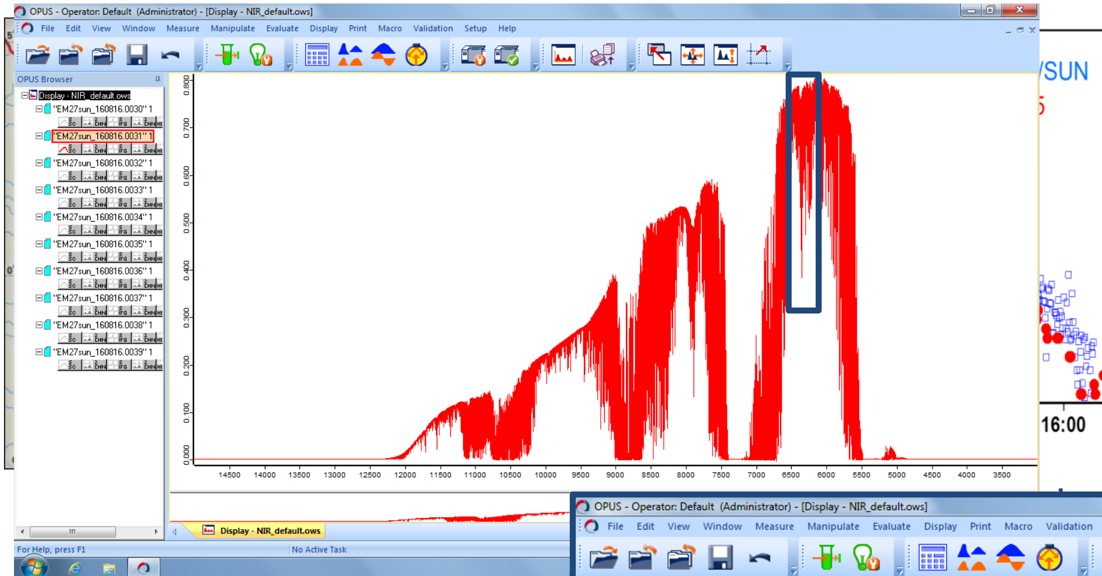
Validation against ground-based TCCON

- TCCON (Total carbon column observing network) network of ground-based Fourier Transform Spectrometers
- Provides precise, accurate total columns of CO_2, CH_4 and other gases
- Ideal for satellite validation – uniformity of instrumentation and data processing methodology across the network
- Lack of TCCON sites in Asia, South America and Africa: deployment of portable FTS's to fill the gaps in validation?

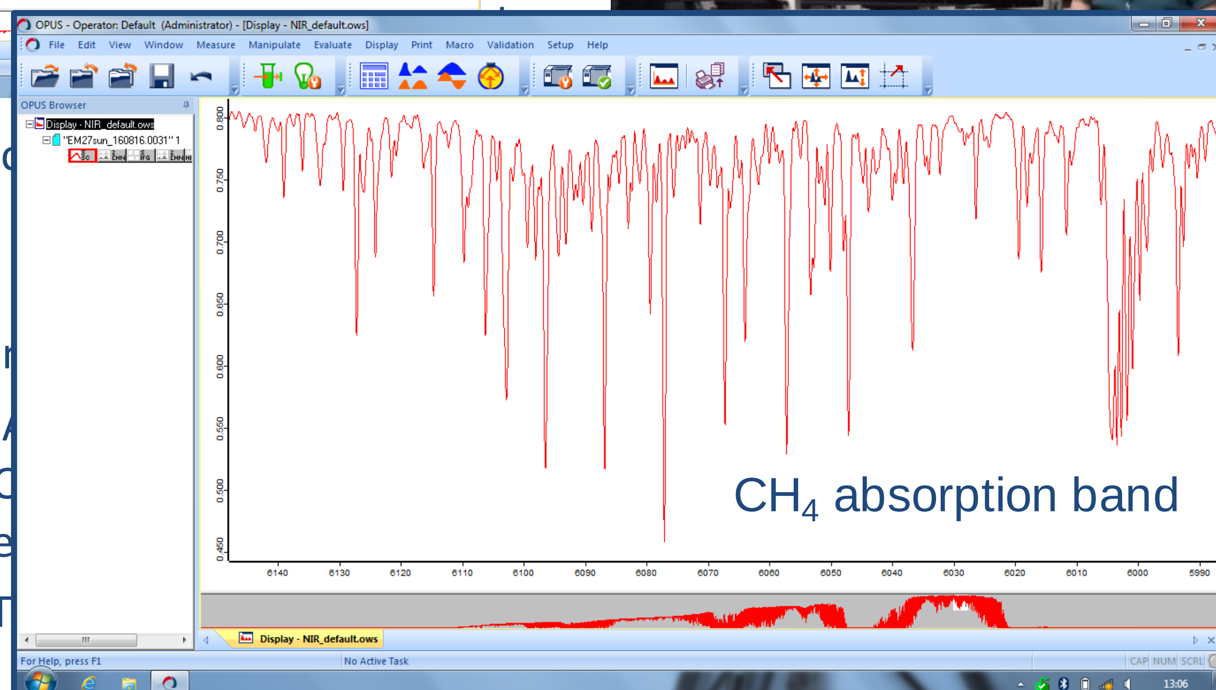
TCCON calibration against in-situ data from aircraft profiles



Deployment of Bruker EM27/SUN FT-IR in Uganda in 2018

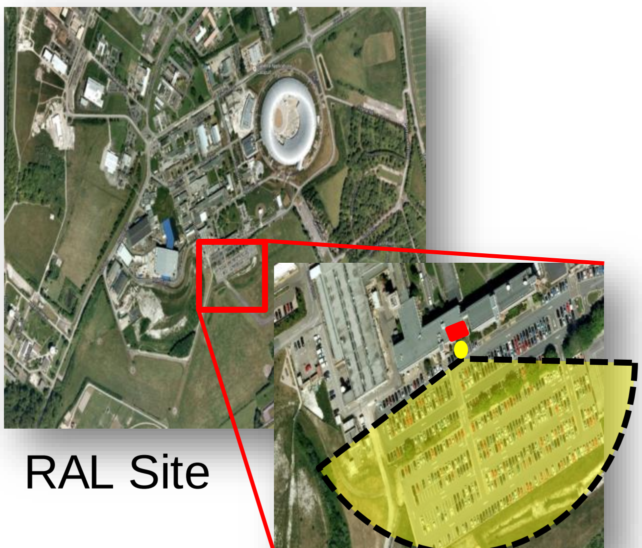


- 5000 to 14500 cm^{-1} at 0.5 c
  to 2.0 µm)
- Internal calibration source
- Portable and robust instru
- Provide validation for GOS
  tropical Africa (gap in TCC
  long term (but < 1 year) de
- Inter-calibrated against KIT
  Network)



Setup of a UK TCCON Site at Harwell

- NCEO and RALSpace Collaboration
- Instrument: Bruker 120HR with Resolution = $0.0015 cm^{-1}$ (OPD 6m)
- Large external Sun tracker with dome



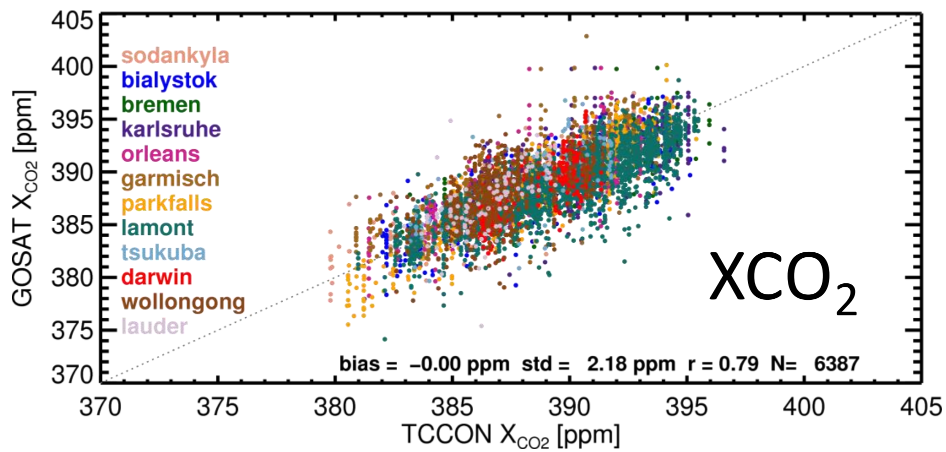
RAL Site

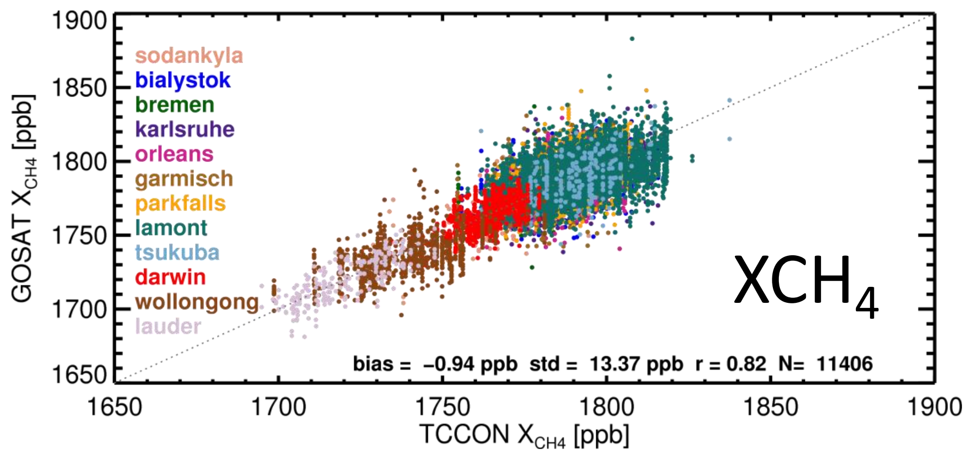
Suntracker and Dome

Bruker FTS

Validation of XCO_2 and XCH_4

- Comparison against 12 TCCON sites (covering different geophysical regimes)
- Co-location criteria: +/- 5°





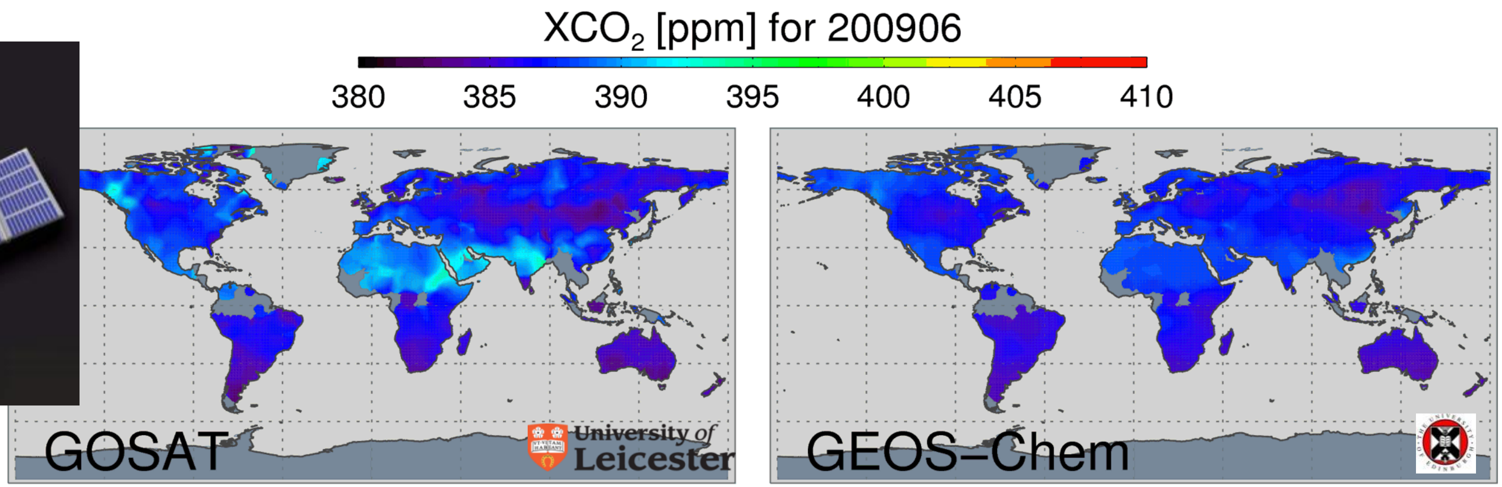
- Data is bias-corrected globally which results in a bias of 0 ppm to TCCON.

- Small (<0.06%) bias between GOSAT and TCCON (no bias correction necessary)
- Relies on model XCO_2 to normalise the XCH_4/XCO_2

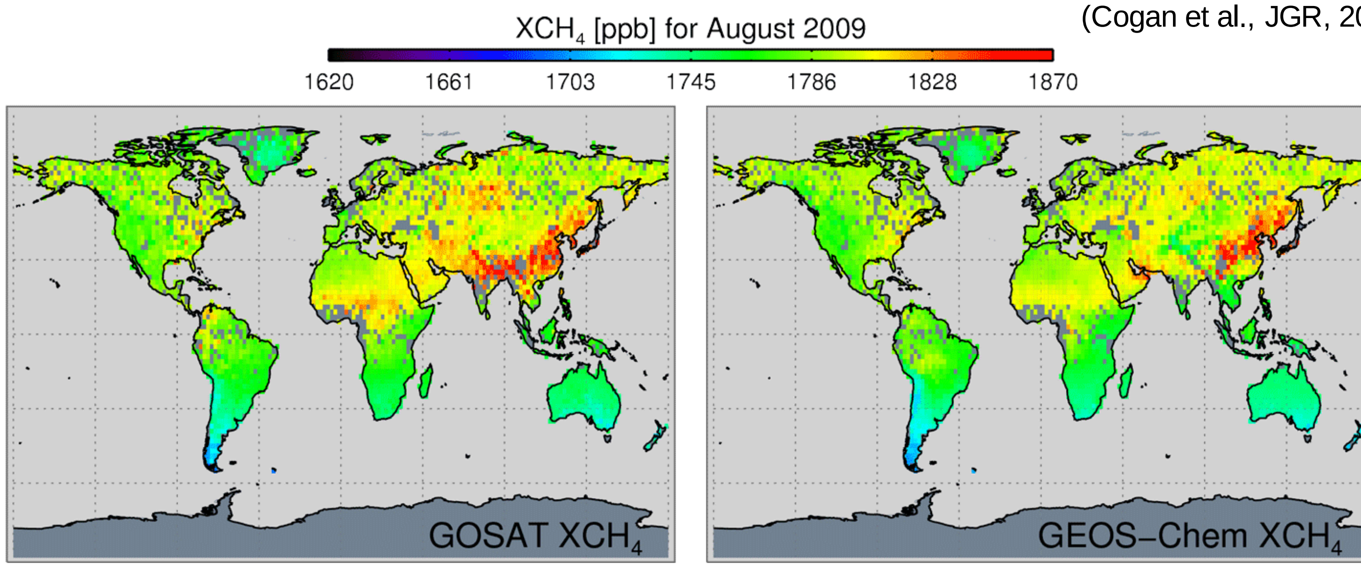
Testing Model Calculations with GOSAT

Dedicated satellite missions provide unprecedented global view of release and uptake of CO_2 and CH_4 by surface processes to critically test and improve models and to track main emission regions

GOSAT – first dedicated GHG satellite



(Cogan et al., JGR, 2012)

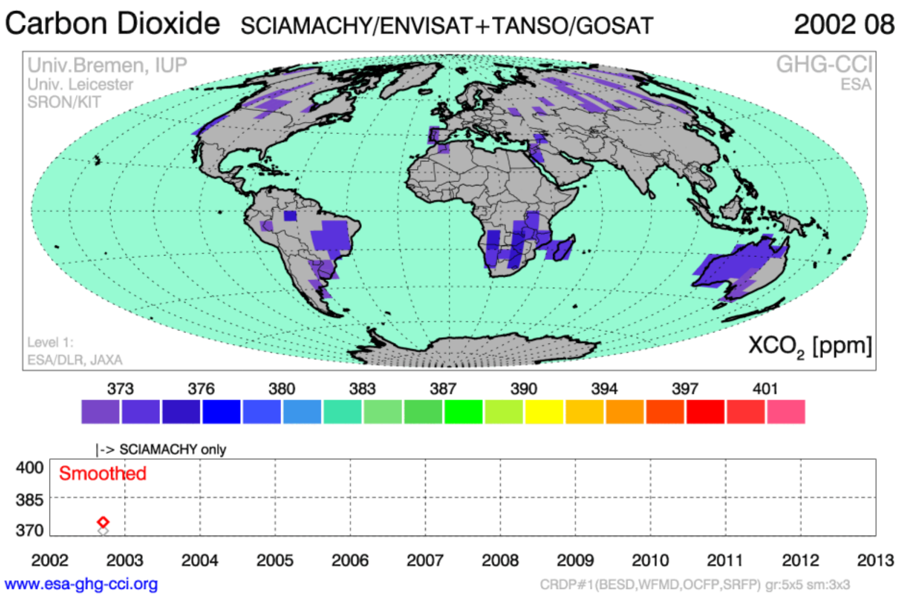


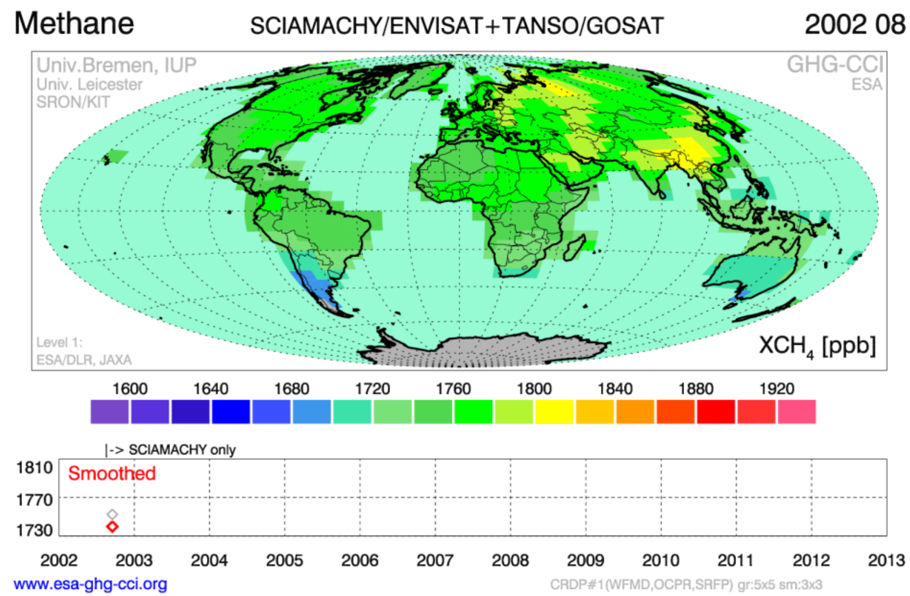
(Parker et al., GRL, 2011)

Data Access

www.leos.le.ac.uk/GHG/data/

More than 10 years of CO_2 and CH_4 from Space

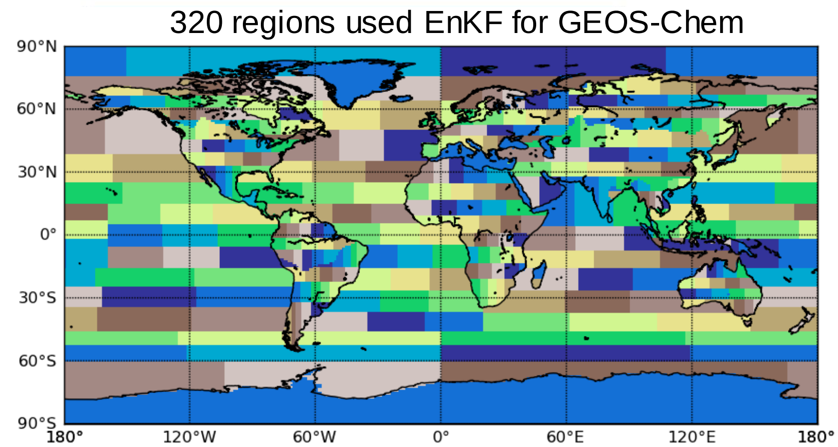




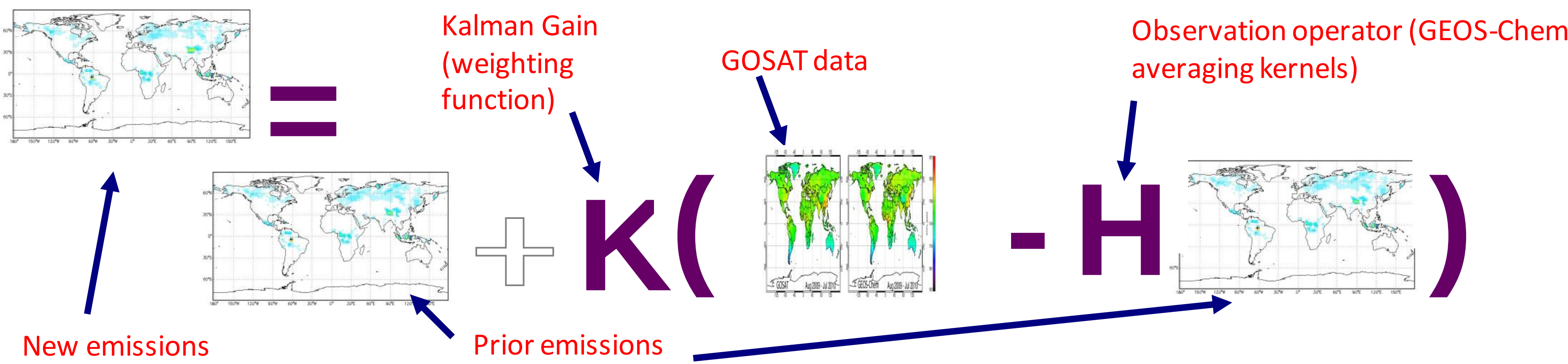
ESA Climate Change Initiative: http://www.esa-ghg-cci.org/

Surface Fluxes

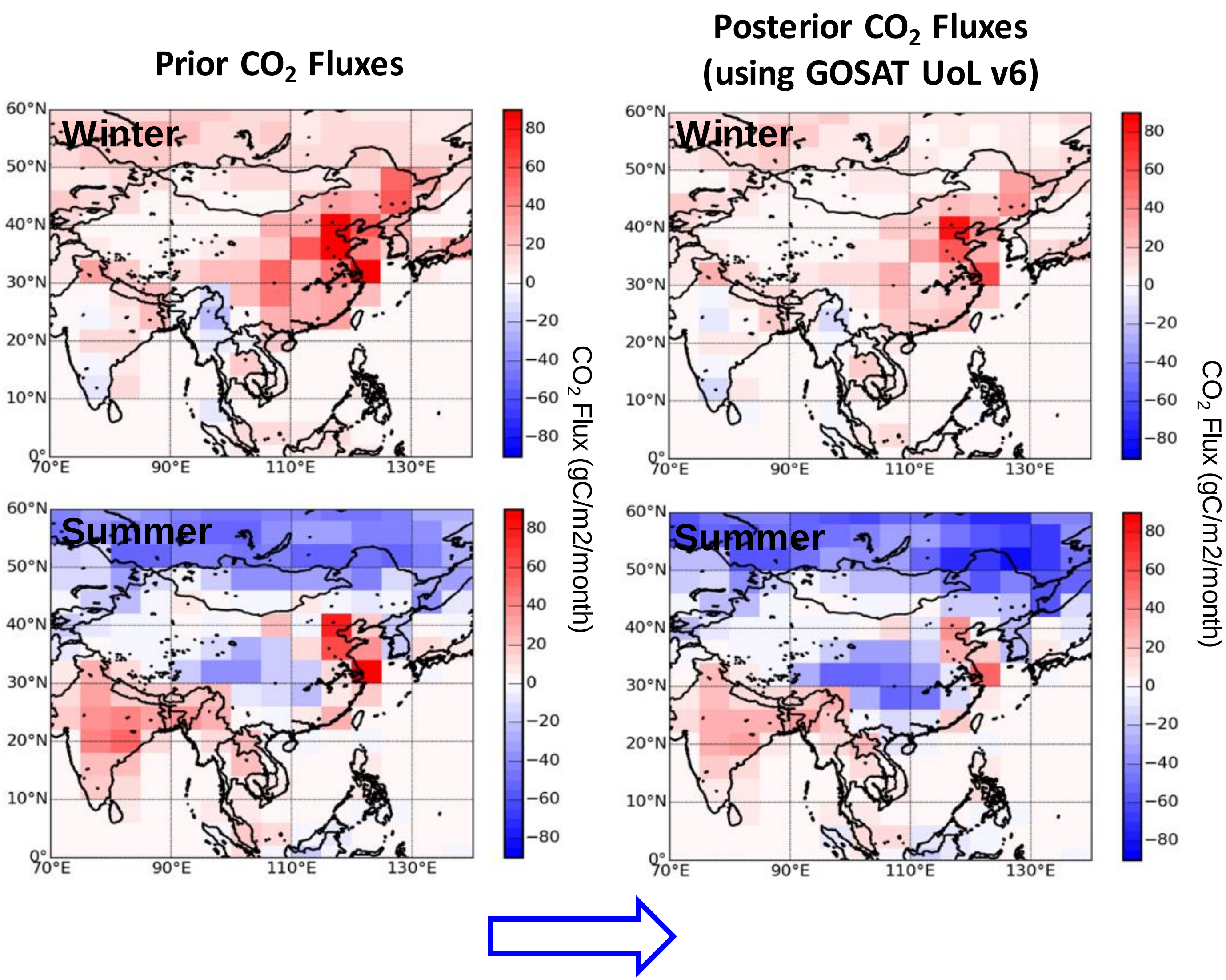
- We need to consider atmospheric transport if we want to link atmospheric CO_2 to surface fluxes
- This is done by assimilation of satellite data into an offline transport model
- Example: Ensemble Kalman Filter for GEOS-Chem which optimizes CO_2 or CH_4 fluxes for 320 regions (land and ocean)



Ensemble Kalman Filter (EnKF)



Example: Estimating CO_2 Surface Fluxes from GOSAT over China



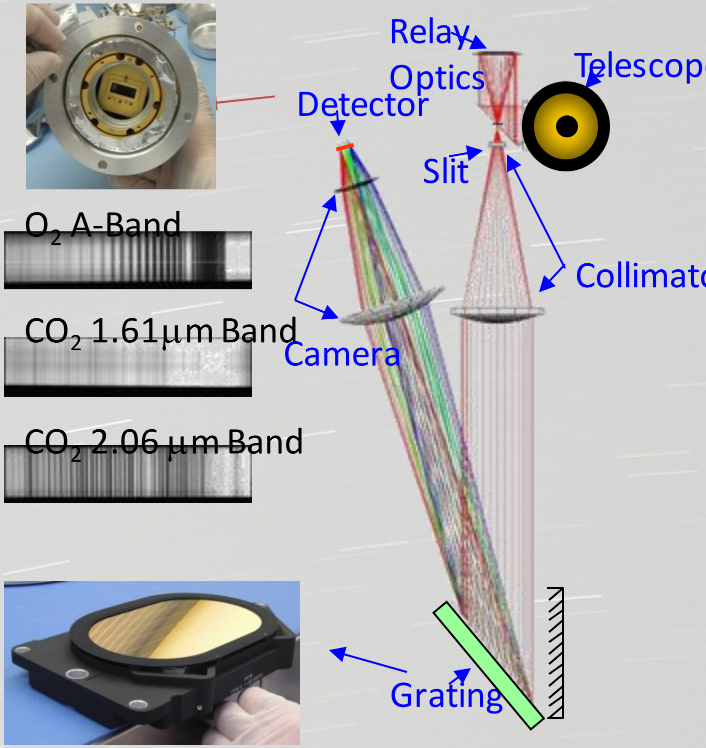
Lower emissions (winter) and larger uptake (summer)

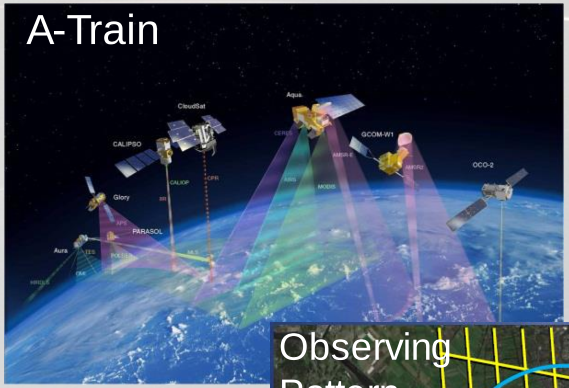
GEOS-Chem with Ensemble Kalman Filter (L. Feng and P. Palmer, U. Edinburgh)

Launch of NASA OCO-2 from Vandenberg AFB in California on 2 July 2015 at 2:56 a.m. PDT

What is OCO-2 ?

- First dedicated CO_2 mission by NASA
- Copy of the failed OCO-1 mission (launched in 2009)
- High resolution gratin spectrometer that measures reflected sunglint in the near and shortwave-infrared
- OCO-2 flies at the head of A-Train, but 217 km East of AQUA
- OCO-2 carries out nadir and sunglint (ocean) and target (over validation sites) observations
- The ground track is 10 km width with 8 across track pixels of area 3km^2
- OCO-2 generate 100x more soundings than GOSAT with higher SNR

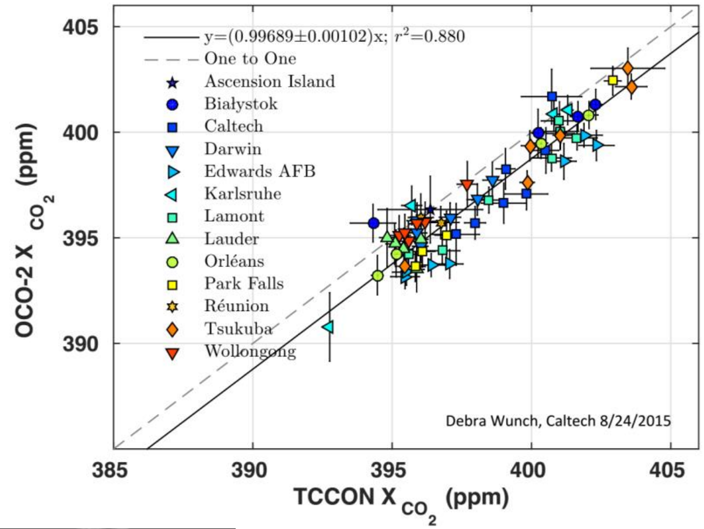




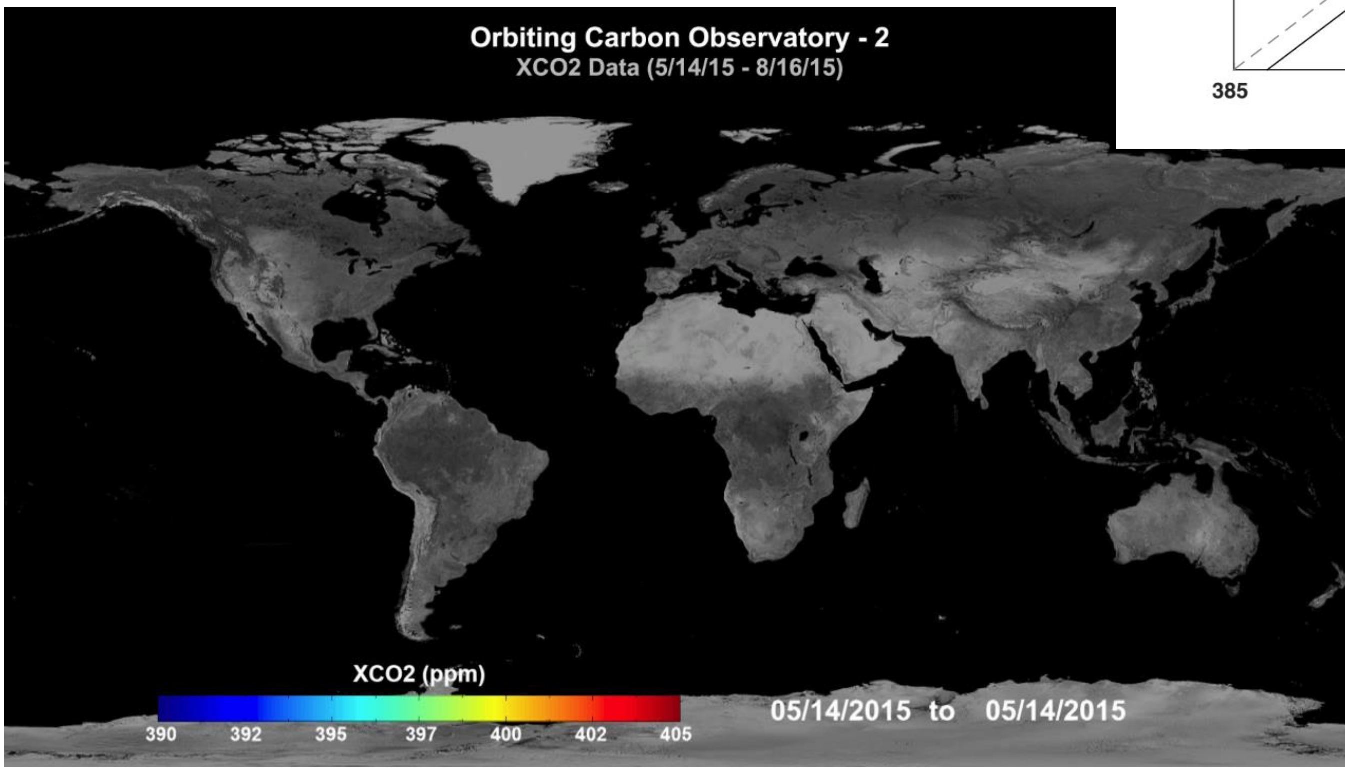
OCO-2 CO_2 Results

OCO-2 offers CO_2 (+ SIF) observations with much higher precision and coverage than GOSAT

Validation against TCCON

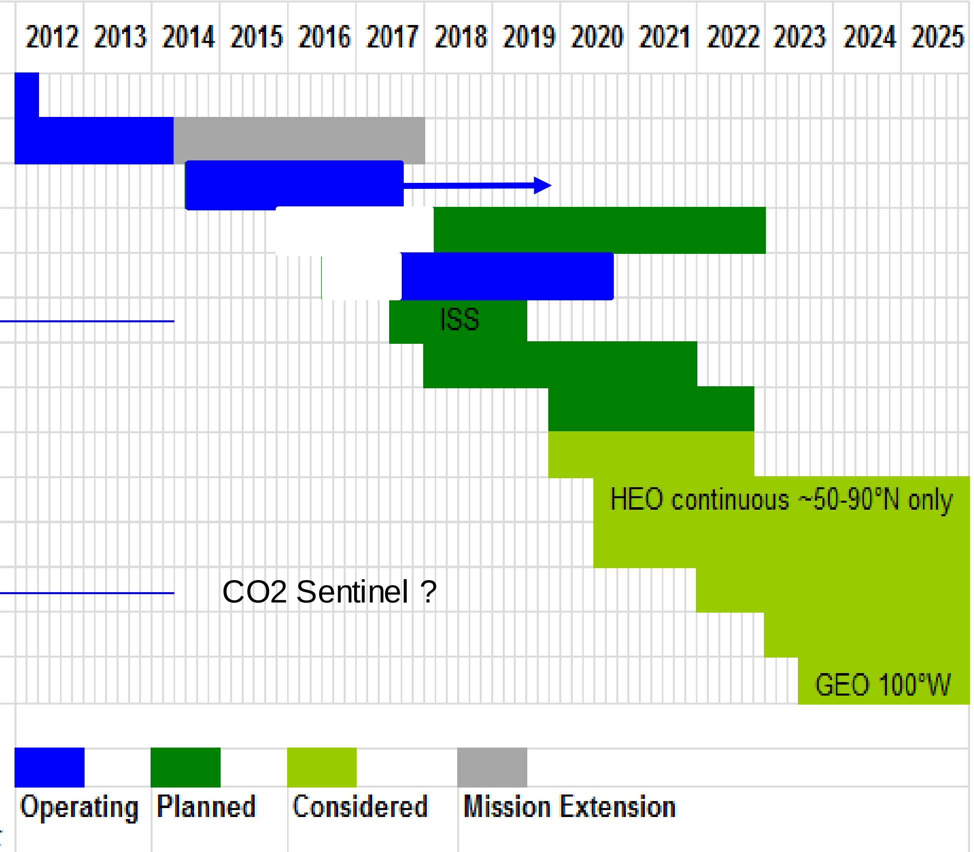


A Quick Look at the First 13 Months of Operations:



Current and Planned GHG Missions

Satellite, Instrument (Agencies)	CO_2	CH_4	FOV
ENVISAT SCIAMACHY (ESA)	•	•	30x60 km^2
GOSAT TANSO-FTS (JAXA-NIES-MOE)	•	•	10.5 km (d)
OCO-2 (NASA)	•		1.29x2.25 km^2
Sentinel-5P TROPOMI (ESA)		•	7x7 km^2
TanSat (CAS-MOST-CMA)	•		1x2 km^2
~~OCO-3 (NASA)~~	~~•~~		~~~4 km^2~~
GOSAT-2 TANSO-FTS (JAXA-NIES-MOE)	•	•	10.5 km (d)
MERLIN (DLR-CNES)		•	0.135 km (w)
MicroCarb (CNES)	•		25 km^2
PCW-PHEOS-FTS (CSA)	?	•	10x10 km^2
MetOpSG Sentinel-5 (ESA-EUMETSAT)		•	7x7 km^2
~~CarbonSat (ESA)~~	~~•~~	~~•~~	~~2x3 km^2~~
ASCENDS (NASA)	•		0.100 km (w)
GEO-CAPE (NASA)		•	4x4 km^2
(GEOCARB)			



Based on information from various sources

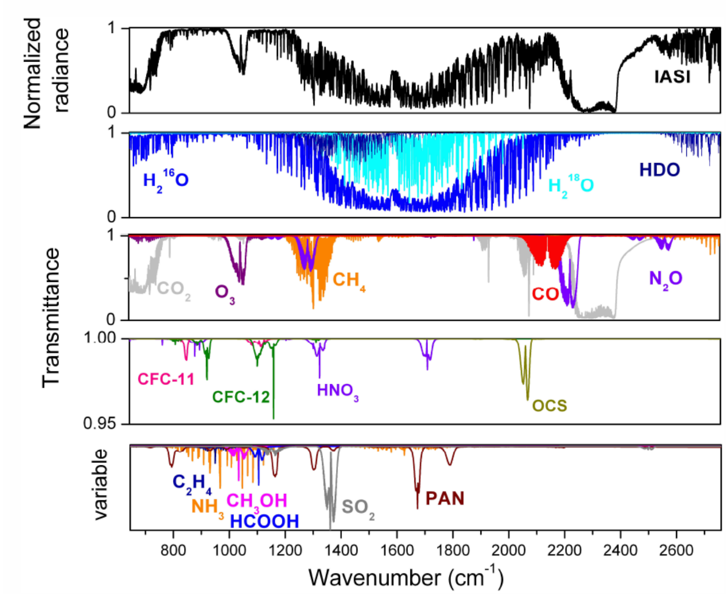
Proposed or funding not confirmed

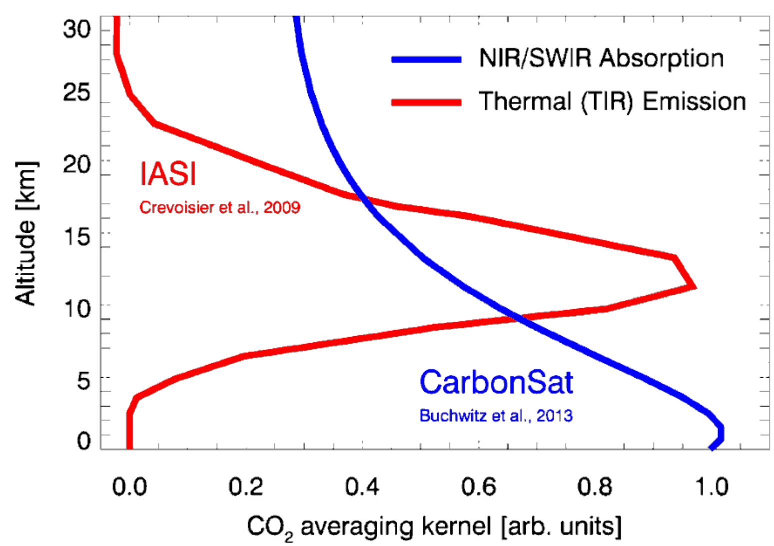
d = diameter
w = width of a narrow strip along orbit track

Over the next decade, a succession of missions with a range of CO_2 and CH_4 measurement capabilities will be deployed in both polar and geostationary orbits

Thermal IR Sounders for GHGs

- CO_2 and CH_4 absorption is also present in the thermal infrared part of the spectrum
- The light source is the emission from the Earth's surface and not the Sun → measurements possible during both day and night
- Measurement of atmospheric gases requires thermal contrast to the surface thus peak sensitivity is in free troposphere with little sensitivity to boundary layer
- Sensors: ESA IASI, NASA AIRS and NASA TES





Summary

- Remote sensing from satellites allows measuring the global distribution of greenhouse gases → especially beneficial for regions poorly sampled by surface networks
- However, it is an indirect measurement so careful validation and calibration is needed to ensure the accuracy and precision
- We now have the first dedicated GHG missions in space (GOSAT, OCO-2) and we hope for a continuous presence in space in the future using a range of technologies (including active sensing)

Section 3:

Computer-based Activity

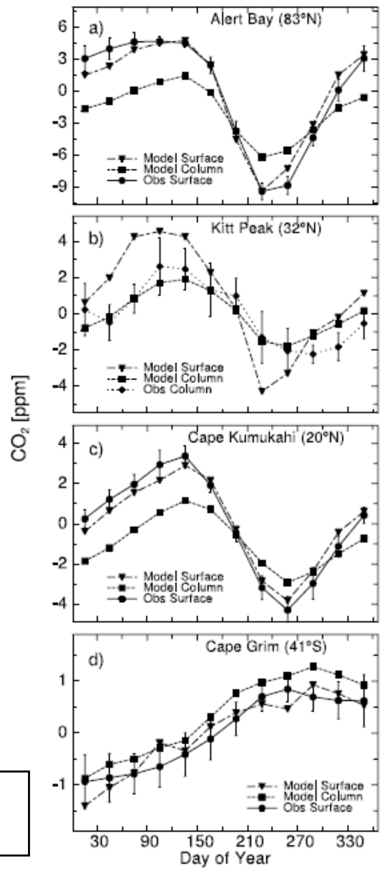
Main Goals of the Activity

- Visualize the main aspects of the global carbon cycle as observed by GOSAT such as global distribution and seasonal cycle of CO_2
- Compare to observations from a thermal-IR sounder (AIRS) and from an in-situ surface station
- Explain your observations and summarize them in brief Powerpoint presentation

Data Sources and Tools

- We will use GOSAT CO_2 (Shortwave-infrared) columns from the ESA Climate Change Initiative and analyse them with IDL
- AIRS thermal-infrared CO_2 data available from the NASA Giovanni web-portal
- NOAA surface in-situ data from the NOAA ESRL webpage

Seasonal Cycle for surface and total column CO2



Triangles: surface
Square: Total column

Figure 6. Modeled surface (triangles) and column (squares) CO_2 mixing ratios at (a) Alert Bay, Canada, (b) Kitt Peak, USA, (c) Cape Kumukahi, USA, and (d) Cape Grim, Australia. At Alert Bay, Cape Kumukahi, and Cape Grim, surface measurements from the NOAA/CMDL network are shown with circles and standard deviation error bars. At Kitt Peak, data from *Yang et al.* [2002] for solar zenith angles less than 80° are shown with diamonds and standard deviation error bars. To construct the model estimate of the column at Kitt Peak, we sampled the model at levels above 790 hPa, corresponding to the height of Kitt Peak (2083 m).

Olsen and Anderson, JGR, 2006

Seasonal Cycle for total column and free-tropospheric CO2

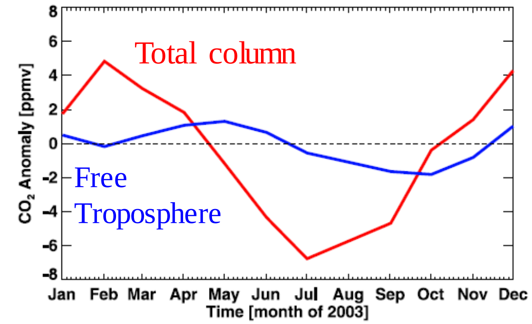


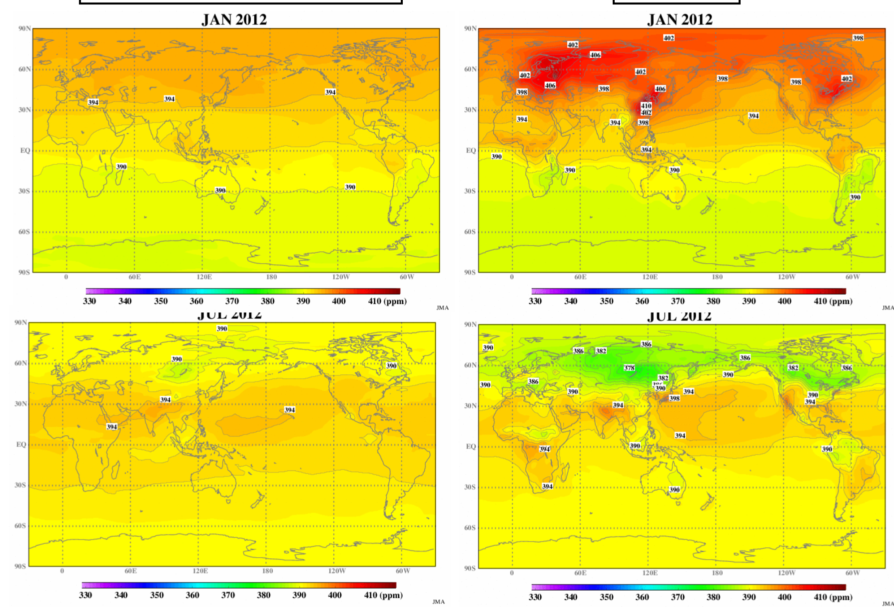
Figure 2. CO_2 anomaly over North America detected by SCIAMACHY (red) and AIRS (blue).

Barkley et al., GRL, 2006

North-South Variations

Free Troposphere (6km)

Surface



http://ds.data.jma.go.jp/ghg/kanshi/info_kanshi_e.html