Microwave spectrum

Measurement, modelling and information content

Alan Geer

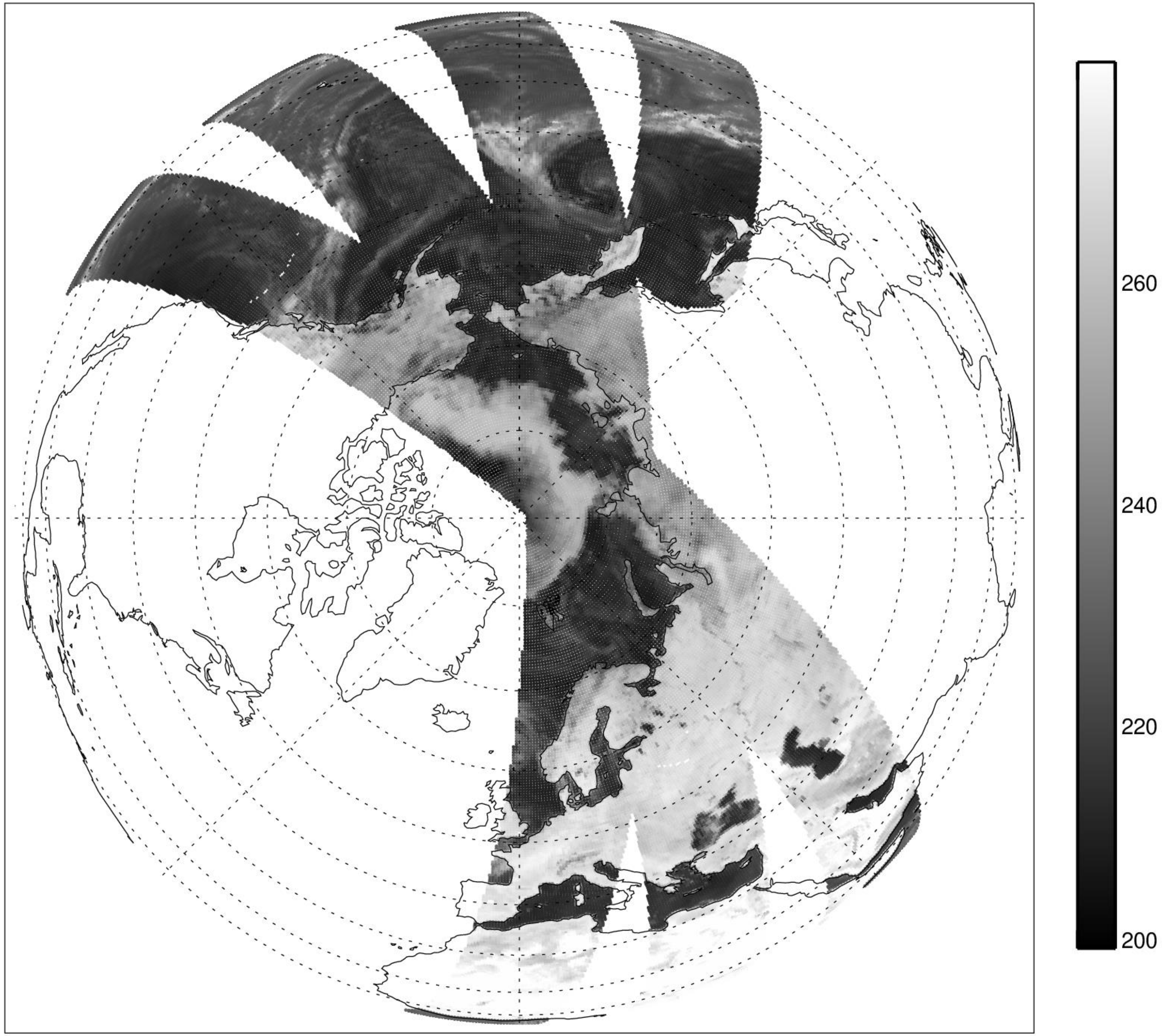
Thanks to: Peter Bauer, Bill Bell

EUMETSAT/ECMWF NWP-SAF satellite data assimilation training course, 11 – 15 March, 2024

Advanced Scanning Microwave Radiometer (AMSR-2)

Observation composite for 1st Nov 2021

Brightness temperatures [Kelvin] at 37 GHz, v-polarised



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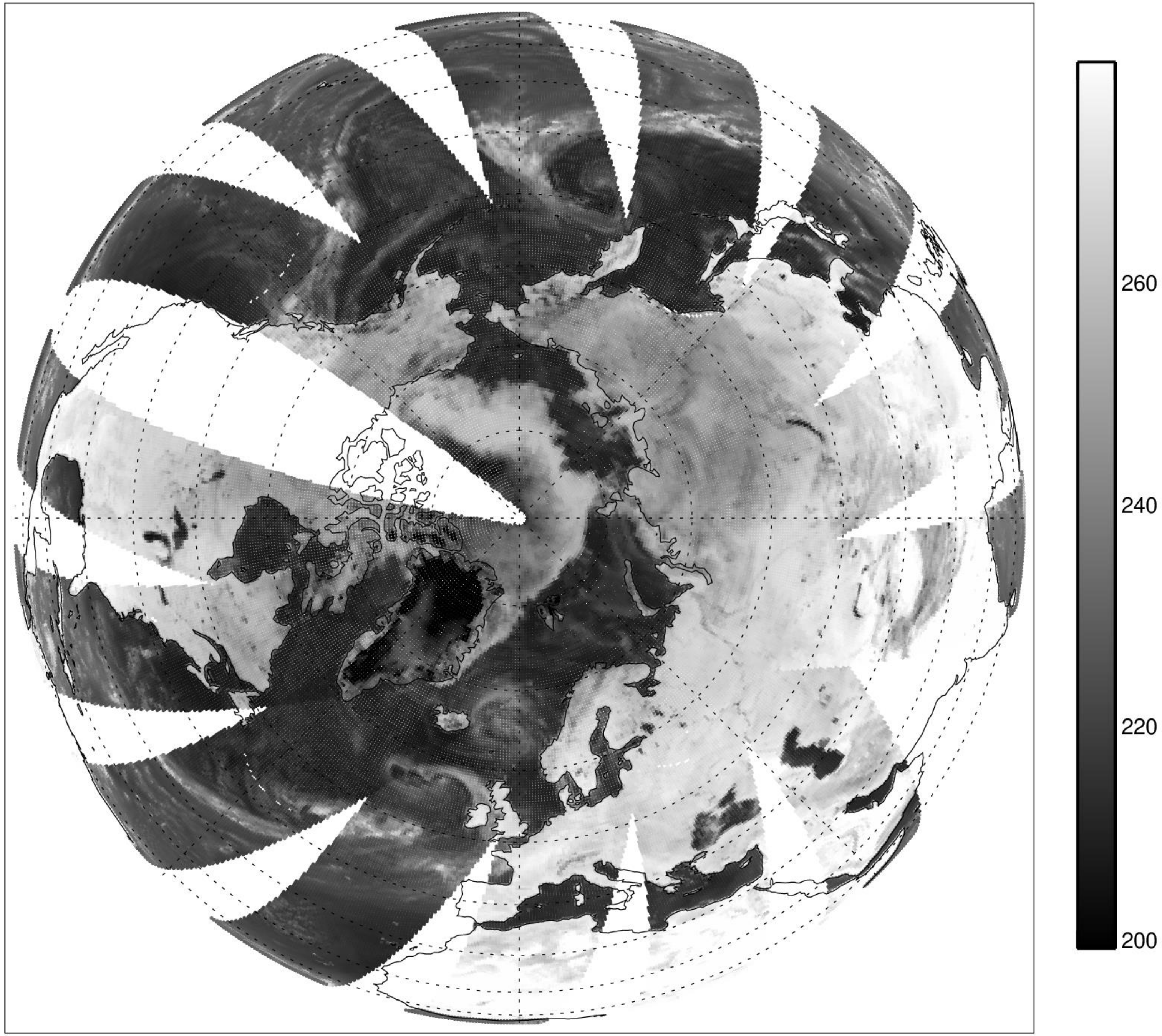

ECMWF

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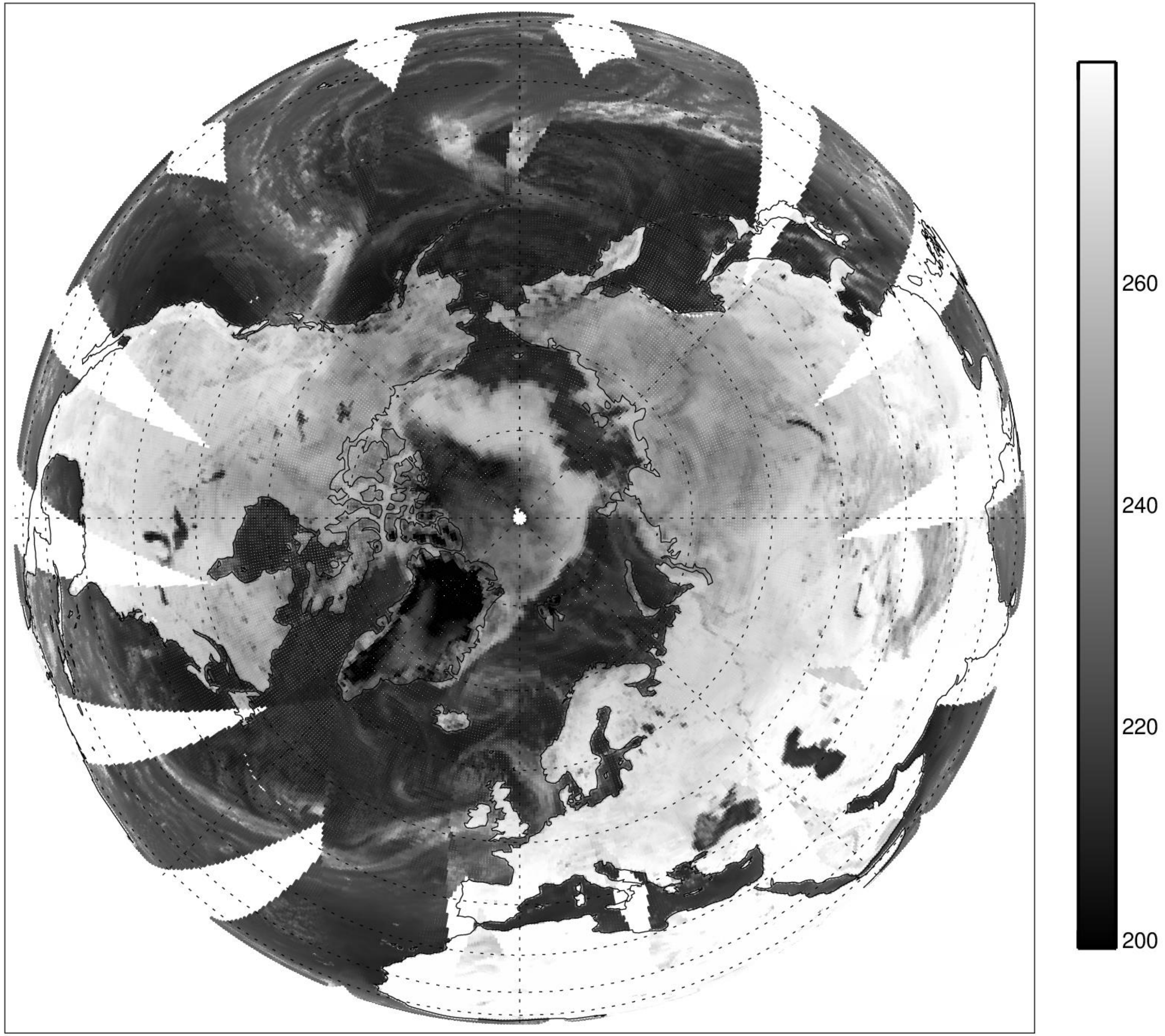

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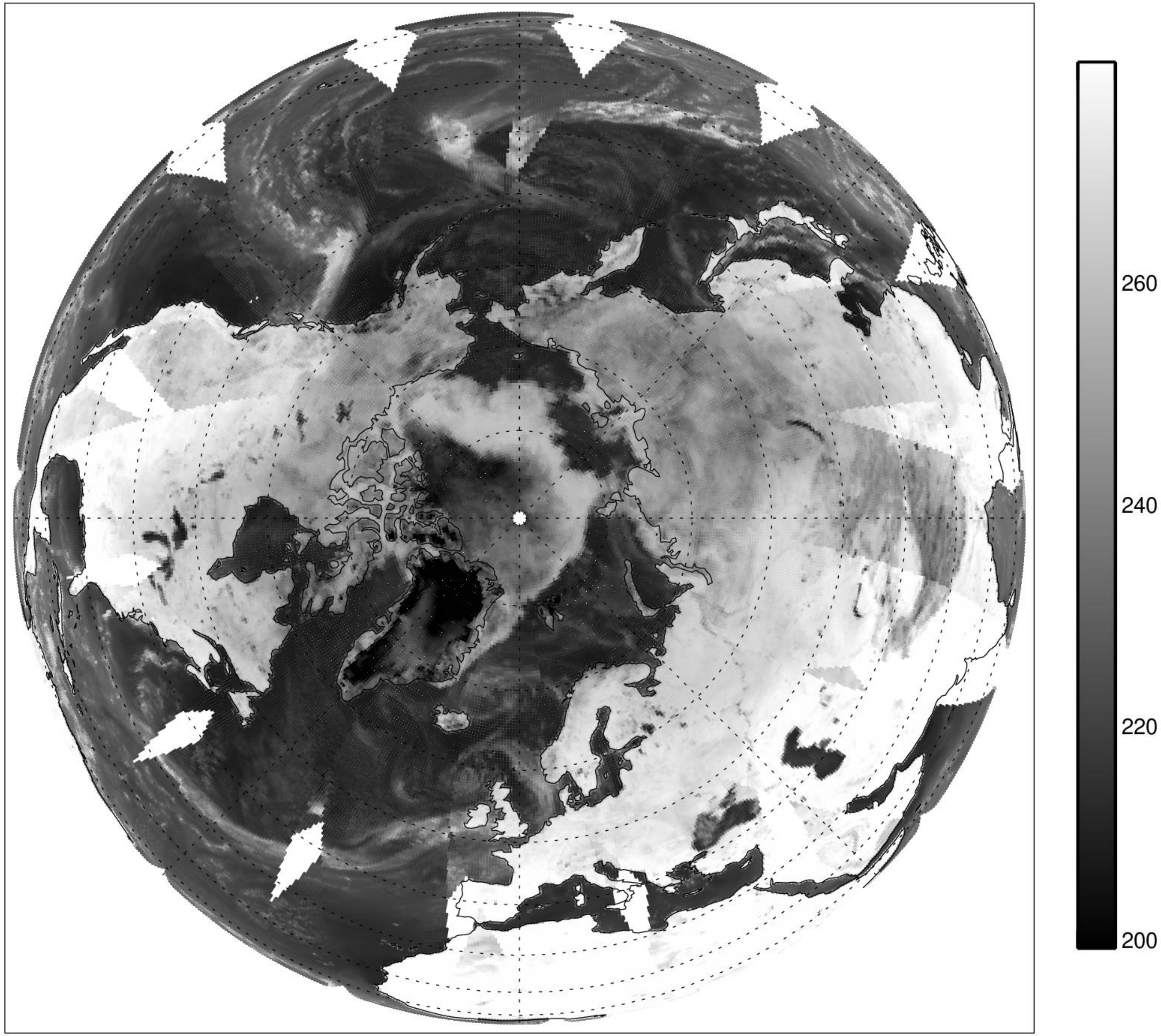
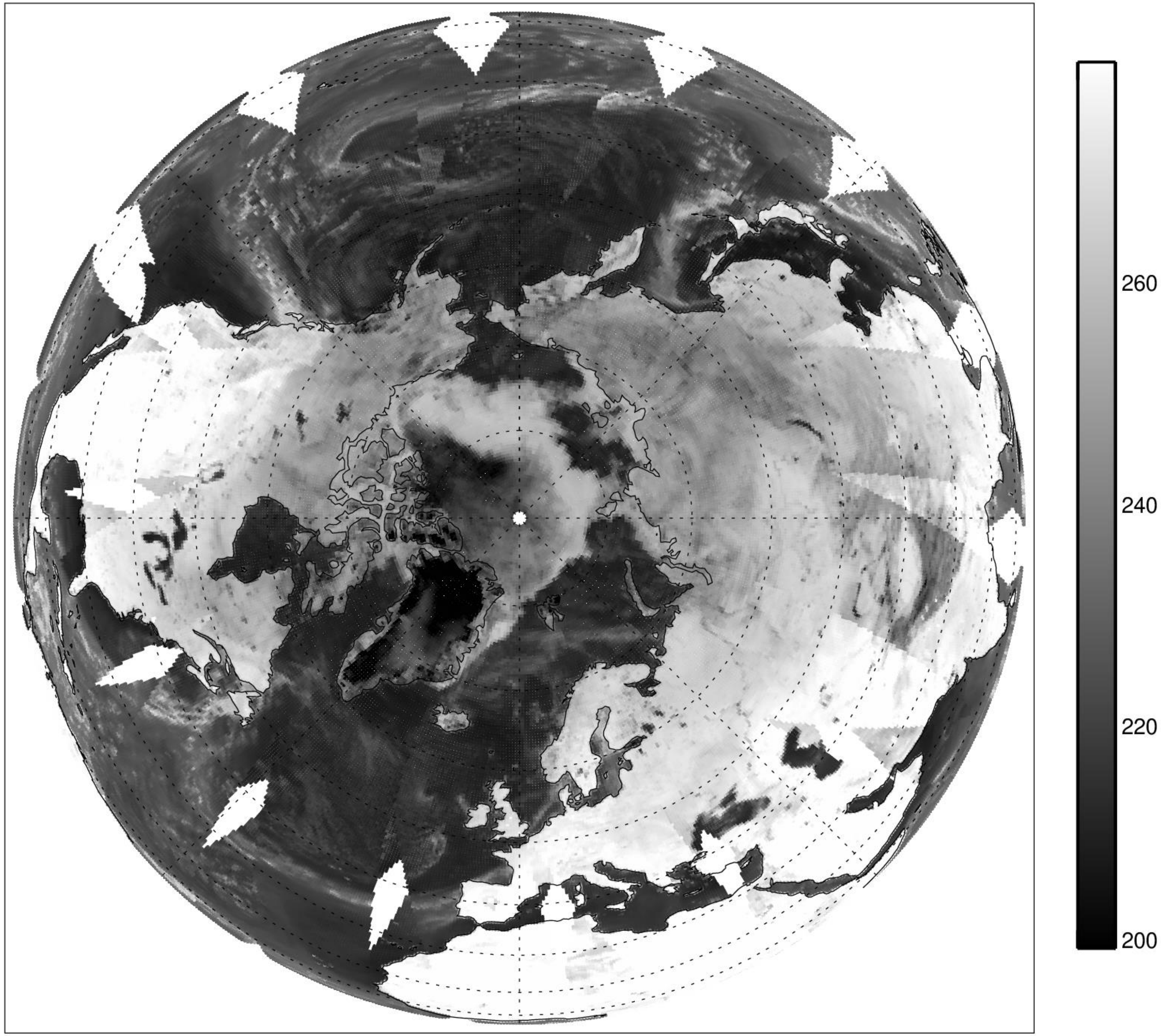


ECMWF

Advanced Scanning Microwave Radiometer (AMSR-2)

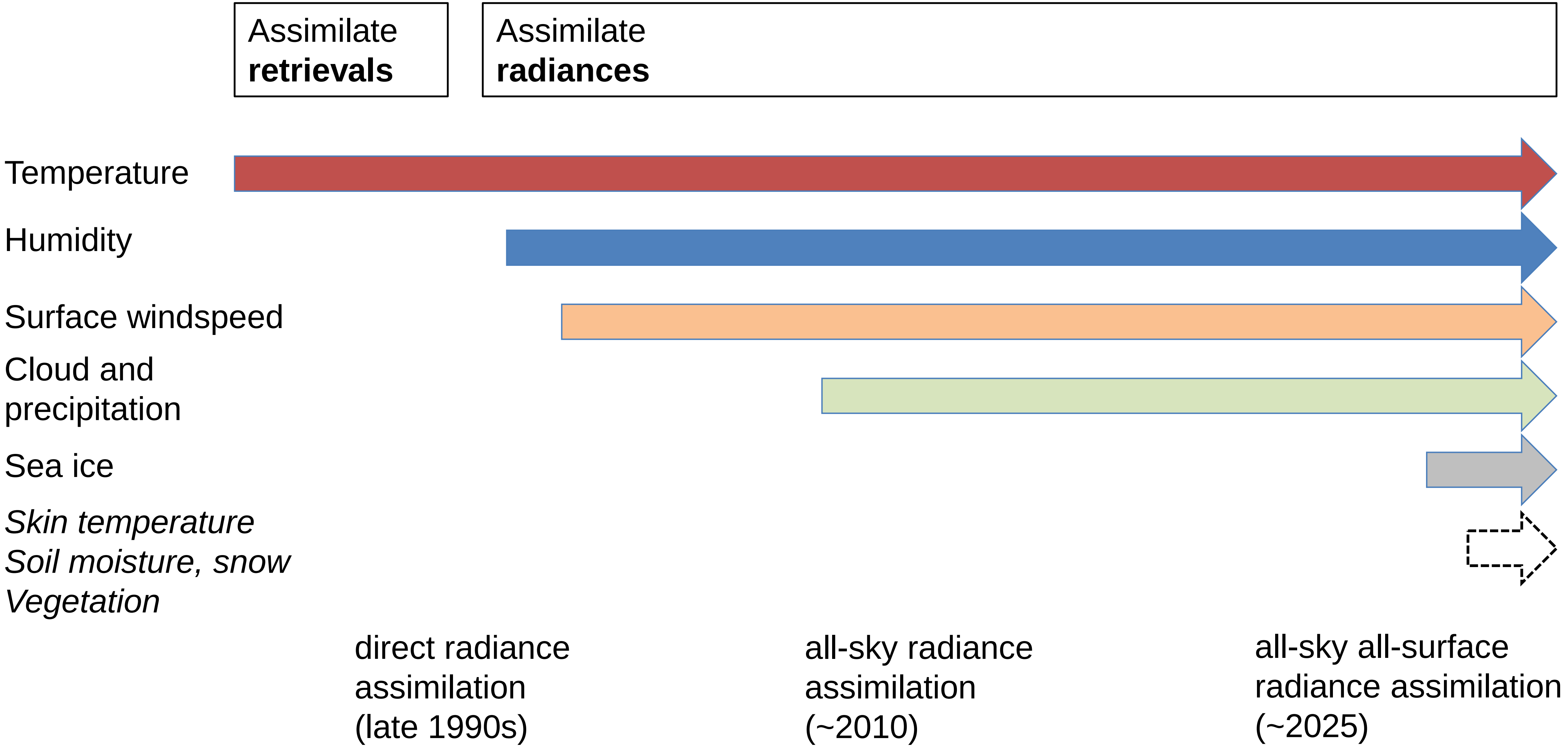
Observation composite for 2nd Nov 2021

Radiances shown as brightness temperatures [Kelvin] at 37 GHz, v-polarised



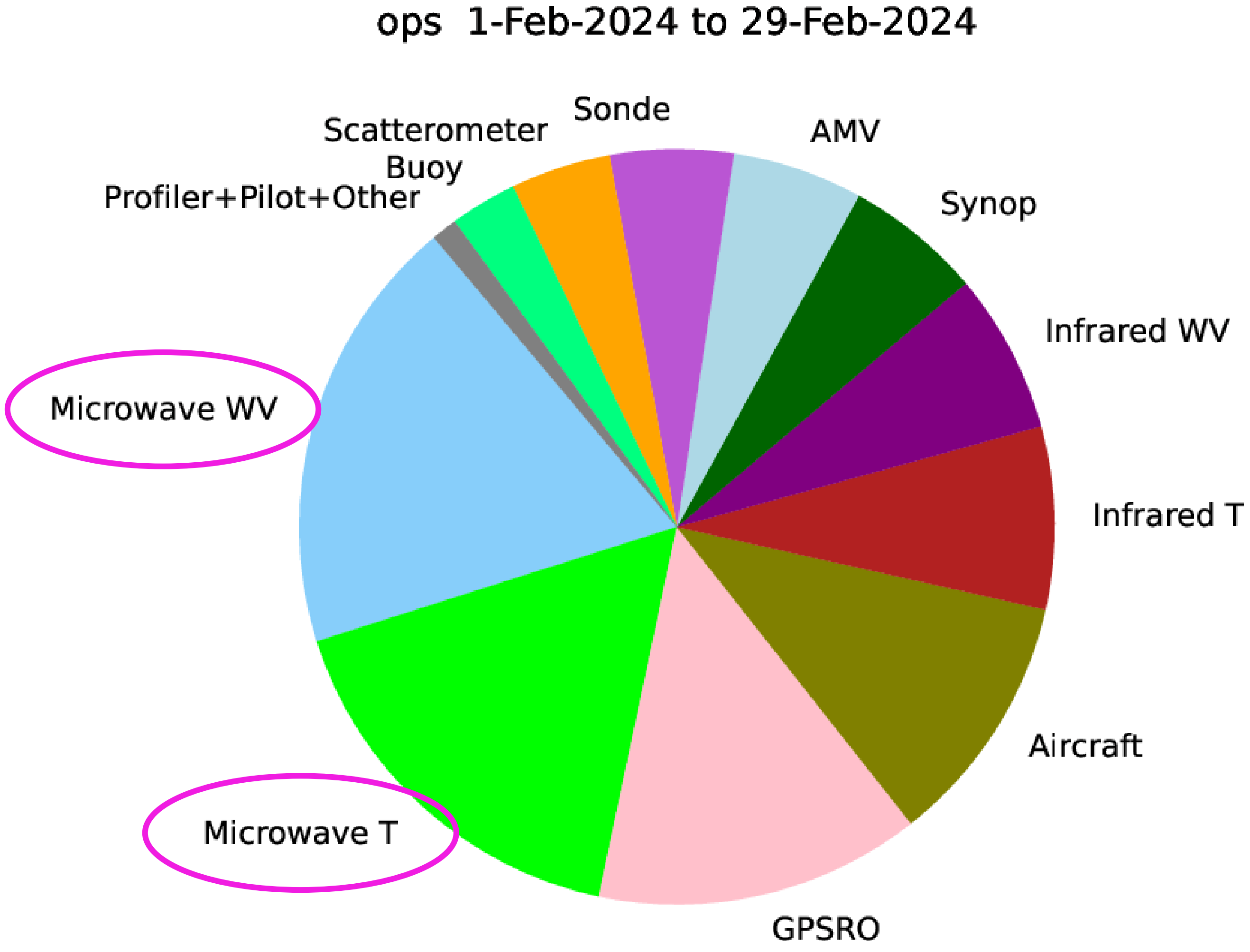
ECMWF

Rough timeline of satellite microwave data assimilation in ‘atmospheric’ DA

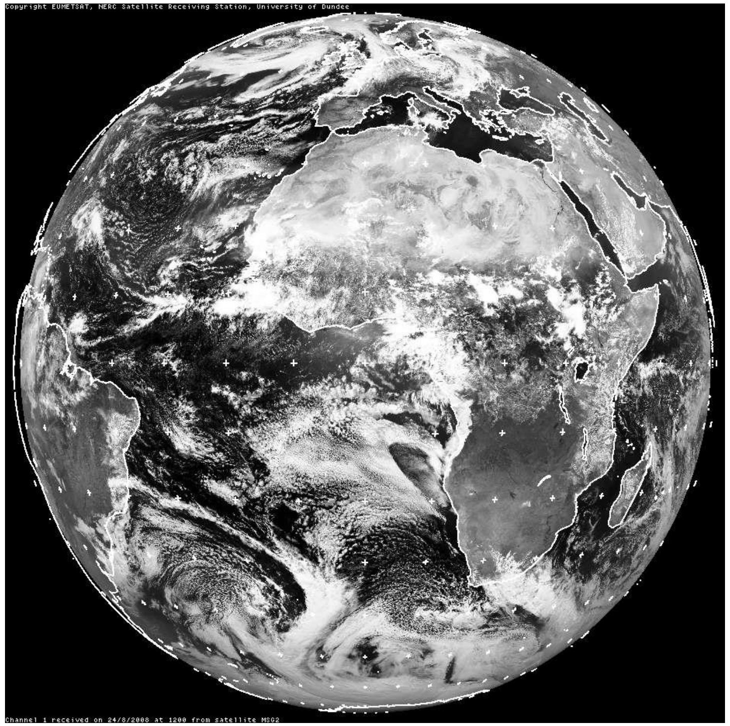


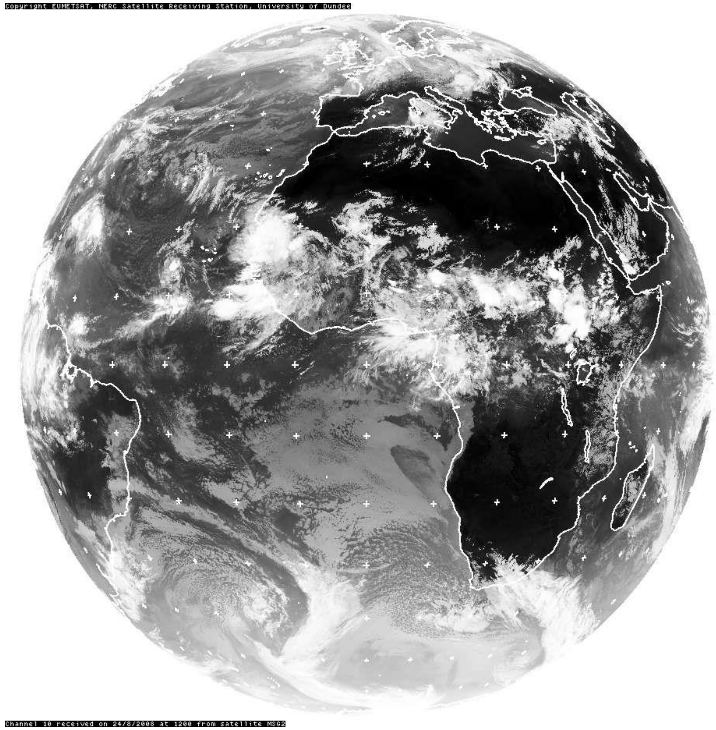
Relative impact of observations at ECMWF: February 2024

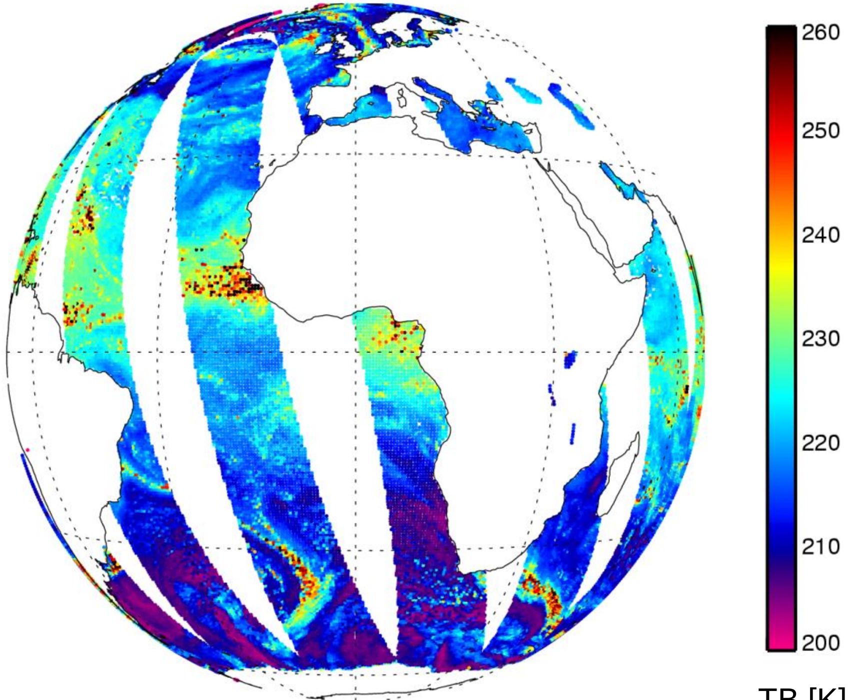
Relative sensitivity of 24 hour forecast error to observation impact (FSOI)



Visible, infrared and microwave views of the earth







TB [K]

Visible
SEVIRI channel 1
0.56-0.71 µm

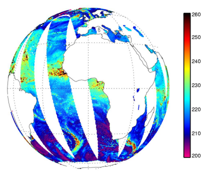
Infrared
SEVIRI channel 10
11-13 µm

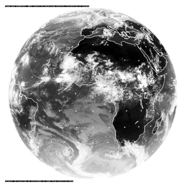
*reverse colour scale – bright is really cold/dim

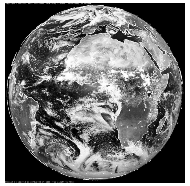
Microwave
AMSR-E channel 37v
8108 µm (37 GHz v-pol)

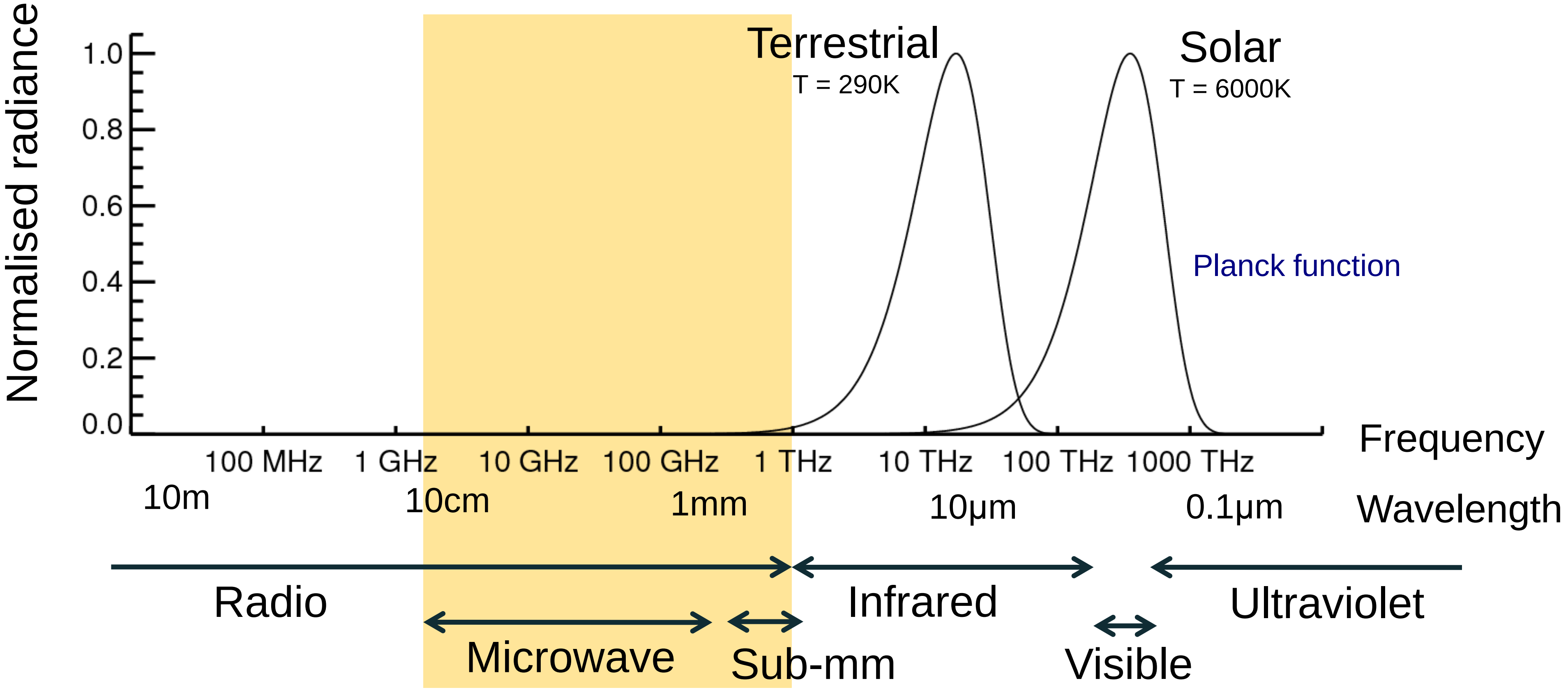
Window channels 24th August 2008 at around 12UTC

Where is the microwave in the electromagnetic spectrum?





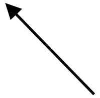


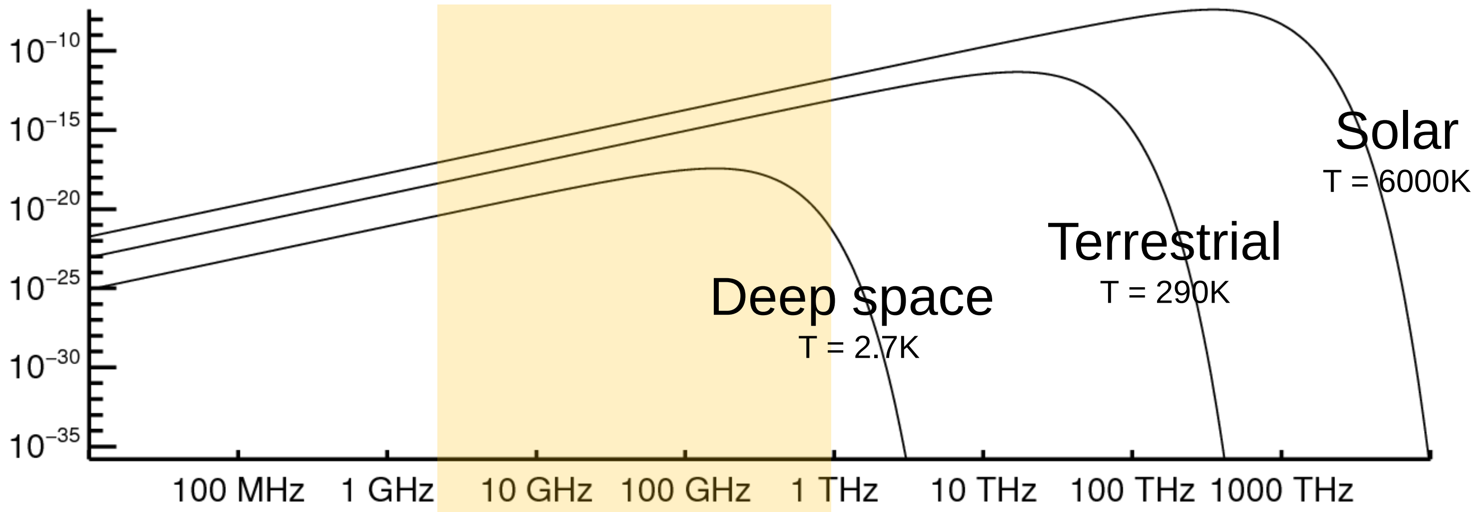


How much energy?

Planck Function Radiance
W m^{-2} sr^{-1} Hz^{-1}

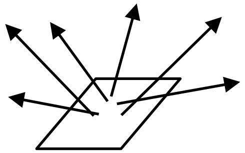
Travelling in a beam

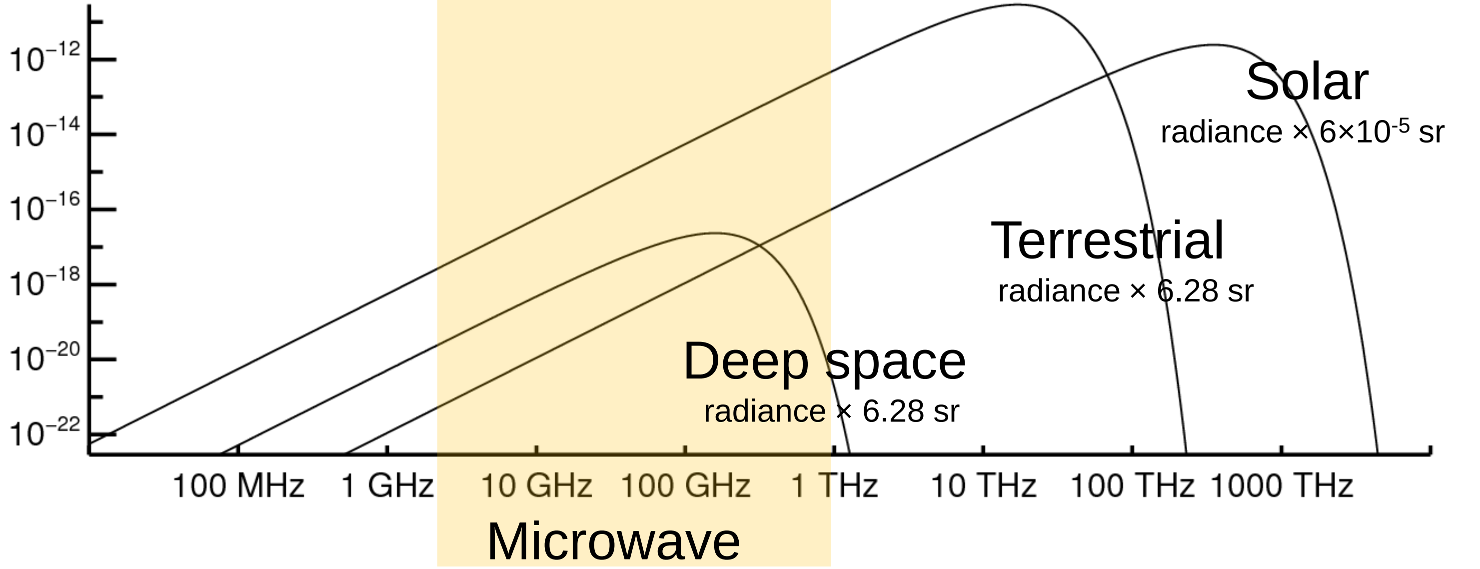




Flux
W m^{-2} Hz^{-1}

Travelling through an area (in one direction)





sr – Steradian (unit of solid angle)

Radiance and brightness temperature

- Radiance: W m^{-2} sr^{-1} Hz^{-1}
  - Watts (energy)
  - per metre squared
  - per unit of “direction” (solid angle)
  - per unit frequency

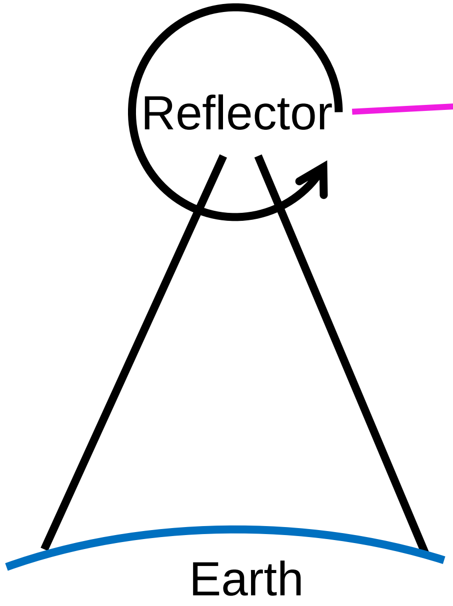
- Planck’s function (Rayleigh-Jeans approximation, valid in microwave)

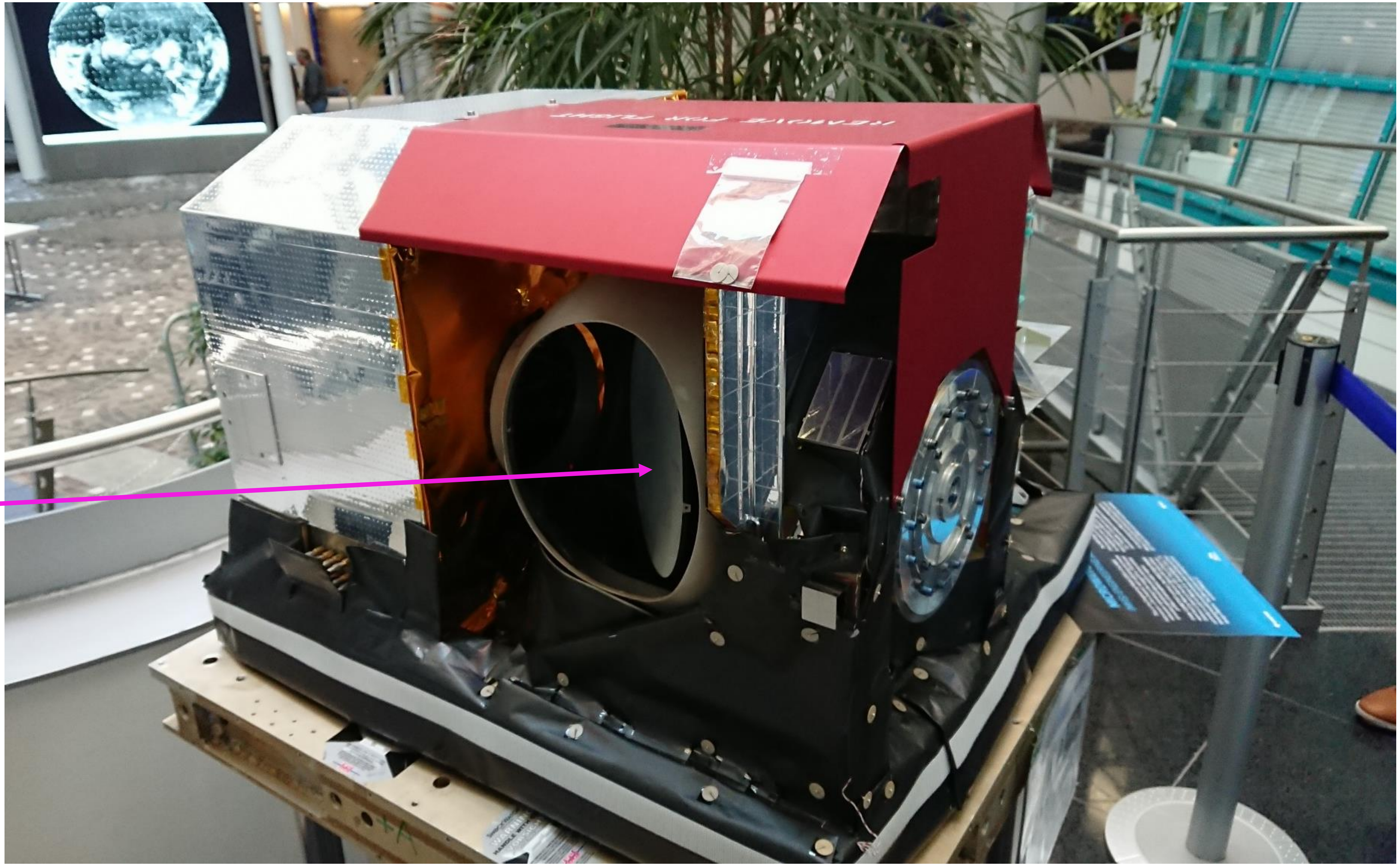
Radiance ⟶ $$B_\lambda(T_B) = \frac{2c}{\lambda^4} k_B T_B$$ ⟵ Brightness temperature

c = speed of light; λ = wavelength; k_B = Boltzmann’s constant

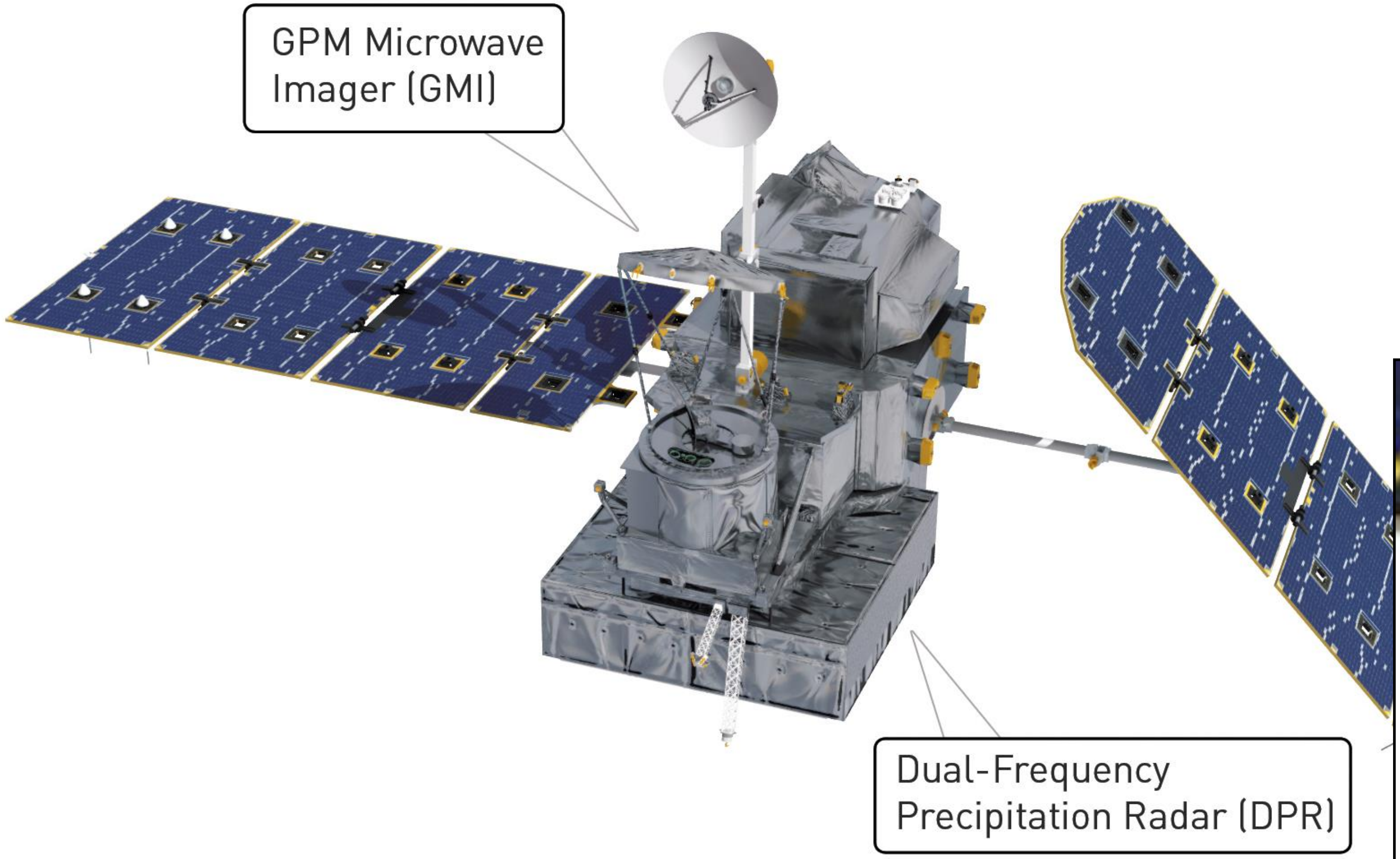
The Microwave Humidity Sounder (MHS) at EUMETSAT

Cross-track sounder



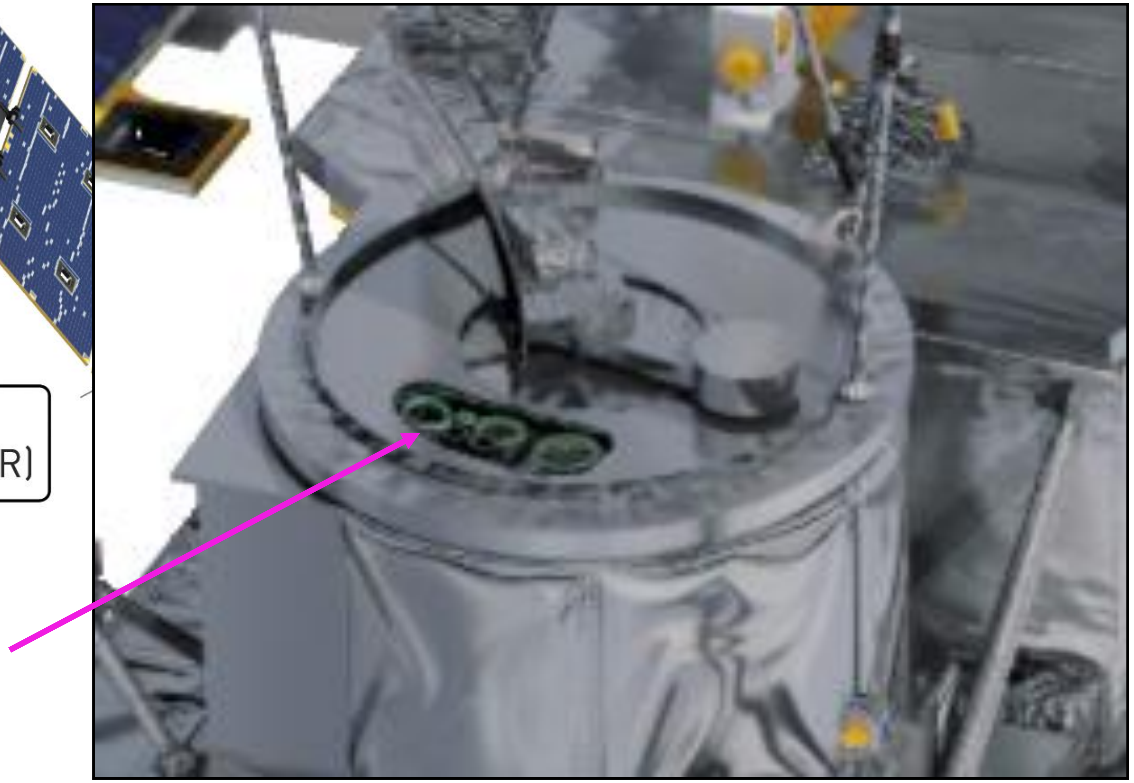


Global precipitation mission (GPM)



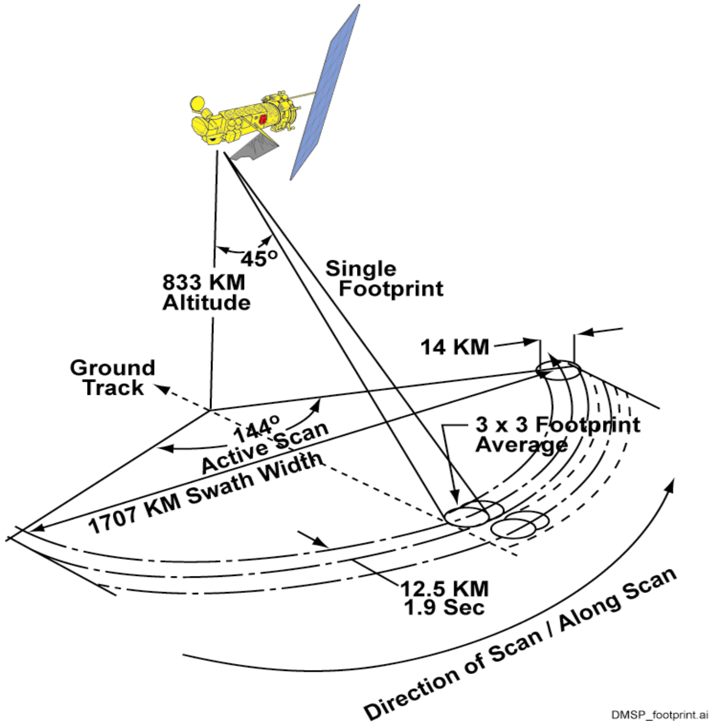
Global precipitation mission:

- Launched Feb 2014



Special Sensor Microwave Imager / Sounder (SSMIS)

Conical scanning geometry

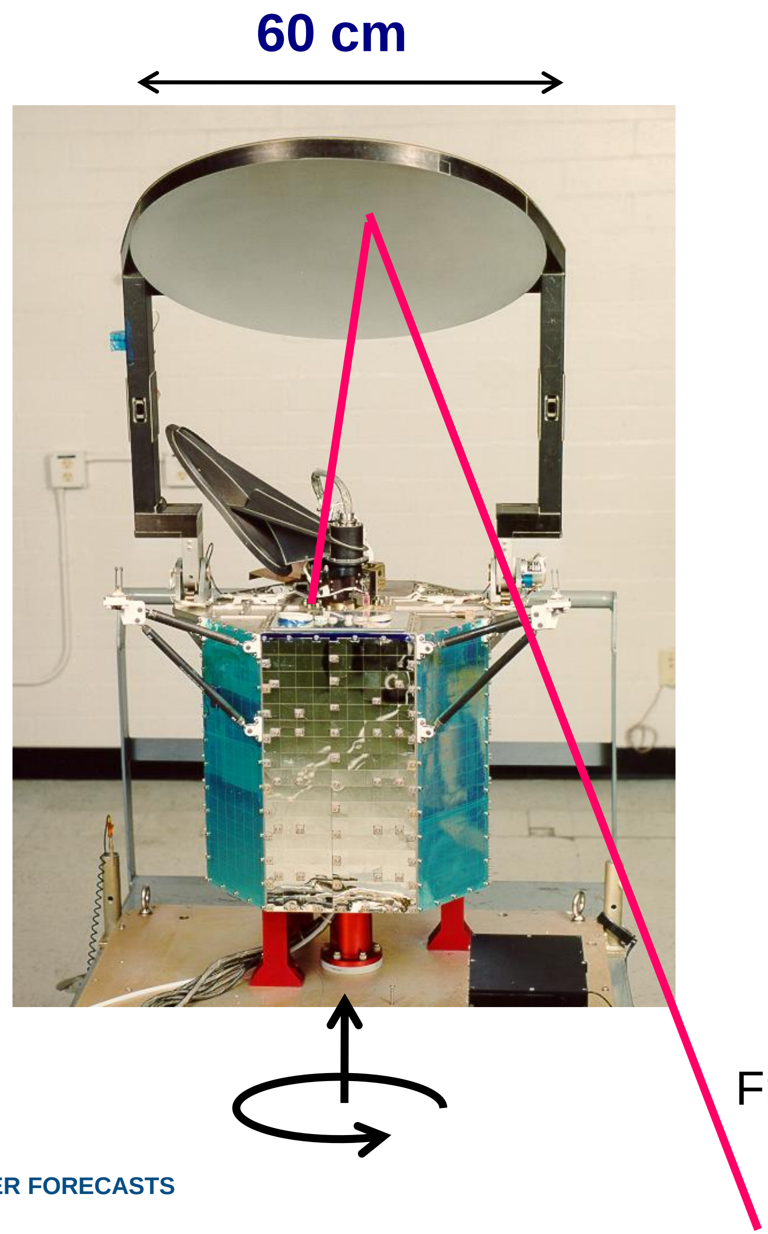


Main Reflector

Cold Calibration Reflector

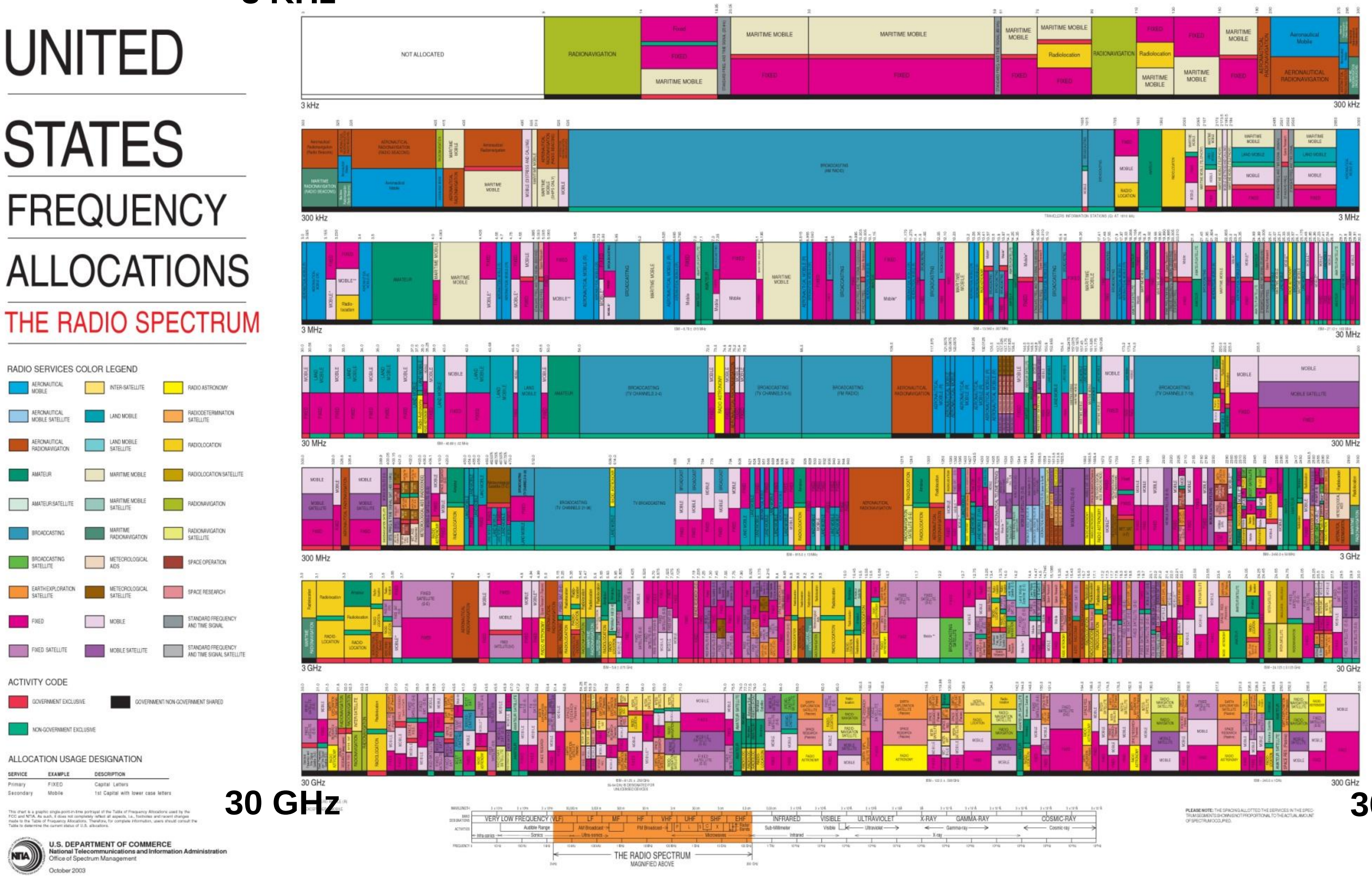
Warm Load

Feedhorns



Other users of the spectrum

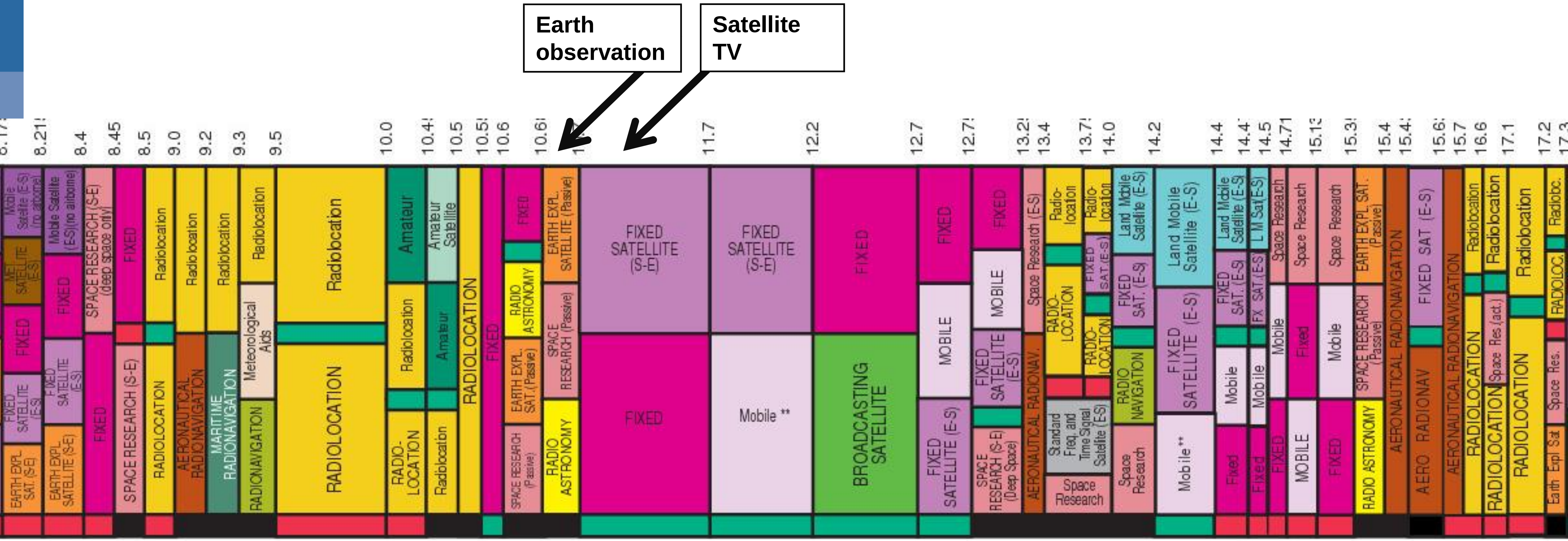
3 KHz



30 GHz

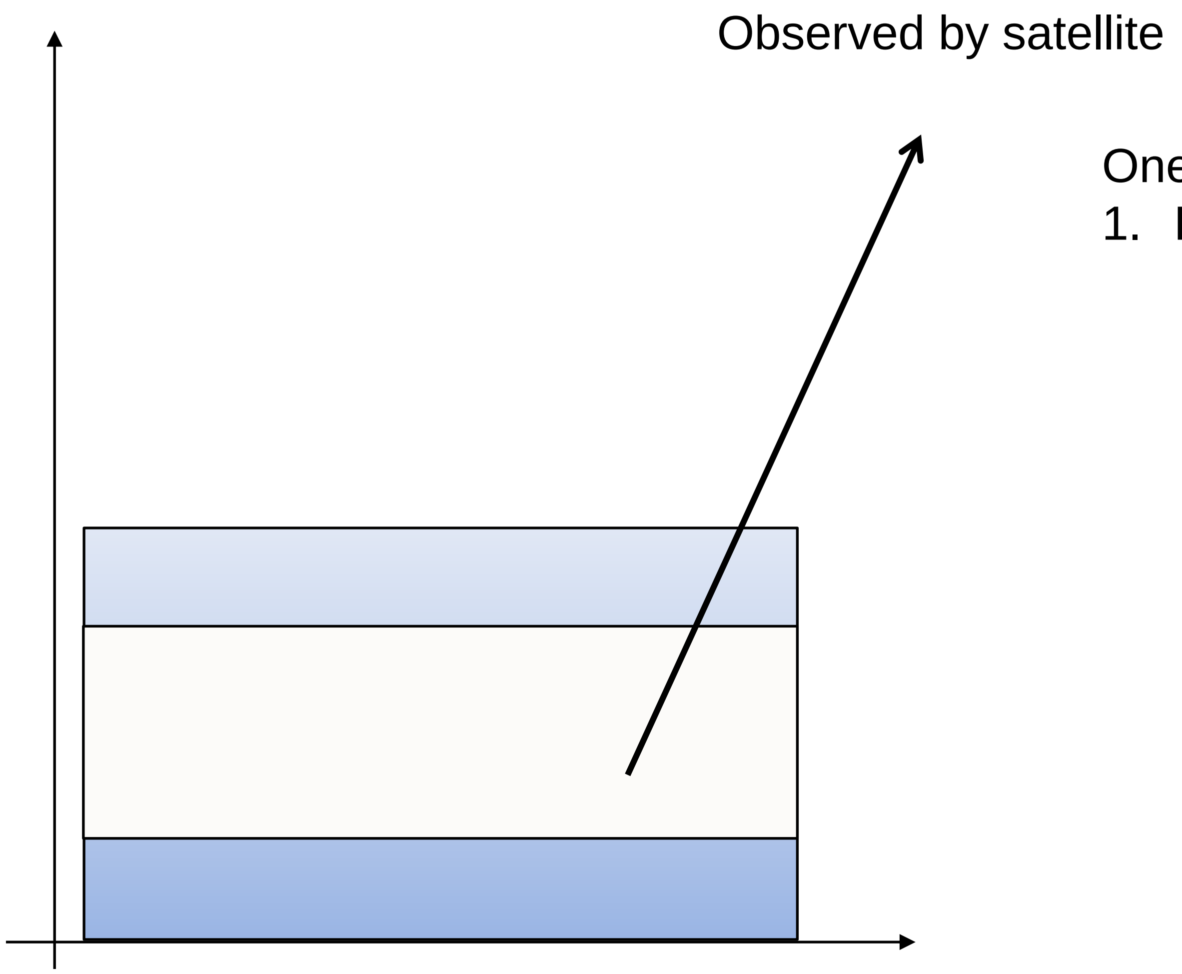
300 GHz

Other users of the spectrum



Information content

Radiative transfer: sounding channels (ignoring scattering)



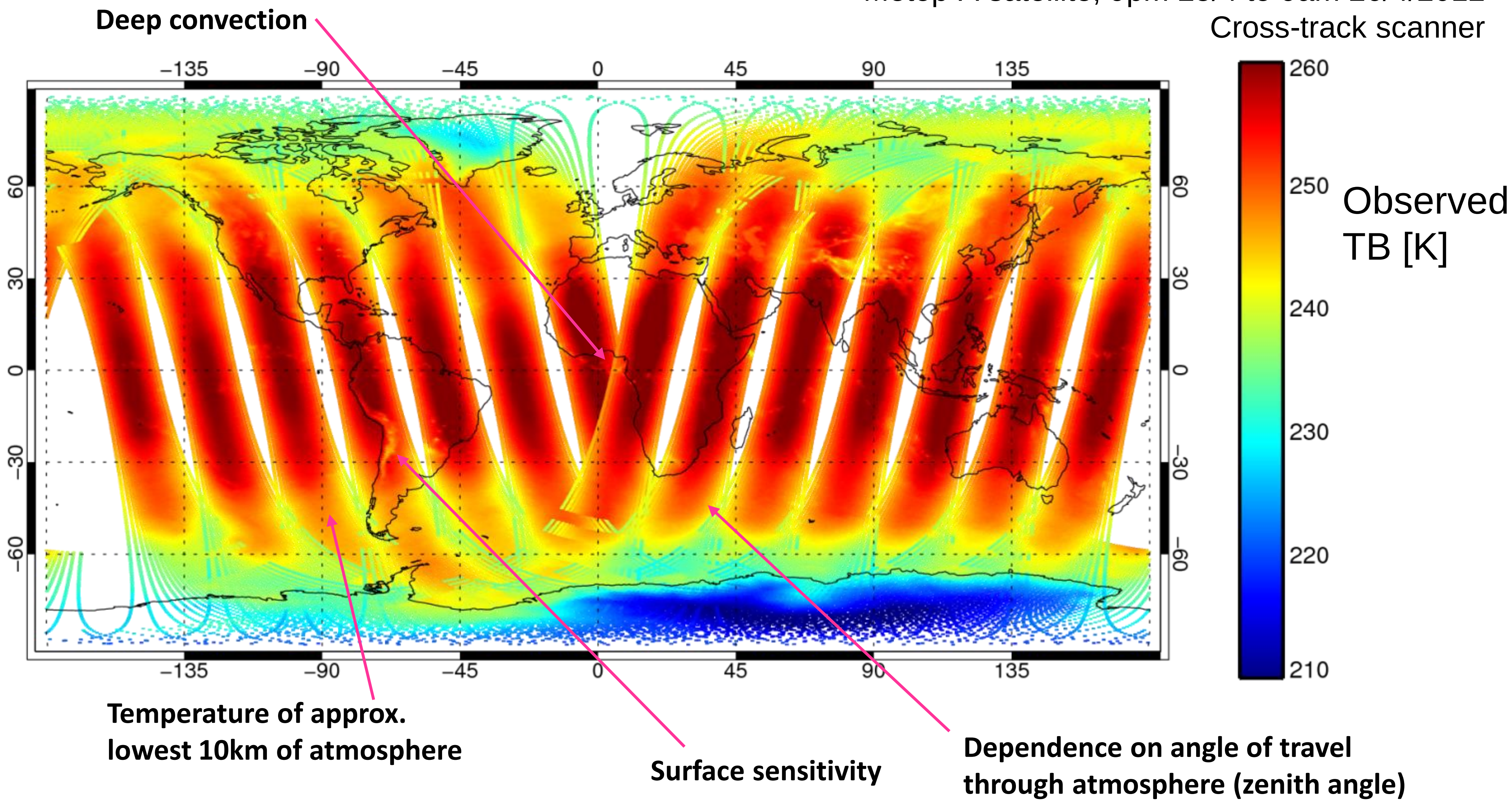
One source of radiation:

1. Radiation emitted by the atmosphere

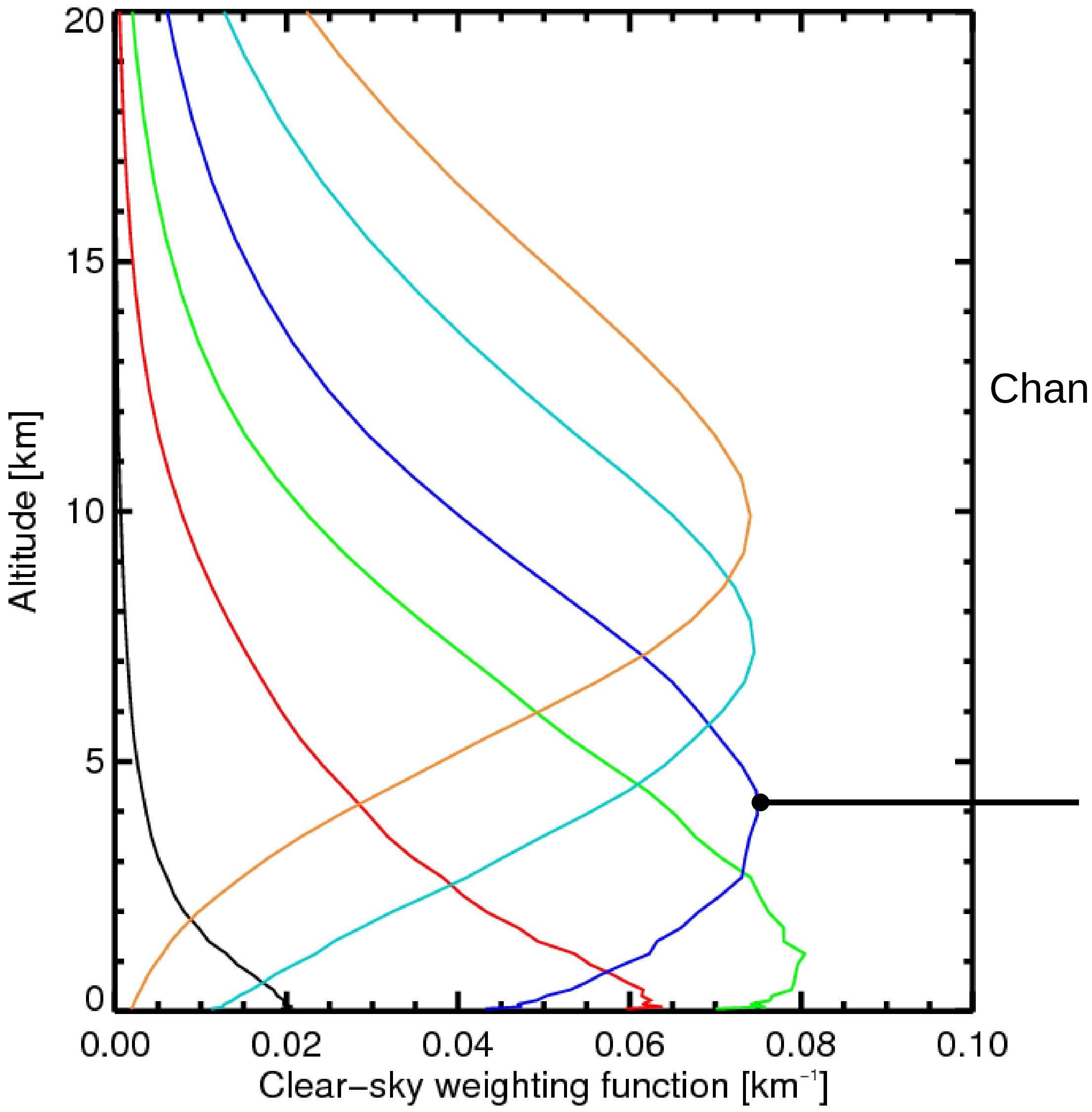
Ocean or land / snow / sea-ice surface

Sensitivities: temperature sounding channels

AMSU-A channel 5 radiances:
Metop-A satellite, 9pm 25/4 to 9am 26/4/2012
Cross-track scanner



Clear sky AMSU-A weighting functions (nadir)

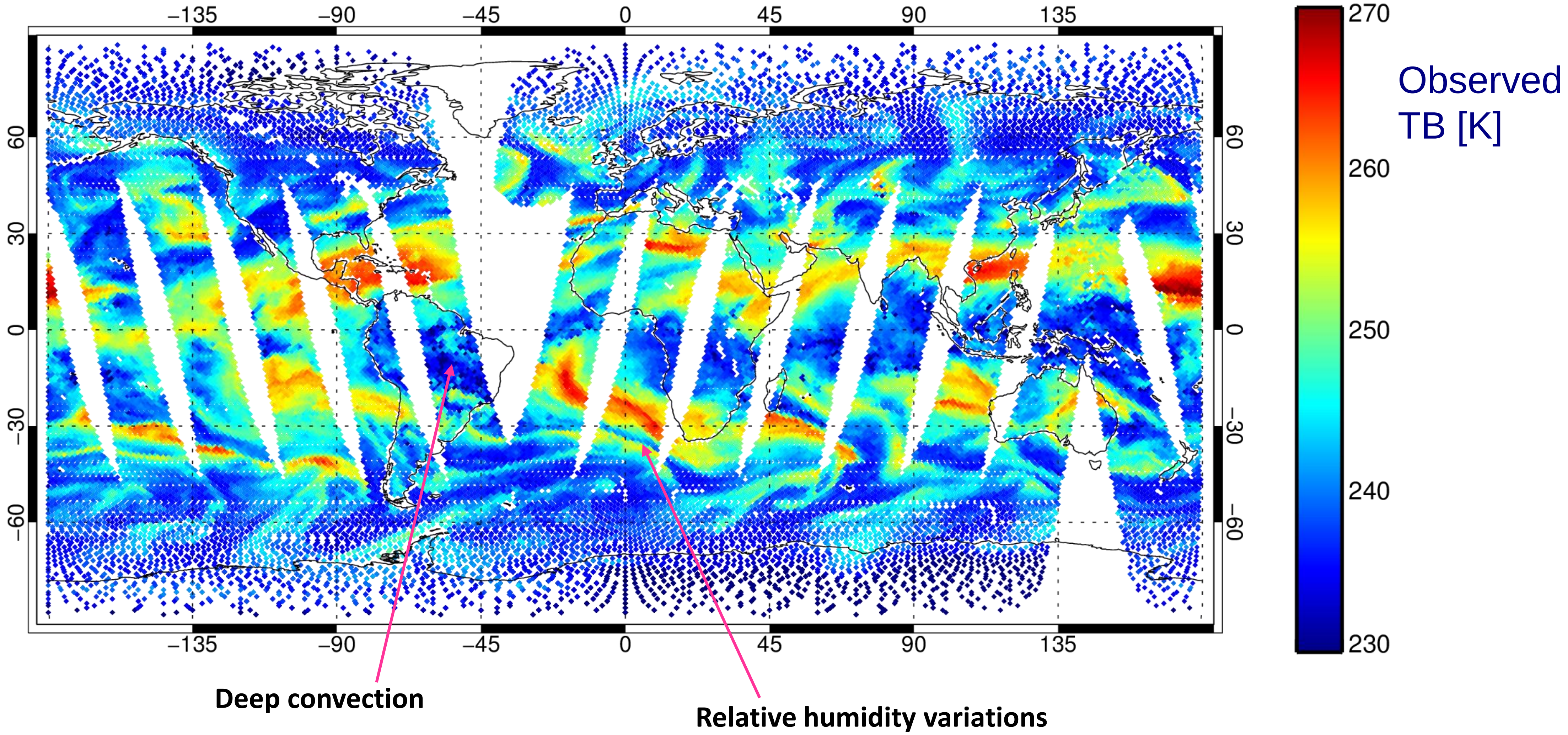


AMSU-A channels are at frequencies mainly sensitive to oxygen, a well-mixed gas: weighting functions are effectively fixed

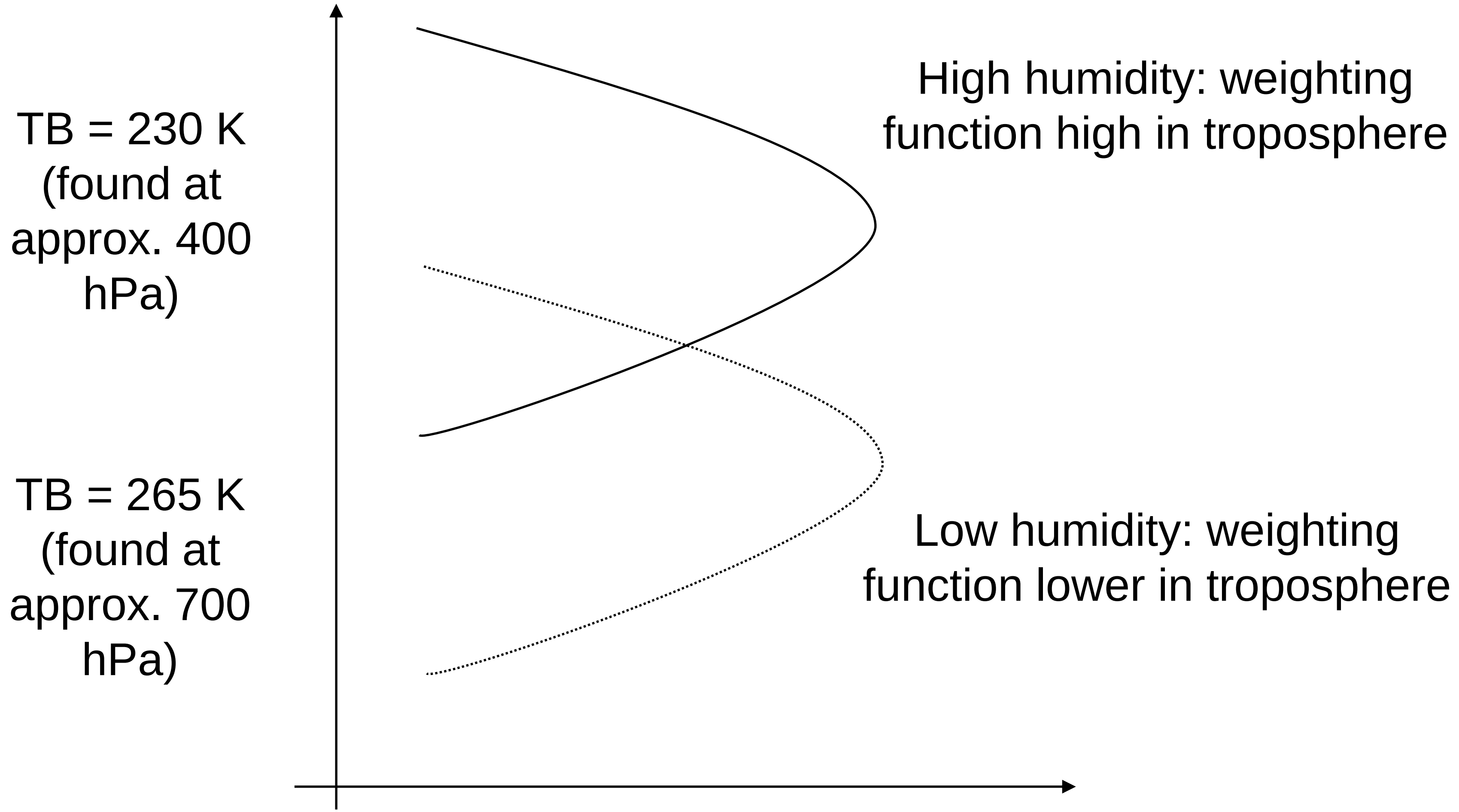
Channel	Transmittance surface to space
7	0%
6	0%
5	5%
4	19%
3	56%
2	92%

Humidity sounding channels

SSMIS F-17 channel 11 (183±1 GHz)
Conical scanning imager and sounder

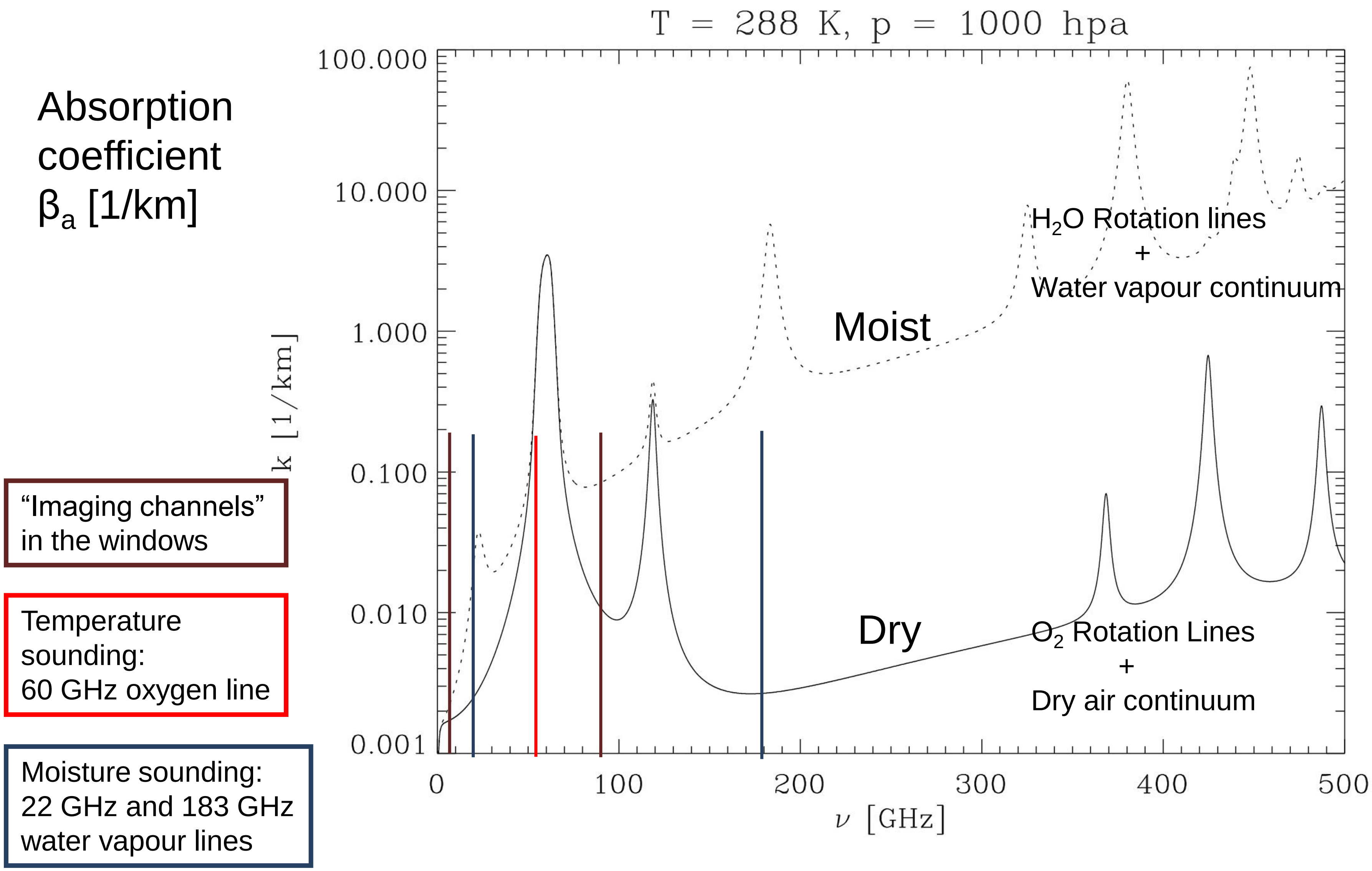


Water vapour is a highly variable gas in the atmosphere: weighting function is not fixed



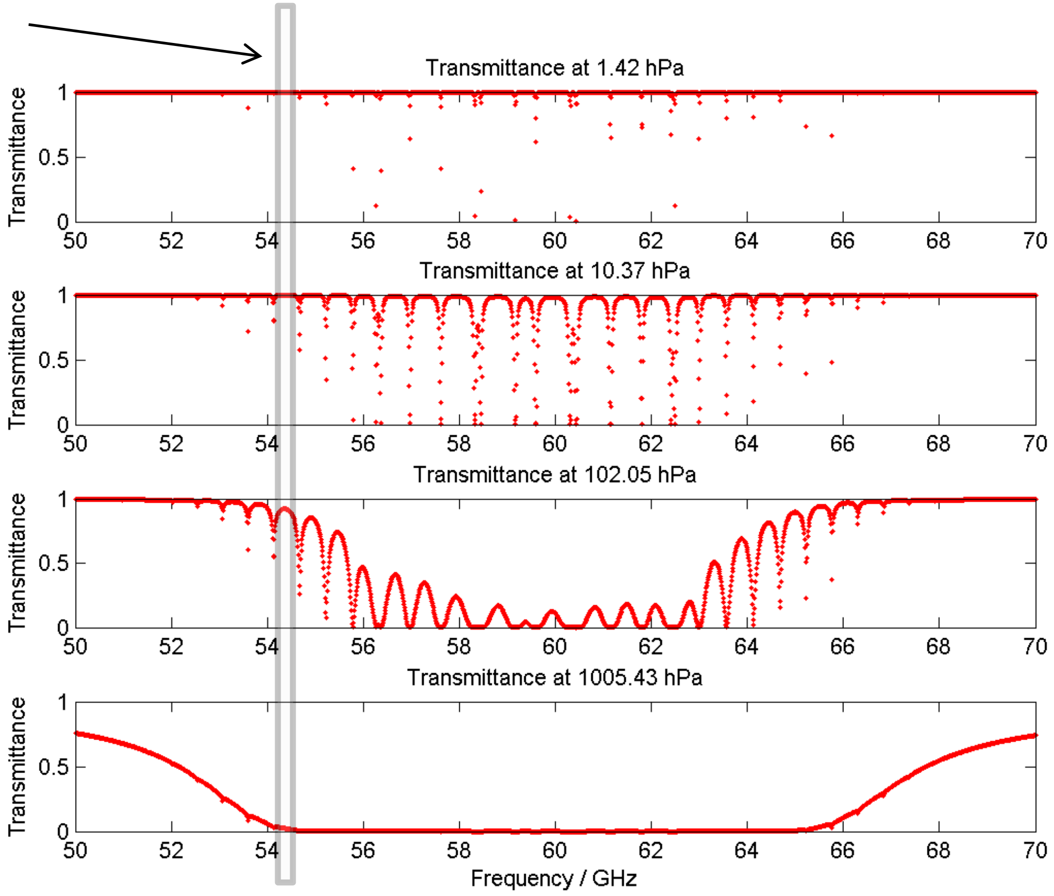
Gas absorption: the microwave spectrum

Absorption coefficient β_a [1/km]



Fine scale structure in the 60 GHz oxygen line

Typical MW radiometer passband at 54.4 GHz

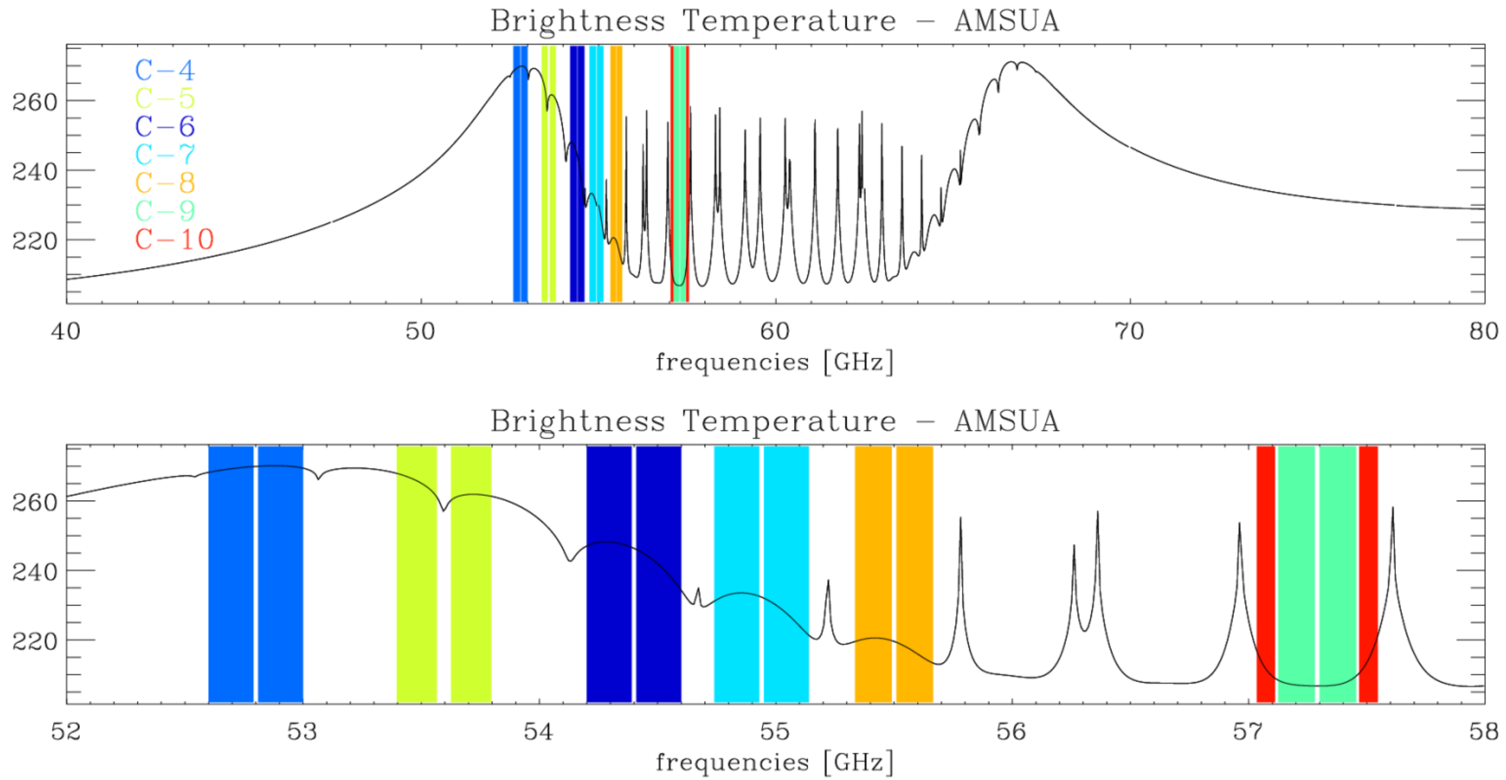


Level to TOA transmittance from Liebe MPM 92 model

Narrow lines ~ several MHz

Increasing pressure broadening

AMSU-A 50 – 60 GHz channels

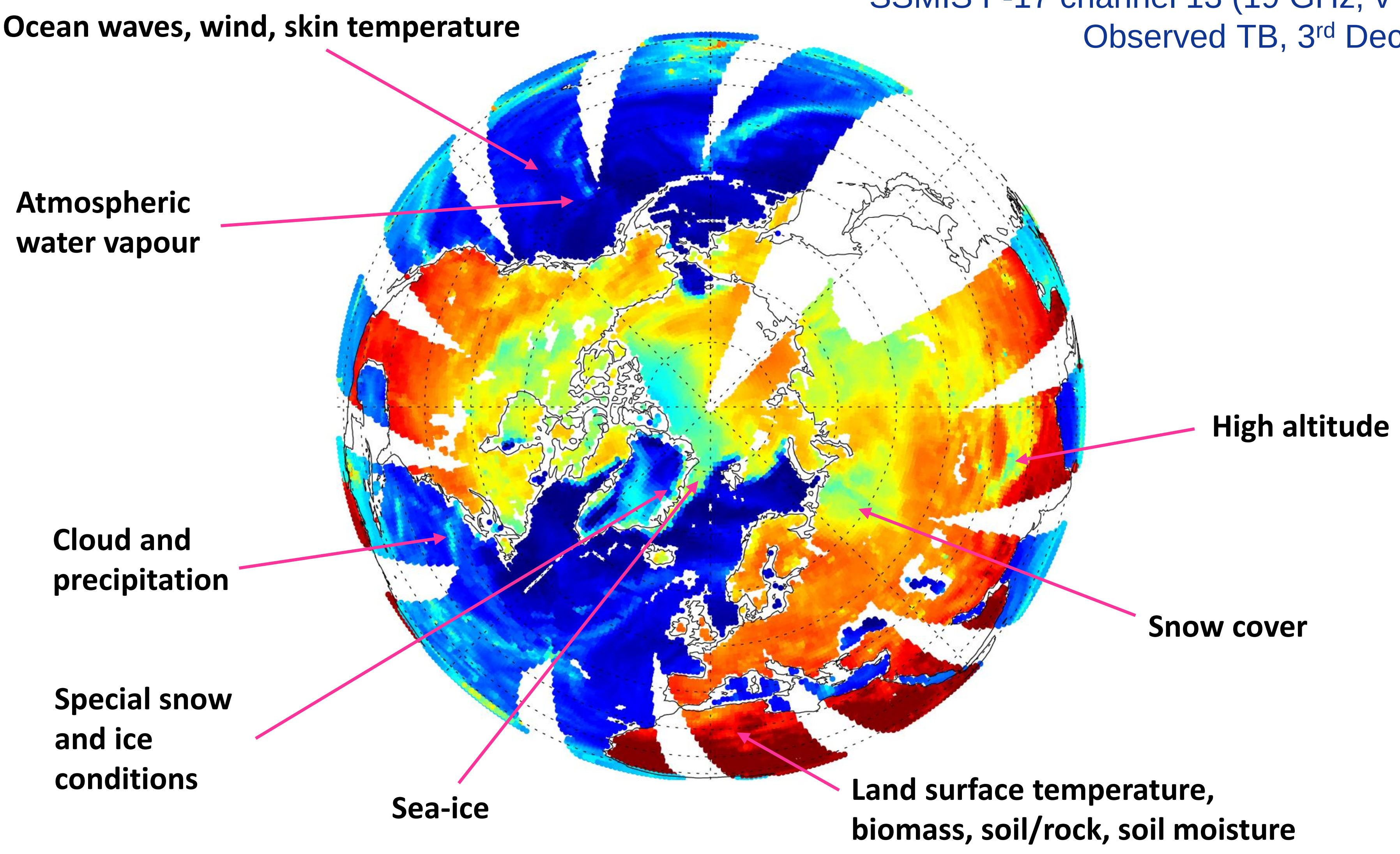


Channel positions and bandwidths are based on trade-offs aimed at simultaneously optimising :

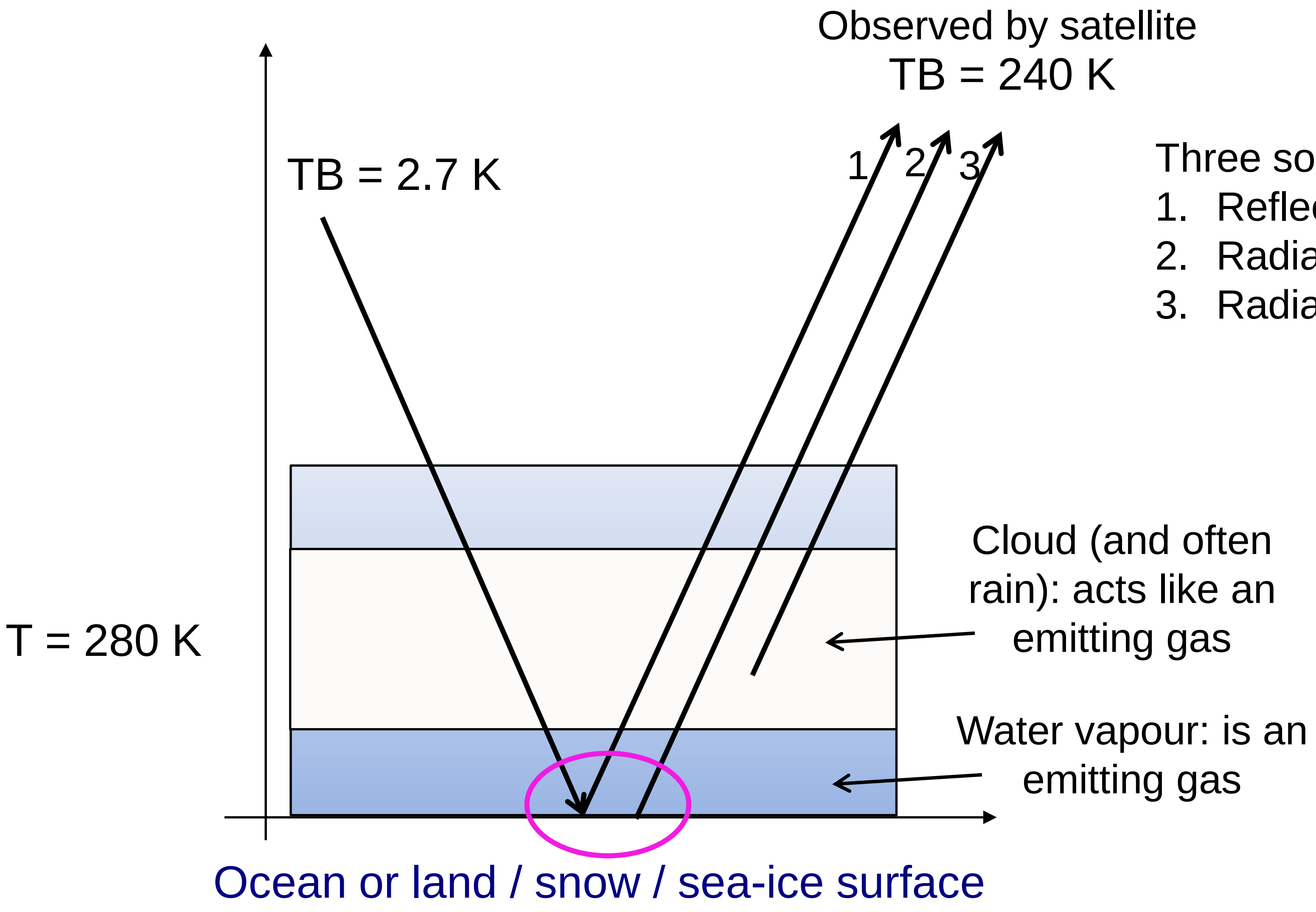
- width of the band (wider bands give lower noise)
- *flatness* of optical depth across the band (narrow weighting functions)

Information content: window (i.e. surface sensitive) channels

SSMIS F-17 channel 13 (19 GHz, v polarisation)
Observed TB, 3rd December 2014



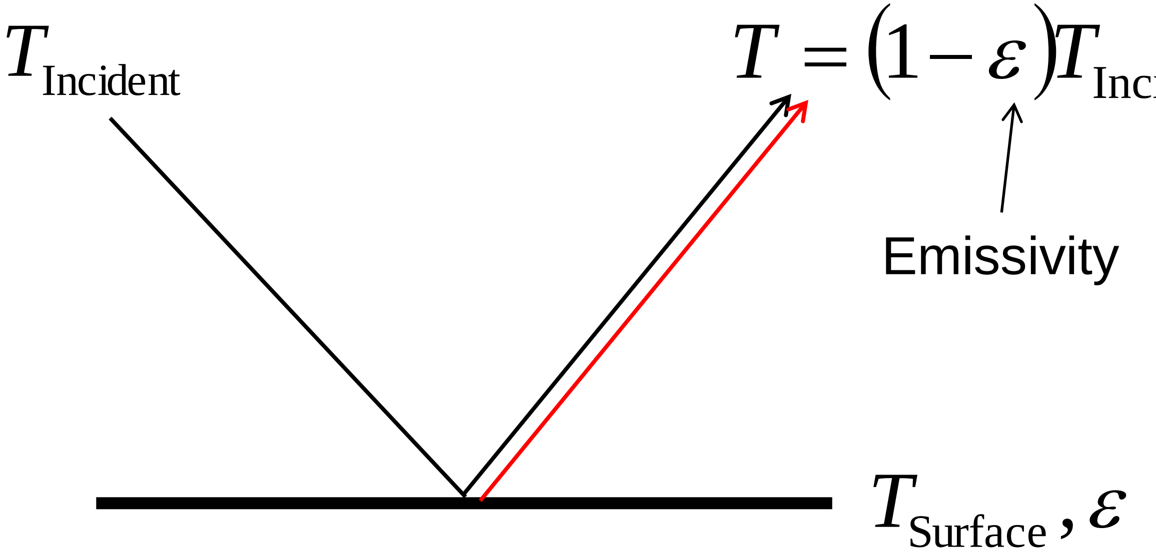
Radiative transfer: window channels (ignoring scattering)



Three sources of radiation:

1. Reflected downwelling
2. Radiation emitted by the surface
3. Radiation emitted by the atmosphere

Describing the surface interaction: specular emissivity



Direct reflection   Emission

$$T = (1-\varepsilon)T_{\text{Incident}} + \varepsilon T_{\text{Surface}}$$

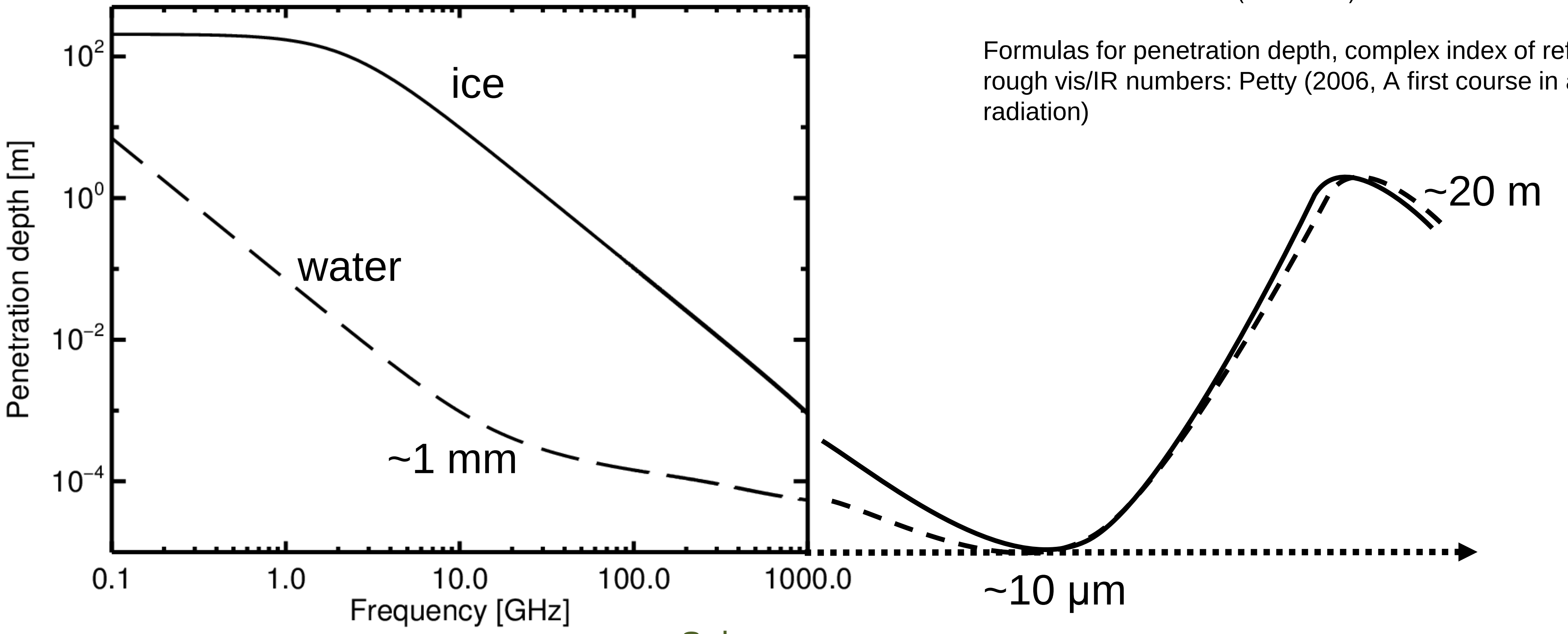
Emissivity

Water and ice: penetration depth

Relative permittivity of pure ice at 263.0 K (up to ~1000 GHz): Mätzler (2006, Microwave dielectric properties of pure ice)

Pure water at 278.0 K (Liebe '89)

Formulas for penetration depth, complex index of refraction, rough vis/IR numbers: Petty (2006, A first course in atmospheric radiation)



Radio-frequency radar: e.g. SAR

L-band e.g. SMOS

Microwave imagers, e.g. AMSR2

Humidity sounders, e.g. MHS

Sub-mm, e.g. ICI

Hyperspectral infrared., e.g. IASI

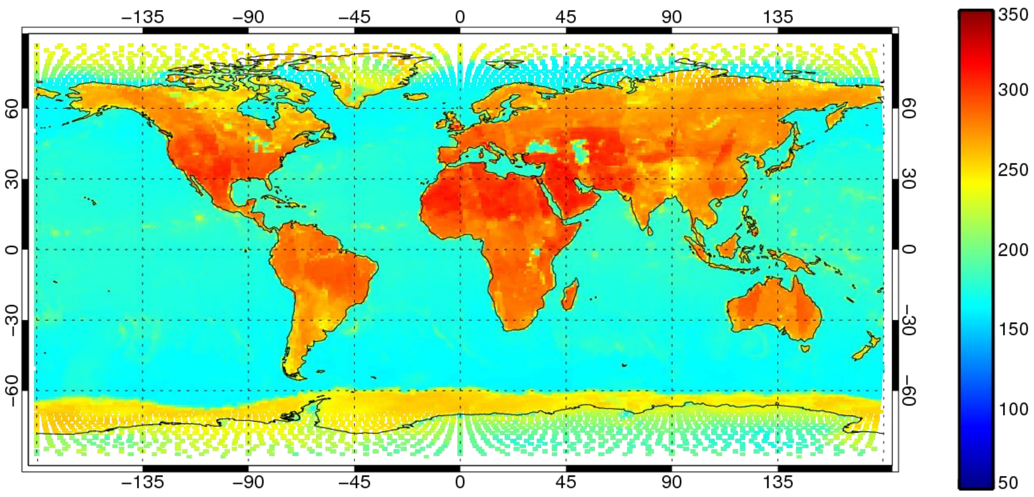
Visible

Surface reflection and emission: ocean

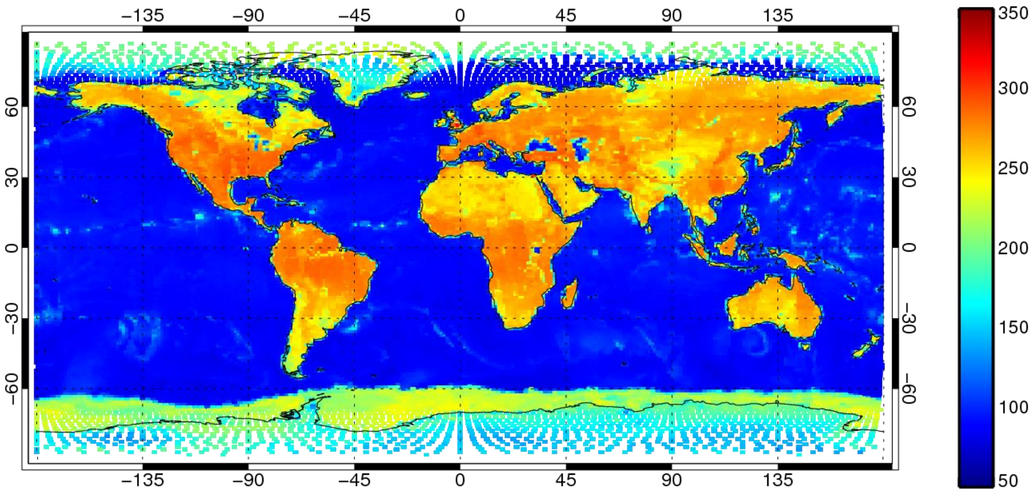
- Plane water surface: low emissivity - Fresnel equations
- Macro structure: waves, swell – geometric optics
- Micro structure, e.g. cm: diffraction from capillary waves
- Foam: much higher emissivity than water
- Correction for non-specular reflection

Approximately – a surface wind speed dependence

Ocean surface: is strongly polarised and reflective at low frequencies



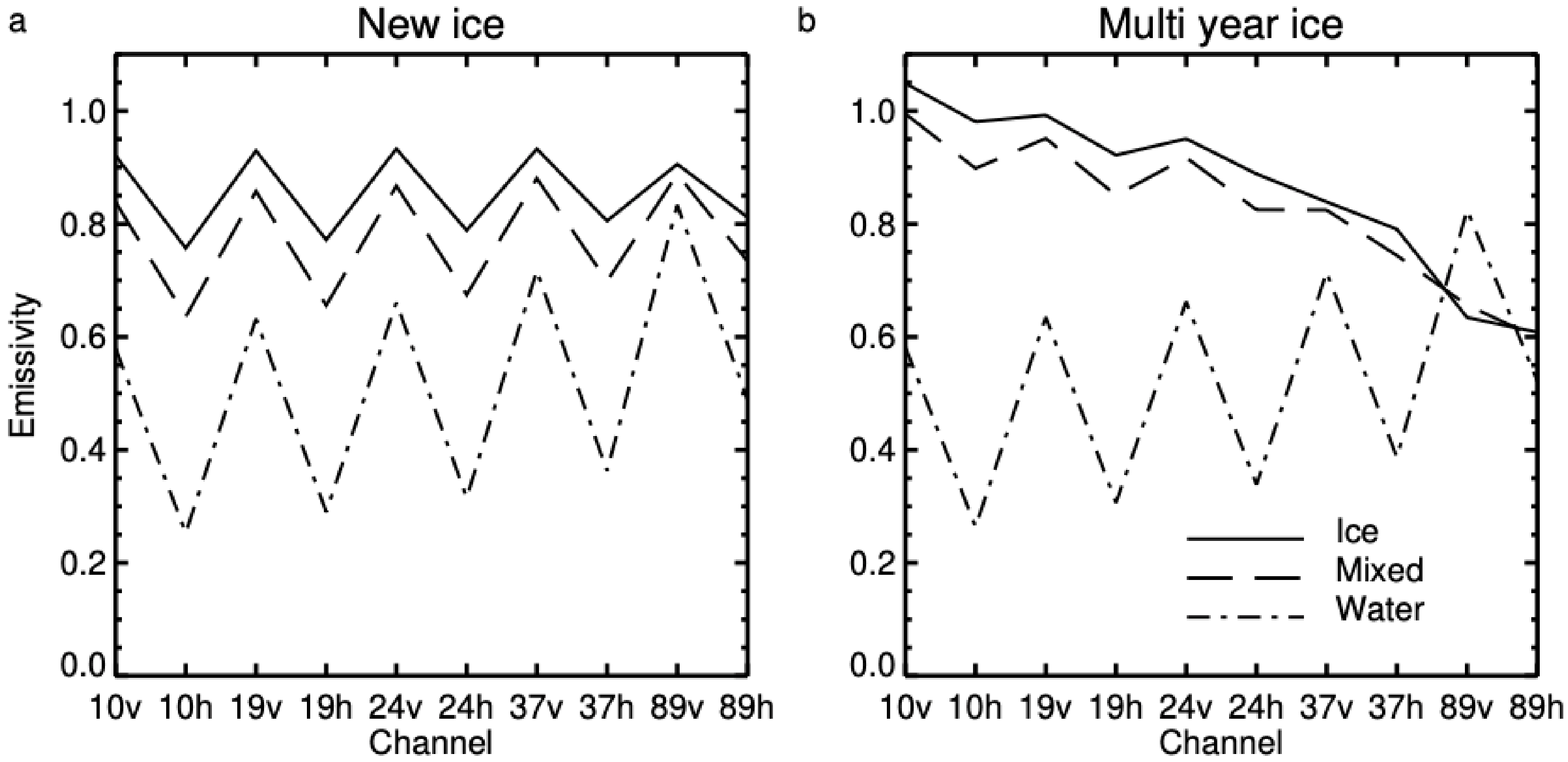
TB [K]
10 GHz v-pol



Ocean TB:
~150 K vertical (v)-polarisation
~90 K horizontal (h)-polarisation

TB [K]
10 GHz h-pol

Sea ice surface emissivity



Information content: window (i.e. surface sensitive) channels

SSMIS F-17 channel 13 (19 GHz, v polarisation)
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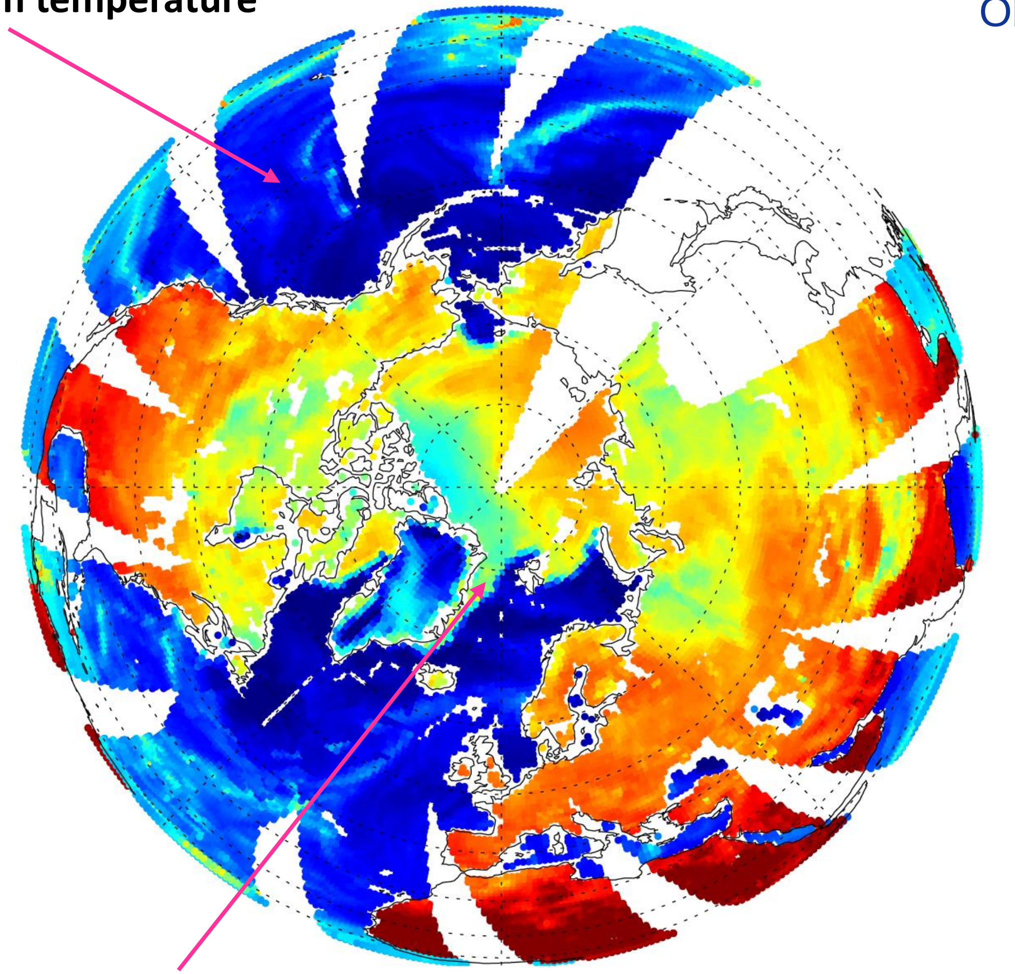
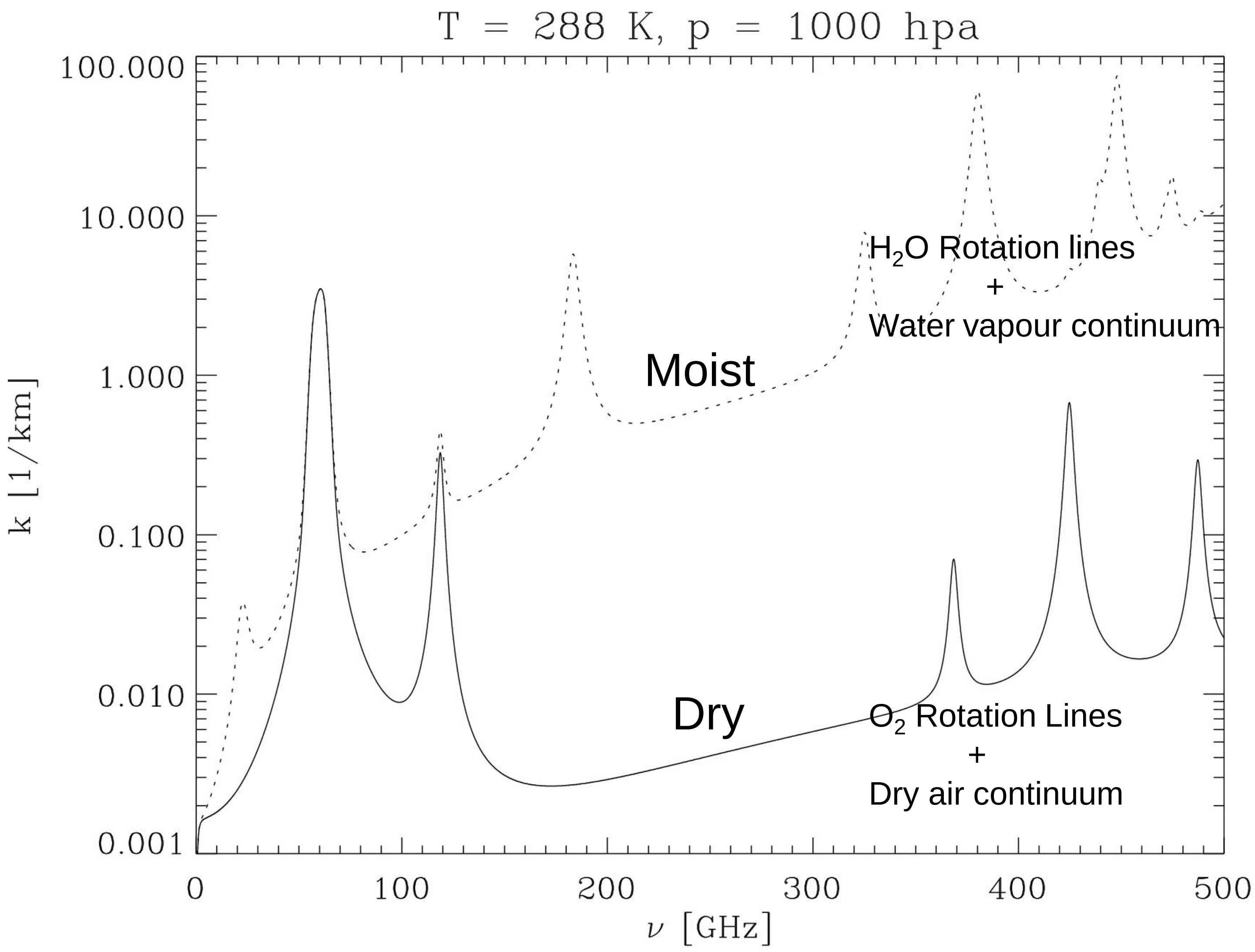


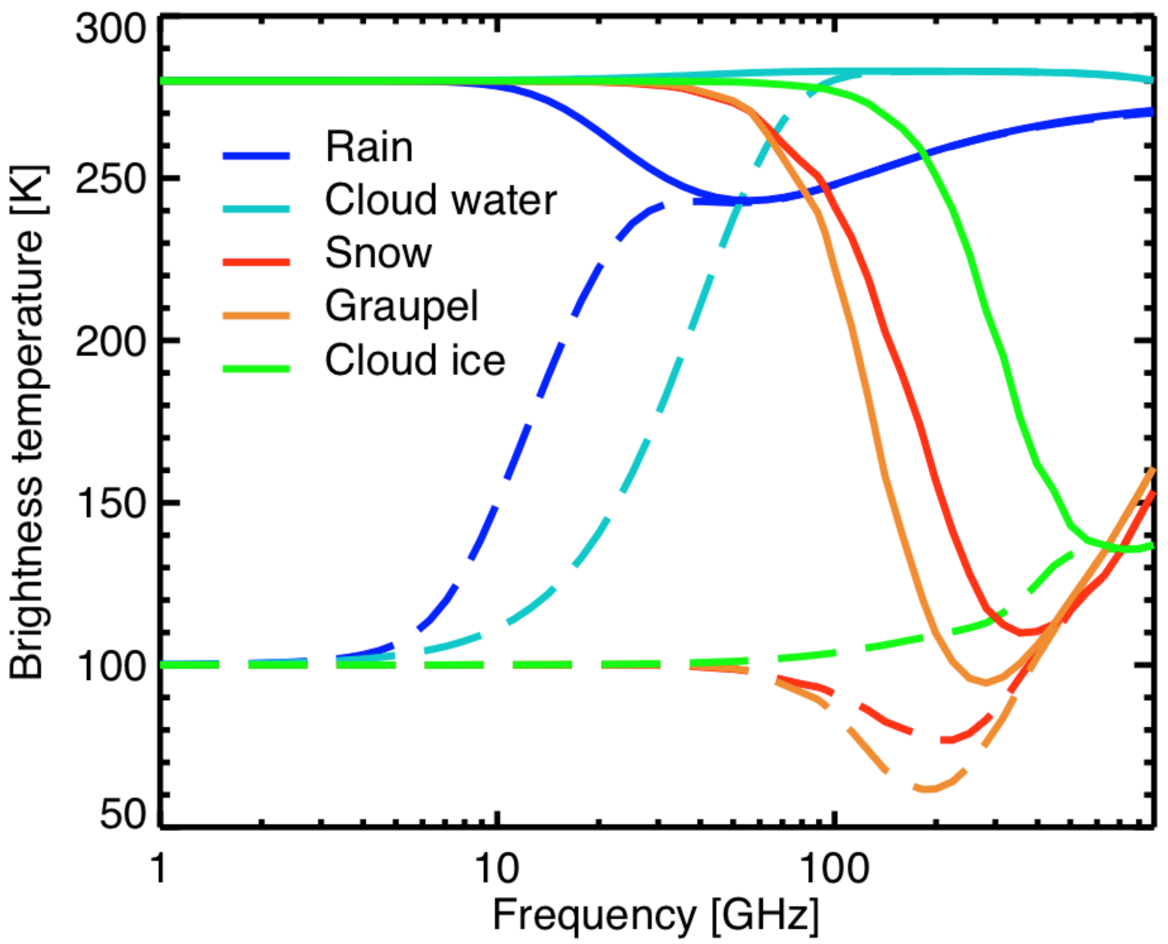
Gas absorption: the microwave spectrum

Absorption coefficient β_a [1/km]



Cloud and precipitation optical properties: the microwave spectrum

More in the next microwave lecture



Slab cloud at 283K above a 280K surface (solid)

Slab cloud at 283K above a 100K surface (dashed)

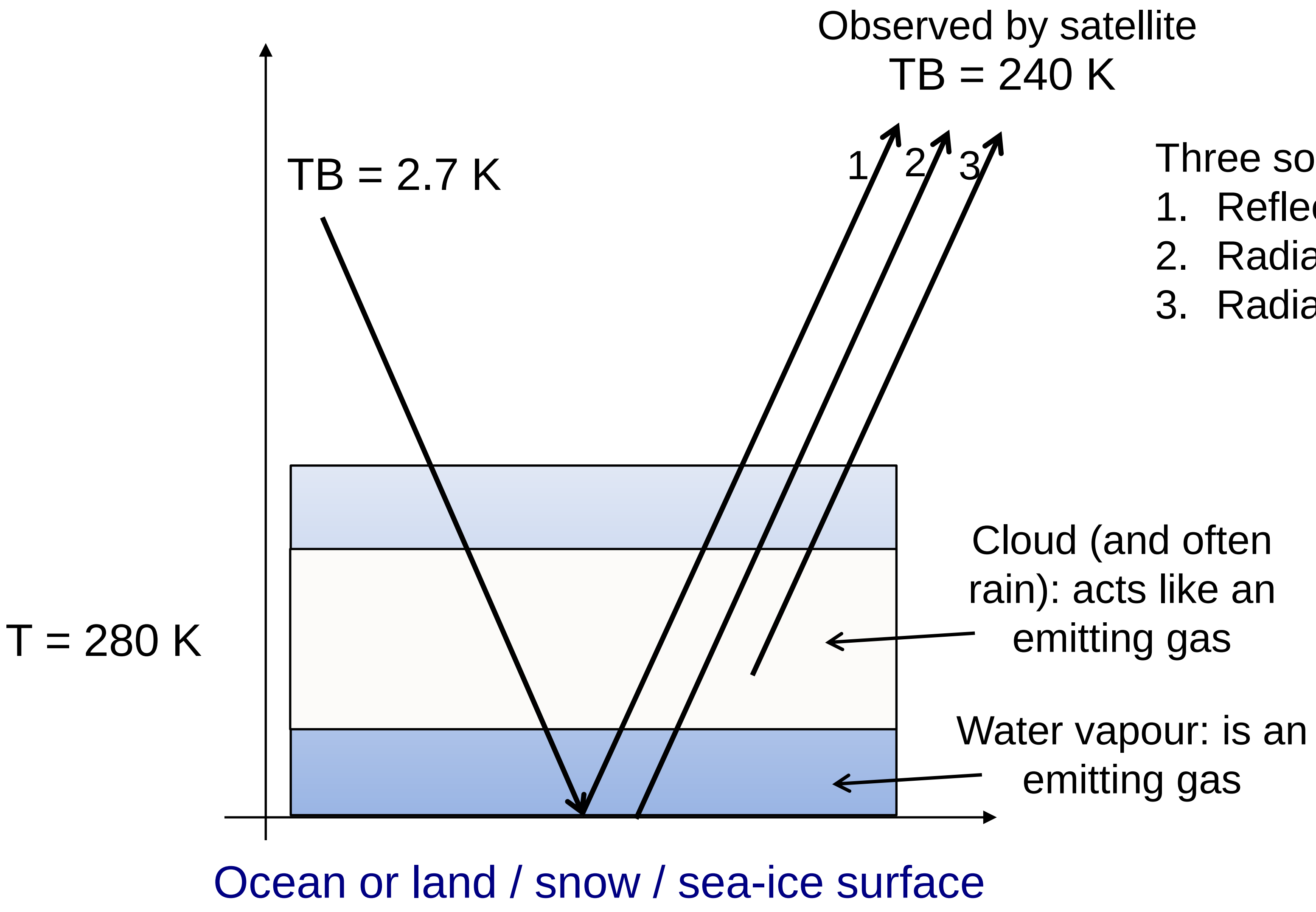
Geer et al. (2021, GMD, Bulk hydrometeor optical properties for microwave and sub-millimetre radiative transfer in RTTOV-SCATT v13.0)

Radiative transfer

(if time permits…)

ECMWF

Radiative transfer: window channels (ignoring scattering)



Three sources of radiation:

1. Reflected downwelling
2. Radiation emitted by the surface
3. Radiation emitted by the atmosphere

Rate of change of radiation travelling through an absorbing medium

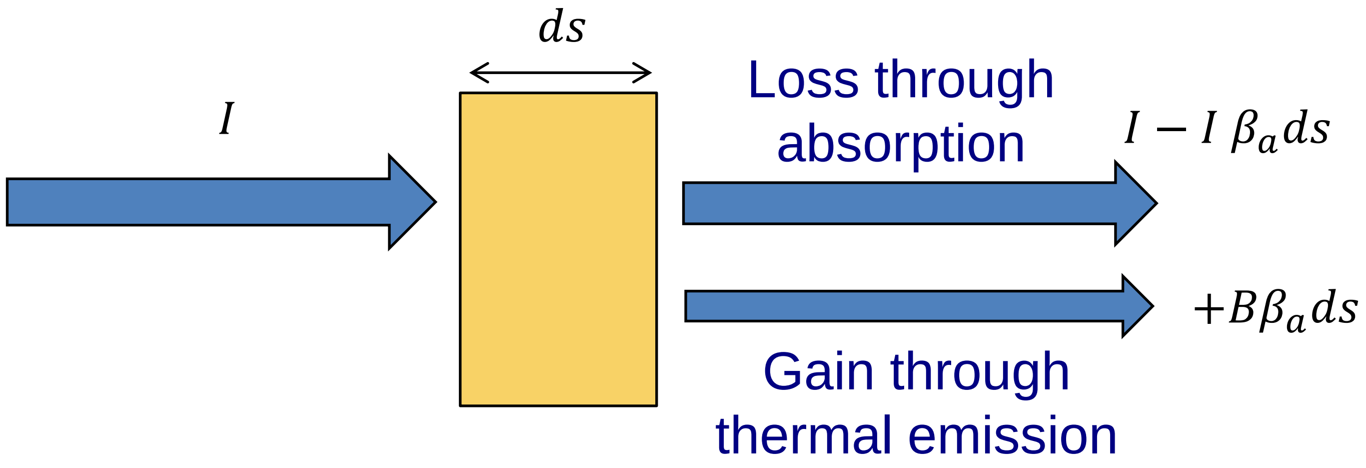
Planck function

Radiance

Change in radiance per distance

$$\frac{dI}{ds} = \beta_a(B - I)$$

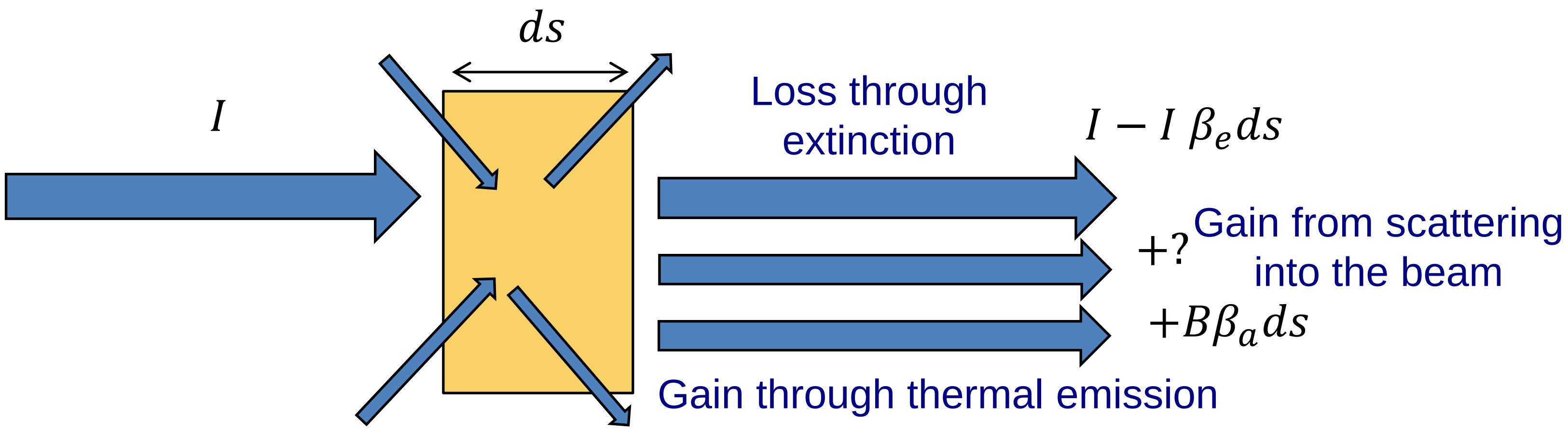
Absorption coefficient



Adding scattering

Extinction coefficient $\beta_e = \beta_a + \beta_s$

Scattering coefficient (describing the amount of scattering out of the beam)



Change in coordinates: optical depth

Change in optical depth $\mathrm{d}\tau$ in a non-scattering atmosphere

$$d\tau = -\beta_a ds$$

Change in optical depth $\mathrm{d}\tau$ including extinction by scattering

$$d\tau = -(\beta_a + \beta_s) ds = -\beta_e ds$$

The full scattering radiative transfer equation

Direction vector

Integral over all solid angle

$$\frac{dI(\hat{\Omega})}{d\tau} = I(\hat{\Omega}) - (1-\omega_s)B - \frac{\omega_s}{4\pi}\int_{4\pi} P(\hat{\Omega},\hat{\Omega}')I(\hat{\Omega}')\,d\hat{\Omega}'$$

Change in optical depth

Single scattering albedo

Scattering phase function

$$\omega_s = \frac{\beta_s}{(\beta_a+\beta_s)}$$

- Without scattering, just integrate this equation along the path travelled by the radiation (Tony's first lecture)
- With scattering, this can be complex to solve:

  $I(\hat{\Omega})$, the radiance in one direction, depends on radiance from all other directions: $I(\hat{\Omega}')$
  and all levels depend on each other

The full scattering radiative transfer equation

Radiative transfer solver

$$\frac{dI(\hat{\Omega})}{d\tau} = I(\hat{\Omega}) - (1-\omega_s)B - \frac{\omega_s}{4\pi}\int_{4\pi} P(\hat{\Omega},\hat{\Omega}')I(\hat{\Omega}')\,d\hat{\Omega}'$$

Direction vector

Integral over all solid angle

Change in optical depth

Single scattering albedo

Scattering phase function

$$\omega_s = \frac{\beta_s}{(\beta_a+\beta_s)}$$

+ Surface description (water, sea ice, snow, soil)

Optical properties (gas and hydrometeor), temperature

Gas spectroscopy

Single-particle scattering models

Atmospheric profiles (temperature, pressure, water vapour, hydrometeors)

Questions?