Passive Longwave Remote Sensing of Thermodynamics and Clouds

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NOAA / National Severe Storms Laboratory

ARM Summer Workshop
University of Oklahoma
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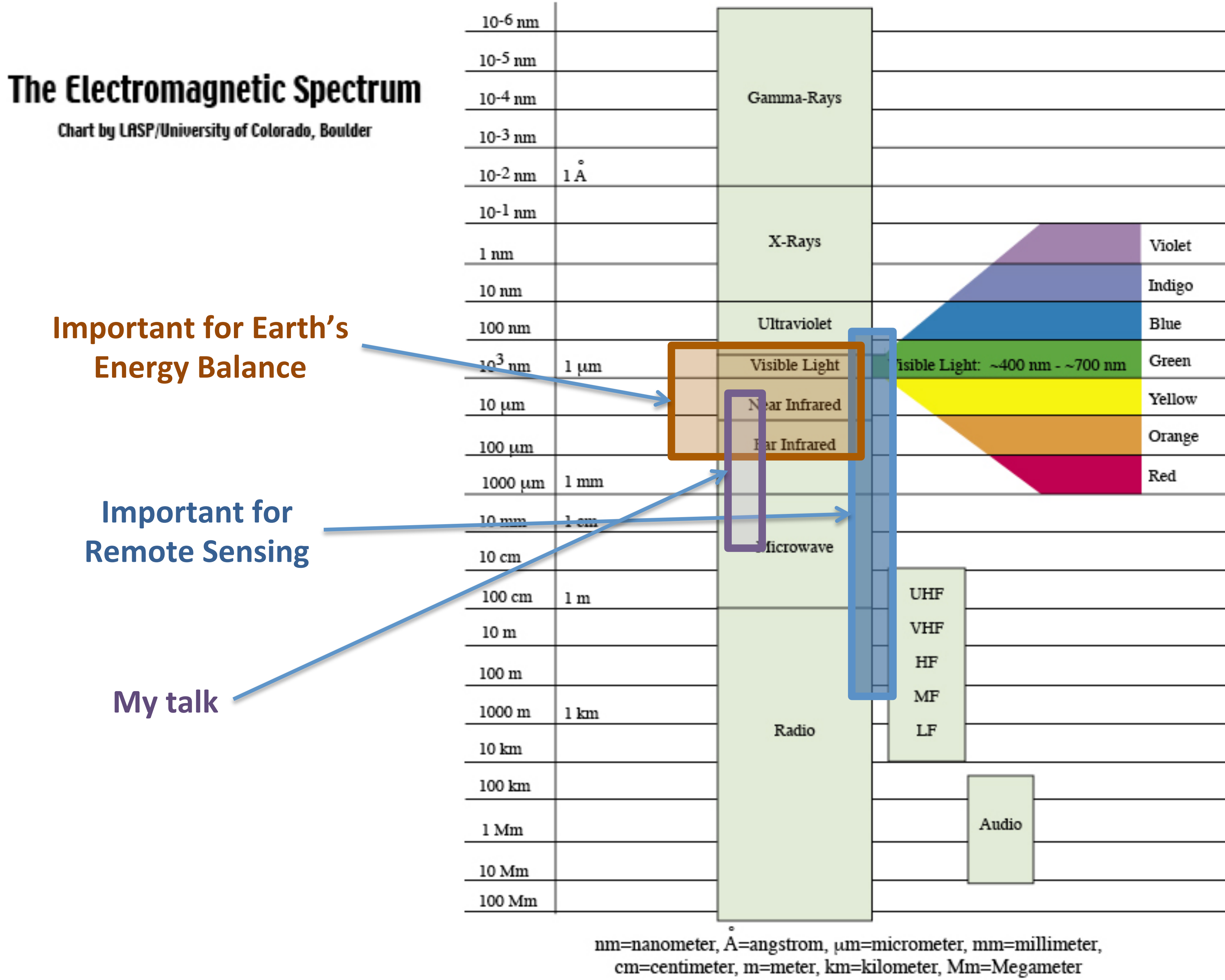
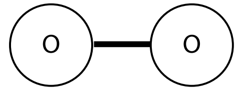
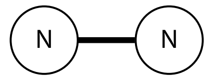
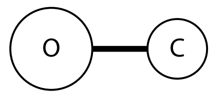
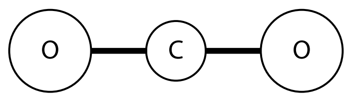
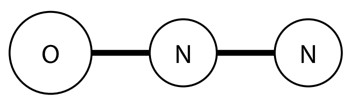
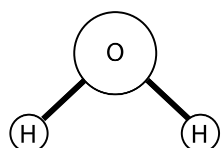
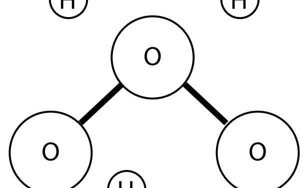
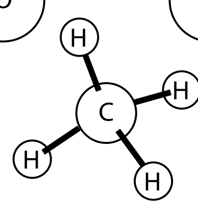
My Goal

I don't want passive remote sensing be this!

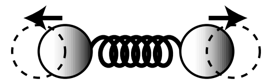


The Electromagnetic Spectrum
Chart by LASP/University of Colorado, Boulder
Important for Earth's Energy Balance
Important for Remote Sensing
My talk
10-6 nm
10-5 nm
10-4 nm
10-3 nm
10-2 nm
1 Å
10-1 nm
1 nm
10 nm
100 nm
103 nm
1 µm
10 µm
100 µm
1000 µm
1 mm
10 cm
100 cm
1 m
10 m
100 m
1000 m
1 km
10 km
100 km
1 Mm
10 Mm
100 Mm
Gamma-Rays
X-Rays
Ultraviolet
Visible Light
Radio
UHF
VHF
HF
MF
LF
Audio
Violet
Indigo
Blue
Green
Yellow
Orange
Red
~400 nm - ~700 nm
nm=nanometer, Å=angstrom, µm=micrometer, mm=millimeter,
cm=centimeter, m=meter, km=kilometer, Mm=Megameter

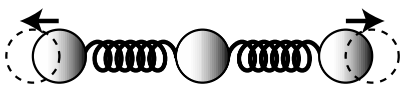
Molecule	Structure		Permanent Electric Dipole Moment?
Oxygen		linear	No (magnetic dipole)
Nitrogen		linear	No
Carbon Monoxide		linear	Yes
Carbon Dioxide		linear	No
Nitrous Oxide		linear	Yes
Water		asymmetric top	Yes
Ozone		asymmetric top	Yes
Methane		spherical top	Yes

Vibration Modes

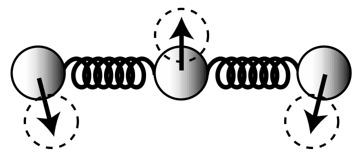
Diatomic (N_2, O_2, CO)



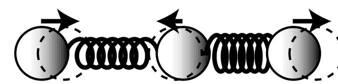
Linear triatomic (CO_2, N_2O)



Symmetric stretch
ν_1

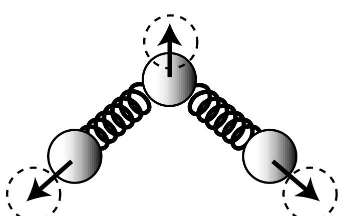


Bending
ν_2

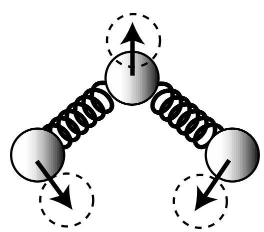


Asymmetric stretch
ν_3

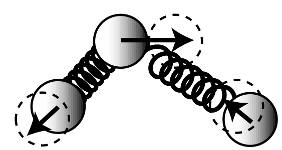
Nonlinear Triatomic (H_2O, O_3)



Symmetric stretch
ν_1



Bending
ν_2



Asymmetric stretch
ν_3

Quantum Physics!

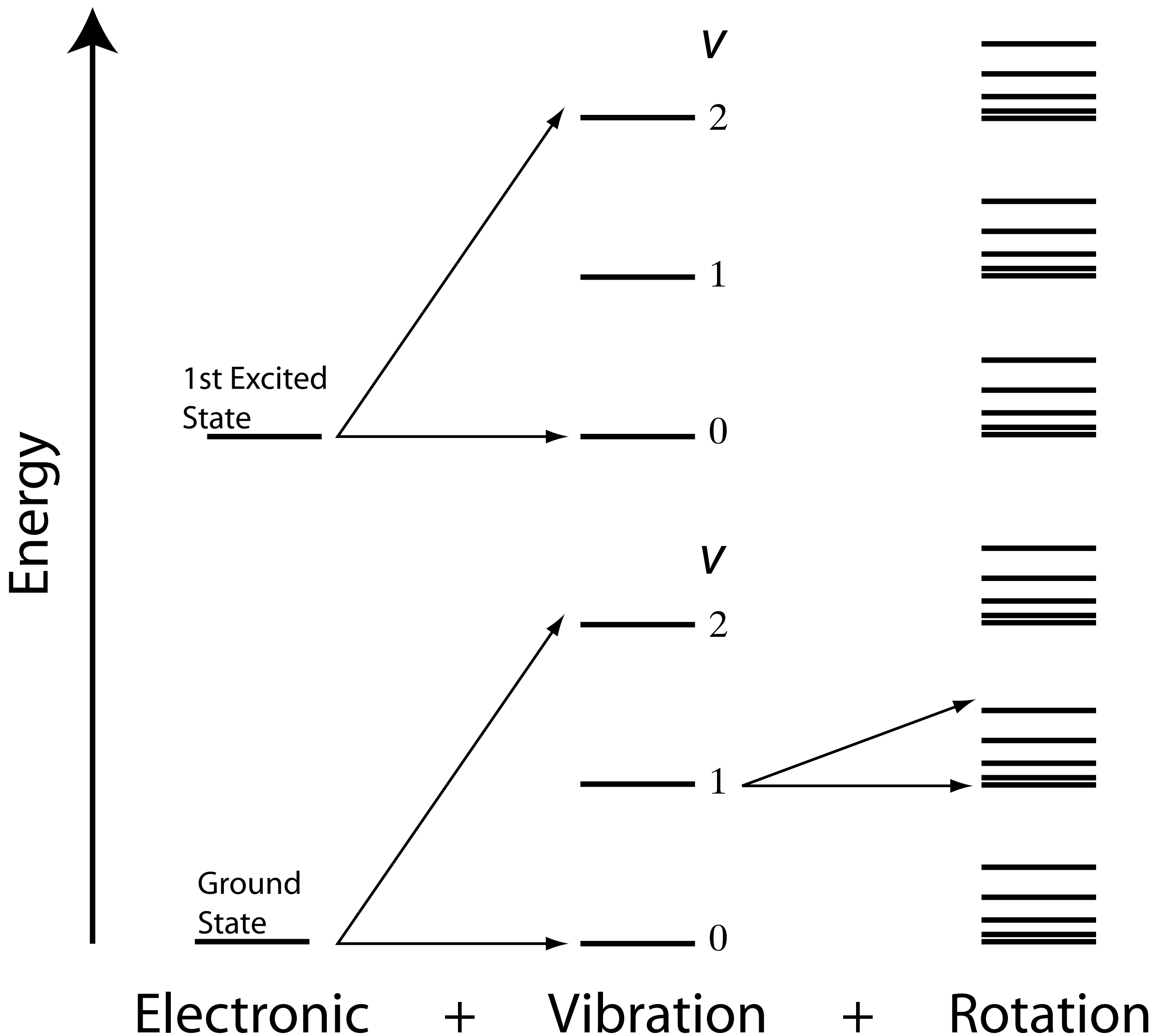
(Woo hoo!)

$$E = h\nu$$

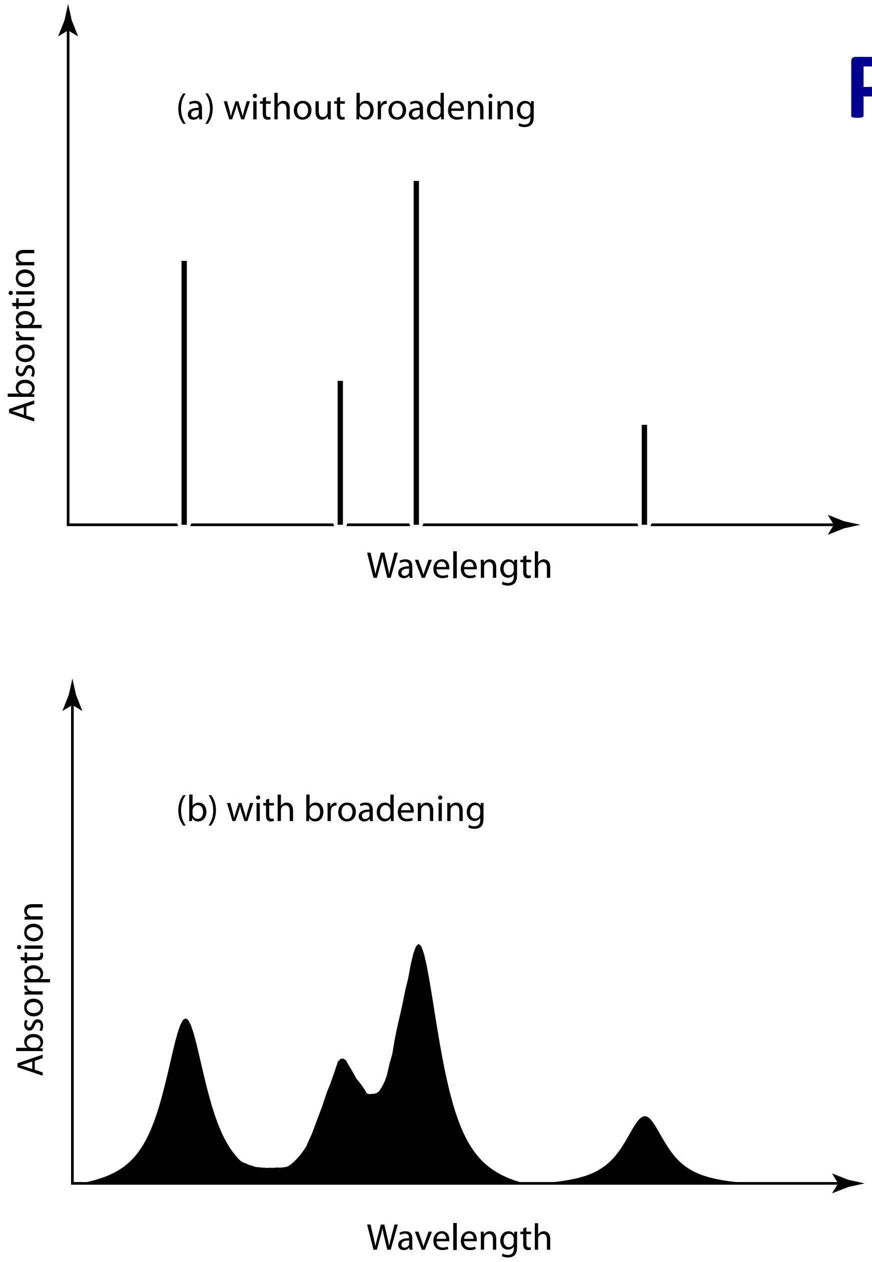
Energy

Frequency

Planck's constant

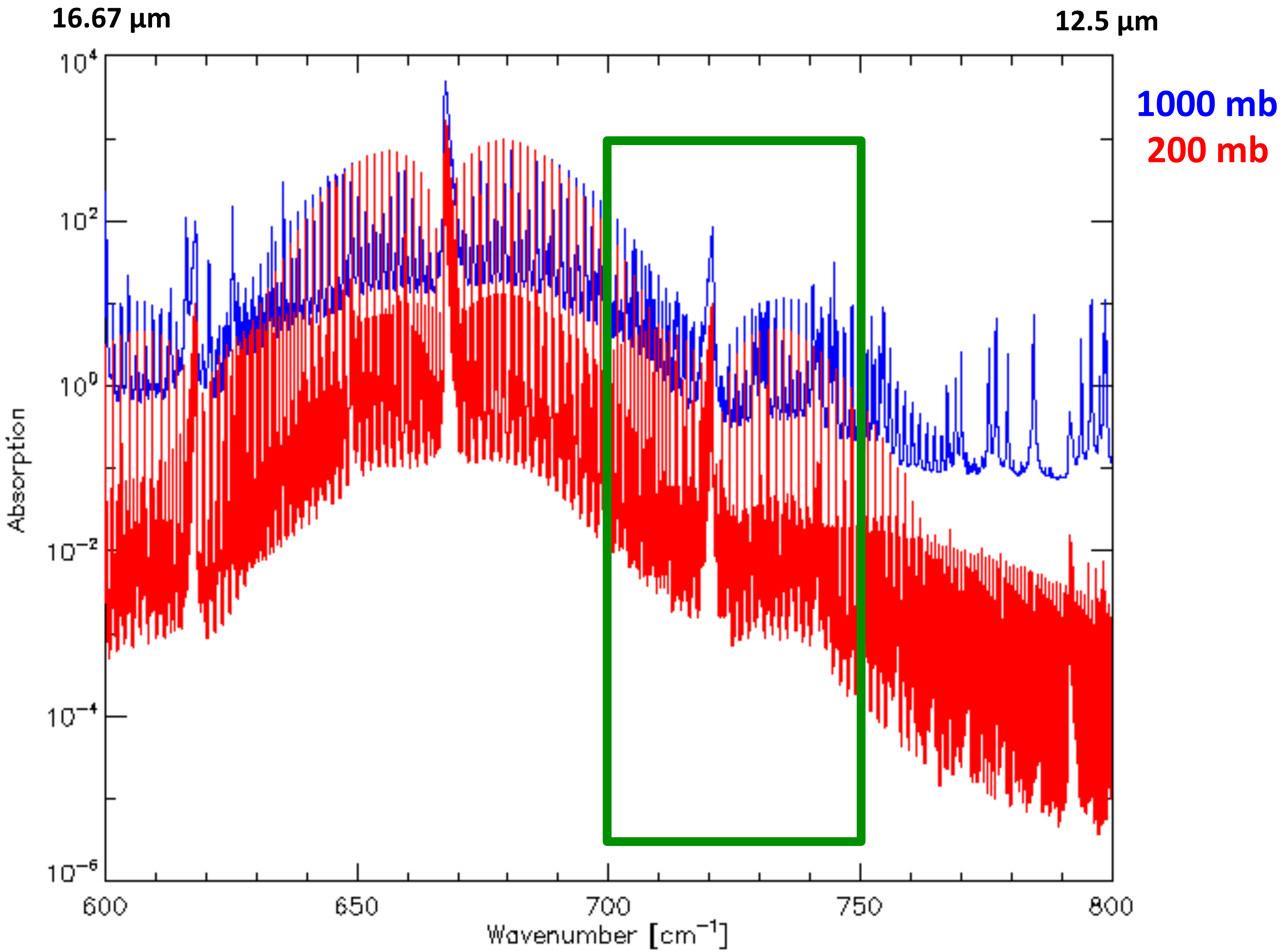


Pressure Broadening

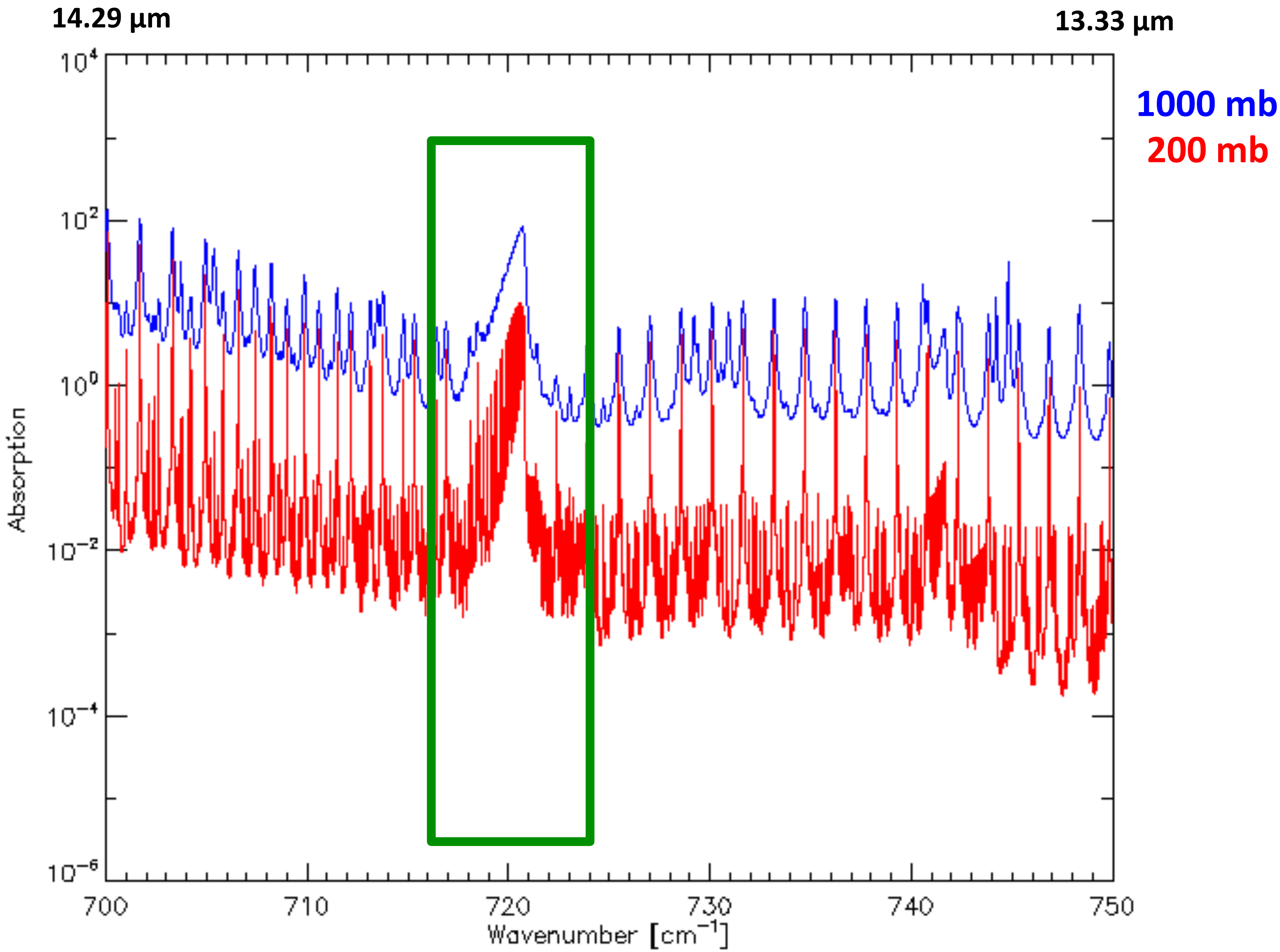


There are other sources of absorption line broadening (e.g., Doppler broadening) but they are much less important in the troposphere

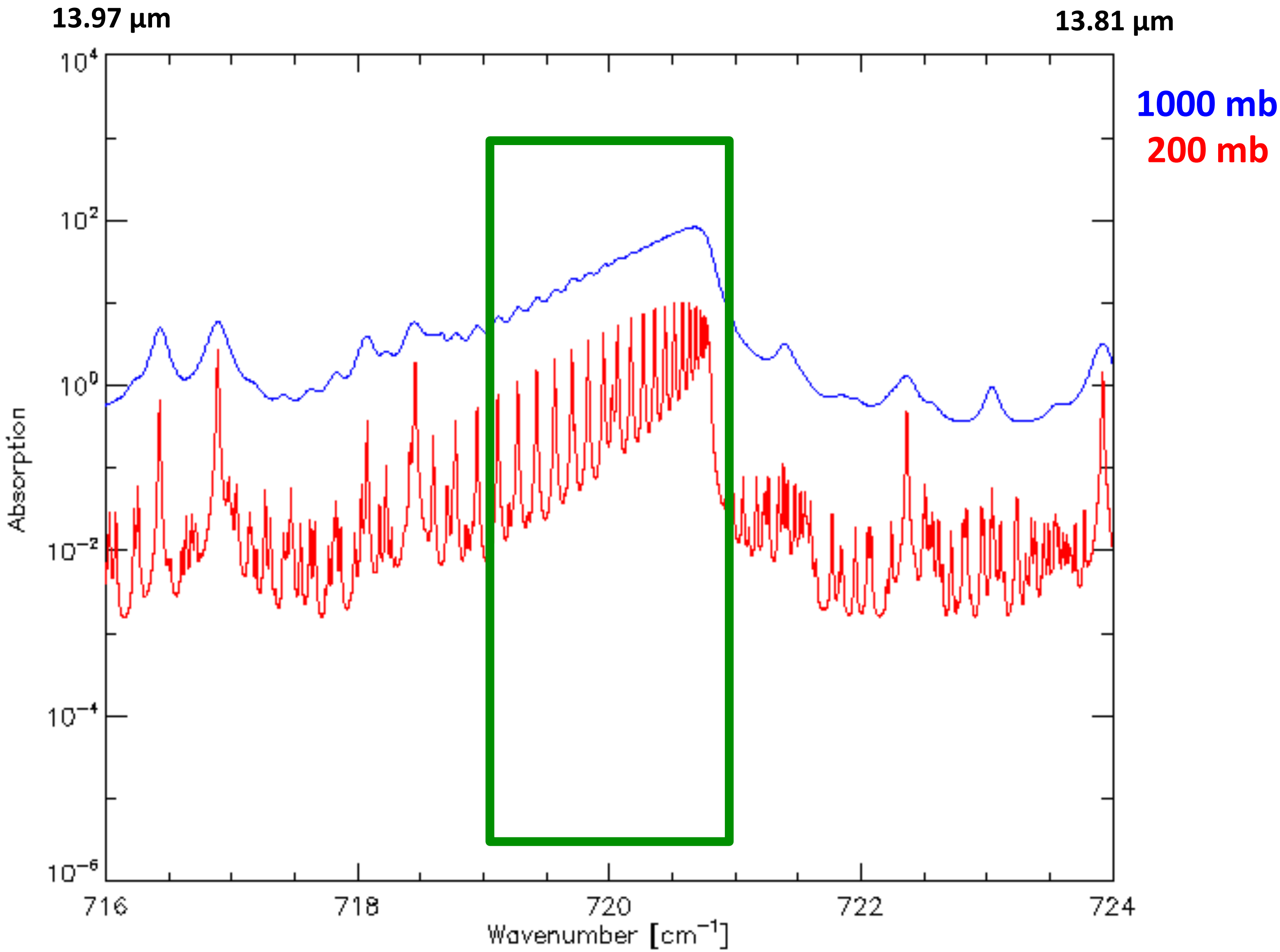
Carbon Dioxide Absorption



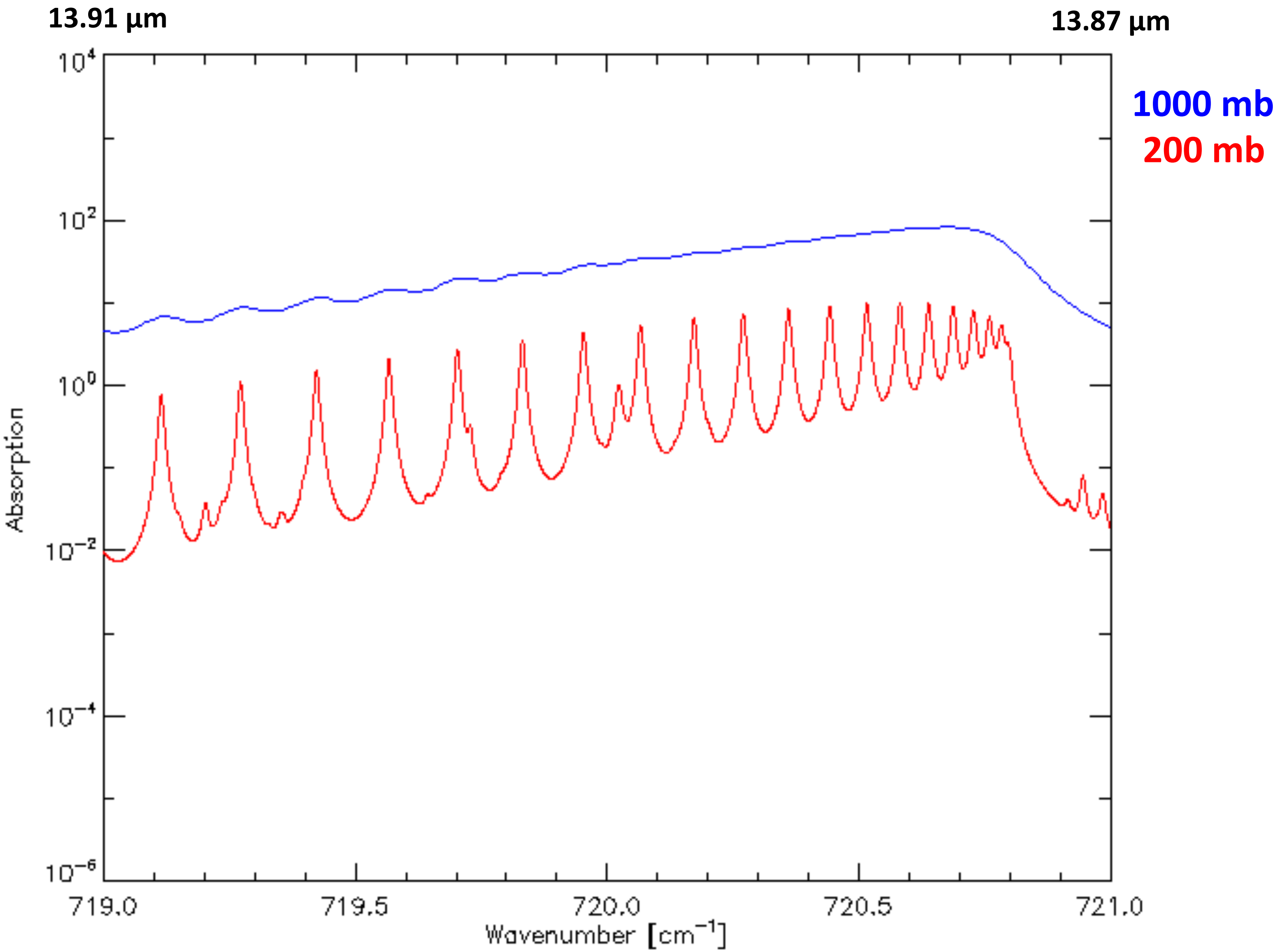
Carbon Dioxide Absorption



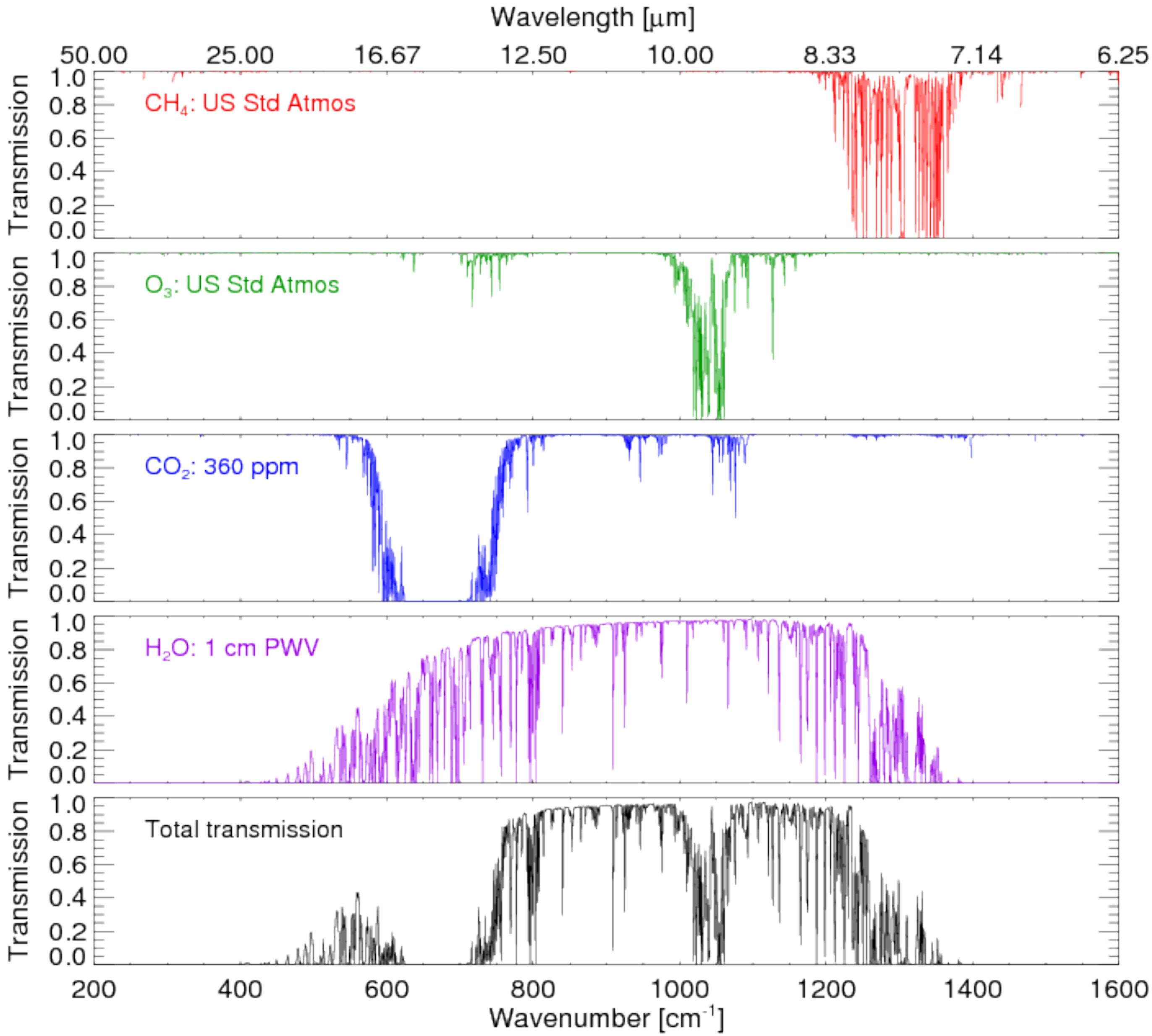
Carbon Dioxide Absorption



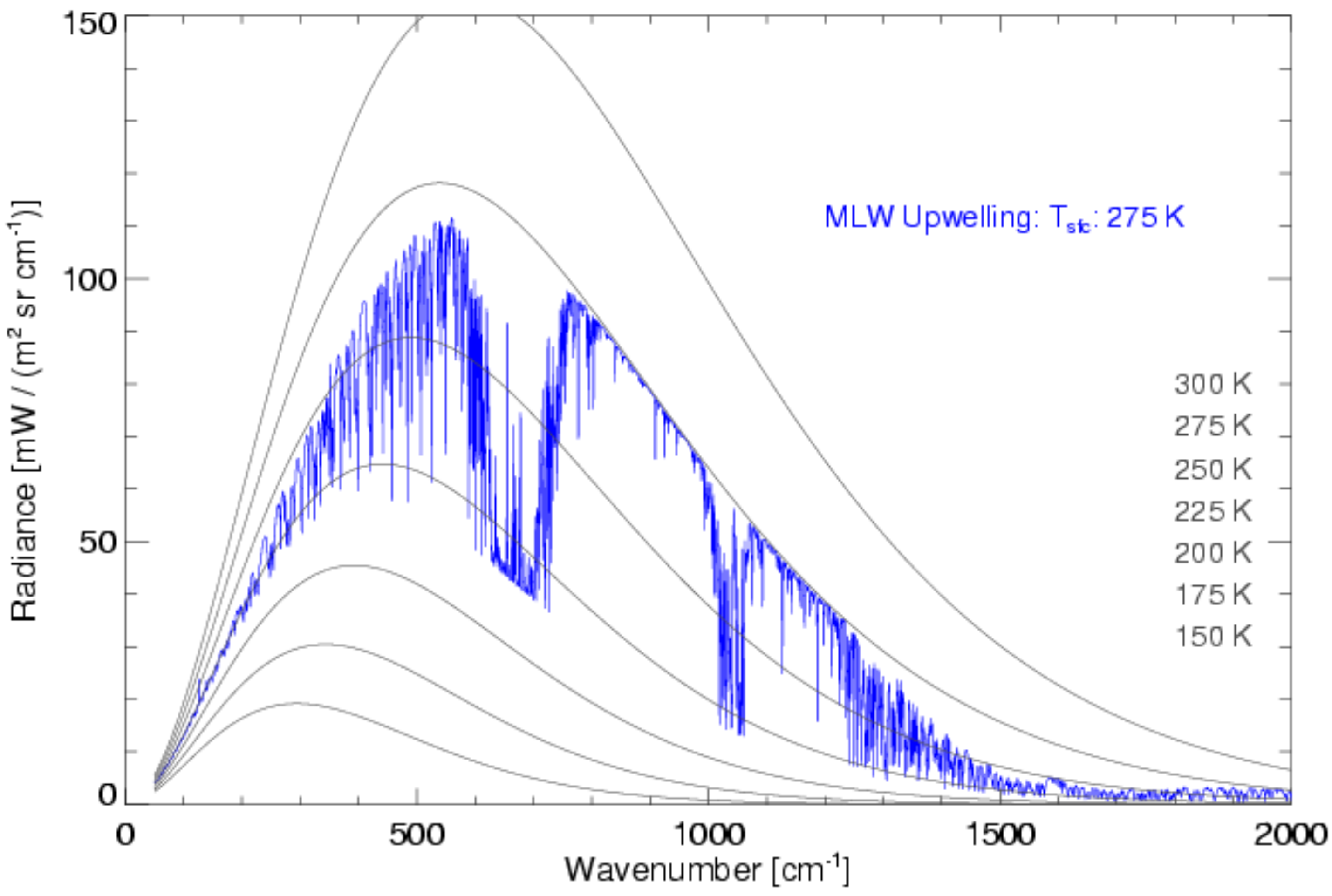
Carbon Dioxide Absorption



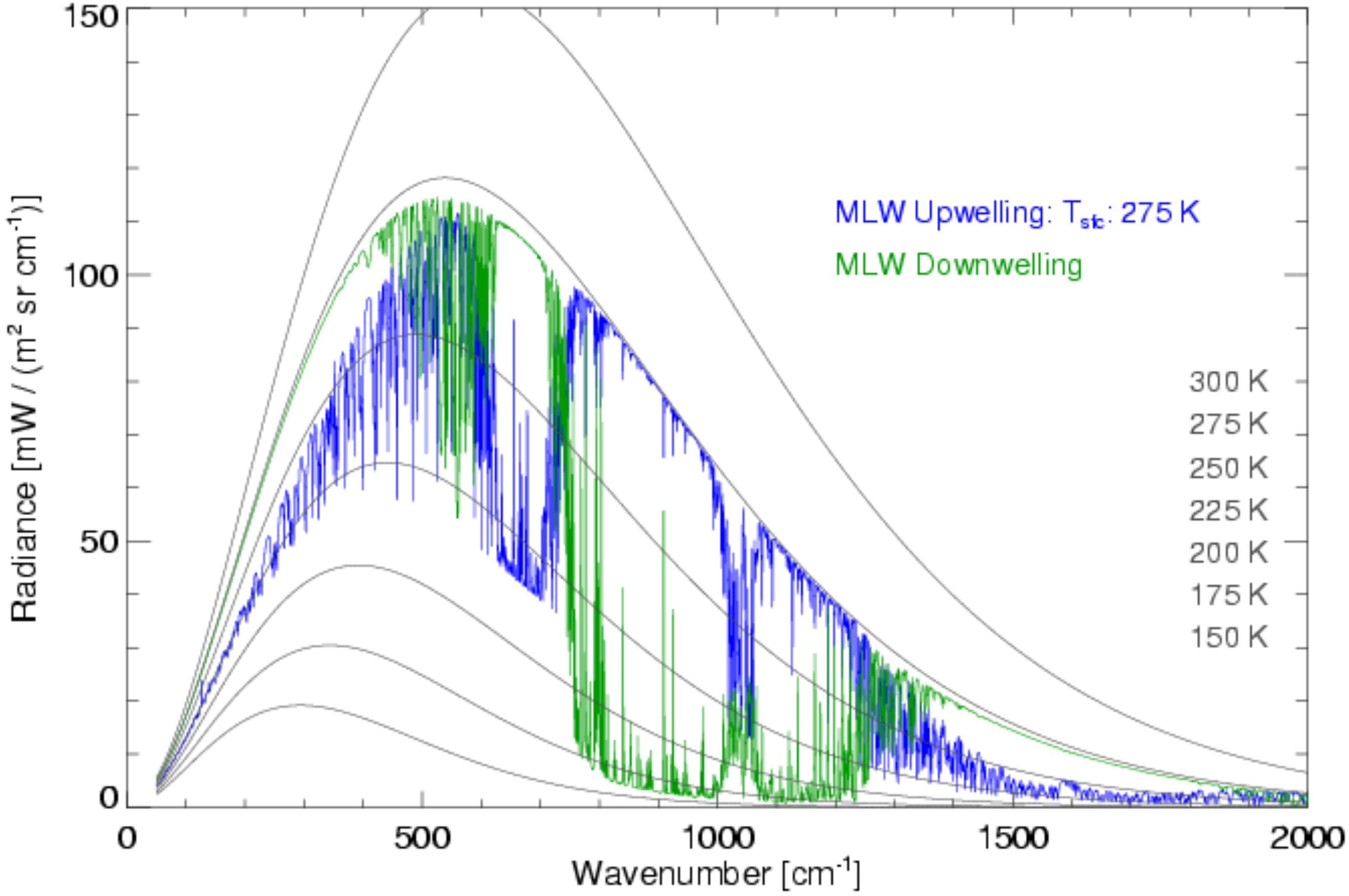
Primary Gas Absorption Bands in IR



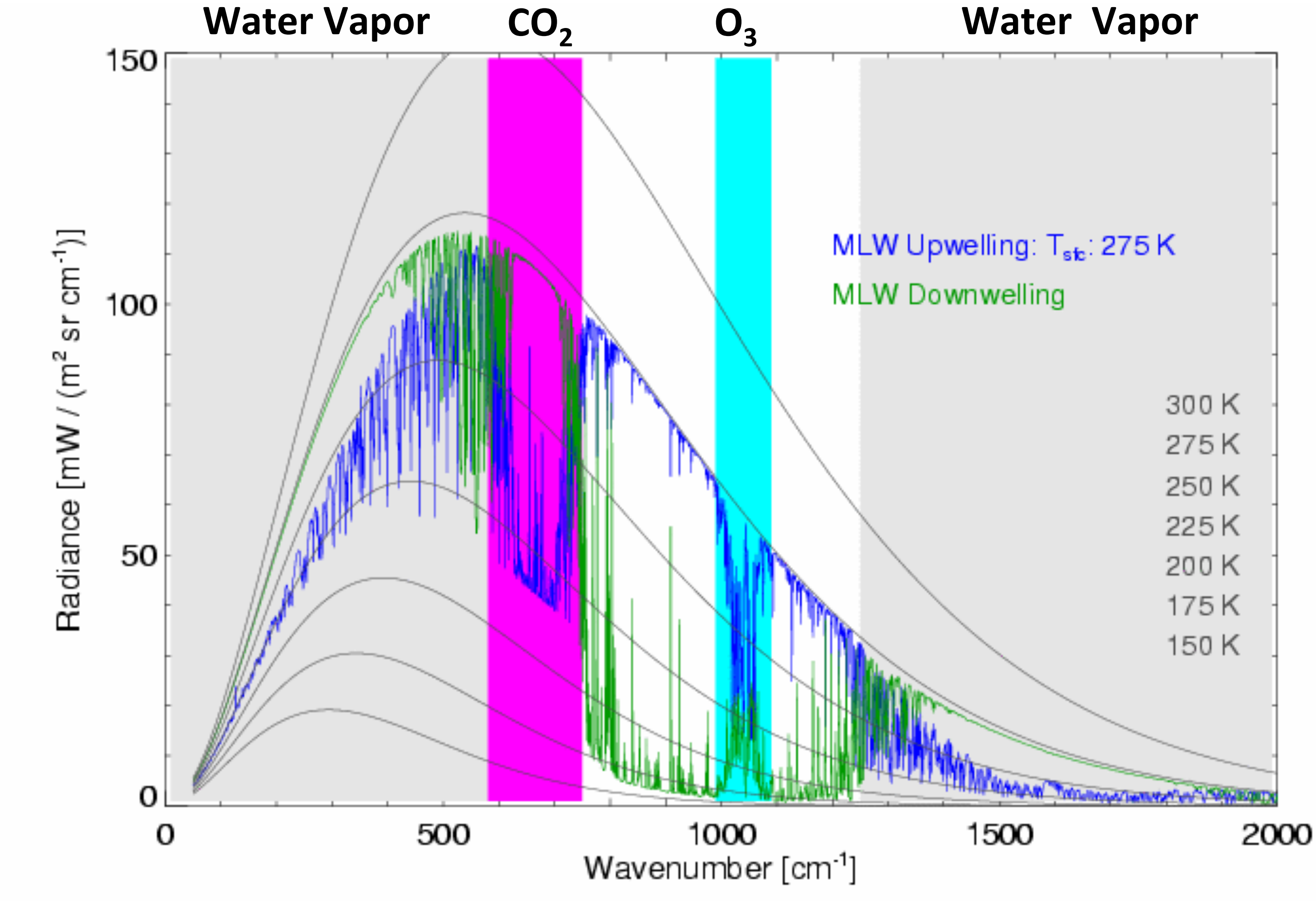
Upwelling LW Radiance at Top of the Atmosphere



Upwelling LW Radiance at Top of the Atmosphere
Downwelling LW Radiance at the Surface



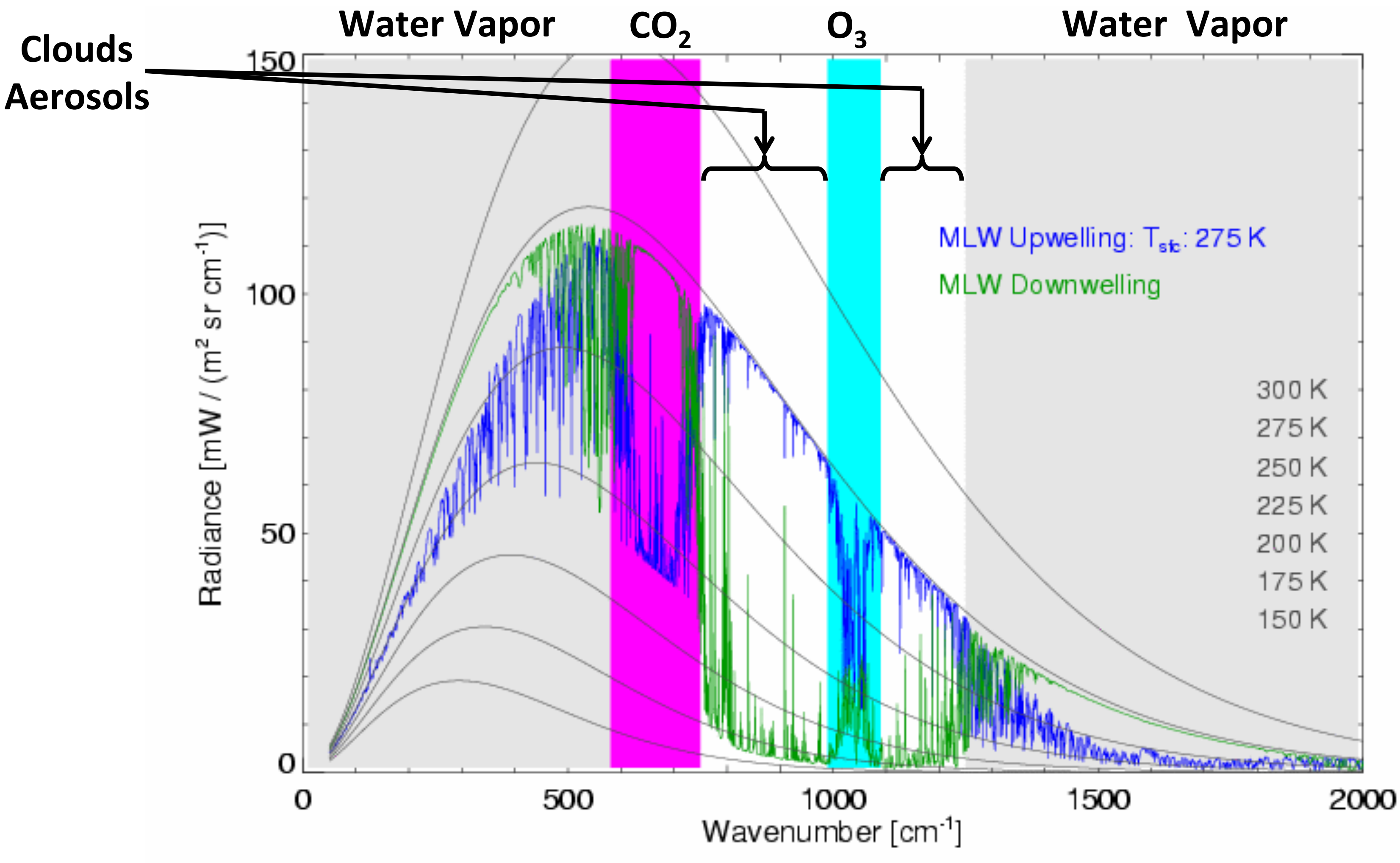
Upwelling LW Radiance at Top of the Atmosphere
Downwelling LW Radiance at the Surface



Trace gases (CFC, CH_4, etc) absorb in various regions

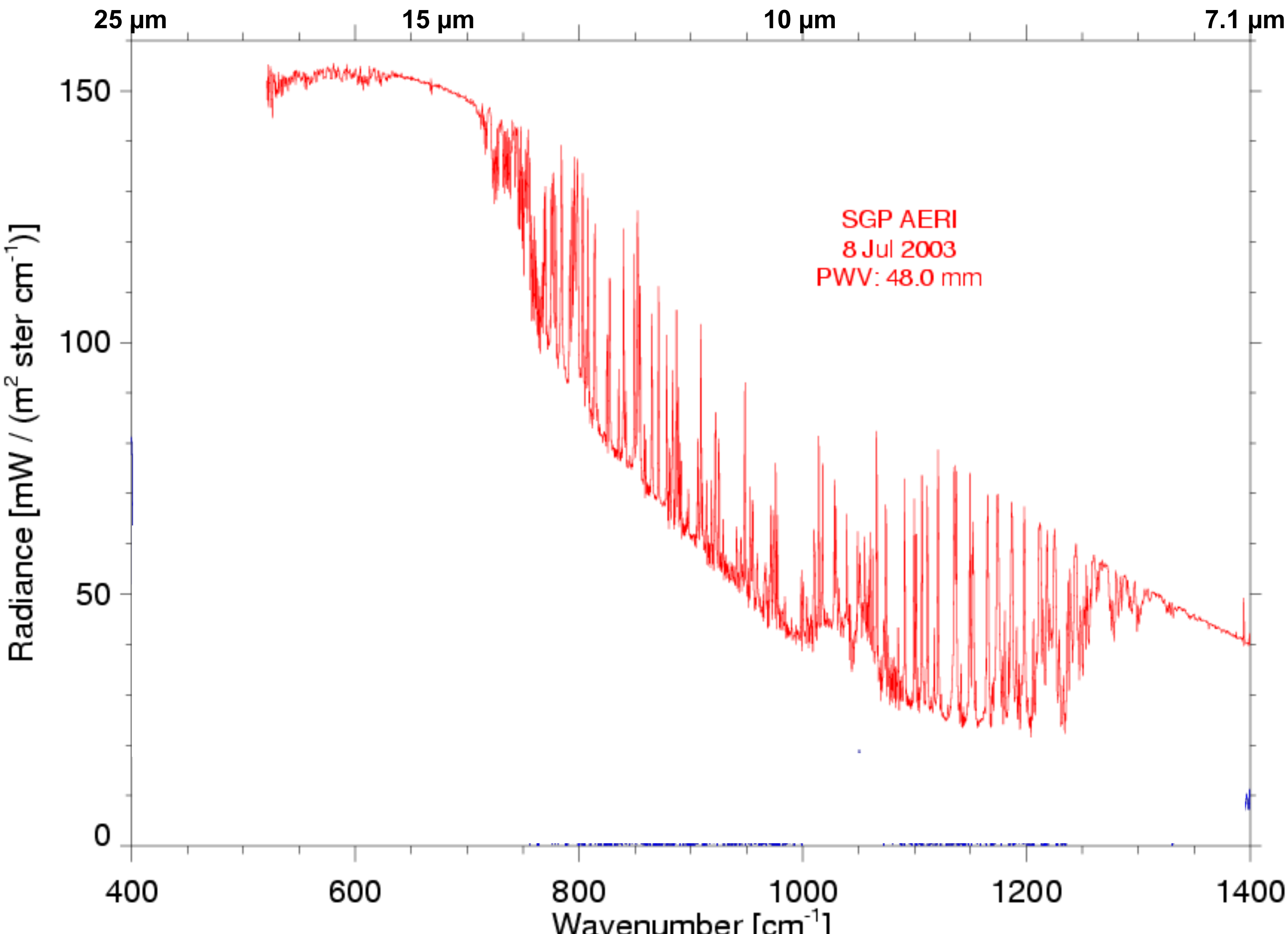
Upwelling LW Radiance at Top of the Atmosphere

Downwelling LW Radiance at the Surface

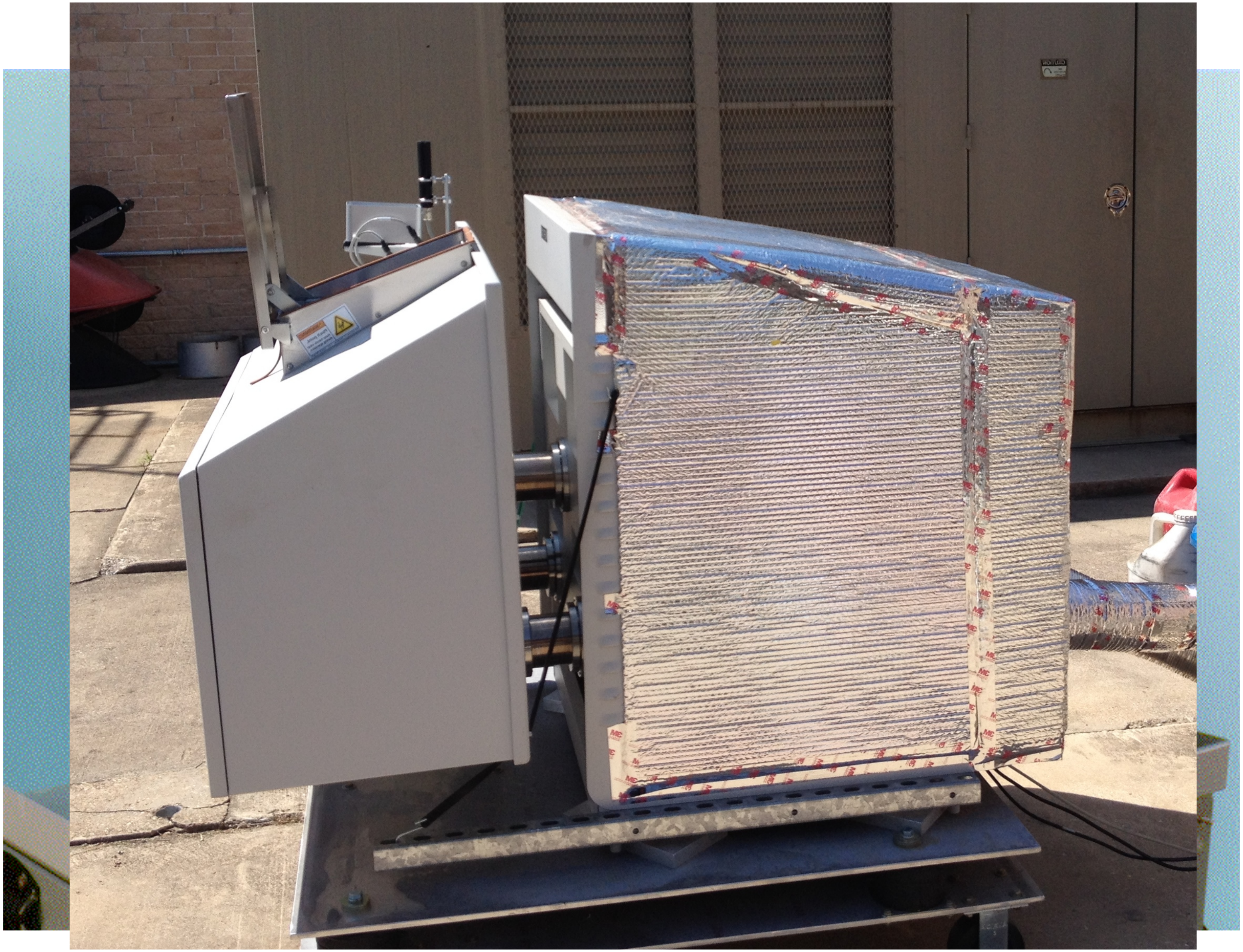


Trace gases (CFC, CH_4, etc) absorb in various regions

Clear Sky Downwelling IR Spectra



Atmospheric Emitted Radiance Interferometer (AERI)



AERI

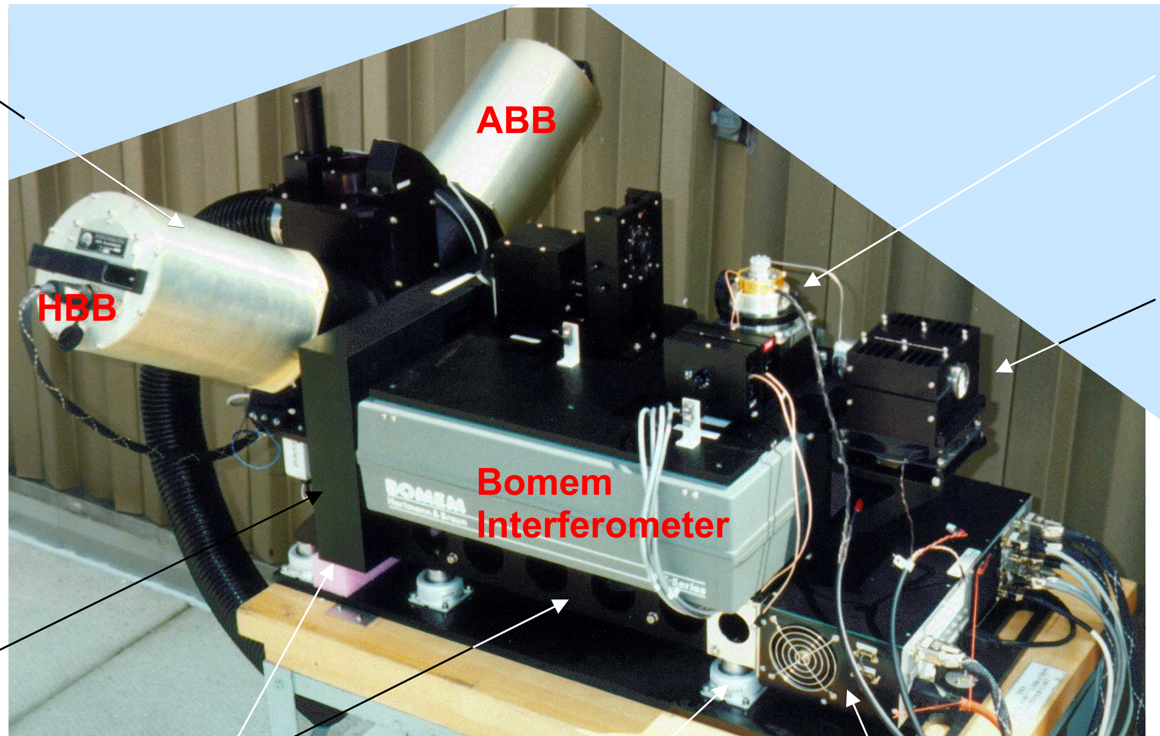
- Measures downwelling infrared radiance at high spectral resolution
- Absolute accuracy is better than 1% of the ambient radiance (3-σ)
  - High emissivity blackbodies (0.9995)
  - BB temperature accuracy NIST-traceable and accurate to 30 mK
- Data used in wide range of research
  - RT model validation/improvement
  - Thermodynamic profiling
  - Cloud property retrievals
  - Aerosol optical depth / composition
  - Trace gas retrievals

AERI Interferometer Assembly

Front End Assembly

Blackbodies
Scene Mirror Assembly
Forced Air Inlet
Rain Sensor
Sun Sensor

IR Detector Dewar with Cooler Cold Finger



Stirling Cooler Compressor

Front-end Closeout (thermal)

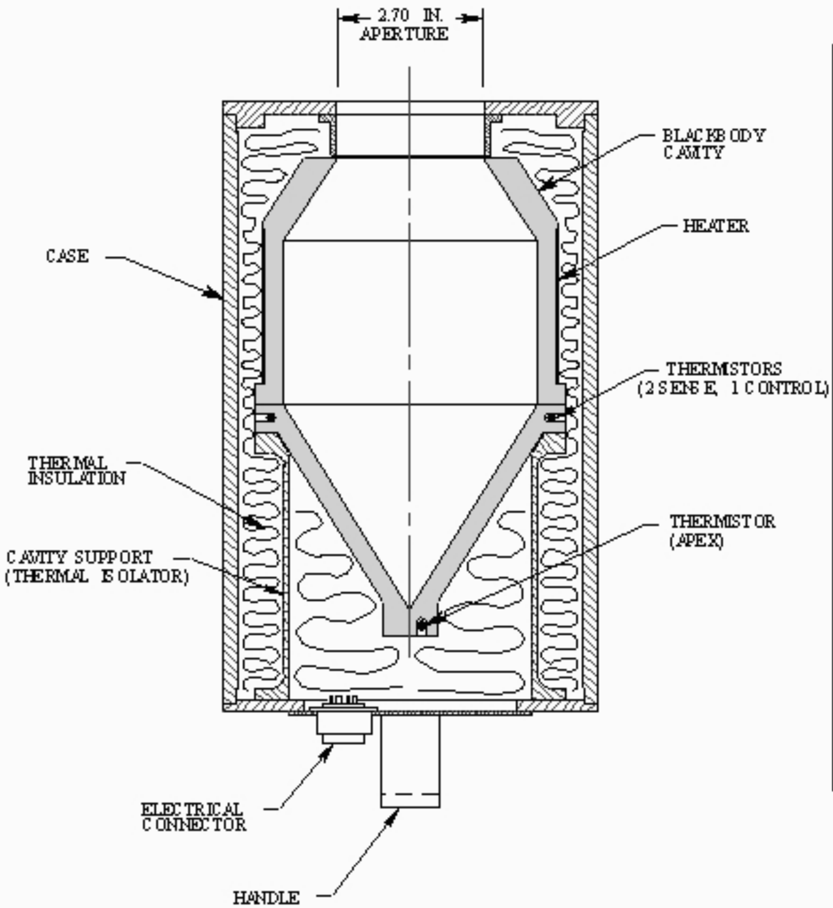
Optics Bench

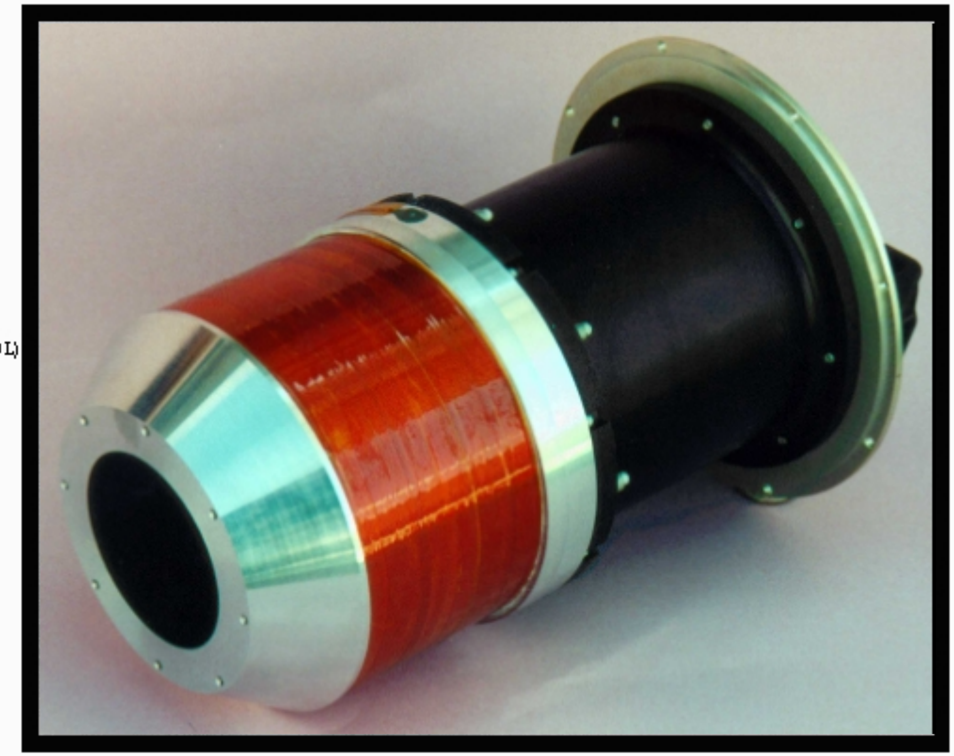
Shock Mounts (4)

Interferometer / AERI Electronics Interface Box

Knuteson et al., JTECH, 2004

Calibration Targets (Blackbodies) are Key to Accurate Radiances

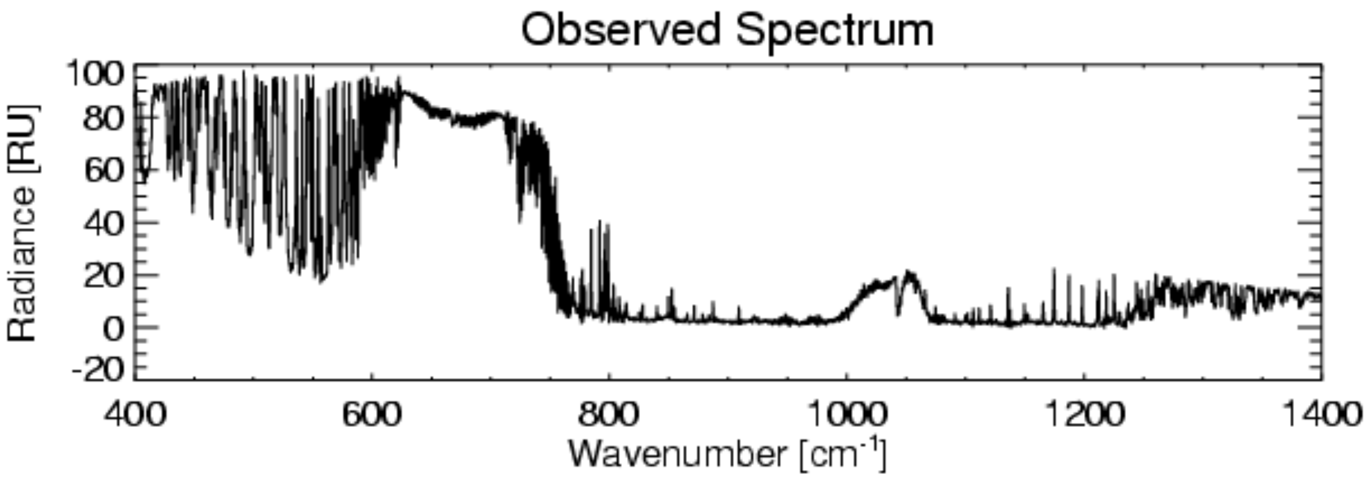




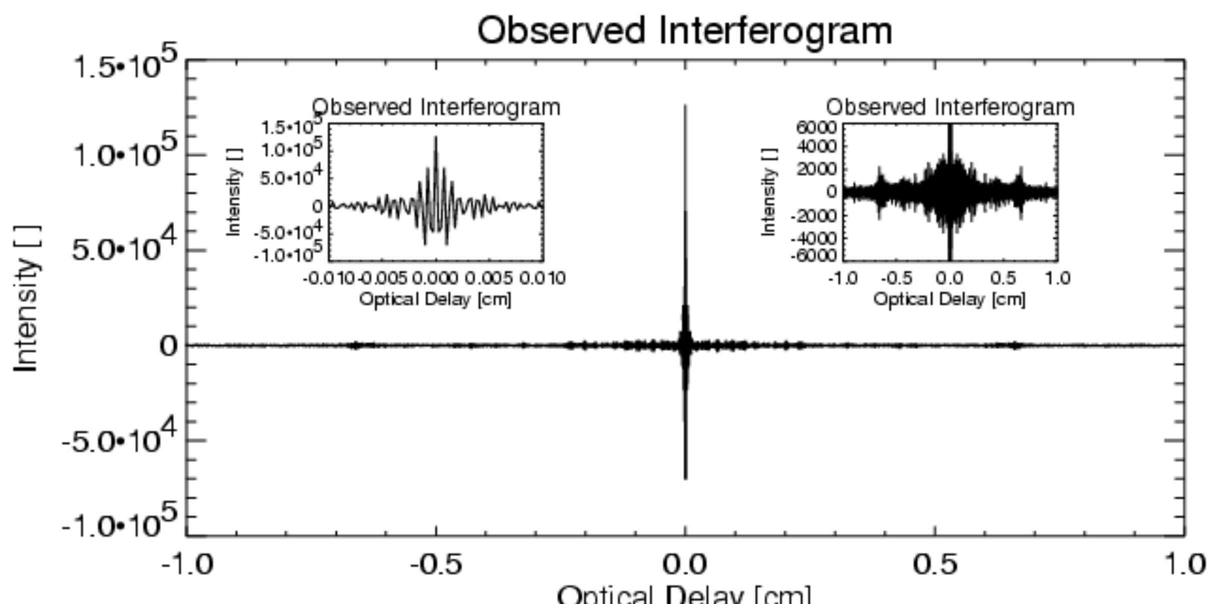
Emissivity > 0.999

How an Interferometer Works

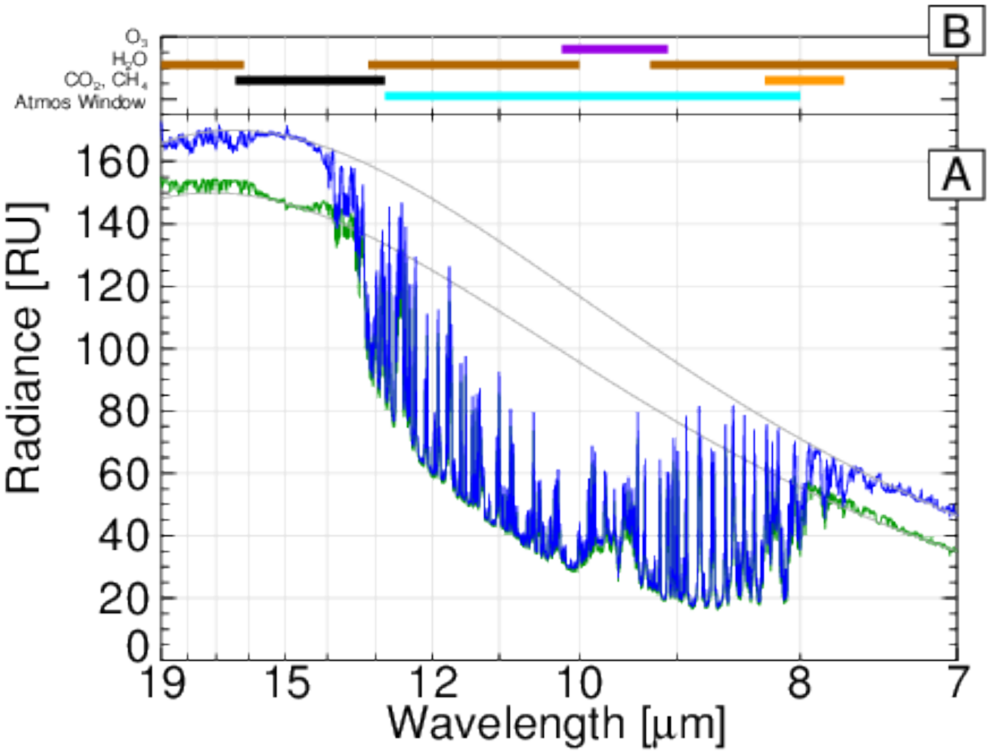
1. Move one mirror slowly back-and-
erference
m) at the
am as a
nirror

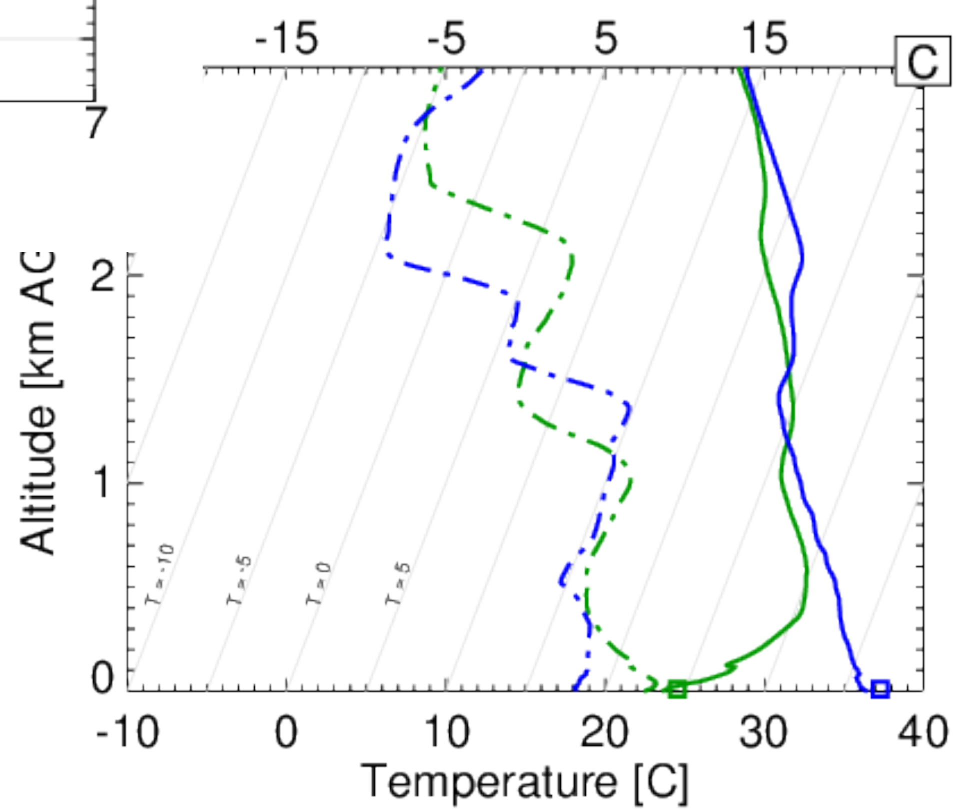


3. Apply a FFT to the interferogram to yield the spectrum



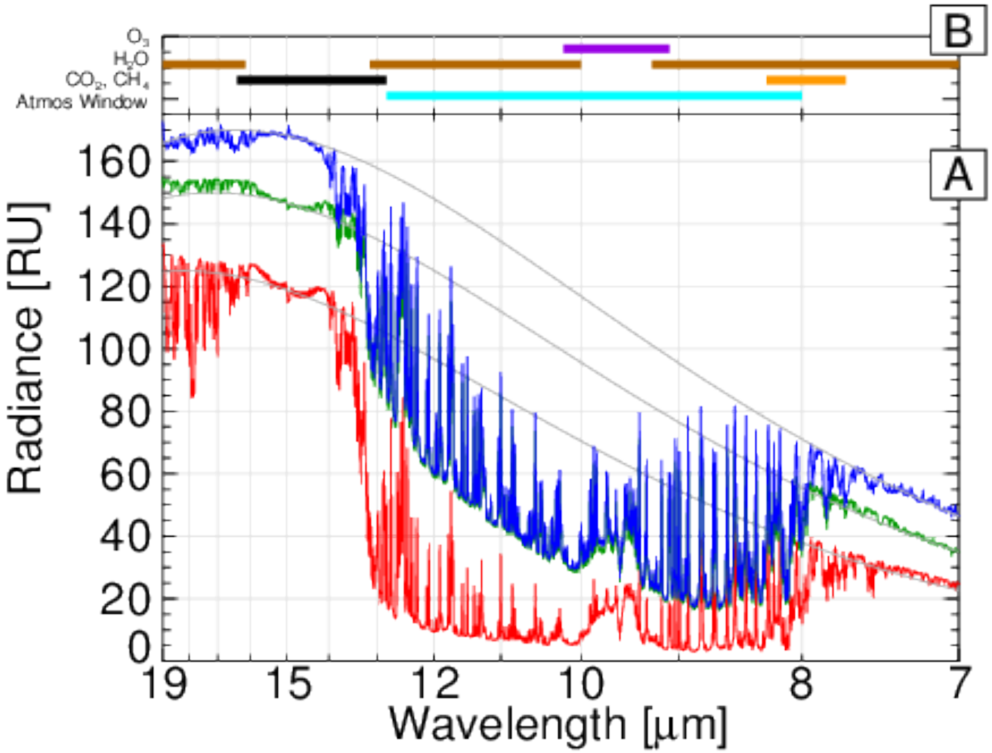
Example Spectra to Retrieved Profiles

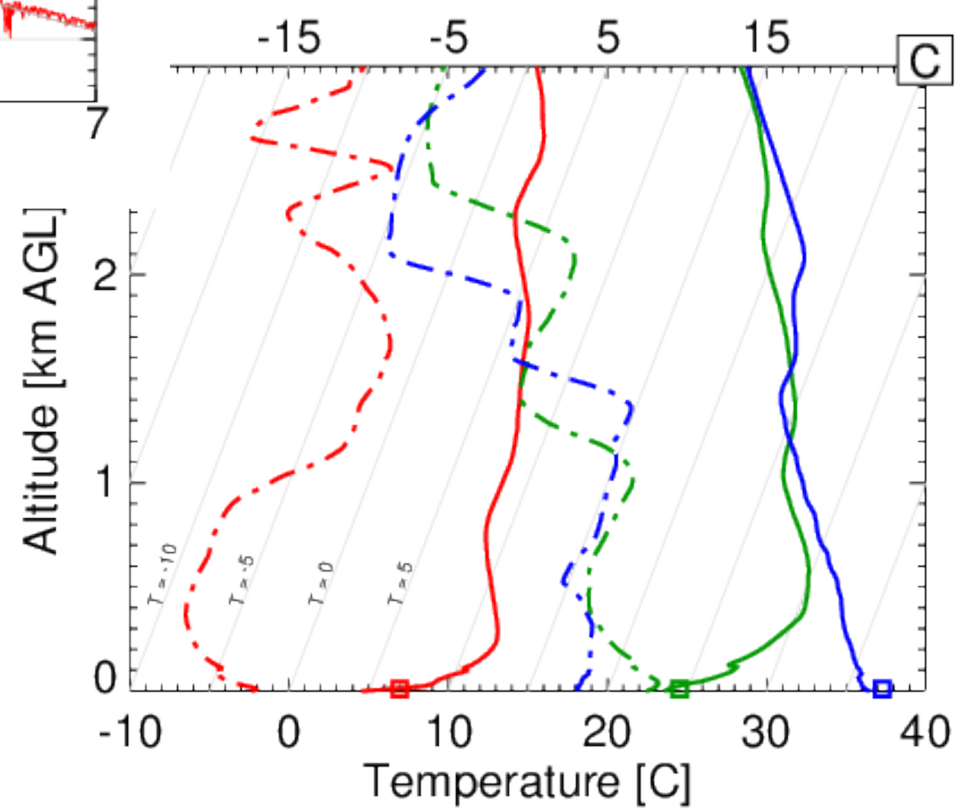




Solid lines: temperature
Dash/dot line: dew point

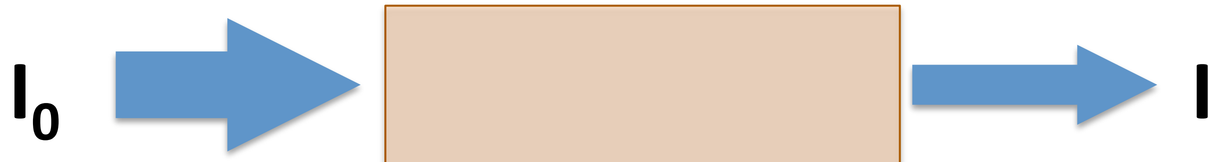
Example Spectra to Retrieved Profiles



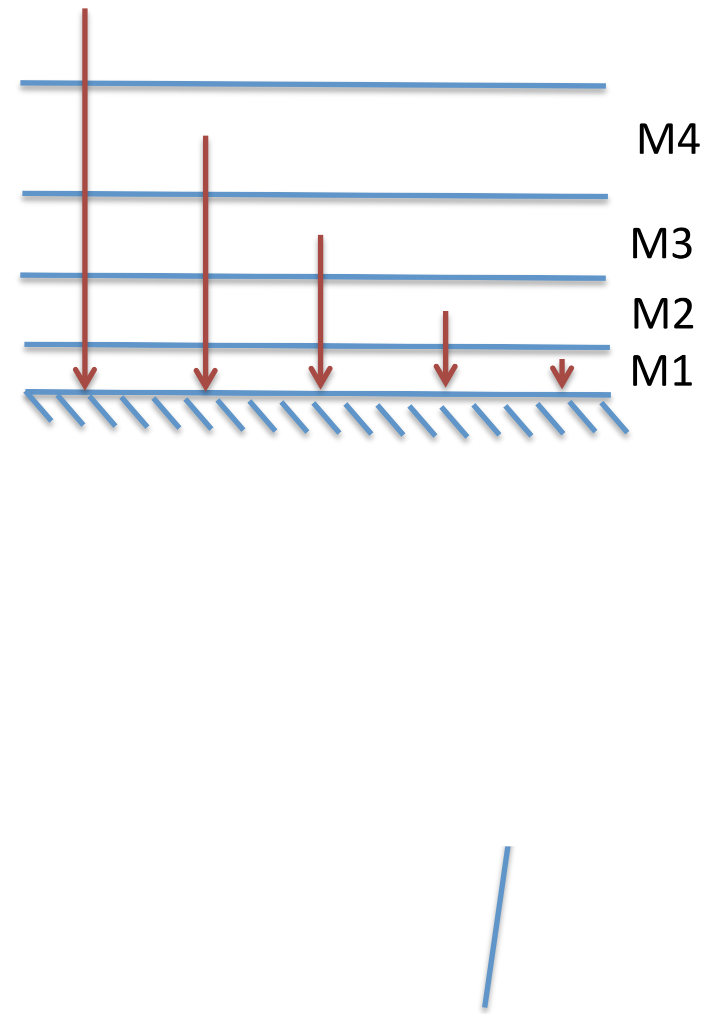


Solid lines: temperature
Dash/dot line: dew point

RT Basics



$$1 = J_\lambda + A_\lambda + \cancel{S_\lambda}$$

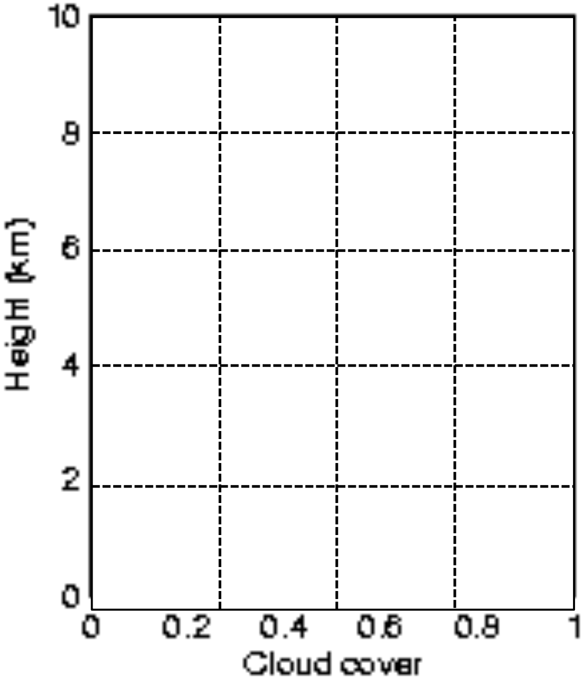


Local Thermodynamic Equilibrium
Absorption = Emission

Emission
from the layer

Transmission
to the surface

Downwelling Clear Sky Case (Example 1a)



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.2

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.8

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 3.2

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 12.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 50.0

T_0=300 K, B(T)=134.4 RU

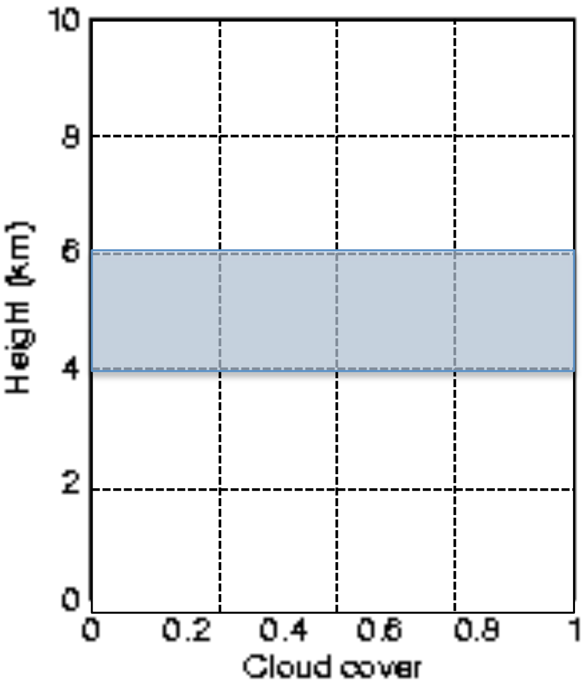
T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

Calculation at 800 cm^{-1} which is 12.5 µm

RU = 1 mW/(m^2 sr cm^{-1})

Downwelling radiance: (1-exp(-0. 2))*(41.2+55.0)/2*exp(-(0. 8+3.2+12.5+50)) +

Downwelling Cloudy Sky Case (Example 1b)



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.2

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.8

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 3.2 ← T_{cloud3} = 10, F_{cld}= 1.0

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 12.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 50.0

T_0=300 K, B(T)=134.4 RU

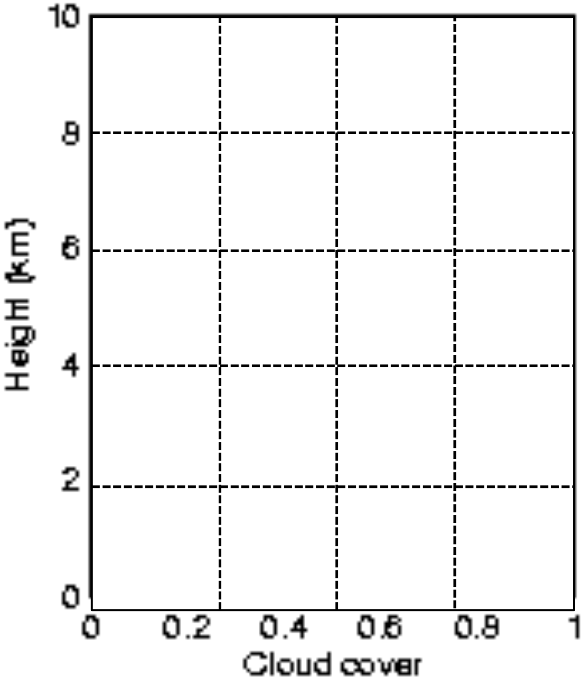
T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

Calculation at 800 cm^{-1} which is 12.5 µm

RU = 1 mW/(m^2 sr cm^{-1})

Downwelling radiance: (1-exp(-0. 2))*(41.2+55.0)/2*exp(-(0. 8+**13.2**+12.5+50)) +

Example 1a vs Example 1b: Why ?



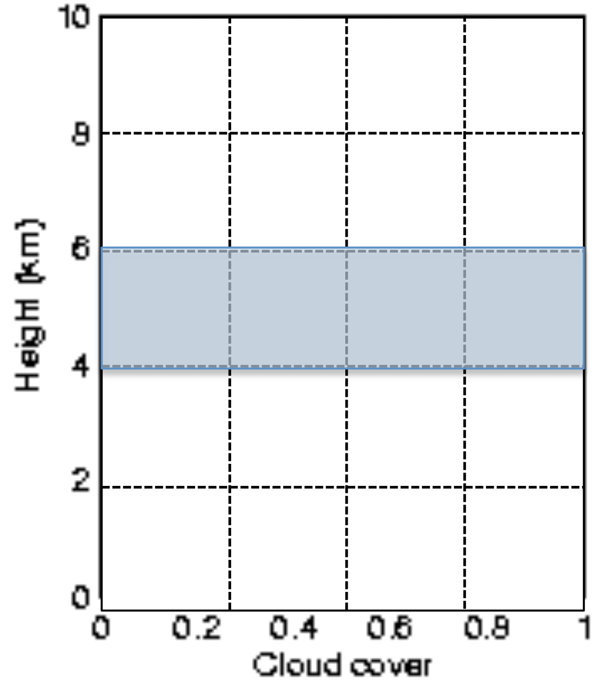
$T_{gas5} = 0.2$

$T_{gas4} = 0.8$

$T_{gas3} = 3.2$

$T_{gas2} = 12.5$

$T_{gas1} = 50.0$



$T_{gas5} = 0.2$

$T_{gas4} = 0.8$

$T_{total3} = 13.2$

$T_{gas2} = 12.5$

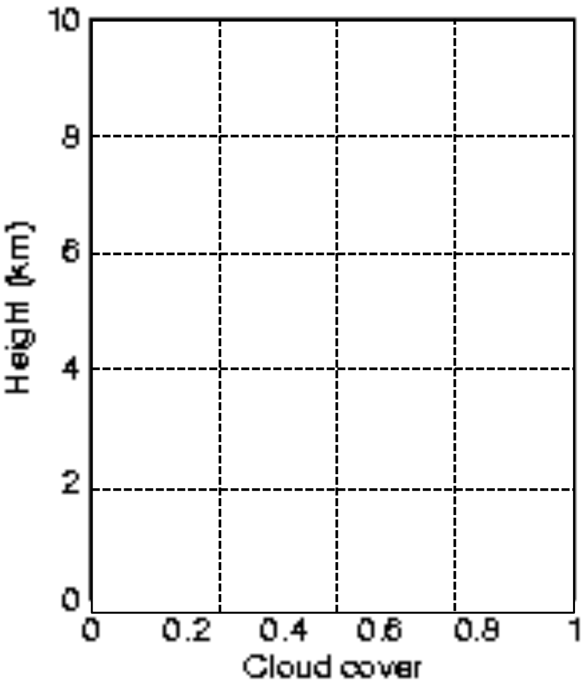
$T_{gas1} = 50.0$

T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

Downwelling Radiance: 133.9 RU

Downwelling Radiance: 133.9 RU

Downwelling Clear Sky Case (Example 1c)



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.2

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.8

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 3.2

T_2=**270** K, B(T)=89.9 RU

T_{gas2} = 12.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 50.0

T_0=300 K, B(T)=134.4 RU

T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

Calculation at 800 cm^{-1} which is 12.5 µm

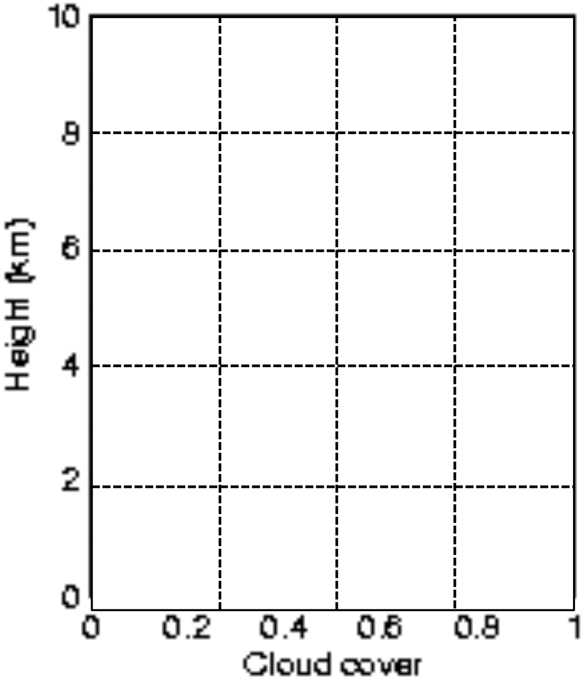
RU = 1 mW/(m^2 sr cm^{-1})

T_2 is 270 instead of 272 K

Example 1a (T_2=272K): Downwelling Radiance: 133.9 RU

Example 1c (T_2=270K): Downwelling Radiance: 133.9 RU

Downwelling Clear Sky Case (Example 1d)



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.2

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.8

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 3.2

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 12.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 50.0

T_0=302 K, B(T)=137.9 RU

T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

Calculation at 800 cm^{-1} which is 12.5 µm

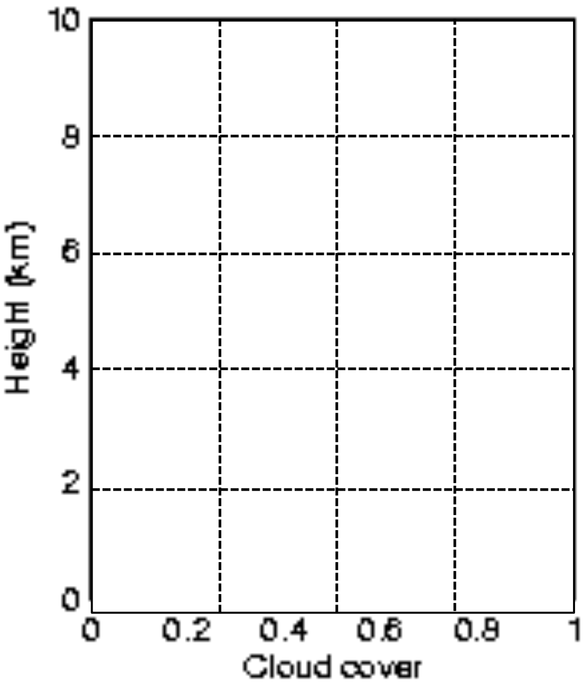
RU = 1 mW/(m^2 sr cm^{-1})

T_0 is 302 instead of 300 K

Example 1a (T_0=300K): Downwelling Radiance: 133.9 RU

Example 1d (T_0=302K): Downwelling Radiance: 137.4 RU

Downwelling Clear Sky Case (Example 1e)



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

T_0=300 K, B(T)=134.4 RU

T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

Calculation at 800 cm^{-1} which is 12.5 µm

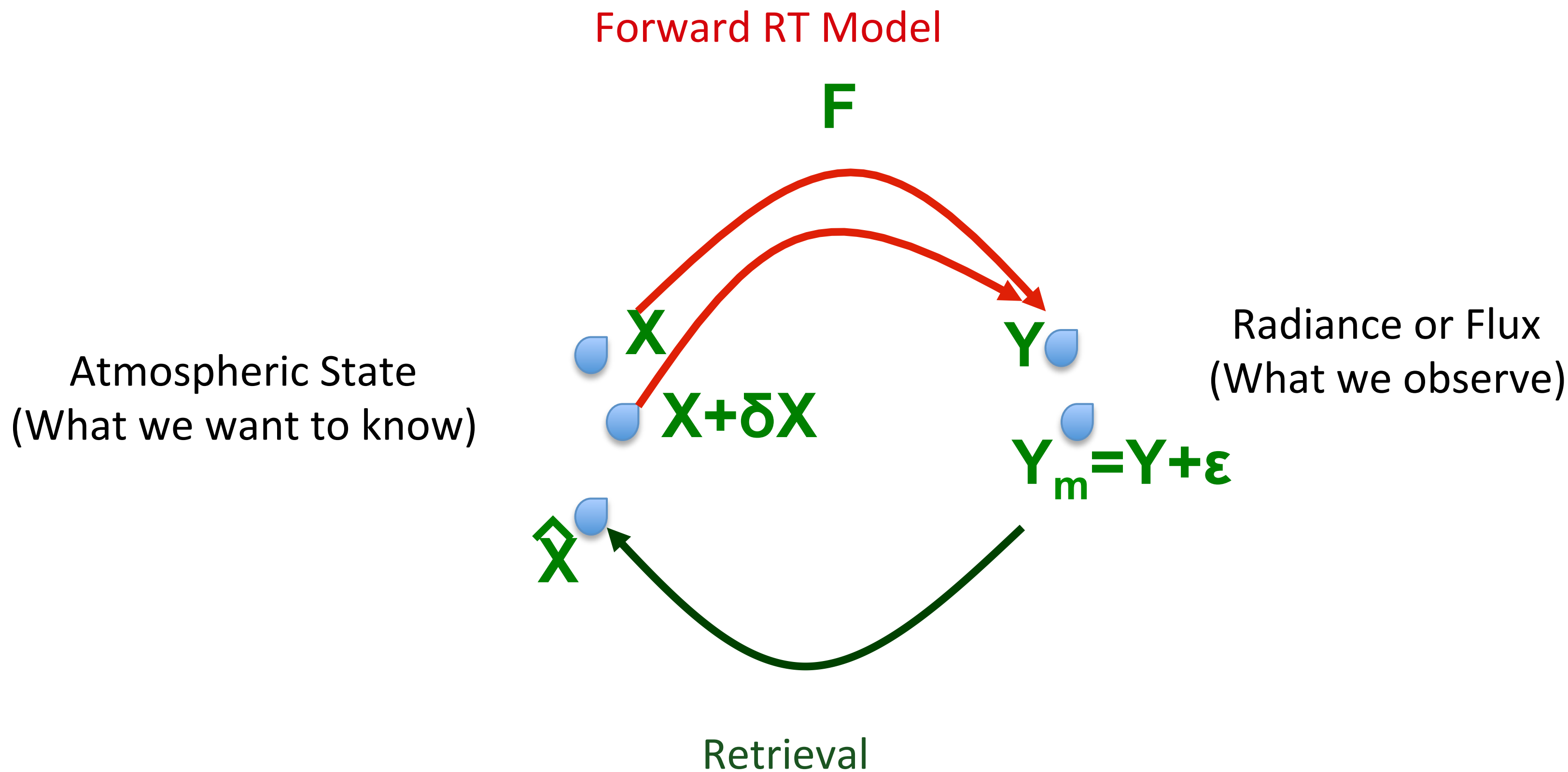
RU = 1 mW/(m^2 sr cm^{-1})

All optical depths are 100x smaller

Example 1a (large tau): Downwelling Radiance: 133.9 RU

Example 1e (small tau): Downwelling Radiance: 59.0 RU

From Radiance to T/Q Profiles

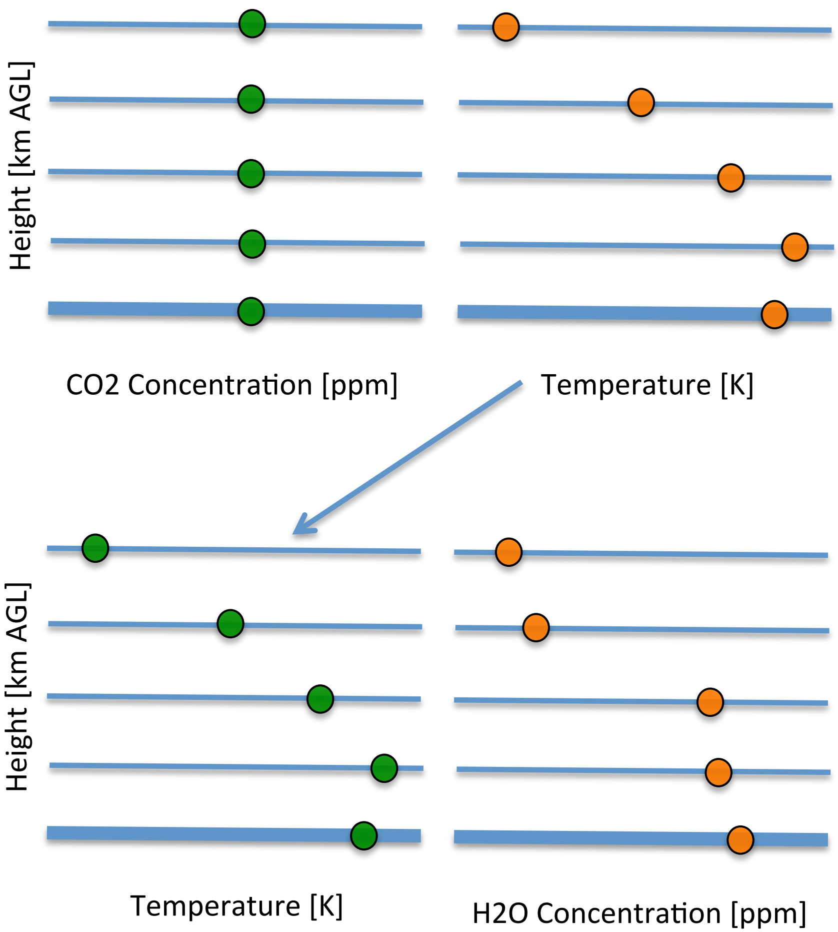


Retrieval Algorithms

- Algorithm must be able to handle ill-conditioned problem with noise

- Two general approaches:
  - Statistical: use a priori data to generate relationships to relate radiance to T(z) and q(z) profile
    - Easy to develop
    - Handles noise well
    - Computationally fast
    - Examples: linear regressions, neural networks, PCA methods, etc
  - Physical: iterative approach whereby a forward RT model is used to derive T(z) and q(z) profile
    - Need a priori data to help constrain solution
    - Computationally slow
    - Provides error bars as part of the retrieval

"Onion Peeling" Physical Retrieval



Retrieving temperature

1. Assume the concentration of some well-mixed gas (CO_2 in infrared, O_2 in microwave)
2. Derive surface temperature using most opaque channel(s)
3. Derive temperature of next level using slightly less opaque channel(s)
4. Continue to get entire profile

Retrieving water vapor

1. Assume the temperature retrieval from above is "accurate"
2. Derive surface WV concentration using most opaque channel(s)
3. Derive WV of next level using slightly less opaque channel(s)
4. Continue to get entire profile

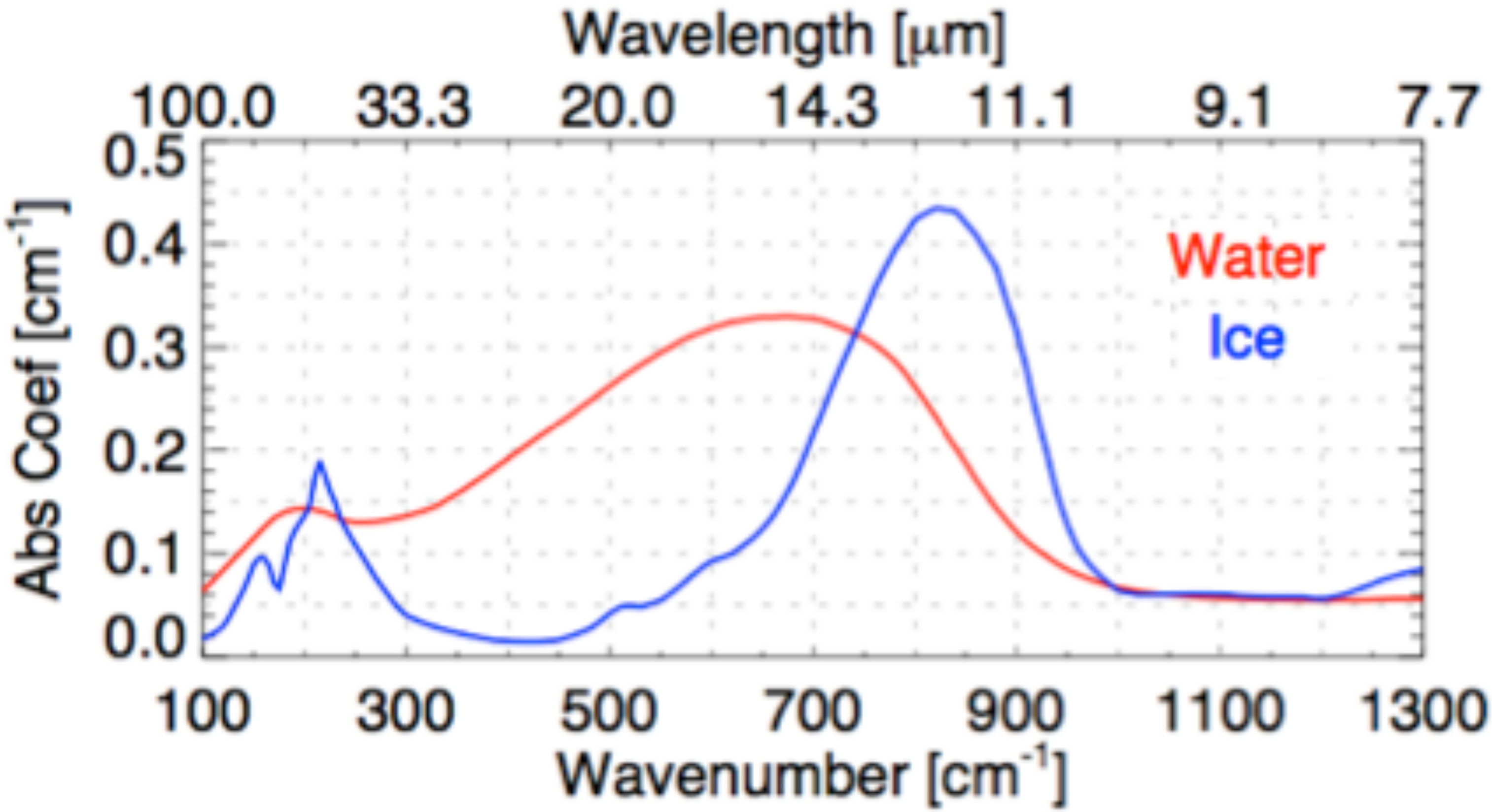
Solution will have correlated error!

Clear skies are "simple"…

…clouds (and aerosols) greatly complicate radiative transfer calculations

- Different compositions (liquid, ice, soot, sulfate, etc) have different spectral absorption bands

IR Absorption Coefficients of Ice and Water



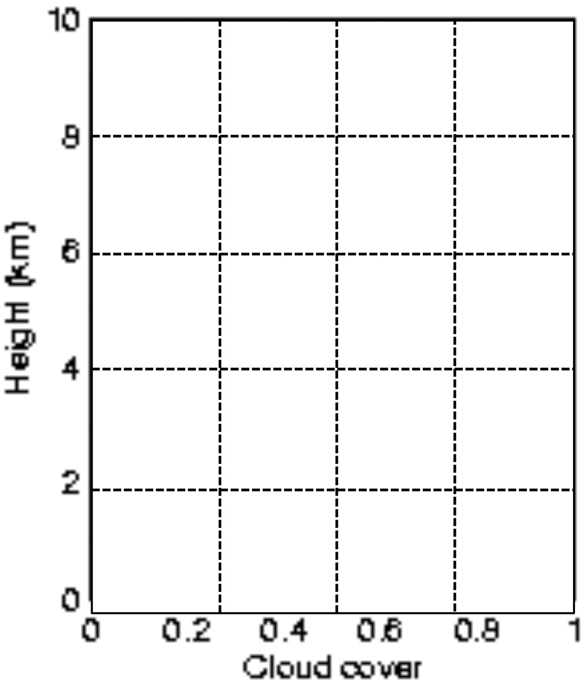
Clear skies are "simple"…

…clouds (and aerosols) greatly complicate radiative transfer calculations

- Different compositions (liquid, ice, soot, sulfate, etc) have different spectral absorption bands
- Different size distributions (monomodal, bimodal, etc)
- Spherical and nonspherical particles
- Very inhomogeneous distribution
  - Within an atmospheric layer
  - Between different layers
- Absorption and ***scattering***

But we are going to leave scattering for another day

Downwelling Clear Sky Case (Example 2a)



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

T_0=300 K, B(T)=134.4 RU

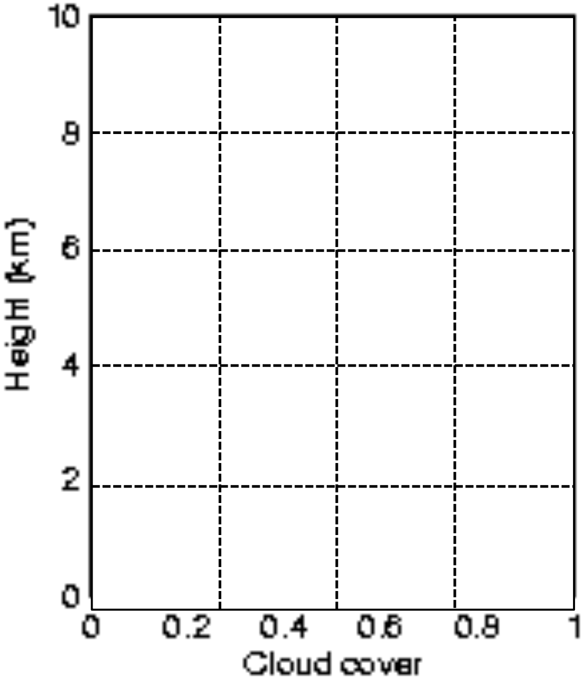
T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

Calculation at 800 cm^{-1}
which is 12.5 µm

RU = 1 mW/(m^2 sr cm^{-1})

Downwelling radiance: (1-exp(-0.002))*(41.2+55.0)/2*exp(-(0.008+0.032+0.125+0.5)) +

Upwelling Clear Sky Case (Example 2b)



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

T_0=300 K, B(T)=134.4 RU

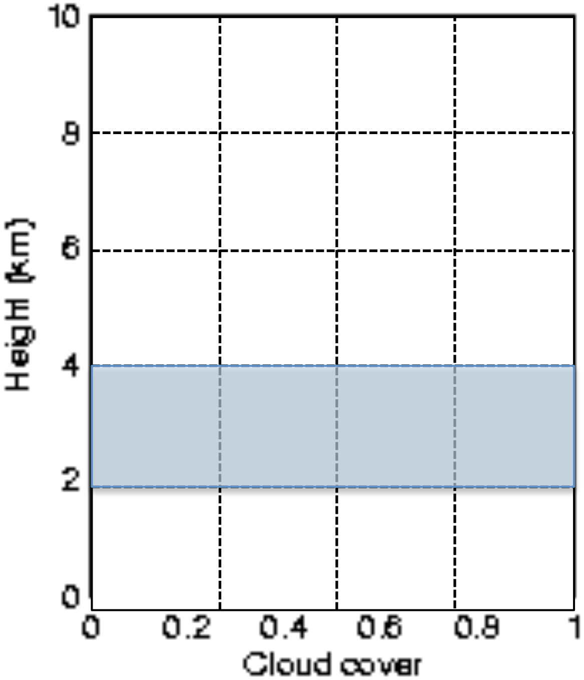
T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

Calculation at 800 cm^{-1} which is 12.5 µm

RU = 1 mW/(m^2 sr cm^{-1})

Upwelling radiance: 152.5*1.0 * exp(-(0.5+0.125+0.032+0.008+0.002)) +

Down and Upwelling Cloudy Sky Case #1



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125

T_{cloud2} = 4, F_{cld}= 1.0

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

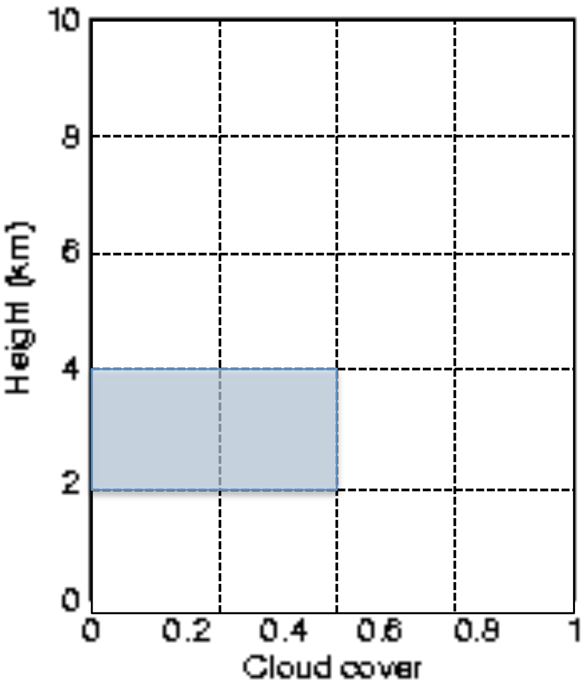
T_0=300 K, B(T)=134.4 RU

T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

R↑ = ? RU

R↓ = ? RU

Down and Upwelling Cloudy Sky Case #2



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125

T_{cloud2} = 4, F_{cld}= 0.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

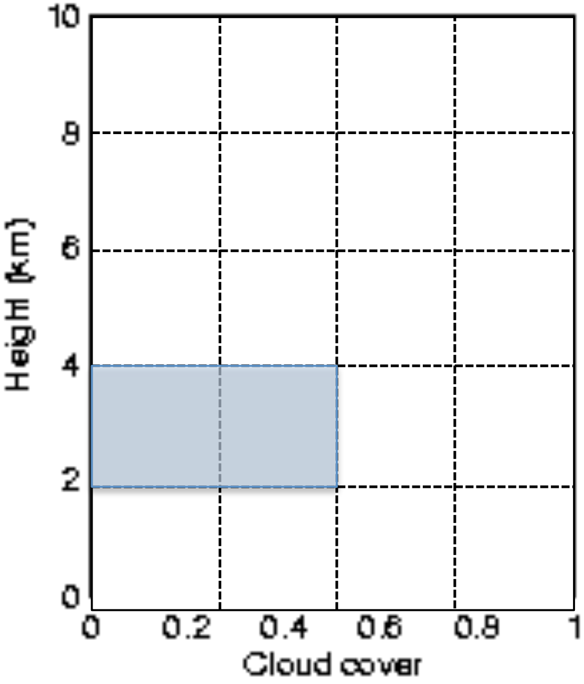
T_0=300 K, B(T)=134.4 RU

T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

$R\uparrow$ = ? RU

$R\downarrow$ = ? RU

Down and Upwelling Cloudy Sky Case #3



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008

T_{cloud4} = 1, F_{cld}= 0.25

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125

T_{cloud2} = 4, F_{cld}= 0.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

T_0=300 K, B(T)=134.4 RU

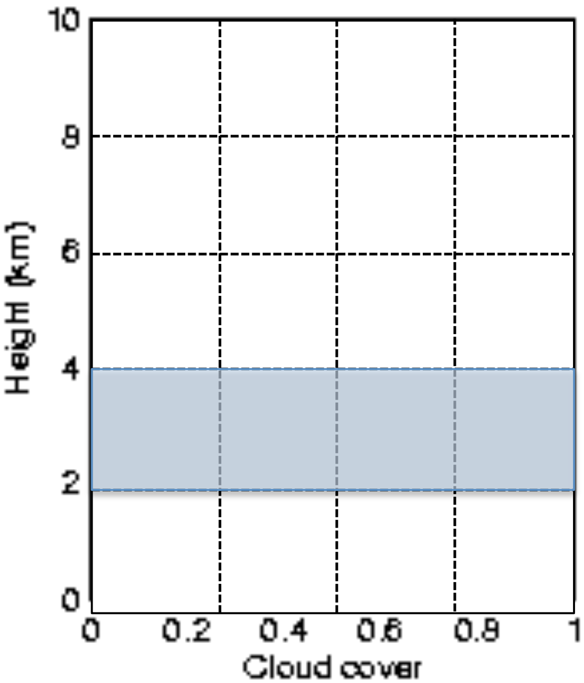
T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

R↑ = ? RU

R↓ = ? RU

Answers

Down and Upwelling Cloudy Sky Case #1



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125 T_{cloud2} = 4, F_{cld}= 1.0

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

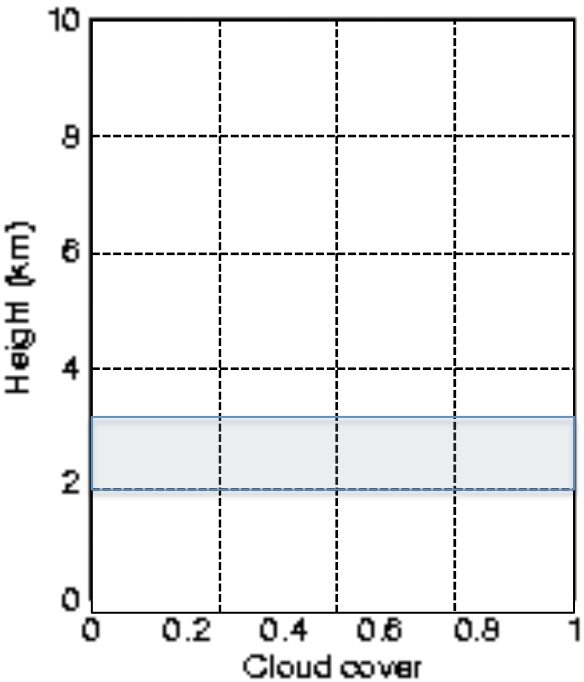
T_0=300 K, B(T)=134.4 RU

T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

R🡅 = 100.05 RU

R🡇 = 108.03 RU

Down and Upwelling Cloudy Sky Case #2



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125

T_{cloud2} = 4, F_{cld}= 0.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

T_0=300 K, B(T)=134.4 RU

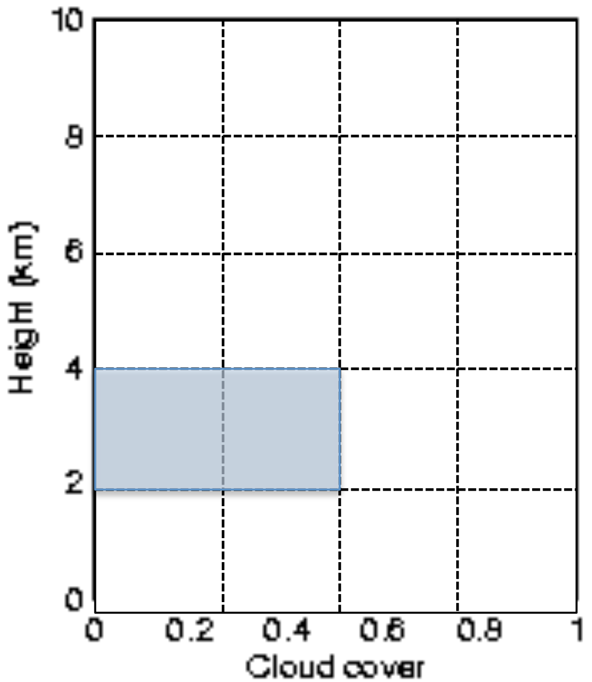
T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

R↑ = 104.05 RU

R↓ = 101.95 RU

Averaging optical depth for clear and cloudy scenes

Down and Upwelling Cloudy Sky Case #2



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125

T_{cloud2} = 4, F_{cld}= 0.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

T_0=300 K, B(T)=134.4 RU

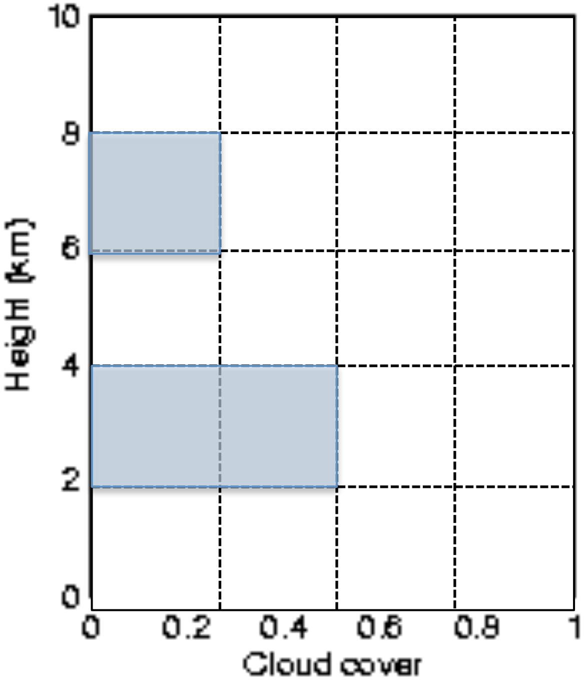
T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

R↑ = 116.80 RU

R↓ = 82.51 RU

Independent Column Approximation (ICA)
(This is much more accurate than the previous)

Down and Upwelling Cloudy Sky Case #3



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008 T_{cloud4} = 1, F_{cld}= 0.25

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125 T_{cloud2} = 4, F_{cld}= 0.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

T_0=300 K, B(T)=134.4 RU

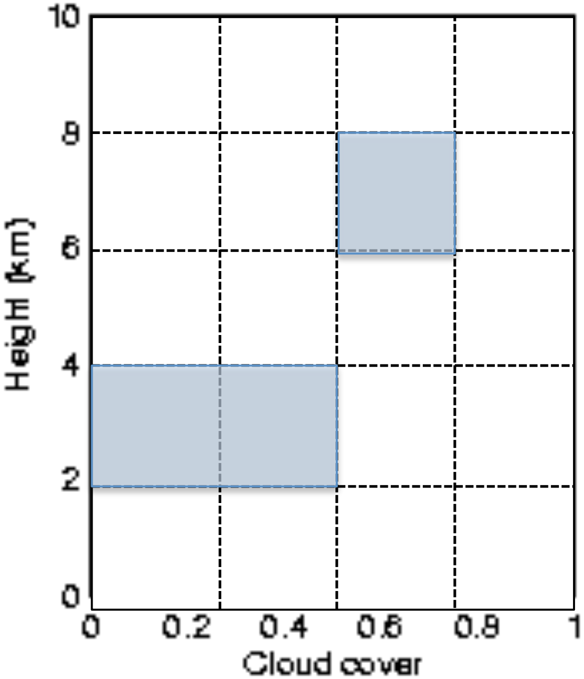
T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

R↑ = 110.96 RU

R↓ = 82.61 RU

Maximum overlap

Down and Upwelling Cloudy Sky Case #3



T_5=230 K, B(T)=41.2 RU

T_{gas5} = 0.002

T_4=244 K, B(T)=55.0 RU

T_{gas4} = 0.008 T_{cloud4} = 1, F_{cld}= 0.25

T_3=258 K, B(T)=71.2 RU

T_{gas3} = 0.032

T_2=272 K, B(T)=89.9 RU

T_{gas2} = 0.125 T_{cloud2} = 4, F_{cld}= 0.5

T_1=286 K, B(T)=111.0 RU

T_{gas1} = 0.500

T_0=300 K, B(T)=134.4 RU

T_{sfc}=310 K, B(T_{sfc})=152.5 RU, Emissivity=1

R↑ = 105.66 RU

R↓ = 87.62 RU

Minimum overlap