ECMWF/EUMETSAT NWP-SAF
Satellite data assimilation
Training Course

23 to 27 March 2015

What do satellite instruments measure ?

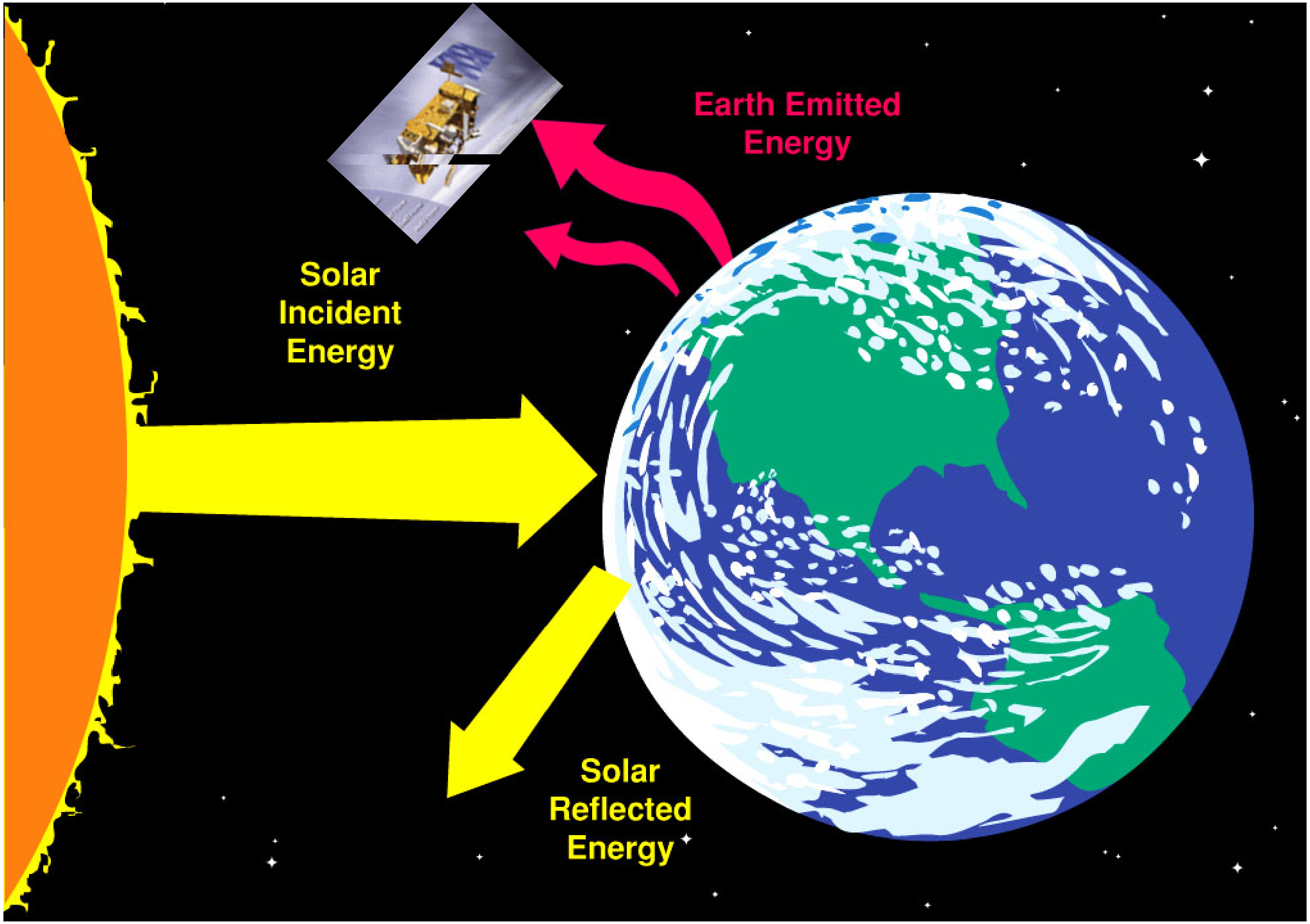
ECMWF/EUMETSAT NWP-SAF Satellite data assimilation Training Course

They **DO NOT** measure TEMPERATURE

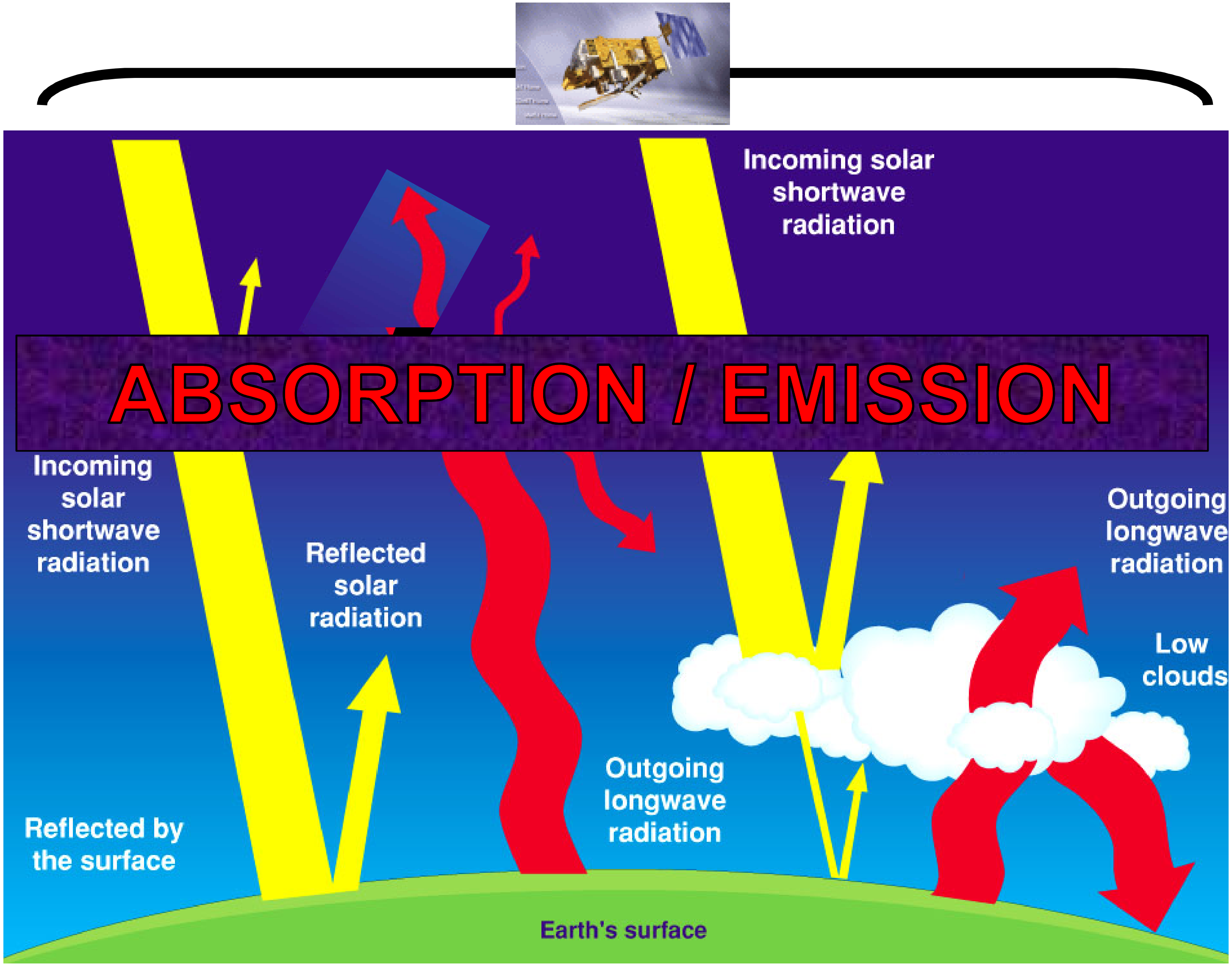
They **DO NOT** measure HUMIDITY or OZONE

They **DO NOT** measure WIND

SATELLITES CAN ONLY MEASURE OUTGOING THERMAL RADIATION FROM THE ATMOSPHERE



SATELLITES CAN ONLY MEASURE OUTGOING THERMAL RADIATION FROM THE ATMOSPHERE



ABSORPTION / EMISSION

What do satellite instruments measure?

Satellite instruments 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

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

Planck source term* depending on temperature of the atmosphere

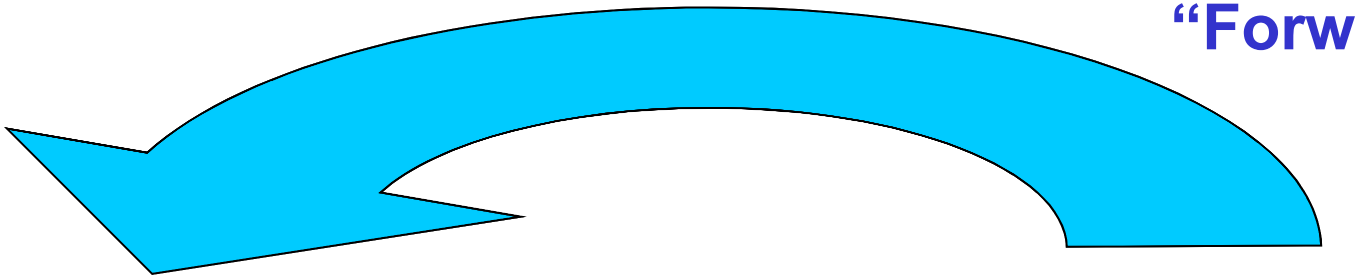
Absorption in the atmosphere

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



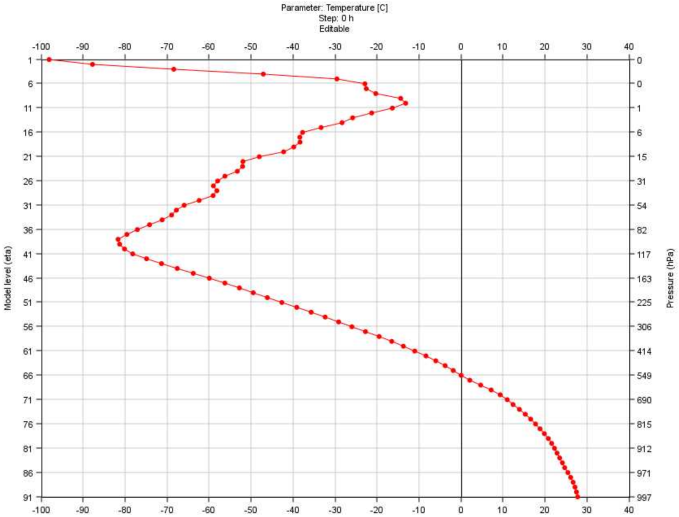
“Forward problem”

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

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

RTTOV Radiative Transfer Model

X (z) → **RTTOV** → **Y** **radiances**



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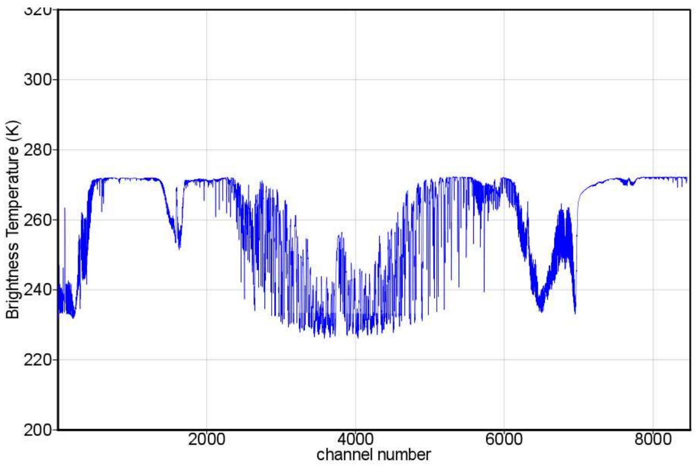
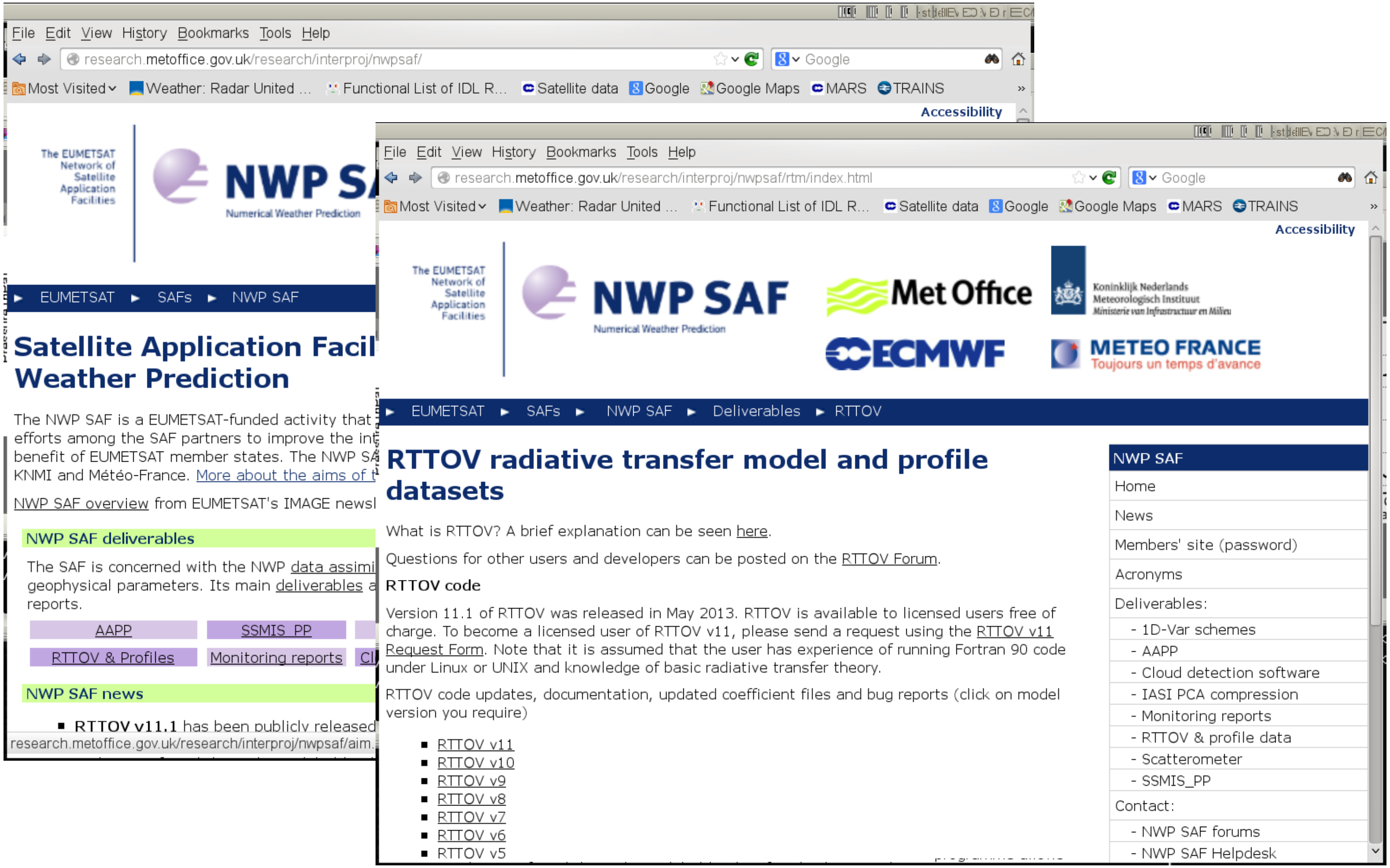


Getting the RTTOV code



Satellite Application Facil
Weather Prediction

The NWP SAF is a EUMETSAT-funded activity that
efforts among the SAF partners to improve the int
benefit of EUMETSAT member states. The NWP SA
KNMI and Météo-France. More about the aims of t

NWP SAF overview from EUMETSAT's IMAGE newsl

NWP SAF deliverables

The SAF is concerned with the NWP data assimi
geophysical parameters. Its main deliverables a
reports.

AAPP	SSMIS_PP
RTTOV & Profiles	Monitoring reports

NWP SAF news

- RTTOV v11.1 has been publicly released

RTTOV radiative transfer model and profile datasets

What is RTTOV? A brief explanation can be seen here.

Questions for other users and developers can be posted on the RTTOV Forum.

RTTOV code

Version 11.1 of RTTOV was released in May 2013. RTTOV is available to licensed users free of charge. To become a licensed user of RTTOV v11, please send a request using the RTTOV v11 Request Form. Note that it is assumed that the user has experience of running Fortran 90 code under Linux or UNIX and knowledge of basic radiative transfer theory.

RTTOV code updates, documentation, updated coefficient files and bug reports (click on model version you require)

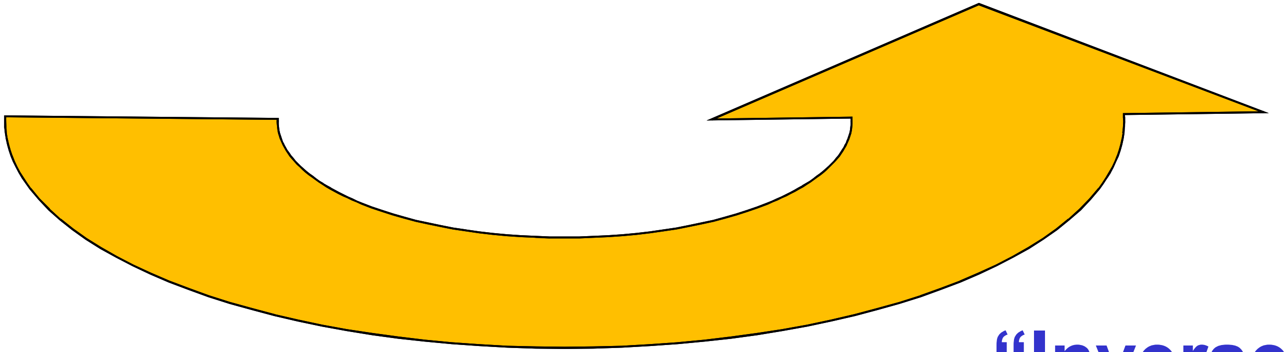
- RTTOV v11
- RTTOV v10
- RTTOV v9
- RTTOV v8
- RTTOV v7
- RTTOV v6
- RTTOV v5

http://research.metoffice.gov.uk/research/interproj/nwpsaf/rtm/index.html

The Radiative Transfer (RT) equation

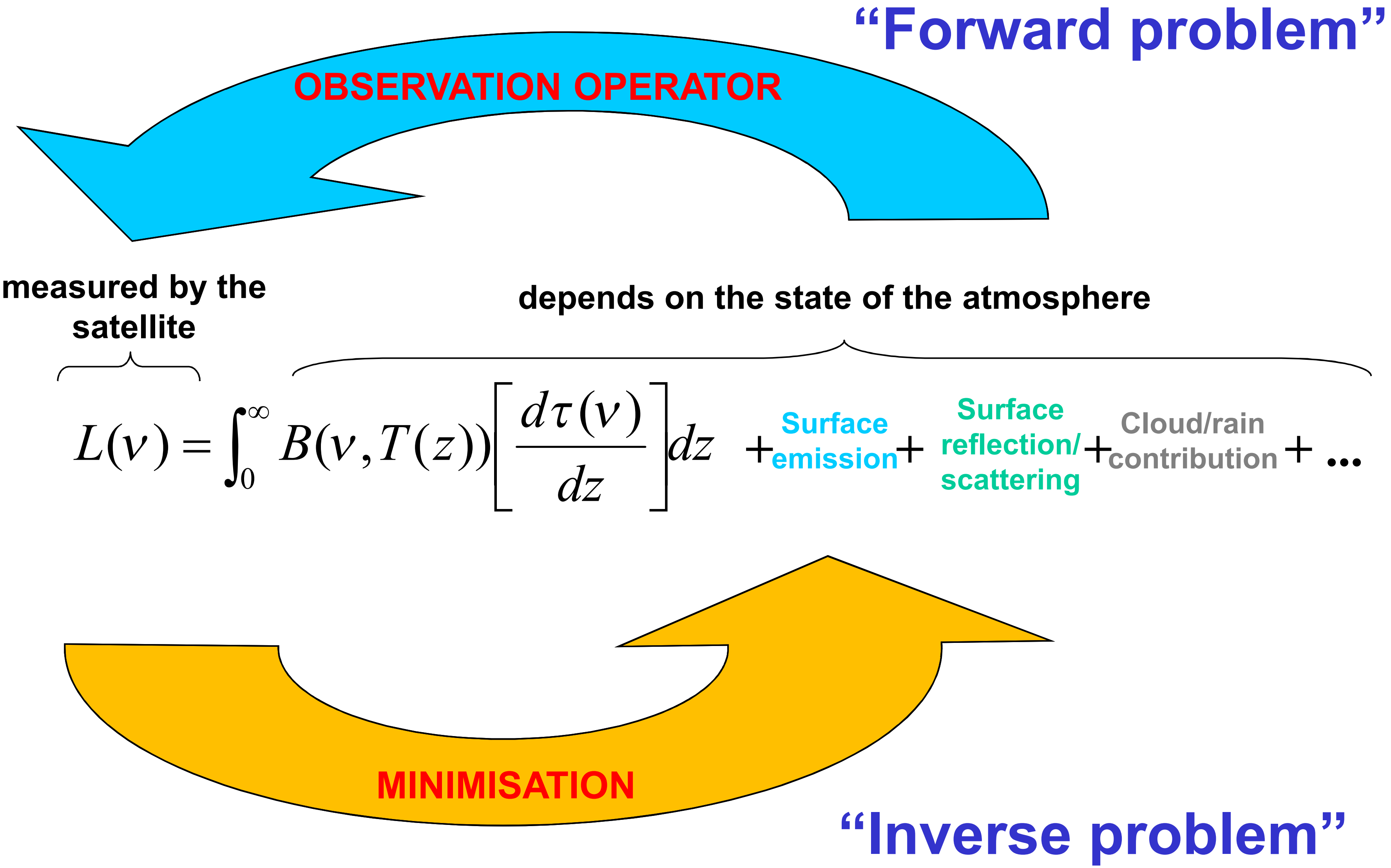
…given the radiance, what is the state of the atmosphere…?

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



“Inverse problem”

The Radiative Transfer (RT) equation



“Forward problem”

OBSERVATION OPERATOR

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

MINIMISATION

“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.

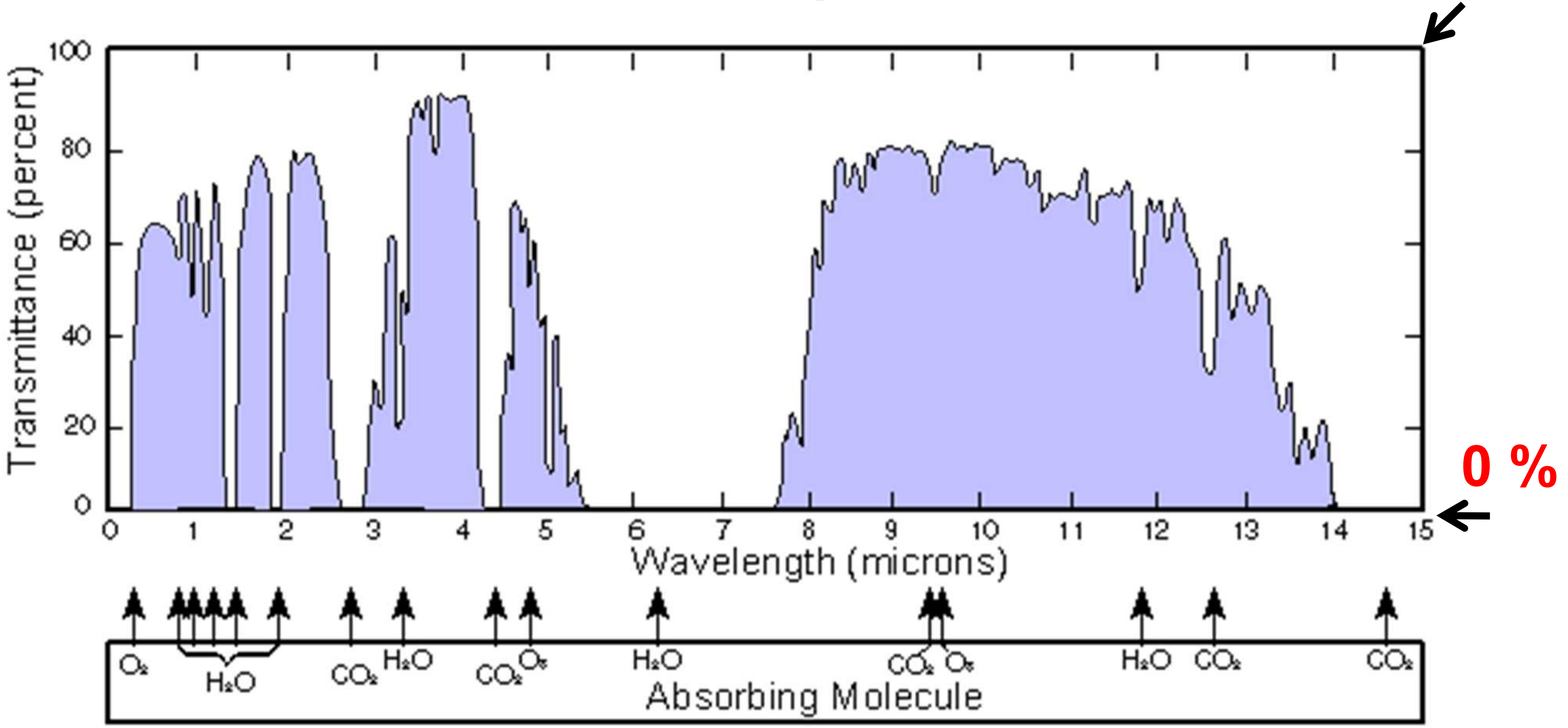
In general, the frequencies / channels used within NWP may be categorized as one of 3 different types …

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

Note:

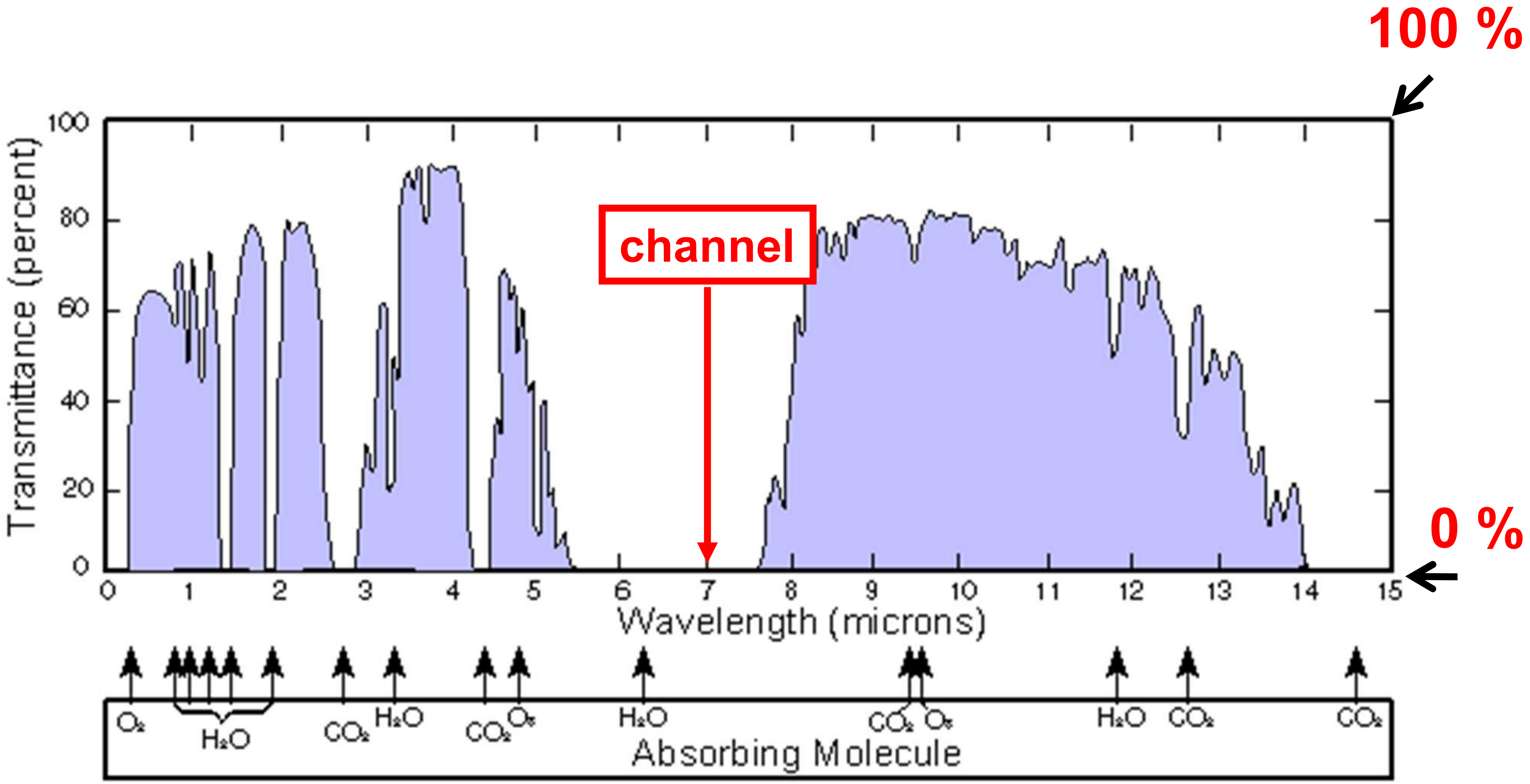
In practice (and often despite their name!) real satellite instruments have channels which are a ***combination*** *of atmospheric sounding and surface sensing channels*

Example:
absorption of infrared radiation in the atmosphere

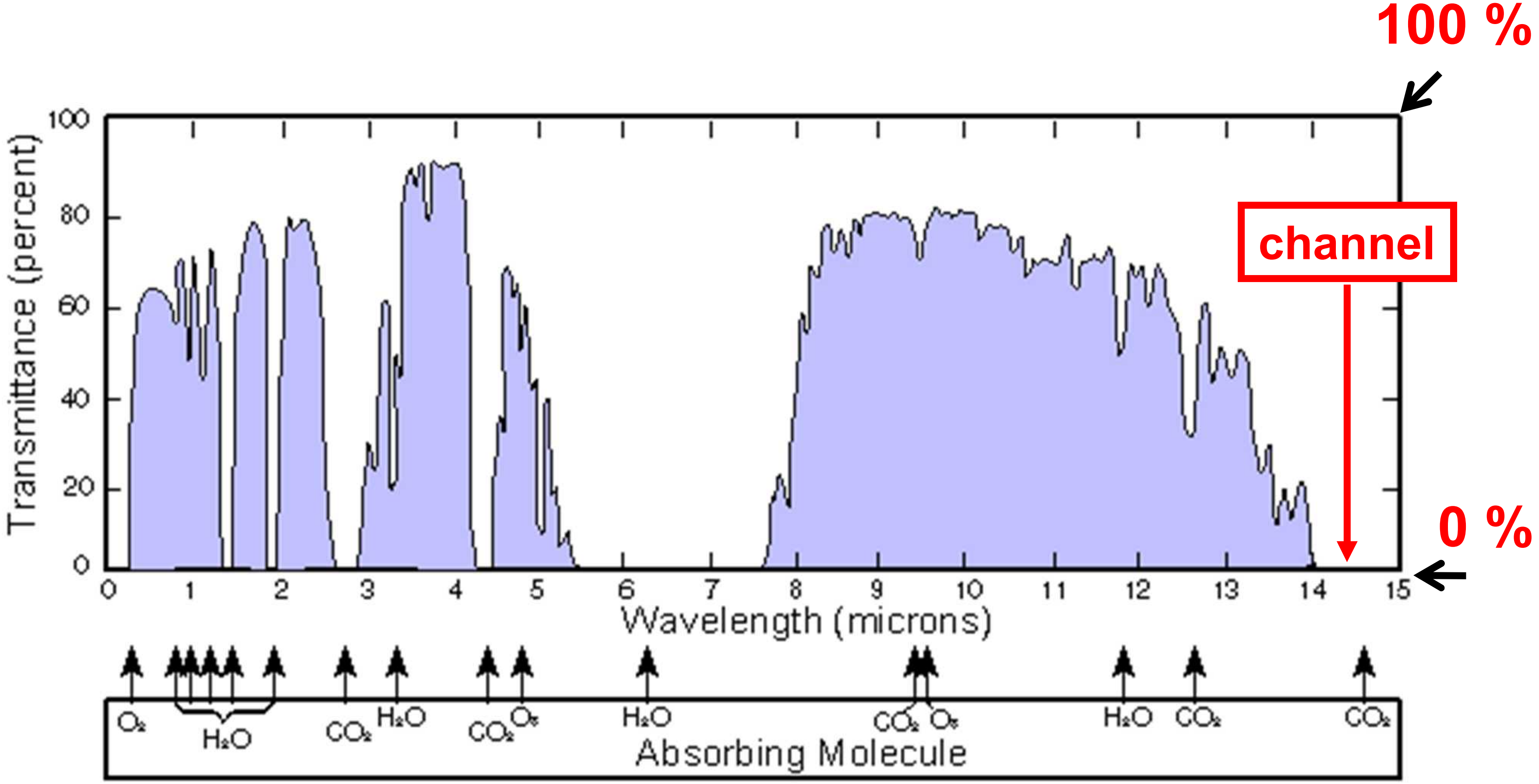


Atmospheric sounding channels

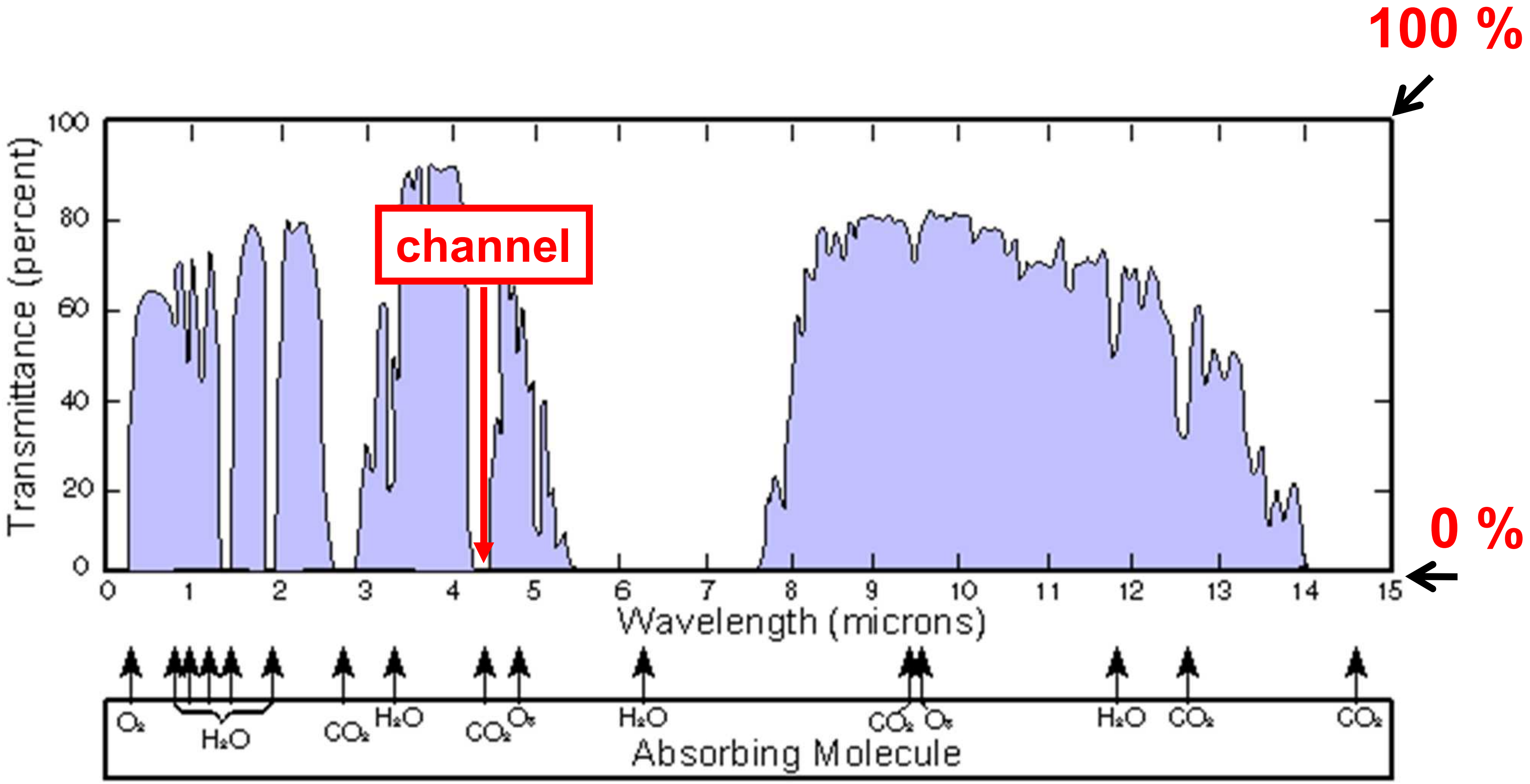
Atmospheric sounding channels



Atmospheric sounding channels



Atmospheric sounding channels



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**….

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

ATMOSPHERIC SOUNDING CHANNELS

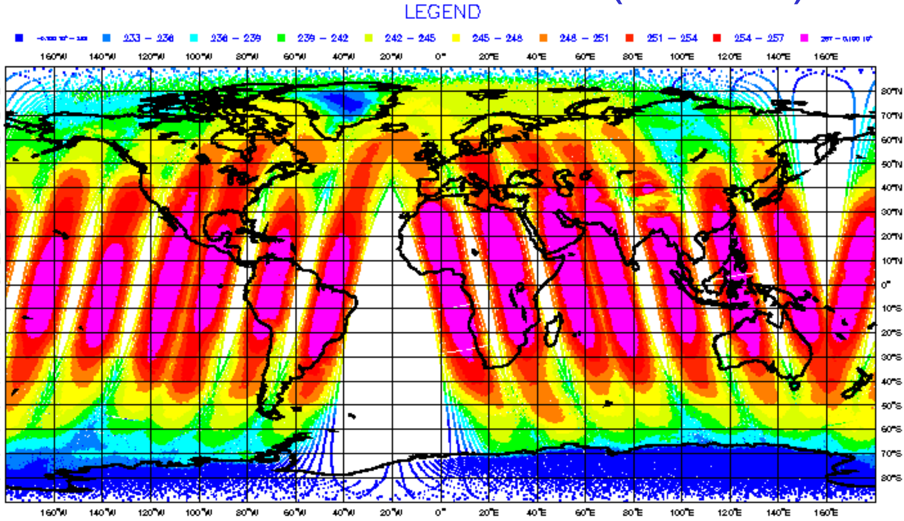
These channels are located in parts of the infra-red and microwave spectrum for which the main contribution to the measured radiance is from the **atmosphere** and can be written:

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

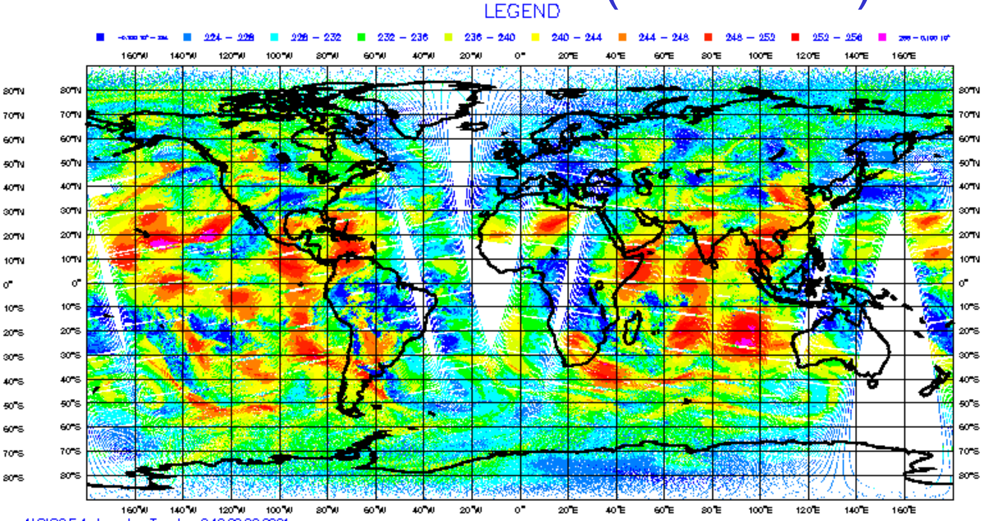
Where B=Planck function
t = transmittance
T(z) is the temperature
z is a height coordinate

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)

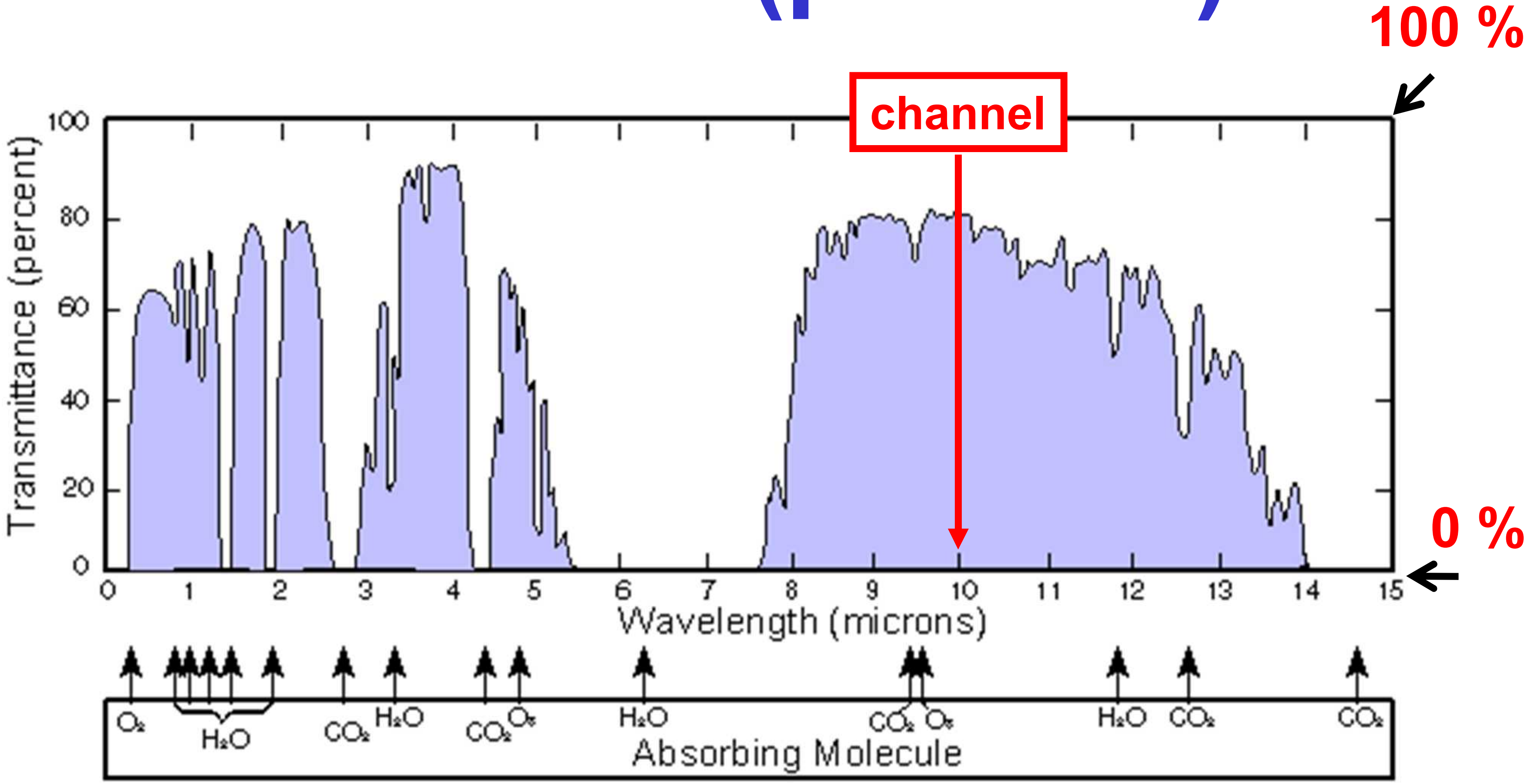


HIRS-channel 12 (6.7micron)

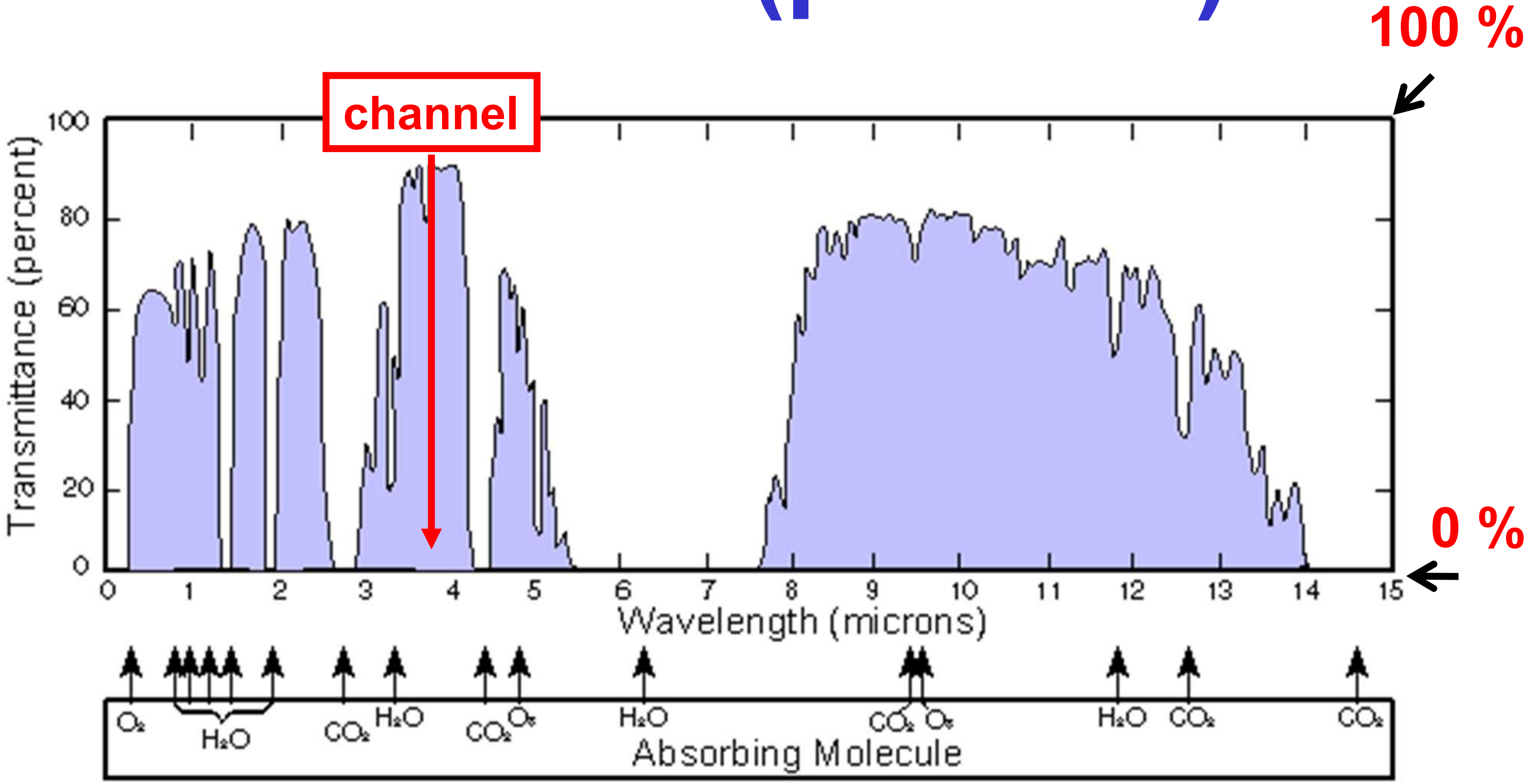


Surface sensing Channels (passive)

Surface sensing Channels (passive)



Surface sensing Channels (passive)



Surface sensing Channels (passive)

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

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

Surface sensing Channels (passive)

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

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

Surface sensing Channels (passive)

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

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

Surface sensing Channels (passive)

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

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

Screen data to remove clouds / rain

SURFACE SENSING CHANNELS (PASSIVE)

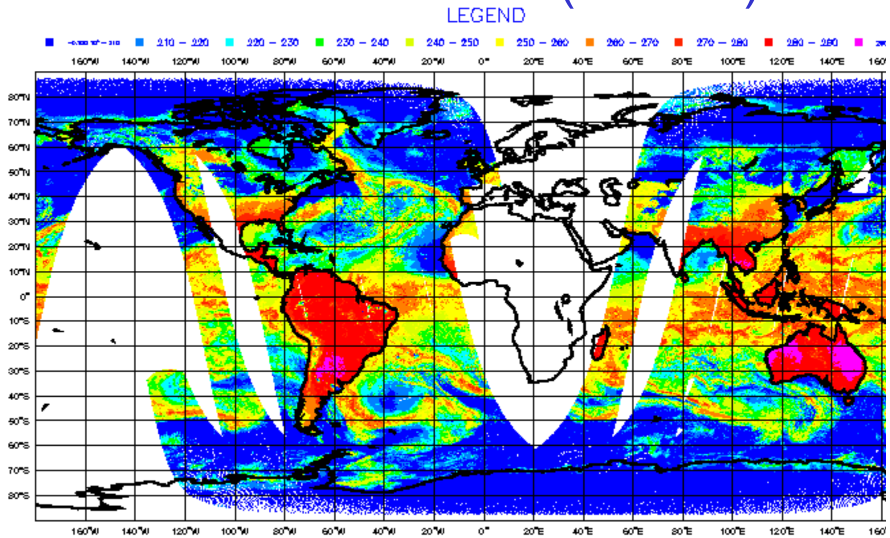
These are located in **window regions** of the infra-red and microwave spectrum at frequencies where there is very little interaction with the atmosphere and the primary contribution to the measured radiance is:

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

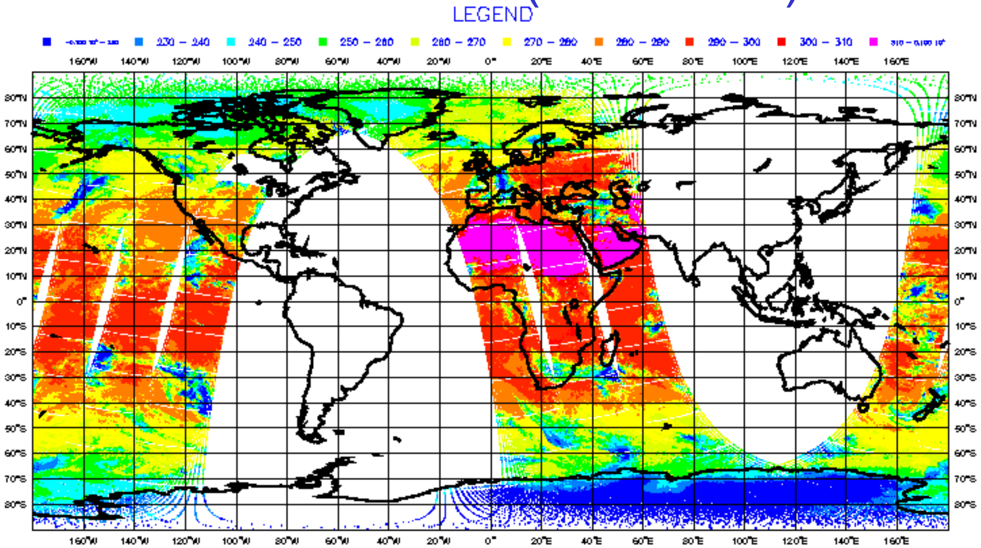
Where T_{surf} is the surface skin temperature and E the surface emissivity

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)

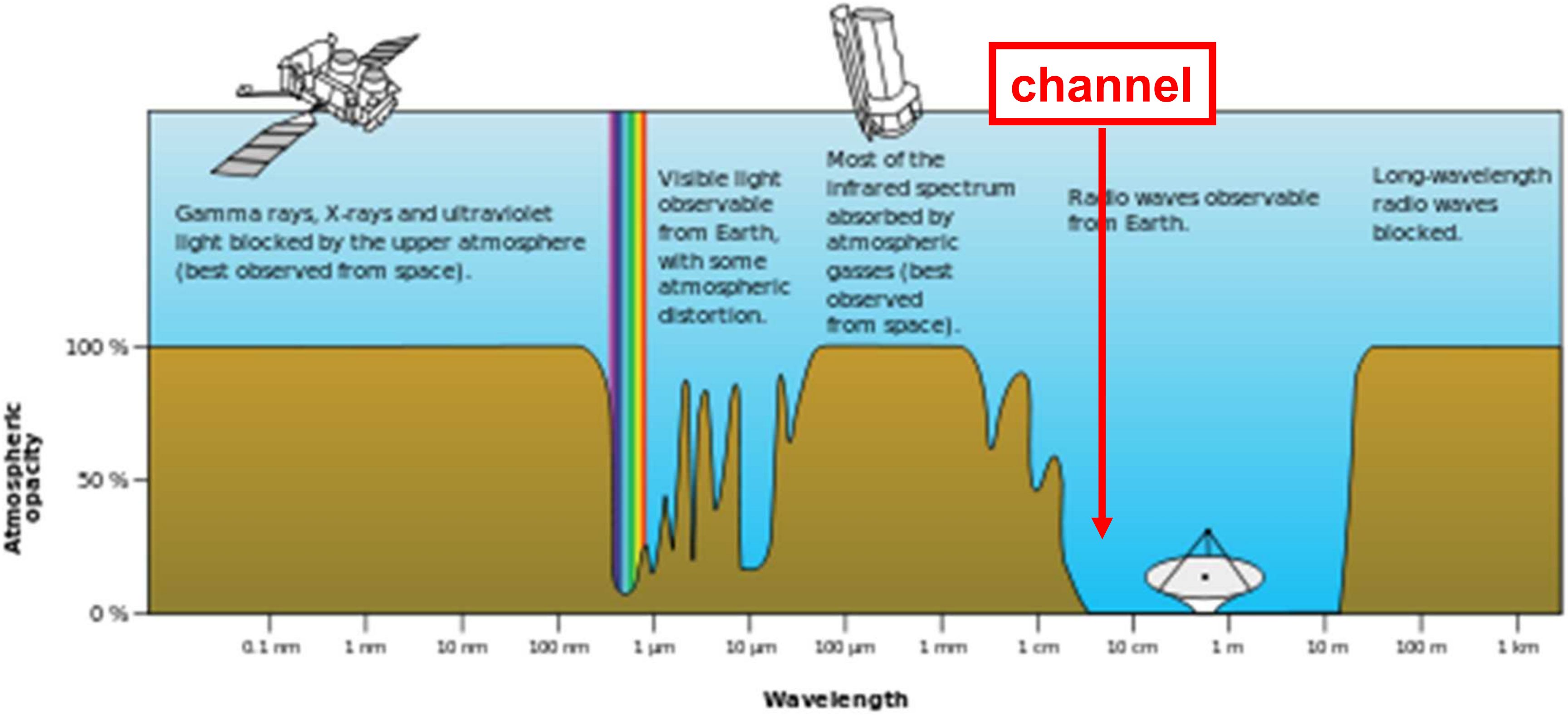


HIRS channel 8 (11microns)



Surface sensing
Channels (active)

Surface sensing Channels (active)



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….

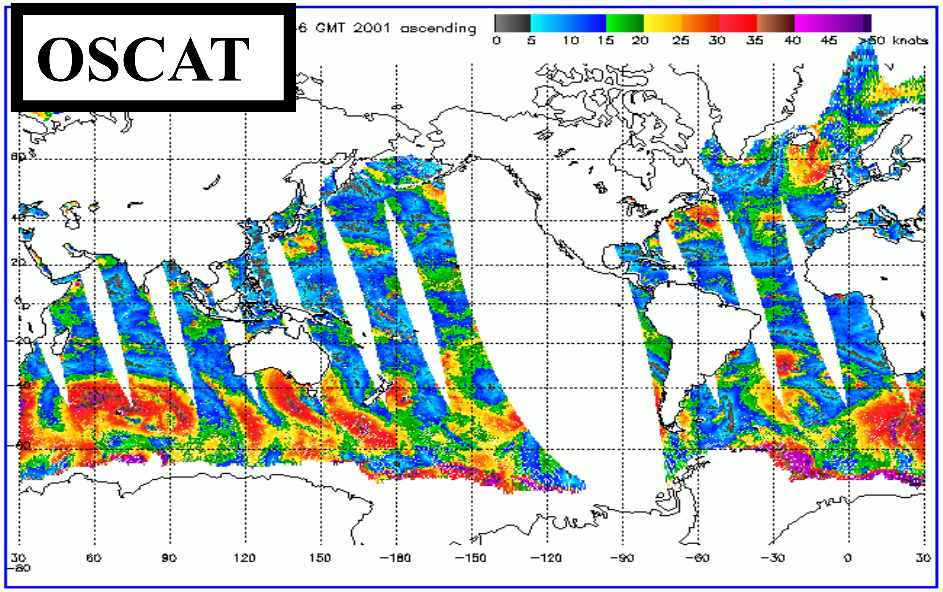
$$L(\nu) = \cancel{\int_0^\infty B(\nu,T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz} + \cancel{\text{Surface emission}} + \text{Surface reflection/ scattering} + \cancel{\text{Cloud/rain contribution}} + \ldots$$

SURFACE SENSING CHANNELS (ACTIVE)

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

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

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

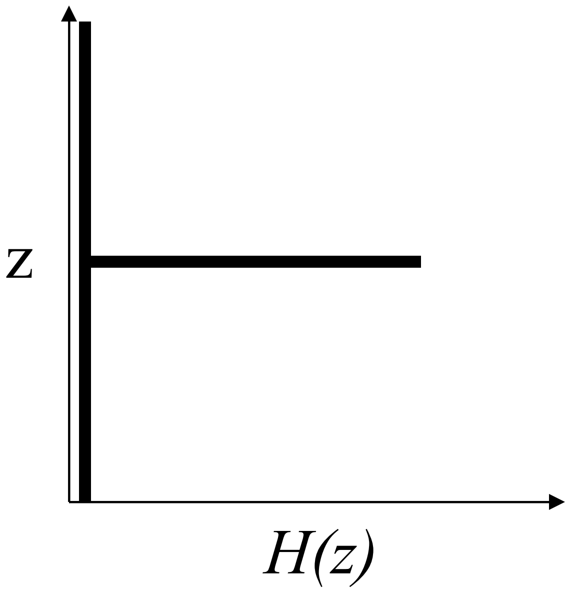
When the primary absorber is a well mixed gas (e.g. oxygen or CO_2) with known concentration it can be seen that the **measured radiance** is essentially a **weighted average of the atmospheric temperature profile**, or

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

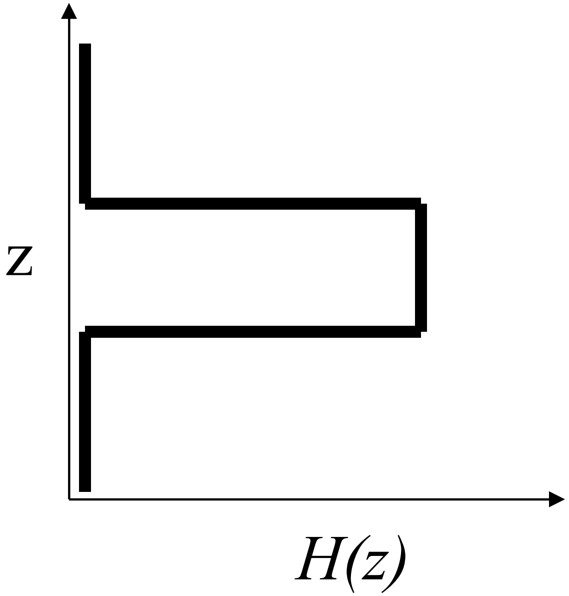
The function ***H(z)*** that defines this vertical average is known as a

WEIGHTING FUNCTION

IDEAL WEIGHTING FUNCTIONS



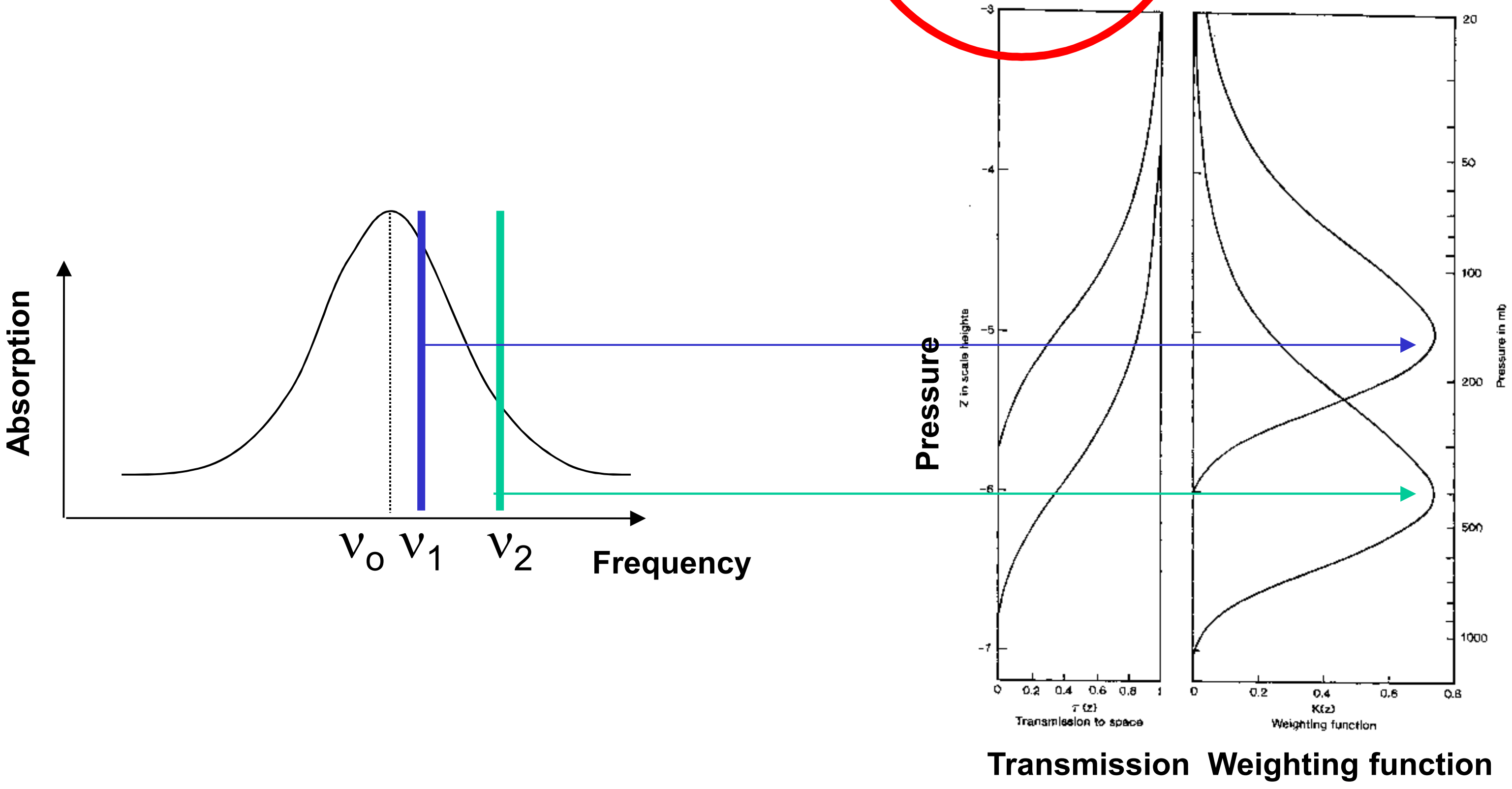
If the weighting function was a delta-function - this would mean that the measured radiance in a given channel is sensitive to the temperature at a single level in the atmosphere.



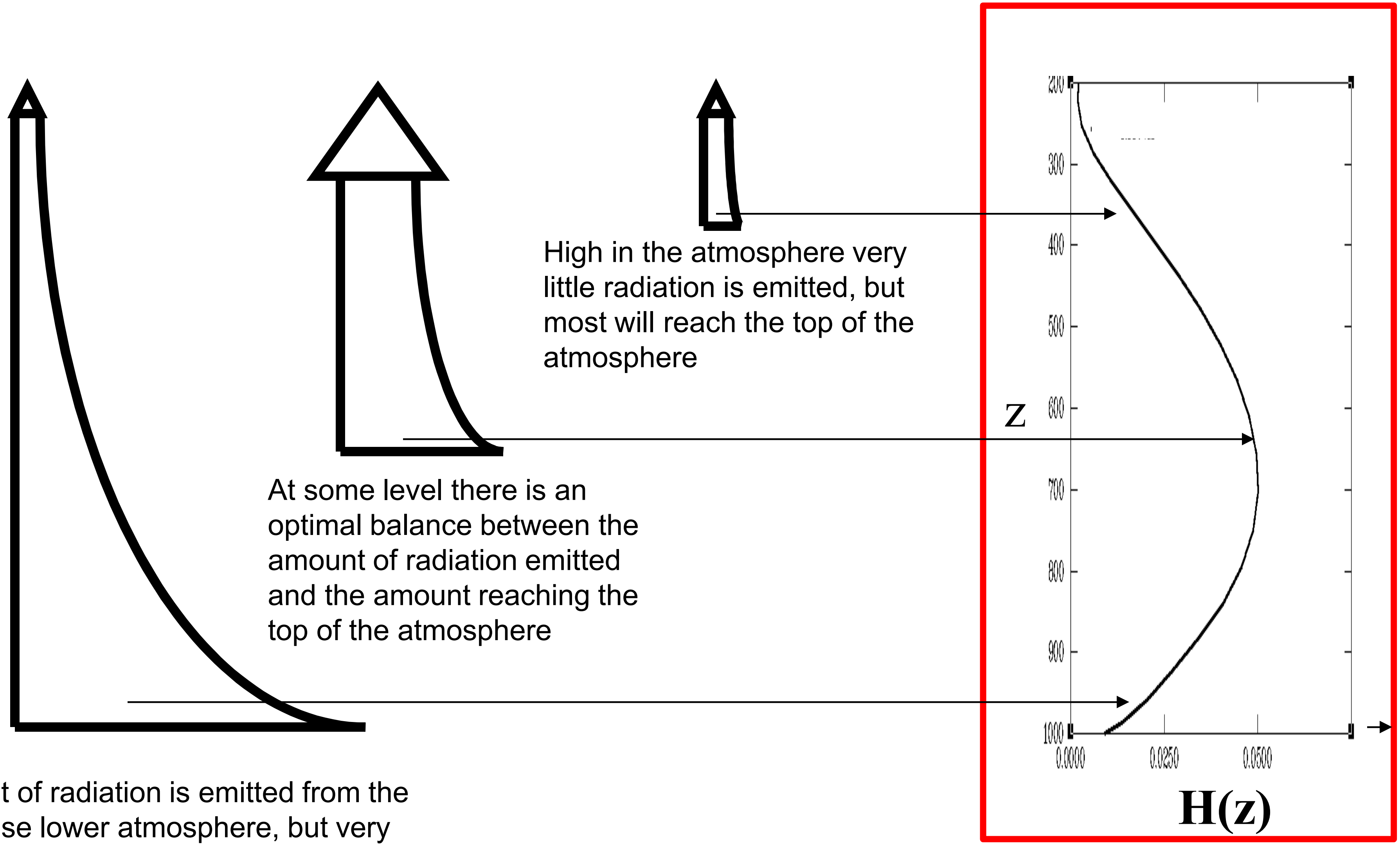
If the weighting function was a box-car function, this would mean that the measured radiance in a given channel was only sensitive to the temperature between two discrete atmospheric levels

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

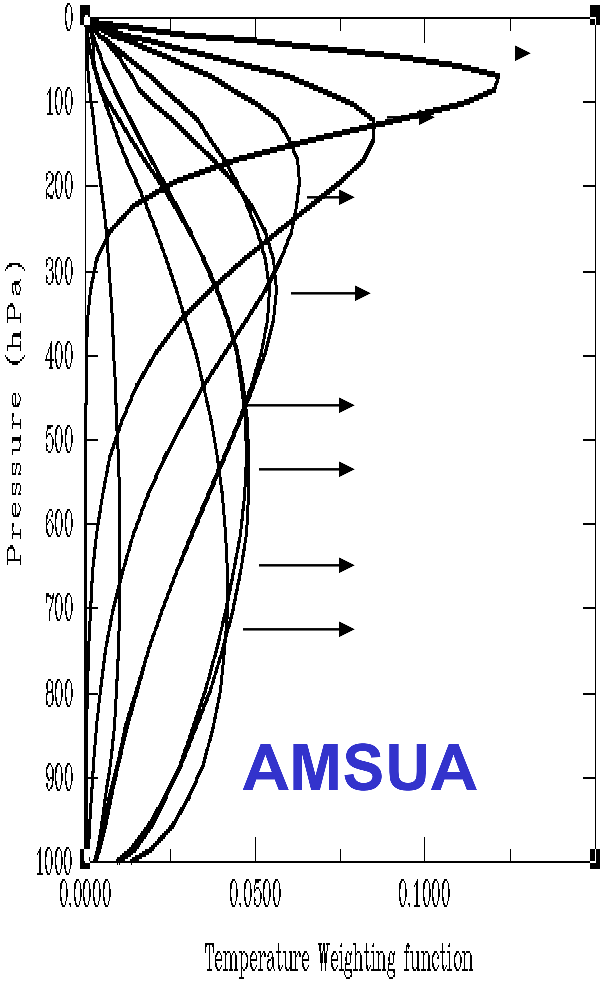
A lot of radiation is emitted from the dense lower atmosphere, but very little survives to the top of the atmosphere due to absorption.

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

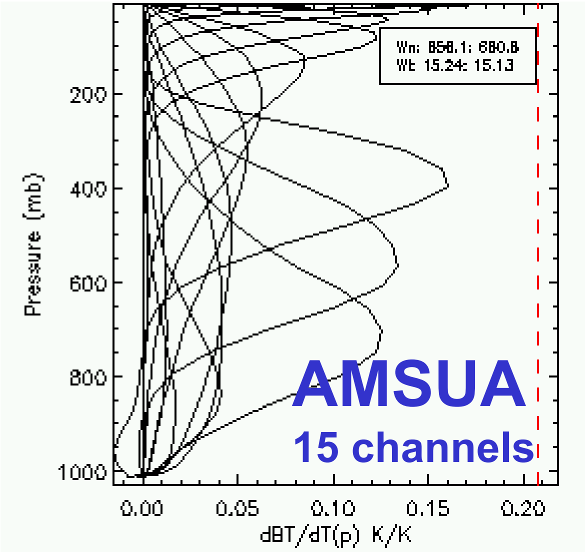
- Channels in parts of the spectrum where the absorption is **strong** (e.g. near the centre of CO2 or O2 lines) peak **high** in the atmosphere

- 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



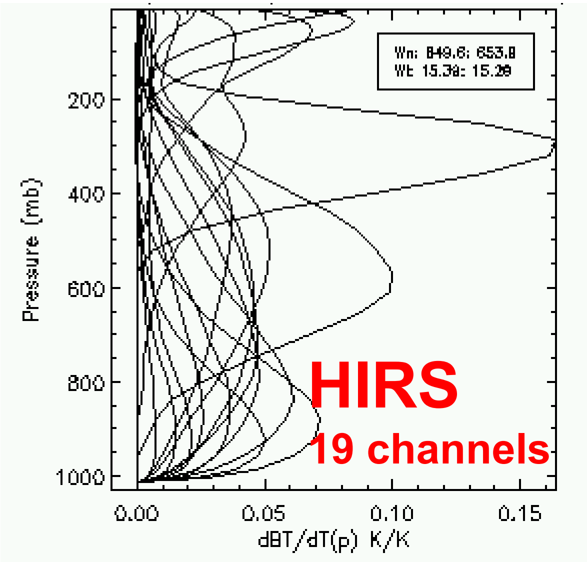
By selecting a **number of channels** with varying absorption strengths we **sample** the atmospheric temperature at **different altitudes**

MORE REAL WEIGHTING FUNCTIONS ...



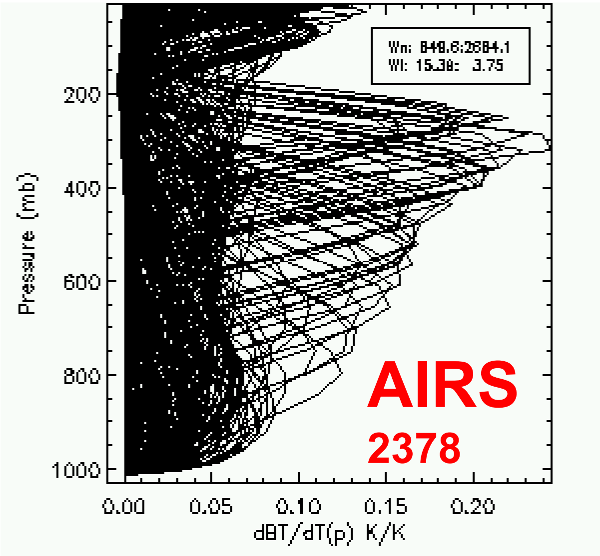
AMSUA

15 channels



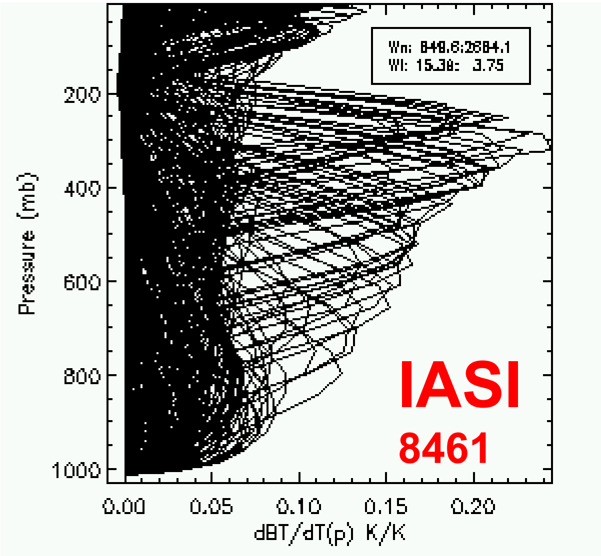
HIRS

19 channels



AIRS

2378



IASI

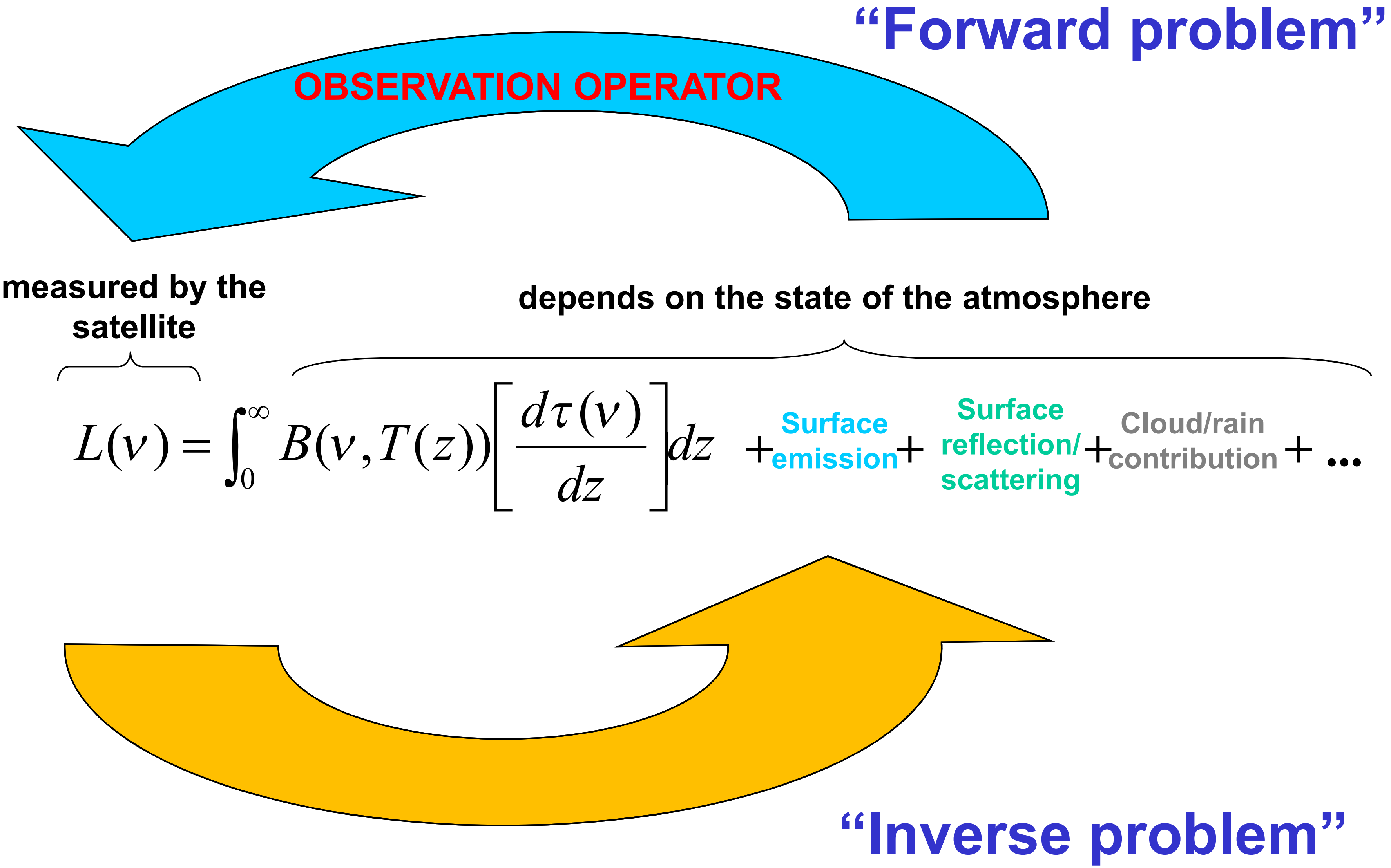
8461

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

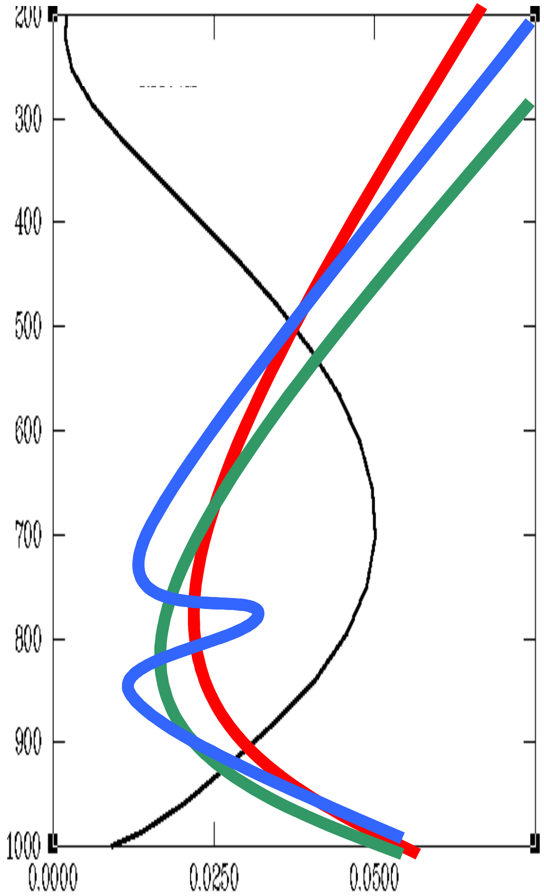


“Forward problem”

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

“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**

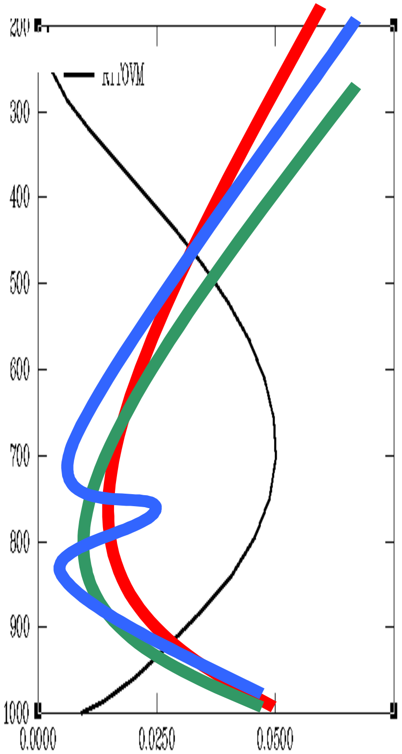
Unfortunately as the weighting functions are generally broad and we have a finite number of channels, the inverse problem is **formally ill-posed** because **an infinite number of different temperature profiles could give the same measured radiances !!!**

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

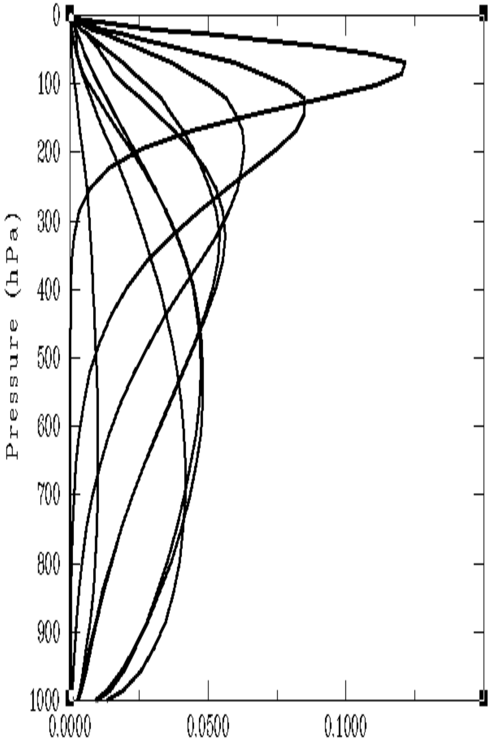
The Inverse problem

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

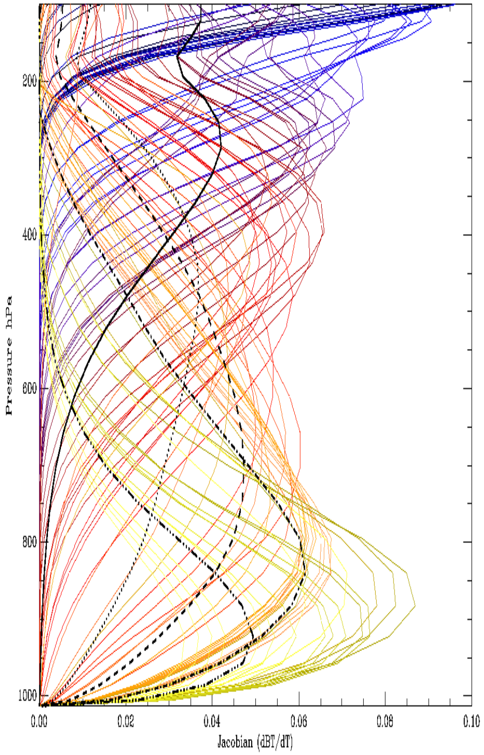
single channel



15 channels (AMSUA)



8463 channels IASI



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

“Retrievals”

and

“Direct Radiance Assimilation”

“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

1. Solutions to reduced inverse problems

We acknowledge that there is a limited amount of information in the measured radiances and re-formulate the ill-posed inverse problem in terms of a **reduced number of unknown variables** that can be better estimated by the data e.g. Deep mean layer temperatures, Total Column Water / Ozone or EOF's (eigenfunctions)

- Unfortunately it is **difficult to objectively quantify the error in these quantities** (which is very important to use the retrieval in NWP) due to the sometimes subjective choice of reduced representation.

- Some **information is lost** in collapsing the radiances in to a single number (e.g. Tropospheric mean layer temperature) that cannot be recovered by the subsequent assimilation system.

- These reduced space estimates are not generally compatible with high resolution NWP.

2. Regression and Library search methods

Using a training sample of temperature profiles matched (collocated) with a sample of training radiances (measured / simulated), a **statistical relationship** is derived that **predicts** e.g atmospheric temperature from a new observed radiance. (e.g. NESDIS operational retrievals or the LMD 3I approach)

- These tend to be **limited by the accuracy / complexity of the training sample / profile library** and will not produce physically important features if they are statistically rare in the training sample.

- The assimilation of these can **destroy important sharp physical features** in the forecast model such as inversions or the tropopause height !

- The algorithms need to be trained for each new satellite leading to a **delay in the data usage**.

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

?

“Retrievals”

and

“Direct Radiance Assimilation”

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“Direct Radiance Assimilation”

…next lecture after the break…

A QUICK REVIEW OF KEY CONCEPTS

•Satellite instruments measure **radiance** (**not** T,Q or wind)

•Sounding radiances are **broad vertical averages** of the temperature profile (defined by the weighting functions)

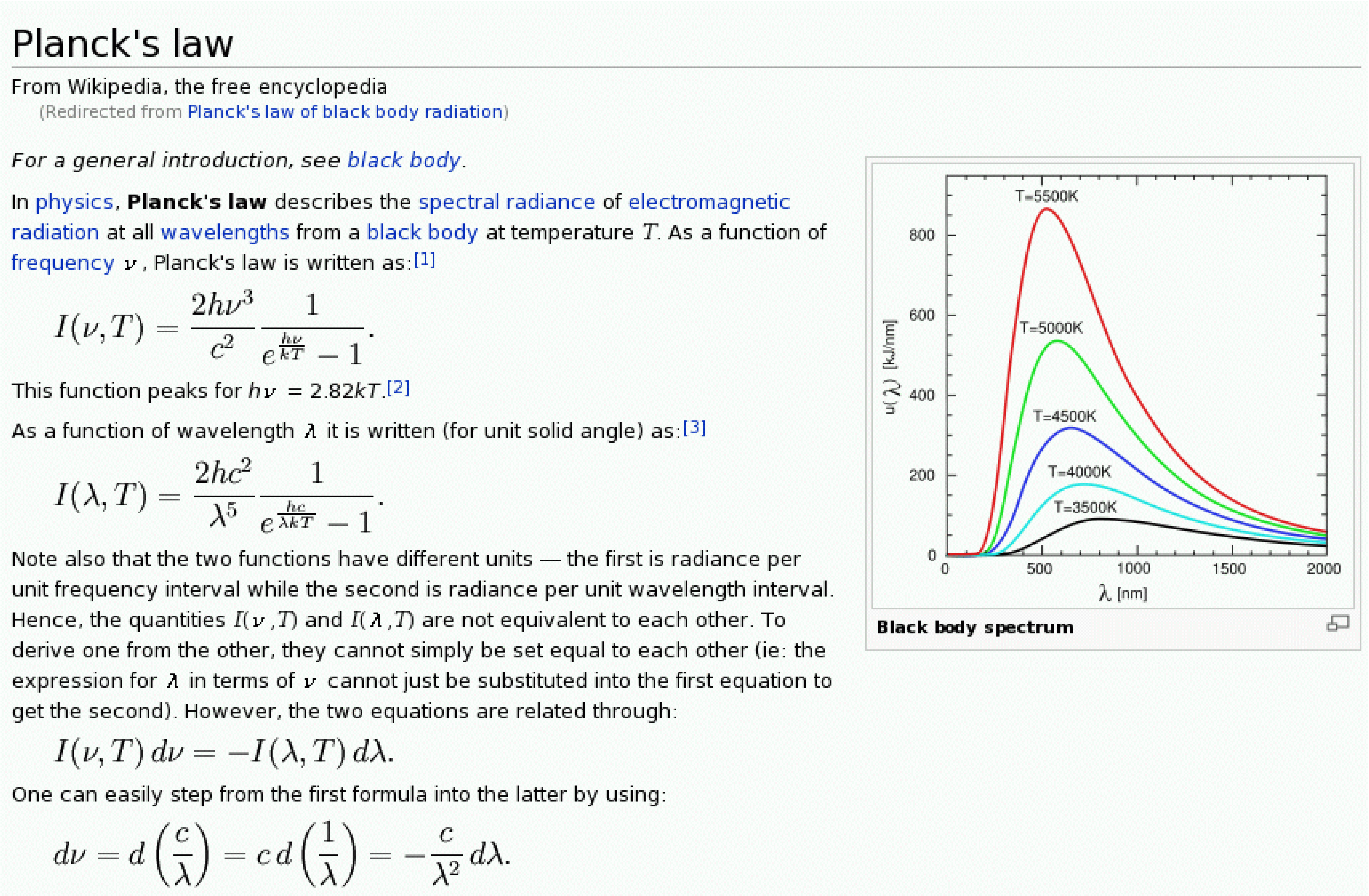
•The estimation of atmospheric temperature from the radiances is **ill- posed** and all retrieval algorithms use some sort of **prior information**

•Retrievals generated outside of the NWP system are difficult to use in assimilation schemes

End…

Questions ?

Planck Source Term
(or B from the RT equation)



Planck's law

From Wikipedia, the free encyclopedia
(Redirected from Planck's law of black body radiation)

For a general introduction, see black body.

In physics, **Planck's law** describes the spectral radiance of electromagnetic radiation at all wavelengths from a black body at temperature T. As a function of frequency ν, Planck's law is written as:[1]

$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}.$$

This function peaks for $h\nu = 2.82kT$.[2]

As a function of wavelength λ it is written (for unit solid angle) as:[3]

$$I(\lambda,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1}.$$

Note also that the two functions have different units — the first is radiance per unit frequency interval while the second is radiance per unit wavelength interval. Hence, the quantities $I(\nu,T)$ and $I(\lambda,T)$ are not equivalent to each other. To derive one from the other, they cannot simply be set equal to each other (ie: the expression for λ in terms of ν cannot just be substituted into the first equation to get the second). However, the two equations are related through:

$$I(\nu,T)\,d\nu = -I(\lambda,T)\,d\lambda.$$

One can easily step from the first formula into the latter by using:

$$d\nu = d\left(\frac{c}{\lambda}\right) = c\,d\left(\frac{1}{\lambda}\right) = -\frac{c}{\lambda^2}\,d\lambda.$$

Black body spectrum