Observation Processing for NWP -II

Satellite Data processing

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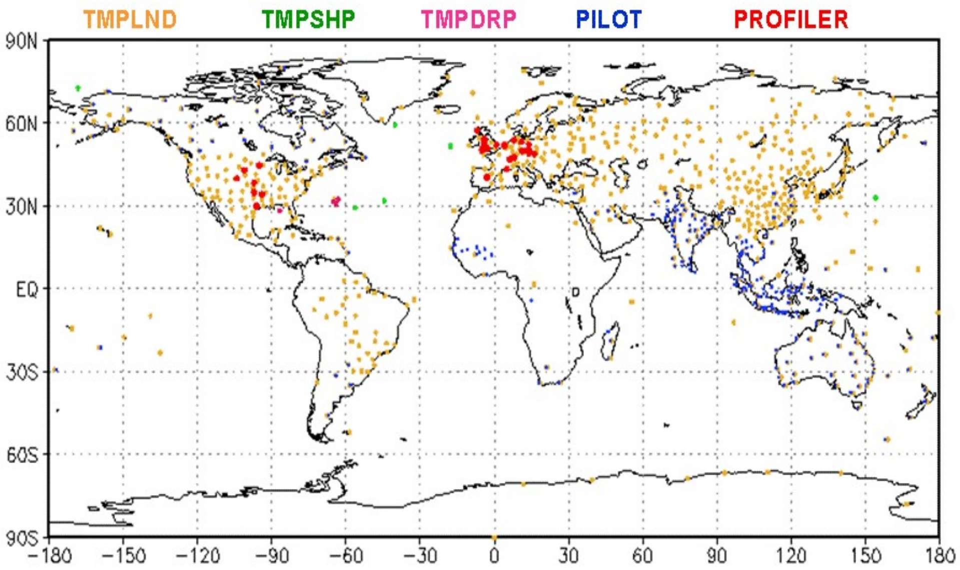
Acknowledgements: Materials/contents from many sources

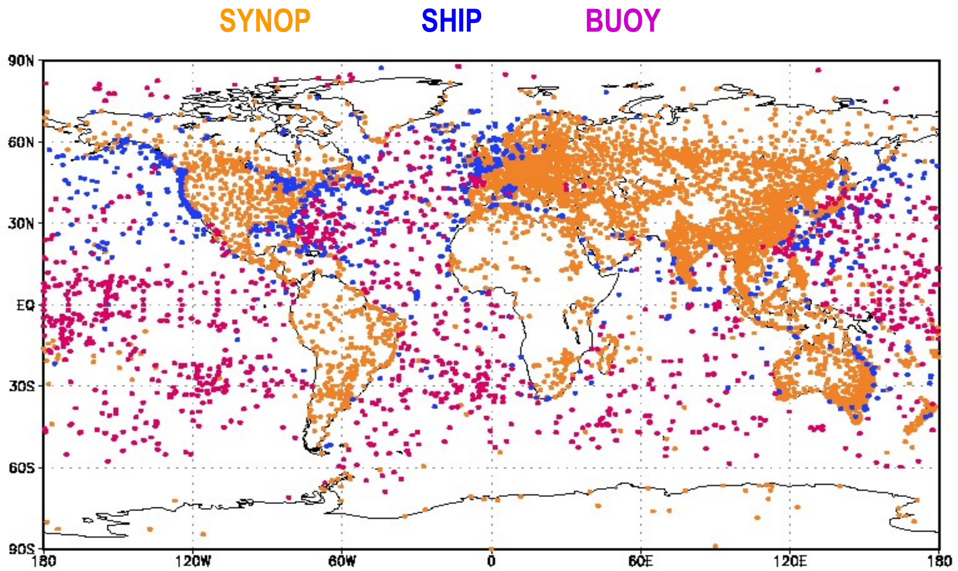
Need for Satellite Data

Conventional observations of temperature, wind, and moisture profiles are confined over the Northern Hemisphere land area

Over the ocean, conventional observations are primarily limited to single level data provided by aircraft, ships, and buoys.

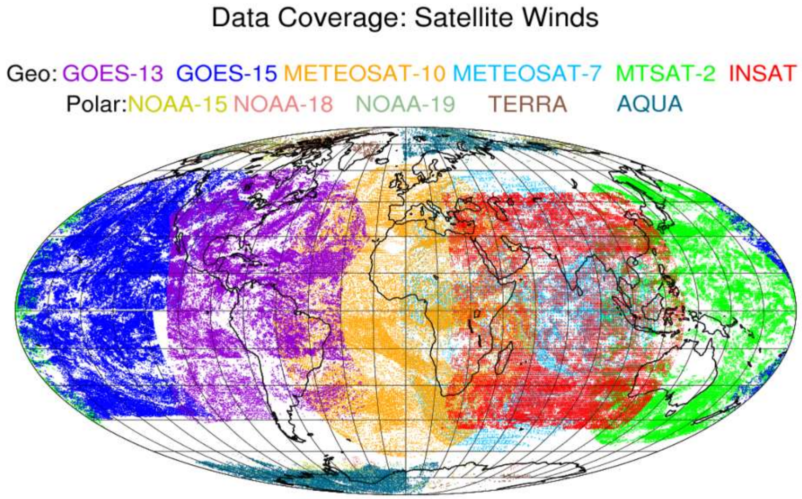
The coverage of these and other ground based observing systems is not sufficient for global atmosphere and ocean research or weather prediction.



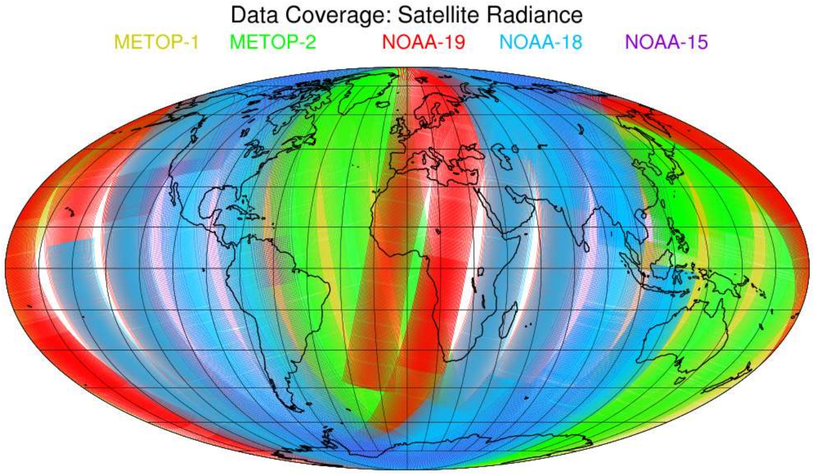


Satellites have offered, and continue to offer an effective way to provide needed observations in data sparse regions and also at very higher resolution

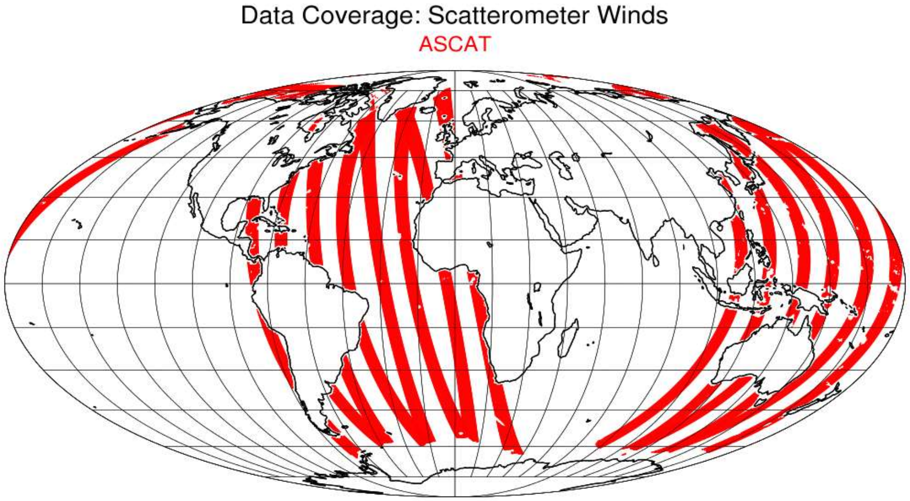
AMVs


Data Coverage: Satellite Winds

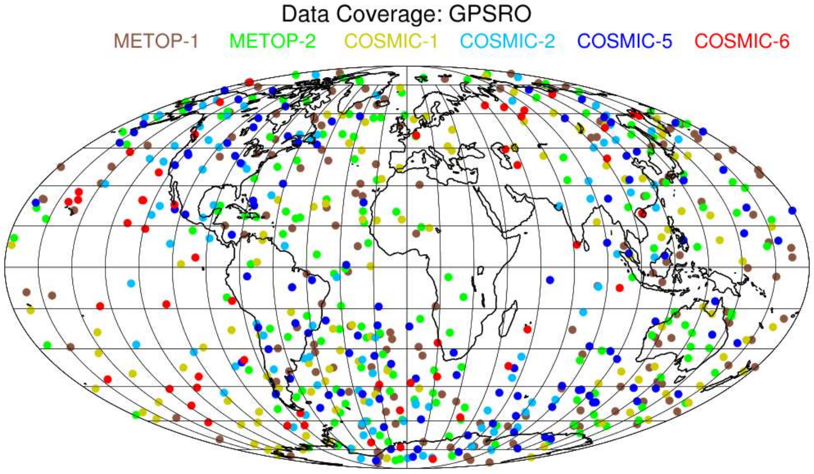
Radiances


Data Coverage: Satellite Radiance

ASCAT


Data Coverage: Scatterometer Winds

GPSRO


Data Coverage: GPSRO

Satellite Data vs. Conventional Data

Satellite Data	Conventional Data
Indirect measurements	Direct measurements
Until recently, low vertical resolution in troposphere	High vertical resolution
Area or volume averages	Point measurements
Variable temporal resolution – asynoptic	Generally low temporal resolution
Good horizontal coverage	Poor horizontal coverage
High horizontal resolution	Low horizontal resolution
Automatic data processing	Human link in data chain
High data volumes	Low data volumes

Some of the main Satellite instruments currently used at NCMRWF

1. ATOVS: Advanced TIROS Operational Vertical Sounder (NOAA-18, 19, Metop series)
    - HIRS (High Resolution Infra-Red Sounder)
    - AMSU-A (Advanced Microwave Sounding Unit-A): Temperature channels
    - AMSU-B/MHS : Humidity channels
2. AMSR-2 : Advanced Microwave Scanning Radiometer onboard GCOM-W1
3. ATMS: Advanced Technology Mircowave Sounder (S-NPP and NOAA-20)
4. SSMI/S: Special Sensor Microwave Imager/Sounder (DMSP)
5. GMI: Global Precipitation Mission (GPM) Microwave Imager

Multispectral LEO

6. IASI: Infrared Atmospheric Sounding Unit (MetOp series)
7. AIRS: Atmospheric Infra-Red Sounder (AQUA)
8. CrIS: Cross-track Infrared Sounder (S-NPP and NOAA-20)

Hyperspectral LEO

9. INSAT-3D(R) Imager and Sounder
10. SEVIRI: Spinning Enhanced Visible and Infra-Red imager (Meteosat series)
11. AHI: Advanced Himawari Imager (Himawari)
12. ABI: Advanced Baseline Imager (GOES)

Multispectral GEO

What do satellite instruments measure?

They **DO NOT** measure TEMPERATURE
They **DO NOT** measure HUMIDITY or OZONE
They **DO NOT** measure WIND

Satellite instruments simply measure the radiance *L* that reaches the top of the atmosphere at given frequency *v* . The measured radiance is related to geophysical atmospheric variables (T,Q,O_3, clouds etc…) by the radiative transfer equation

$$\overbrace{L(\nu)}^{\text{measured by the satellite}} = \overbrace{\int_0^\infty B(\nu,T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \dots}^{\text{Our description of the atmosphere}}$$

Planck source term* depending on temperature of the atmosphere

Absorption in the atmosphere

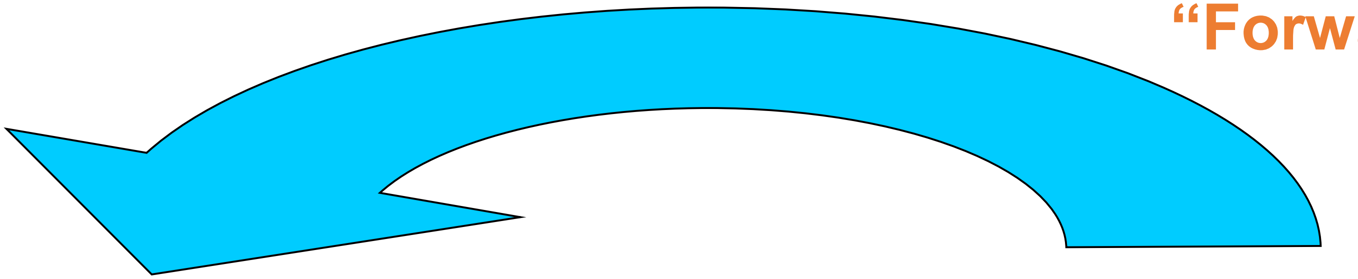
Other contributions to the measured radiances

The Radiative Transfer (RT) equation

$$\overbrace{L(\nu)}^{\text{measured by the satellite}} = \overbrace{\int_0^\infty B(\nu, T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots}^{\text{depends on the state of the atmosphere}}$$

The Radiative Transfer (RT) equation

“Forward problem”

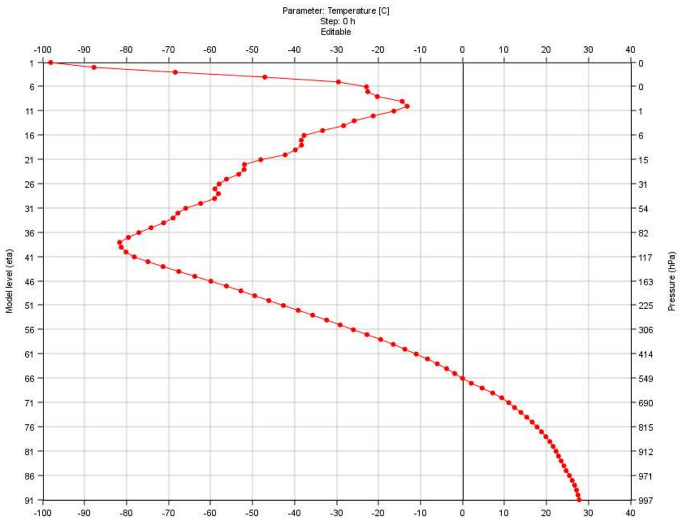


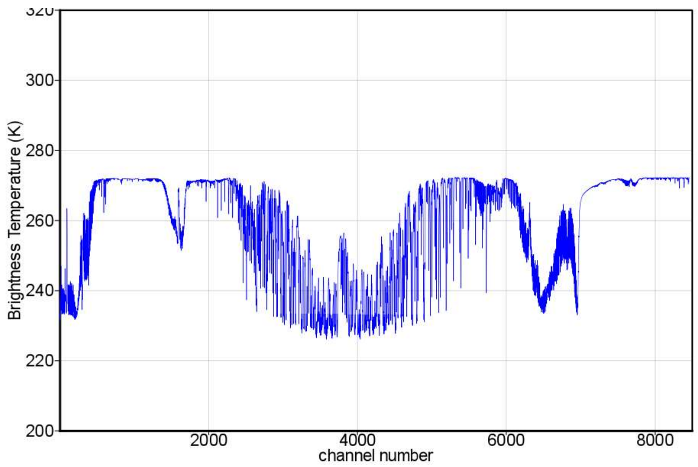
$$\overbrace{L(\nu)}^{\text{measured by the satellite}} = \overbrace{\int_0^\infty B(\nu,T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots}^{\text{depends on the state of the atmosphere}}$$

…given the state of the atmosphere, what is the radiance…?

RTTOV/CRTM Radiative Transfer Model

X (z) → RTTOV/ CRTM → **Y radiances**

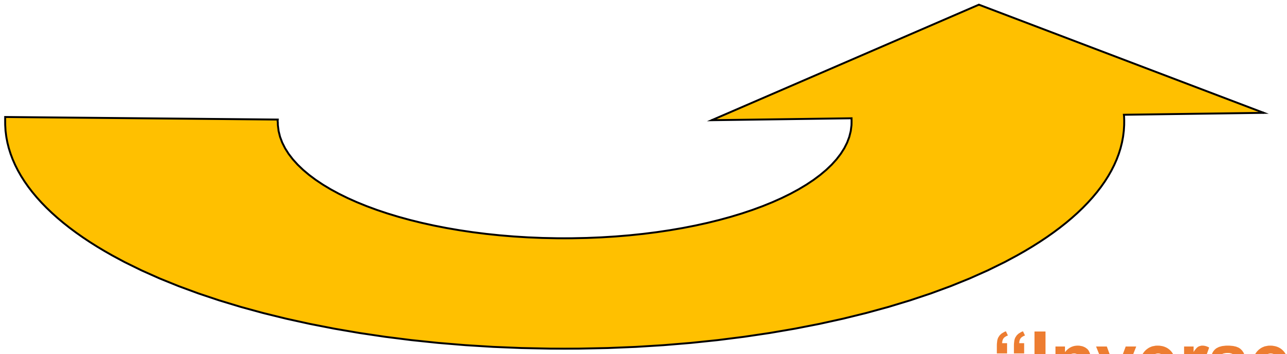




The Radiative Transfer (RT) equation

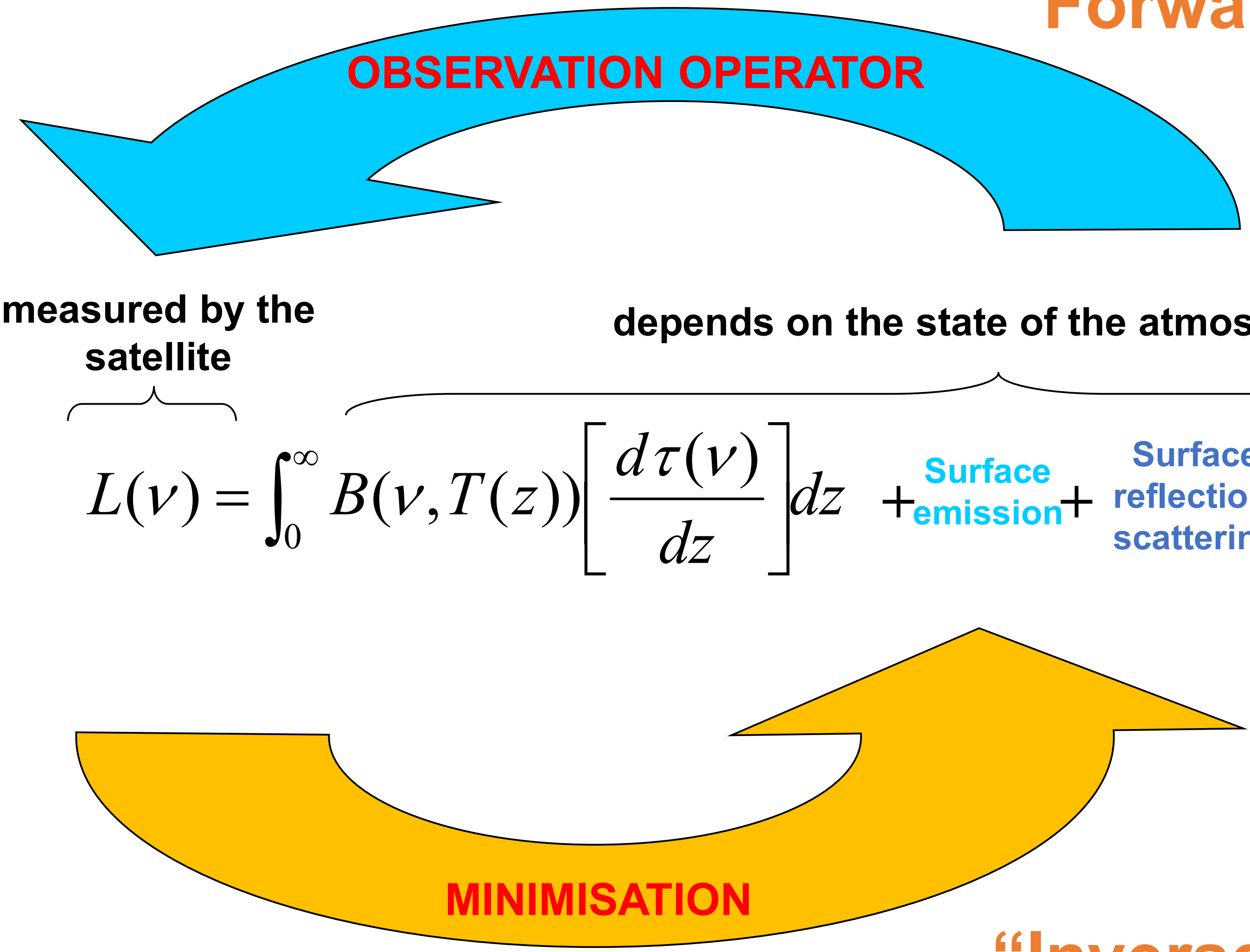
…given the radiance, what is the state of the atmosphere…?

$$\overbrace{L(\nu)}^{\text{measured by the satellite}} = \overbrace{\int_0^\infty B(\nu,T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots}^{\text{depends on the state of the atmosphere}}$$



“Inverse problem”

The Radiative Transfer (RT) equation



“Forward problem”

$$\overbrace{L(\nu)}^{\text{measured by the satellite}} = \overbrace{\int_0^\infty B(\nu,T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots}^{\text{depends on the state of the atmosphere}}$$

“Inverse problem”

How can we simplify the forward and inverse problems?

Channel selection

Measuring radiances in different frequencies (channels)

By deliberately **selecting** radiation at different frequencies or **CHANNELS** satellite instruments can provide information on specific geophysical variables for different regions of the atmosphere.

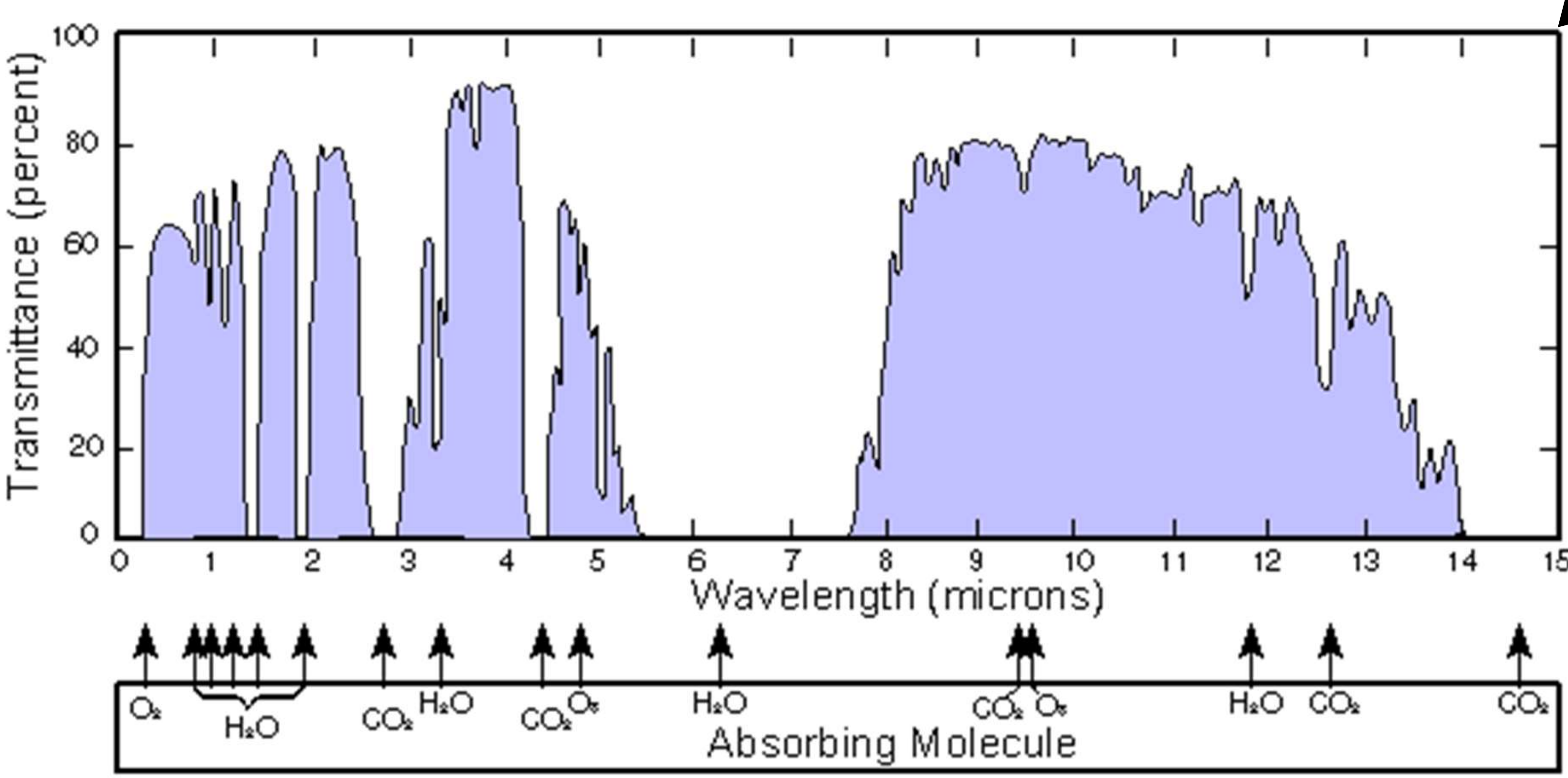
In general, the frequencies / channels used within NWP
may be categorized as one of 3 different types …

1. **atmospheric sounding** channels (**passive** instruments)
2. **surface sensing** channels (**passive** instruments)
3. **surface sensing** channels (**active** instruments)

Note:

In practice (and often despite their name!) real satellite instruments have channels which are a ***combination*** *of atmospheric sounding and surface sensing channels*

Example: absorption of infrared radiation in the atmosphere



100 %

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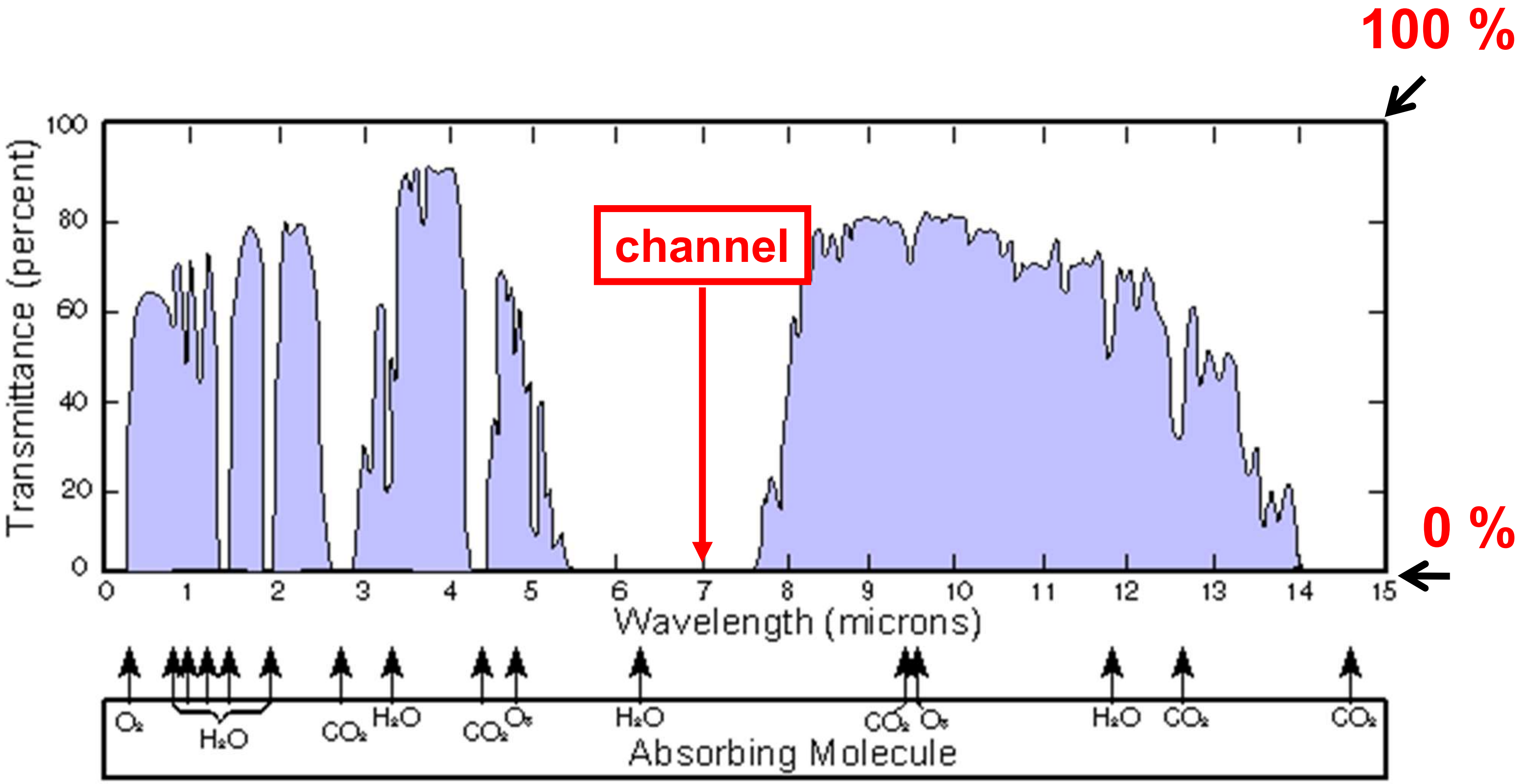
Atmospheric sounding channels

Atmospheric sounding channels



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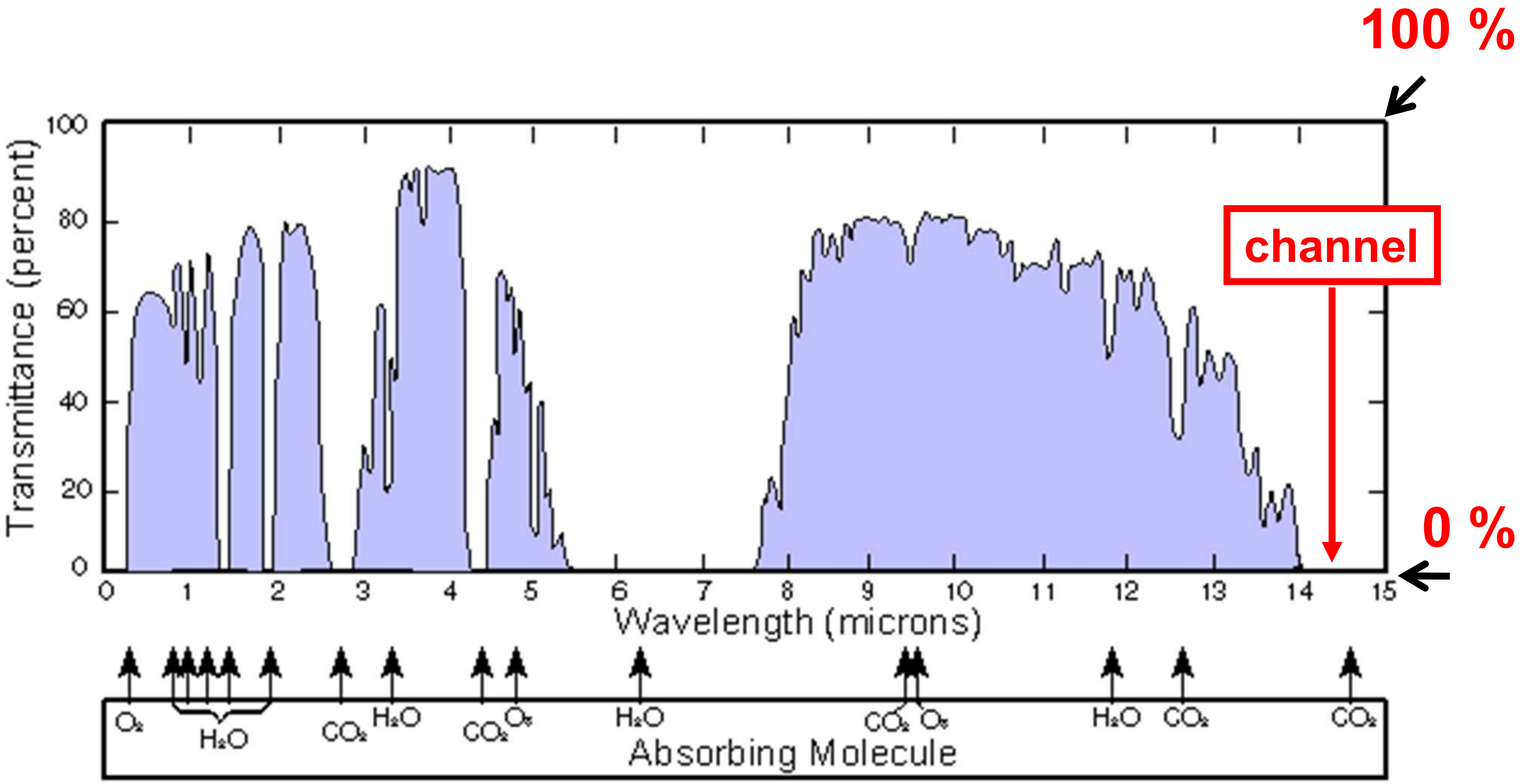
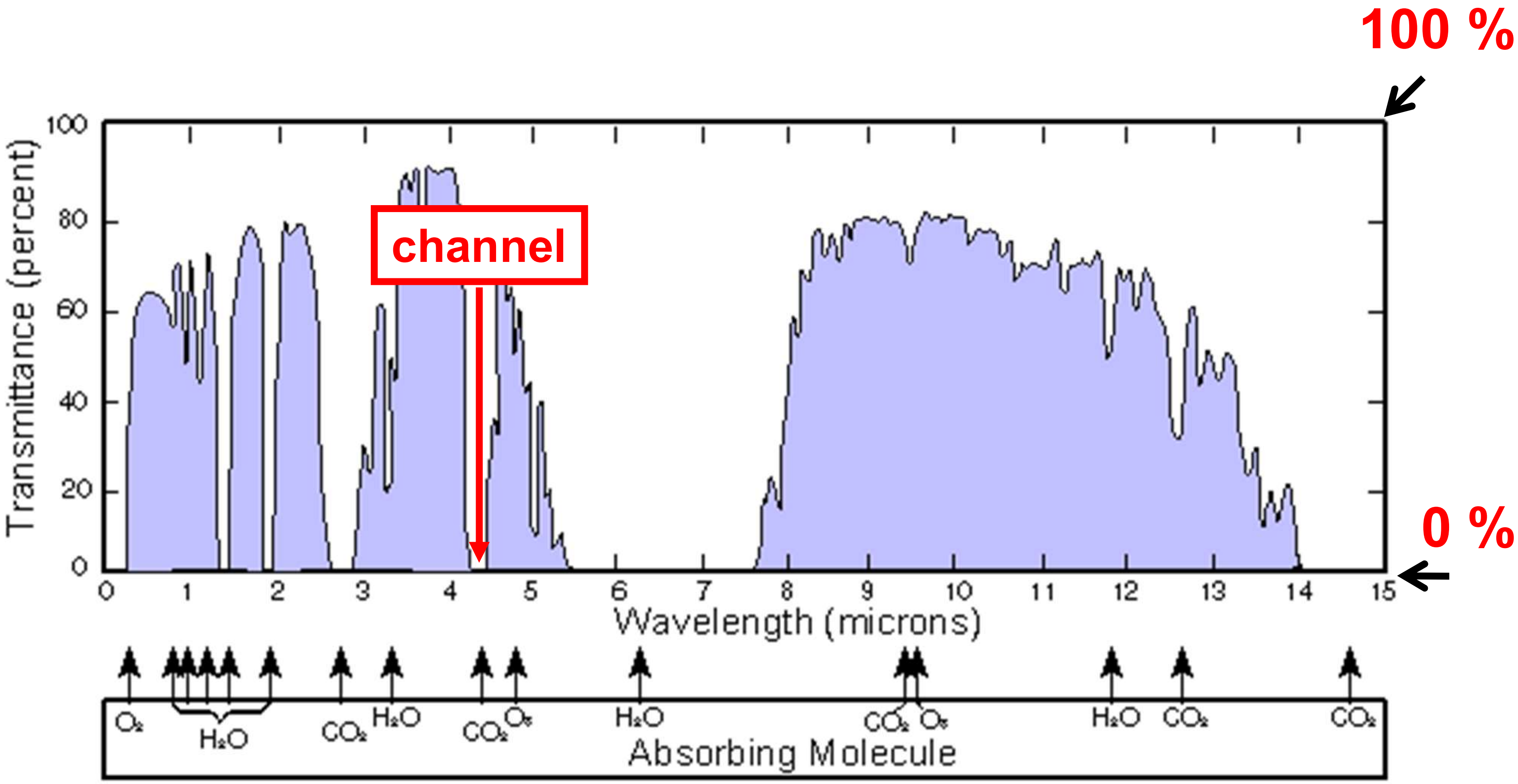
channel

Atmospheric sounding channels



Atmospheric sounding channels



channel

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Atmospheric sounding channels

…selecting channels where there is **no** contribution from the **surface**….

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz \; + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots$$

Atmospheric sounding channels

…selecting channels where there is no contribution from the surface….

$$L(\nu)=\int_0^\infty B(\nu,T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz+\xcancel{\text{Surface emission}}+\xcancel{\text{Surface reflection/scattering}}+\xcancel{\text{Cloud/rain contribution}}+\ldots$$

ATMOSPHERIC SOUNDING CHANNELS

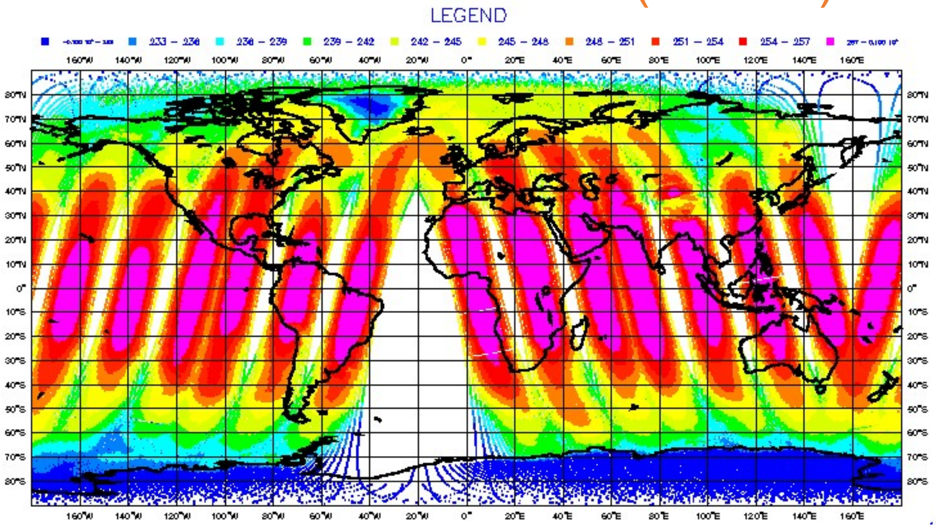
These channels are located in parts of the infra-red and microwave spectrum for which the main contribution to the measured radiance is from the **atmosphere** and can be written:

$$\boxed{L(\nu) \approx \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz}$$

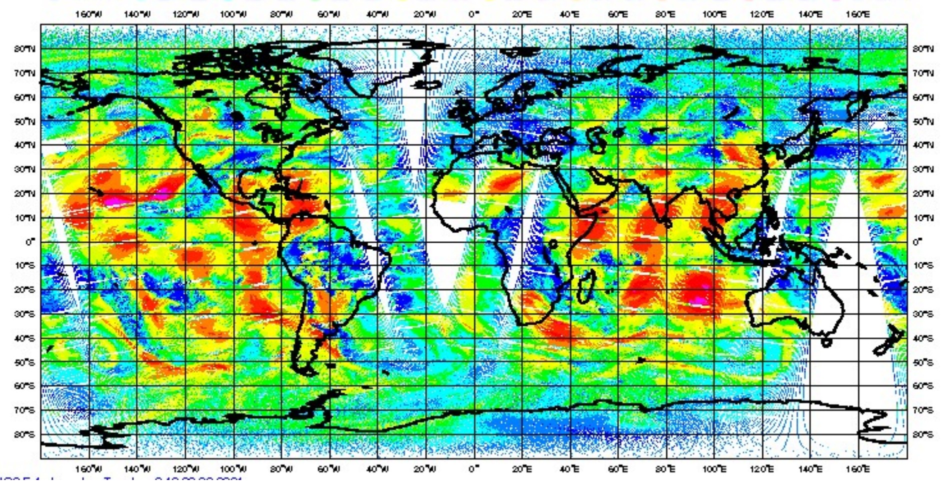
Where B=Planck function
t = transmittance
T(z) is the temperature
z is a height coordinate

That is they try to **avoid** frequencies for which **surface radiation** and cloud contributions are important. They are primarily used to obtain **information about atmospheric temperature and humidity** (or other constituents that influence the transmittance e.g. CO_2).

AMSUA-channel 5 (53GHz)

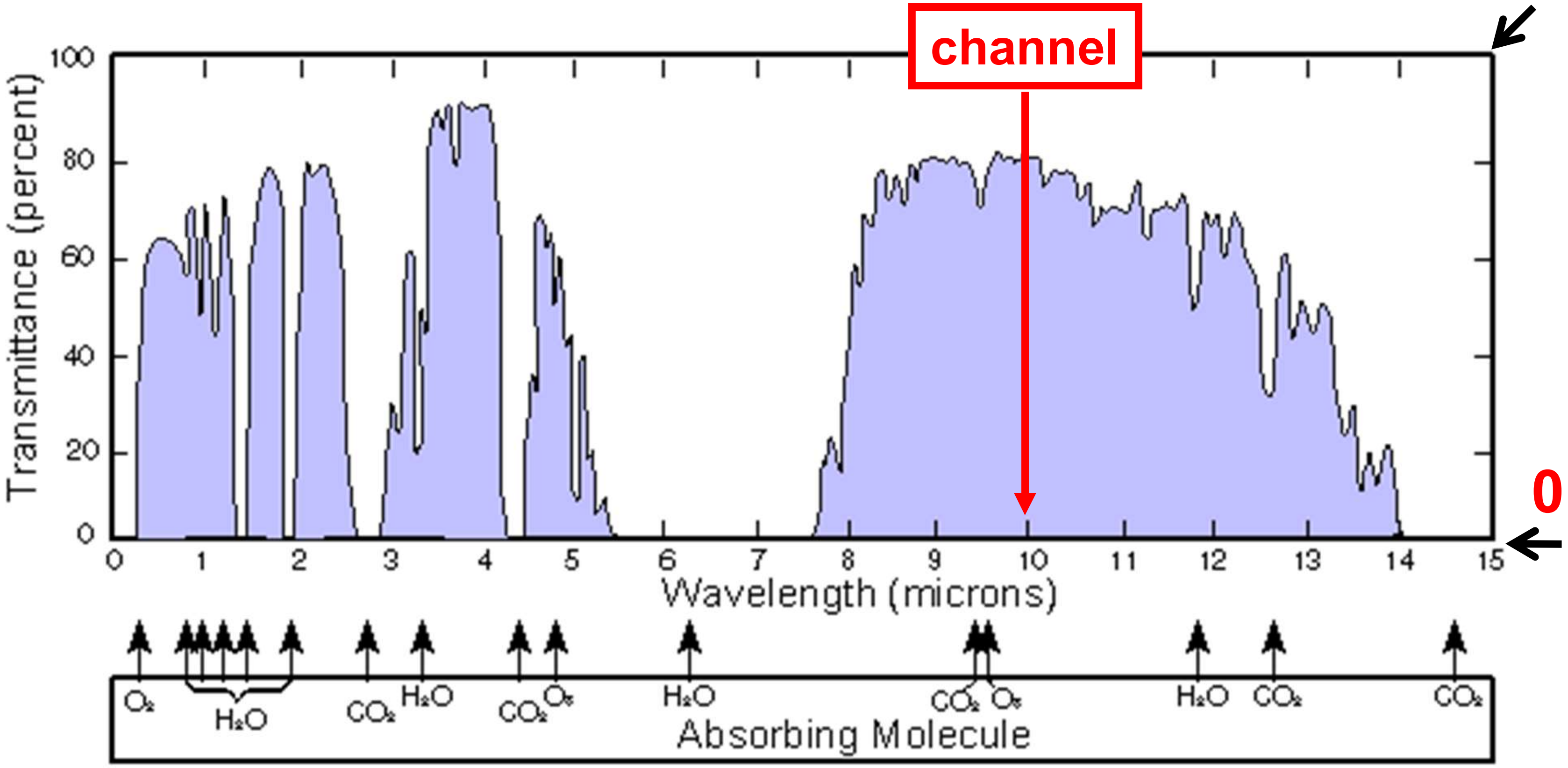


HIRS-channel 12 (6.7micron)



Surface sensing Channels (passive)

Surface sensing Channels (passive)



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channel

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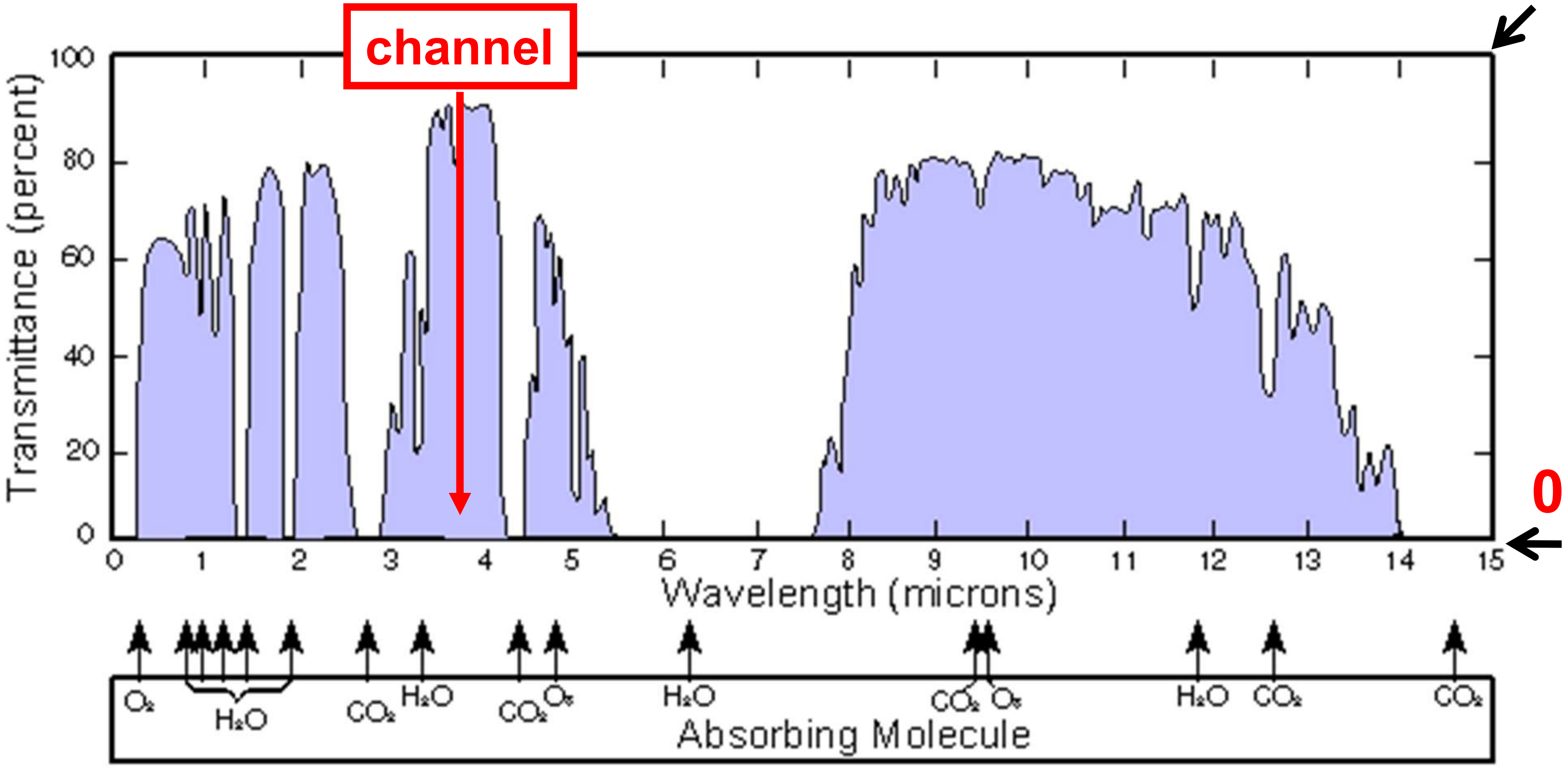
Surface sensing Channels (passive)



channel

100 %

0 %

Surface sensing Channels (passive)

…selecting channels where there is **no** contribution from the **atmosphere**….

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz}\right] dz + \text{Surface emission} + \text{Surface reflection/ scattering} + \text{Cloud/rain contribution} + \dots$$

Surface sensing Channels (passive)

…selecting channels where there is **no** contribution from the **atmosphere**….

$$L(\nu) = \xcancel{\int_0^{\infty} B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz} + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots$$

Surface sensing Channels (passive)

…selecting channels where there is **no** contribution from the **atmosphere**….

$$L(\nu) = \cancel{\int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz}\right] dz} + \text{Surface emission} + \underset{\uparrow}{\cancel{\text{Surface reflection/scattering}}} + \text{Cloud/rain contribution} + \ldots$$

IR ~ zero

Surface sensing Channels (passive)

…selecting channels where there is no contribution from the atmosphere….

$$L(\nu) = \int_0^\infty \xcancel{B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz}\right]} dz + \text{Surface emission} + \xcancel{\text{Surface reflection/scattering}} + \xcancel{\text{Cloud/rain contribution}} + \ldots$$

Screen data to remove clouds / rain

SURFACE SENSING CHANNELS (PASSIVE)

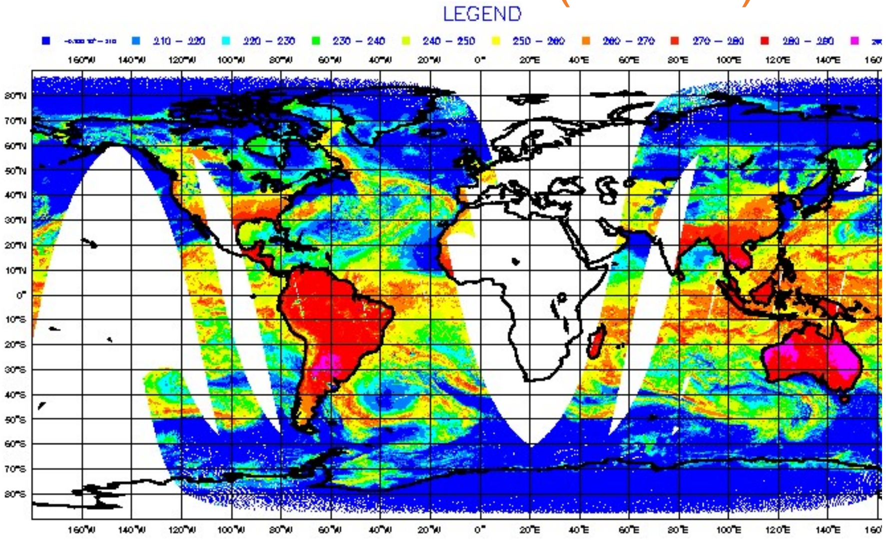
These are located in **window regions** of the infra-red and microwave spectrum at frequencies where there is very little interaction with the atmosphere and the primary contribution to the measured radiance is:

$$\boxed{L(\nu) \approx B[\nu, T_{surf}]\varepsilon(u,v) \quad \text{(i.e. surface emission)}}$$

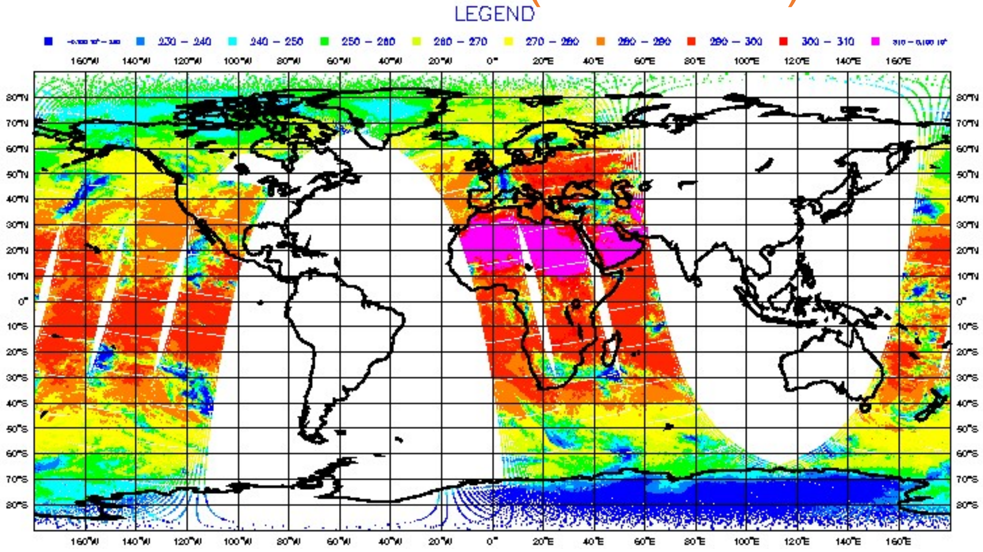
Where T_{surf} is the surface skin temperature and E the surface emissivity

These are primarily used to obtain **information on the surface temperature** and quantities that influence the **surface emissivity** such as wind (ocean) and vegetation (land). They can also be used to obtain information on **clouds/rain** and cloud movements (to provide **wind** information)

SSM/I channel 7 (89GHz)

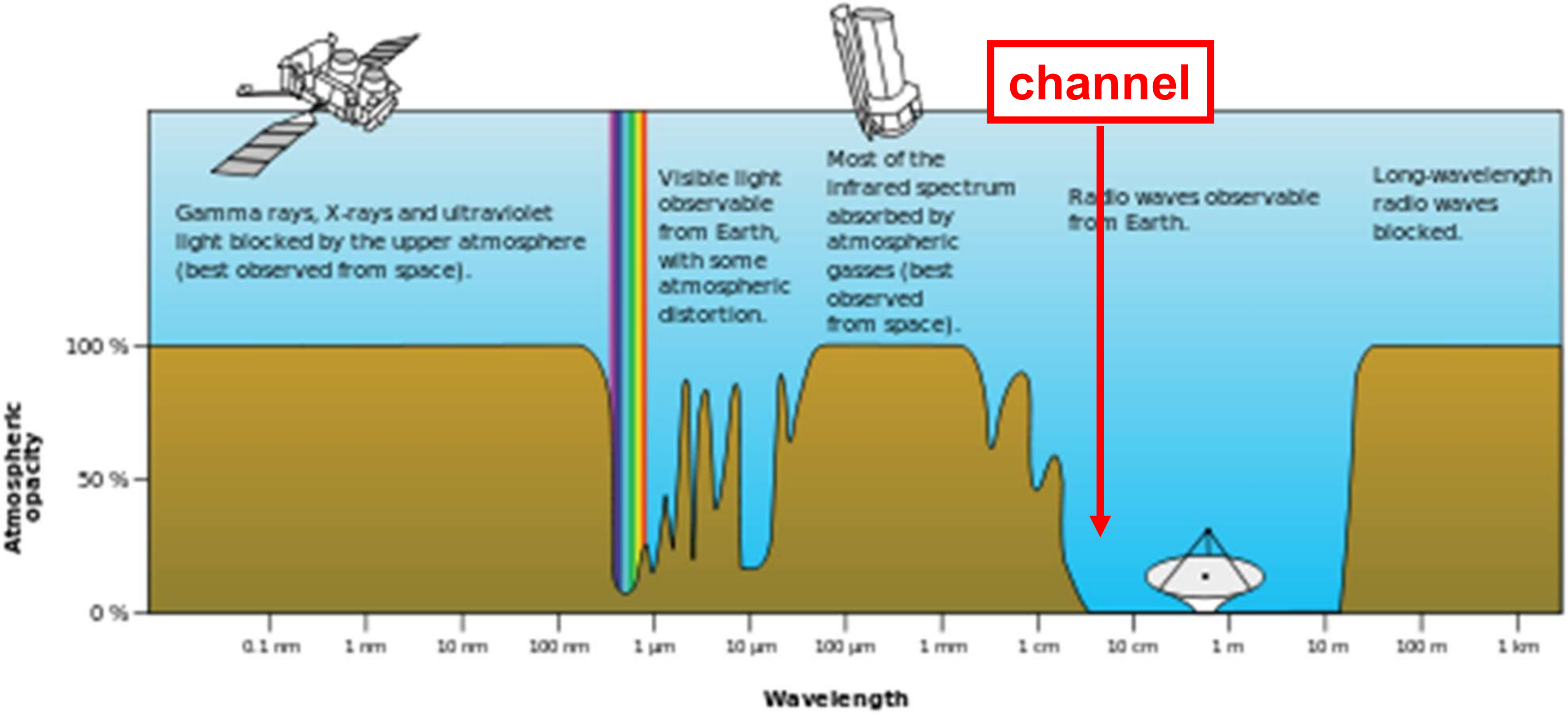


HIRS channel 8 (11microns)



Surface sensing Channels (active)

Surface sensing Channels (active)


channel

SURFACE SENSING CHANNELS (ACTIVE)

…selecting channels where there is no contribution from the atmosphere or emission from the surface....

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots$$

SURFACE SENSING CHANNELS (ACTIVE)

…selecting channels where there is **no** contribution from the **atmosphere** or **emission** from the surface....

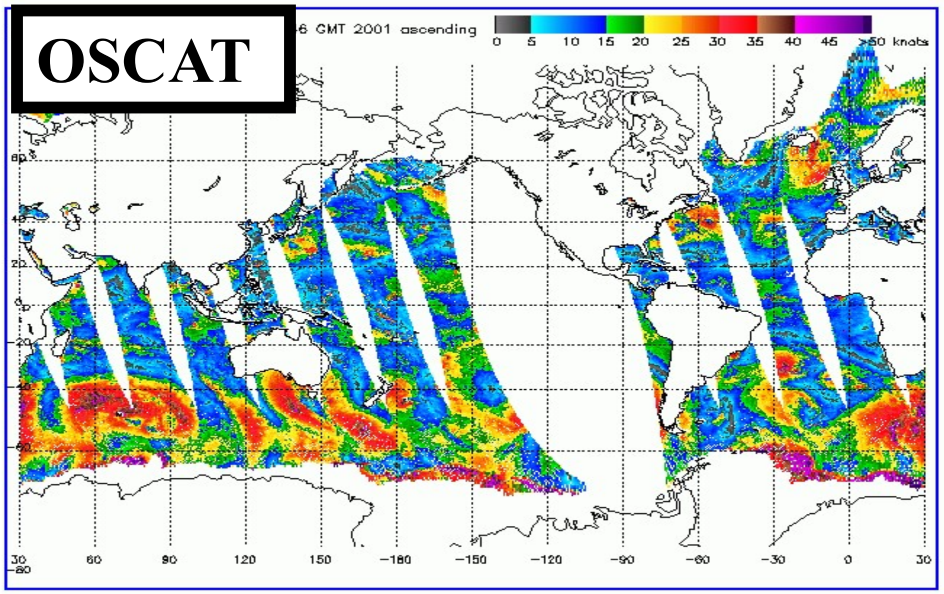
$$L(\nu) = \xcancel{\int_0^\infty B(\nu,T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz} + \xcancel{\text{Surface emission}} + \text{Surface reflection/ scattering} + \xcancel{\text{Cloud/rain contribution}} + \ldots$$

SURFACE SENSING CHANNELS (ACTIVE)

These (e.g. scatterometers) **actively illuminate the surface** in window parts of the spectrum such that

$$L(\nu) = \text{ surface scattering } [\ \varepsilon(u,v)\ ]$$

These primarily provide information on **ocean winds** (via the relationship with sea-surface emissivity) **without** the strong surface temperature ambiguity .



What type of channels are most important for NWP?

Atmospheric Temperature sounding

ATMOSPHERIC TEMPERATURE SOUNDING

If radiation is selected in an **atmospheric sounding channel** for which

$$\boxed{L(\nu) = \int_0^{\infty} B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz}$$

and we define a function

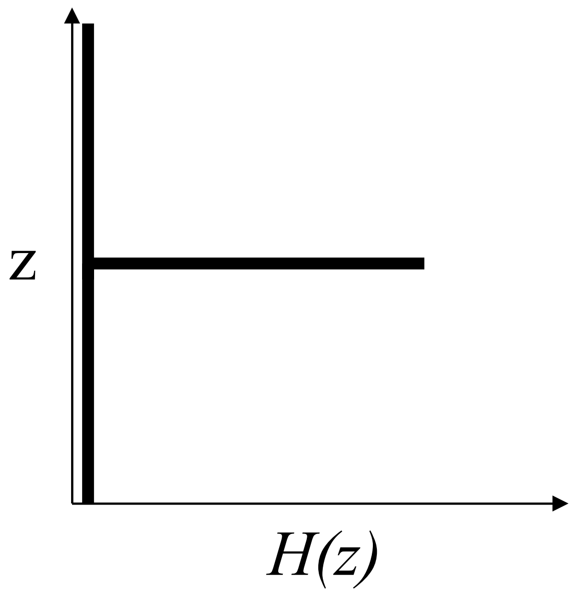
$$\boldsymbol{H(z)} = \left[\frac{d\tau}{dz} \right]$$

When the primary absorber is a well mixed gas (e.g. oxygen or CO_2) with known concentration it can be seen that the **measured radiance** is essentially a **weighted average of the atmospheric temperature profile**, or

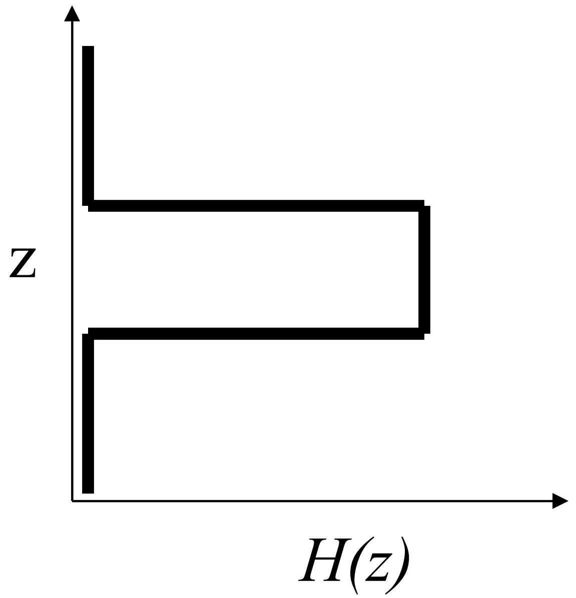
$$\boxed{L(\nu) = \int_0^{\infty} B(\nu, T(z)) \ \boldsymbol{H(z)} dz}$$

The function ***H(z)*** that defines this vertical average is known as a **WEIGHTING FUNCTION**

IDEAL WEIGHTING FUNCTIONS



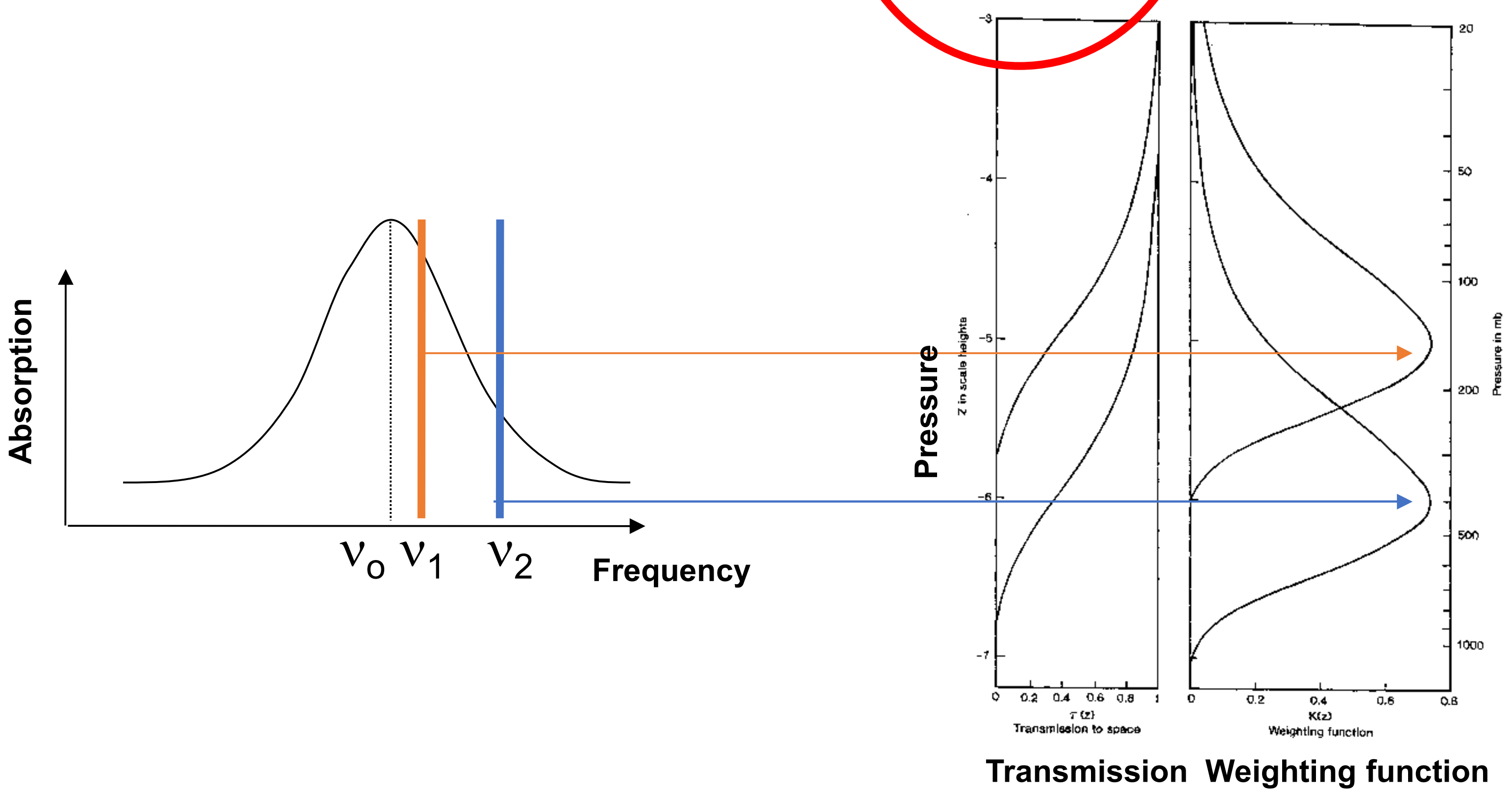
If the weighting function was a delta-function - this would mean that the measured radiance in a given channel is sensitive to the temperature at a single level in the atmosphere.



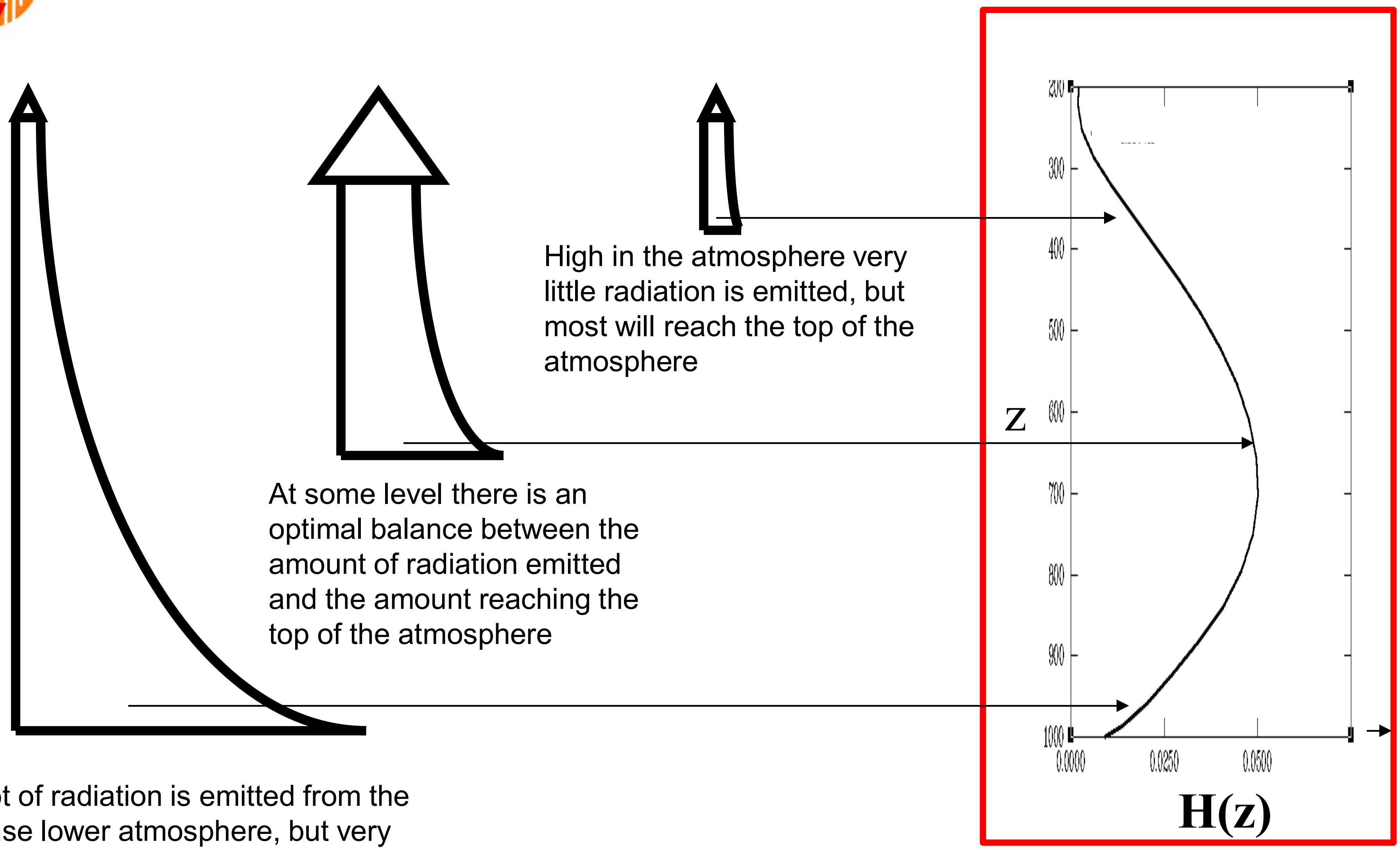
If the weighting function was a box-car function, this would mean that the measured radiance in a given channel was only sensitive to the temperature between two discrete atmospheric levels

REAL ATMOSPHERIC WEIGHTING FUNCTIONS

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz}\right] dz$$



REAL ATMOSPHERIC WEIGHTING FUNCTIONS



High in the atmosphere very little radiation is emitted, but most will reach the top of the atmosphere

At some level there is an optimal balance between the amount of radiation emitted and the amount reaching the top of the atmosphere

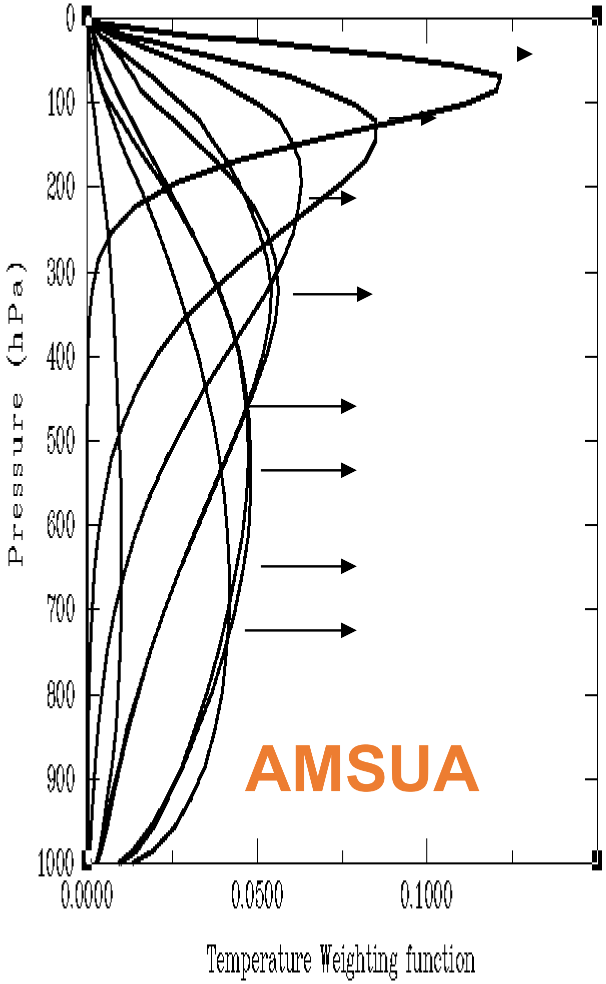
A lot of radiation is emitted from the dense lower atmosphere, but very little survives to the top of the atmosphere due to absorption.

REAL WEIGHTING FUNCTIONS continued...

- The altitude at which the **peak** of the weighting function occurs depends on the **strength** of absorption for a given channel

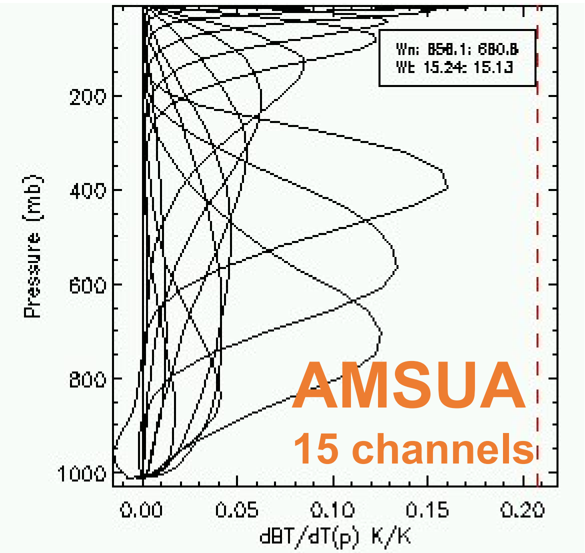
- Channels in parts of the spectrum where the absorption is **strong** (e.g. near the centre of CO2 or O2 lines) peak **high** in the atmosphere

- Channels in parts of the spectrum where the absorption is **weak** (e.g. in the wings of CO_2 O_2 lines) peak **low** in the atmosphere



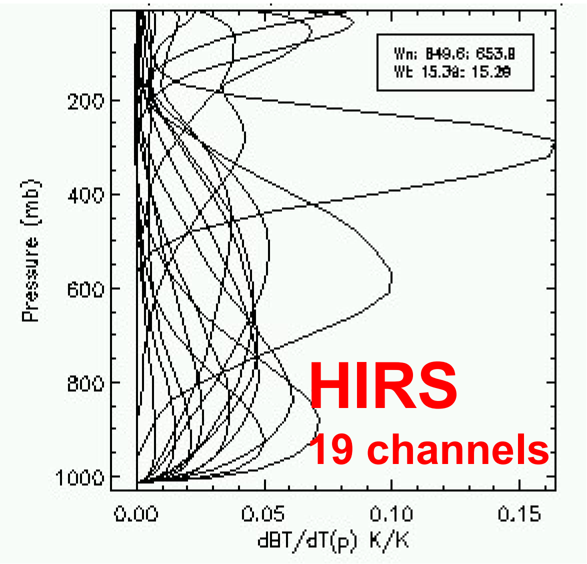
By selecting a **number of channels** with varying absorption strengths we **sample** the atmospheric temperature at **different altitudes**

MORE REAL WEIGHTING FUNCTIONS ...



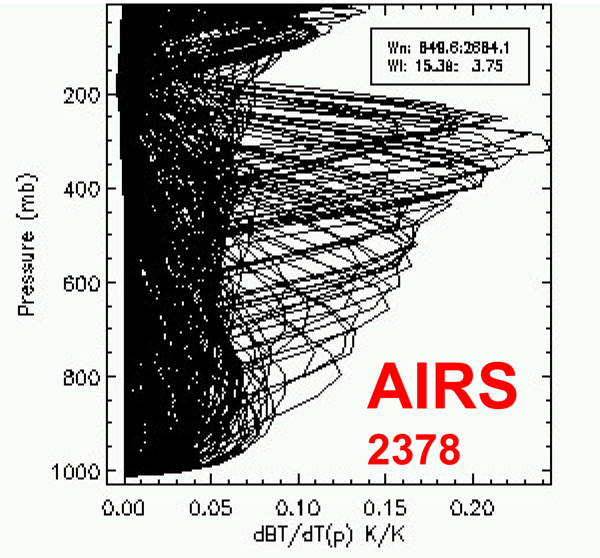
AMSUA

15 channels



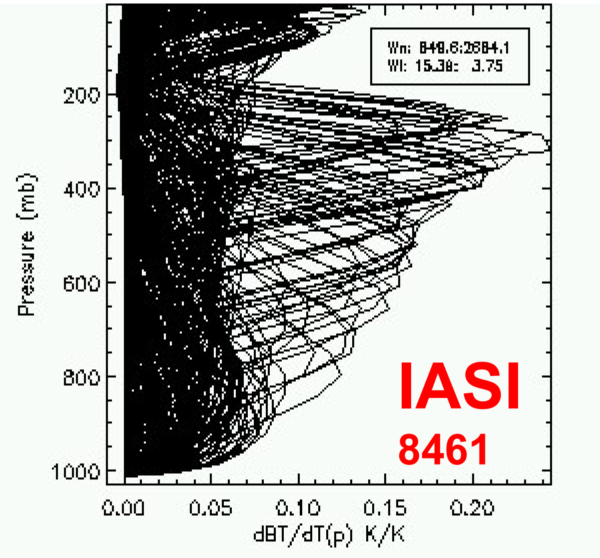
HIRS

19 channels



AIRS

2378



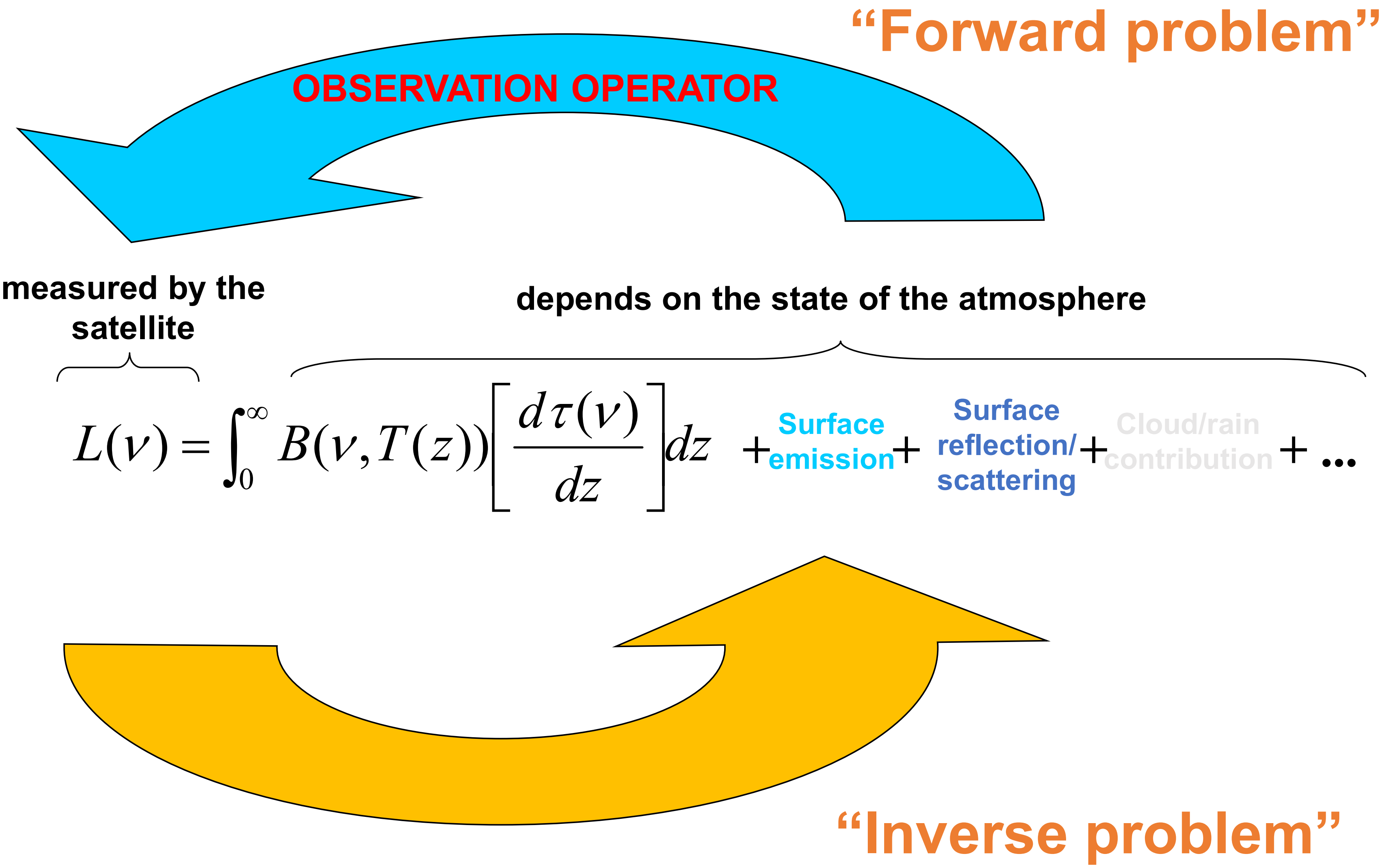
IASI

8461

How do we extract atmospheric information (e.g. temperature) from satellite radiances?

…i.e. how do we solve the inverse problem….

The Radiative Transfer (RT) equation



“Forward problem”

OBSERVATION OPERATOR

$$\overbrace{L(\nu)}^{\text{measured by the satellite}} = \overbrace{\int_0^\infty B(\nu,T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz + \text{Surface emission} + \text{Surface reflection/ scattering} + \text{Cloud/rain contribution} + \ldots}^{\text{depends on the state of the atmosphere}}$$

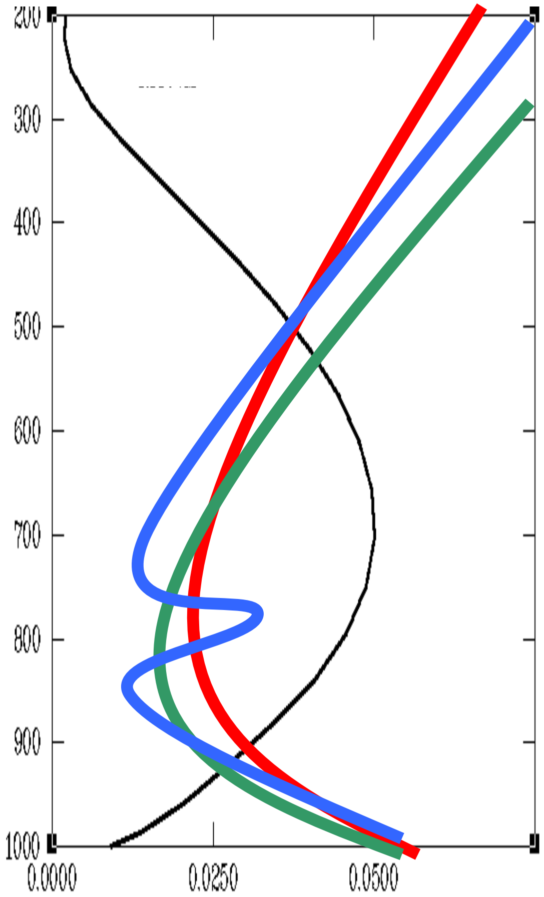
“Inverse problem”

The Inverse problem

If we know the entire atmospheric temperature profile T(z) then we can compute (uniquely) the radiances a sounding instrument would measure using the *radiative transfer equation*. This is the **forward problem**

In order to extract or **retrieve or analyze** the atmospheric temperature profile from a set of measured radiances we must solve the **inverse problem**

Unfortunately as the weighting functions are generally broad and we have a finite number of channels, the inverse problem is **formally ill-posed** because **an infinite number of different temperature profiles could give the same measured radiances !!!**

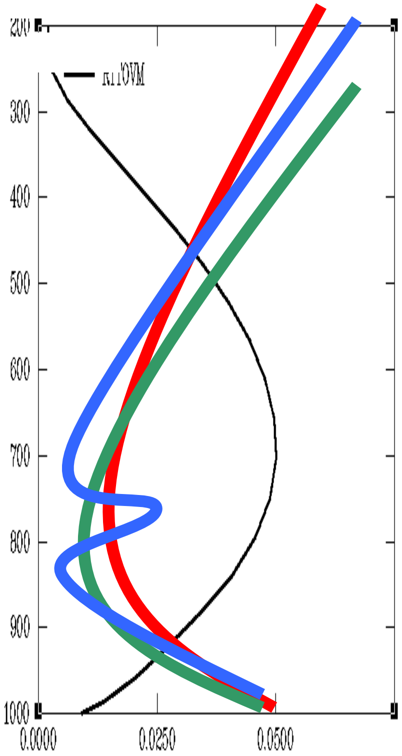


See paper by Rodgers 1976 Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. Rev. Geophys.Space. Phys. 14, 609-624

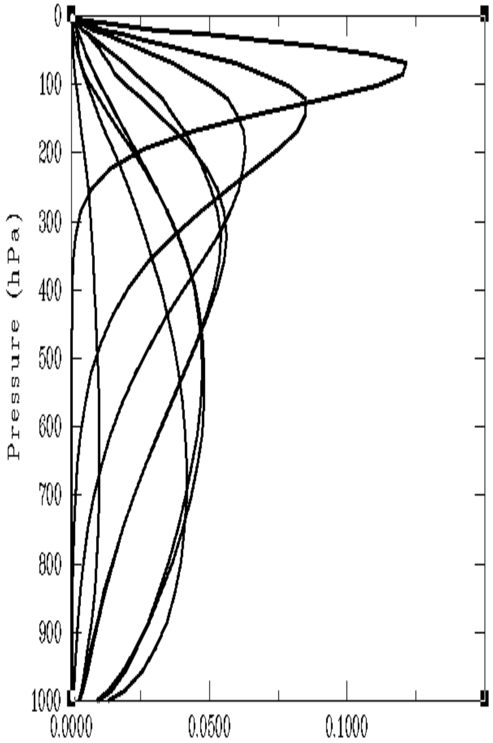
The Inverse problem

Measuring radiation in a greater number of frequencies / channels improves vertical sampling and resolution …

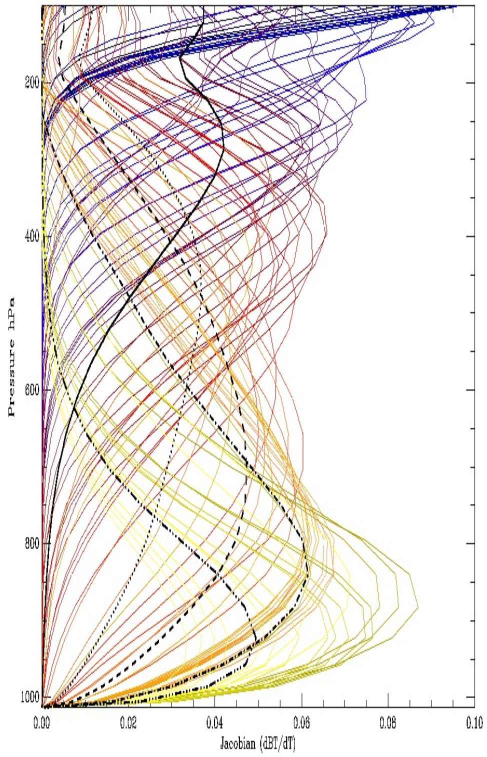
single channel



15 channels (AMSUA)



8463 channels IASI



“Retrievals”

and

“Direct Radiance Assimilation”

…so to solve the inverse problem we need to bring in additional information ….

“Retrievals”

and

“Direct Radiance Assimilation”

$$Y_{\text{radiances}} \longrightarrow X\ (z)$$

SATELLITE RETRIEVAL ALGORITHMS

The **linear data assimilation schemes** used for NWP in the past at such as **Optimal Interpolation (OI)** were unable to assimilate radiance observations directly (as they were nonlinearly related to the analysis variables) and the radiances had to be **explicitly converted to temperature products** before the analysis.

This conversion was achieved using a variety of **retrieval algorithms** that differed in the way they used **prior information**

All retrieval schemes use some (either explicit of implicit) form of **prior information** to supplement the information of the measured radiances in order to solve the inverse problem

Two different types of retrieval have been used in the past for NWP:

1. Solutions to reduced inverse problems
2. Regression / Neural Net (statistical) methods

… But do we really need to do explicit retrievals for NWP ?

“Retrievals”

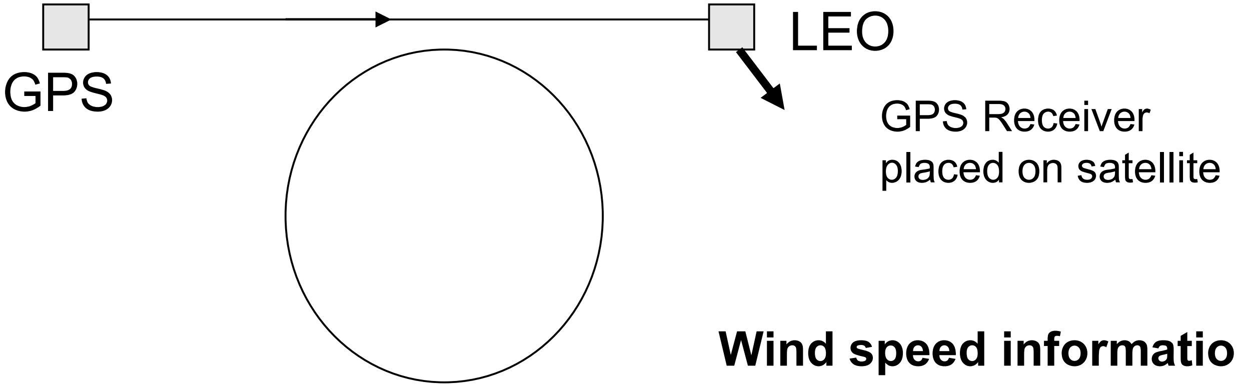
and

“Direct Radiance Assimilation”

GPS Measurements

Measurements made using GPS signals

GPS Radio Occultation (Profile information)

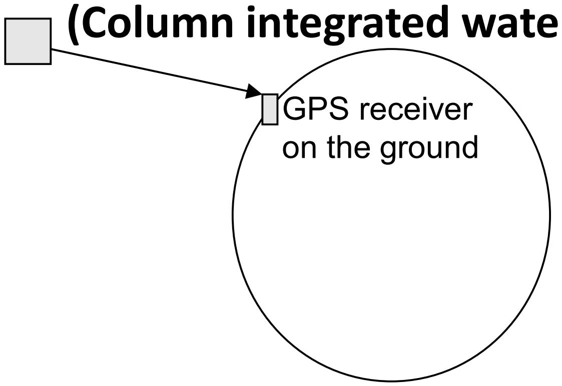


LEO

GPS

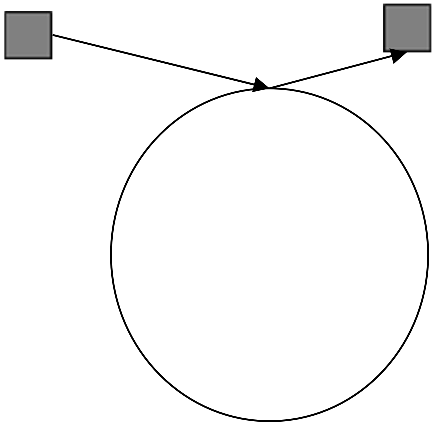
GPS Receiver
placed on satellite

Ground-based GPS
(Column integrated water vapour)



GPS receiver
on the ground

Wind speed information from scattered signal



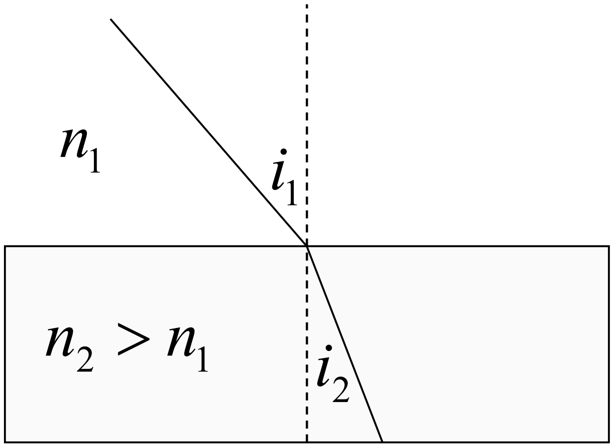
The basic GPS-RO physics – Snel's Law

- **Refractive index**: Speed of an electromagnetic wave in a vacuum divided by the speed through a medium.

$$\boxed{n = \frac{c}{v}}$$

- Snel's Law of refraction

$$\boxed{n_1 \sin i_1 = n_2 \sin i_2}$$



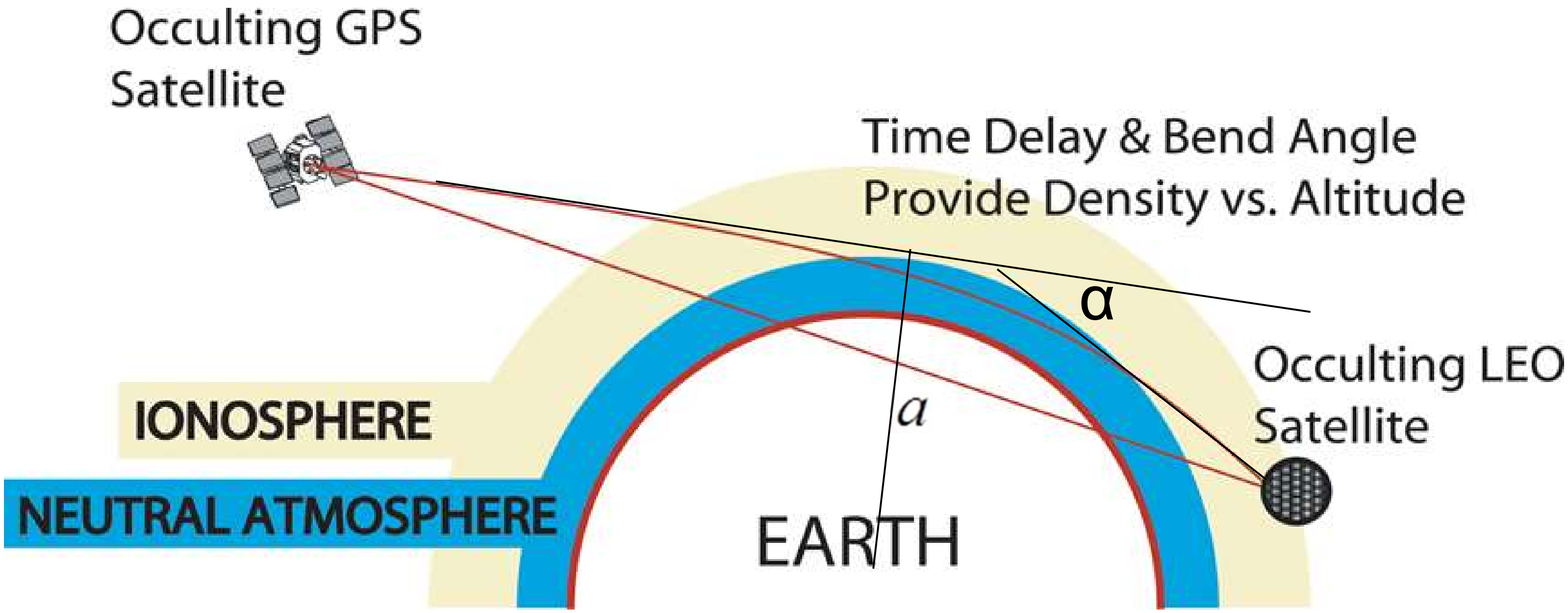
GPS-RO: Basic idea

The GPS satellites are primarily a tool for positioning and navigation These satellites emit radio signals at L1= 1.57542 GHz and L2=1.2276GHz (~20 cm wavelength).

The GPS signal velocity is modified in the ionosphere and neutral atmosphere because the refractive index is not unity, **and the path is bent because of gradients in the refractive index**.

GPS-RO is based on analysing the bending caused by the neutral atmosphere along ray paths between a GPS satellite and a receiver placed on a low-earth-orbiting (LEO) satellite.

GPS RO geometry



Setting occultation: as the LEO moves behind the earth we obtain a profile of bending angles, $\underline{\alpha}$, as a function of impact parameter, $\underline{a}$. The impact parameter is the distance of closest approach for the straight line path.

GPS RO characteristics

- Good vertical resolution. **Around 70% of the bending occurs over a ~450km section of ray-path**, centred on the tangent point (point closest to surface) – **it has a broad horizontal weighting function, with a ~Gaussian shape to first order!**

- All weather capability: not affected by cloud or rain.

- The bending is ~1-2 degree at the surface, falling exponentially with height. The scale-height of the decay is approximately the density scale-height.

- A profile of bending angles from ~60km tangent height to the surface takes about 2 minutes. Tangent point drifts in the horizontal by ~200 km during the measurement.

Ray Optics Processing of the GPS RO Observations

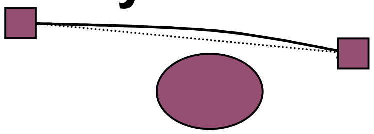
GPS receivers do not measure temperatures/ray bending directly!

The GPS receiver on the LEO satellite measures a time series of phase-delays $\phi(i-1)$, $\phi(i)$, $\phi(i+1)$,… at the two GPS frequencies:

L1 = 1.57542 GHz
L2 = 1.22760 GHz

The phase delays are "**calibrated**" to remove **special and general relativistic effects** and to remove the GPS and LEO clock errors ("**Differencing**", see Hajj et al. (2002), JASTP, **64**, 451 – 469).

Calculate **Excess phase delays**: remove straight line path delay, $\Delta\phi(i)$.



A time series of Doppler shifts at L1 and L2 are calculated by differentiating the **excess phase delays** with respect to time.

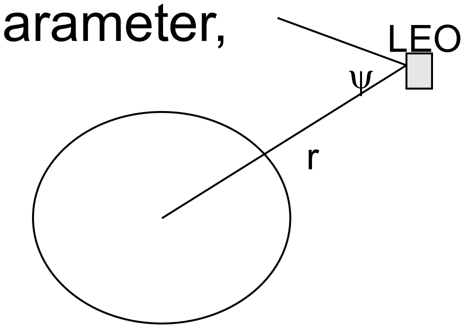
Processing of the GPS-RO observations

The ray bending caused by gradients in the atmosphere and **ionosphere** modify the L1 and L2 Doppler values, but **deriving the bending angles, α, from the Doppler values is an ill-posed problem (an infinite set of bending angles could produce the Doppler)**.

The problem made well posed by **assuming** the impact parameter, given by

$$\boxed{a = nr\sin\psi}$$

has the same value at both the satellites.



Given accurate position and velocity estimates for the satellites, **and making the impact parameter assumption**, the bending angle, α, and impact parameter value can be derived simultaneously from the Doppler shift.

Data assimilation algorithms and key elements