Simulation of cloud-contaminated mm-wave spectra using the ARTS-1-1 scattering model

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RT Workshop
22 June 2004
Bredbeck

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DOIT (Discrete Ordinate ITerative) method

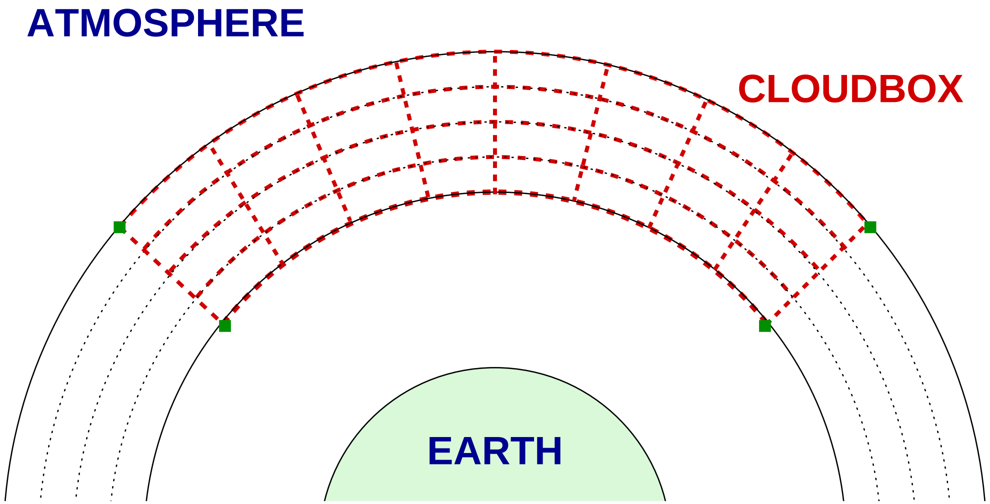
Vector radiative transfer equation:

$$\frac{\mathrm{d}\mathbf{I}}{\mathrm{d}s}(\mathbf{n},\nu,T) = -\langle\mathbf{K}(\mathbf{n},\nu,T)\rangle\mathbf{I}(\mathbf{n},\nu,T) + \langle\mathbf{a}(\mathbf{n},\nu,T)\rangle B(\nu,T) + \int_{4\pi}\mathrm{d}\mathbf{n}'\langle\mathbf{Z}(\mathbf{n},\mathbf{n}',\nu,T)\rangle\mathbf{I}(\mathbf{n}',\nu,T)$$

$\mathbf{I}(\mathbf{n},\nu,T) = (I,Q,U,V)$ - Stokes vector
$\langle\mathbf{K}(\mathbf{n},\nu,T)\rangle$ - Ensemble averaged exinction matrix
$\langle\mathbf{a}(\mathbf{n},\nu,T)\rangle$ - Ensemble averaged absorption vector
$\langle\mathbf{Z}(\mathbf{n},\mathbf{n}',\nu,T)\rangle$ - Ensemble averaged phase matrix
$B(\nu,T)$ - Planck function

$\mathbf{n},\mathbf{n}'$ - Propagation and incoming directions
ν, T - Frequency and temperature
$\mathrm{d}s$ - Pathlength element

DOIT - Cloudbox (scattering domain)



Scattered radiation field is calculated inside the cloudbox using **DOIT method**.

Definition of cloudbox:

- corner points ⇔ atmospheric grid points
- 3D atmosphere: $[p_1, p_2, \alpha_1, \alpha_2, \beta_1, \beta_2]$

DOIT - Discretization of radiation field

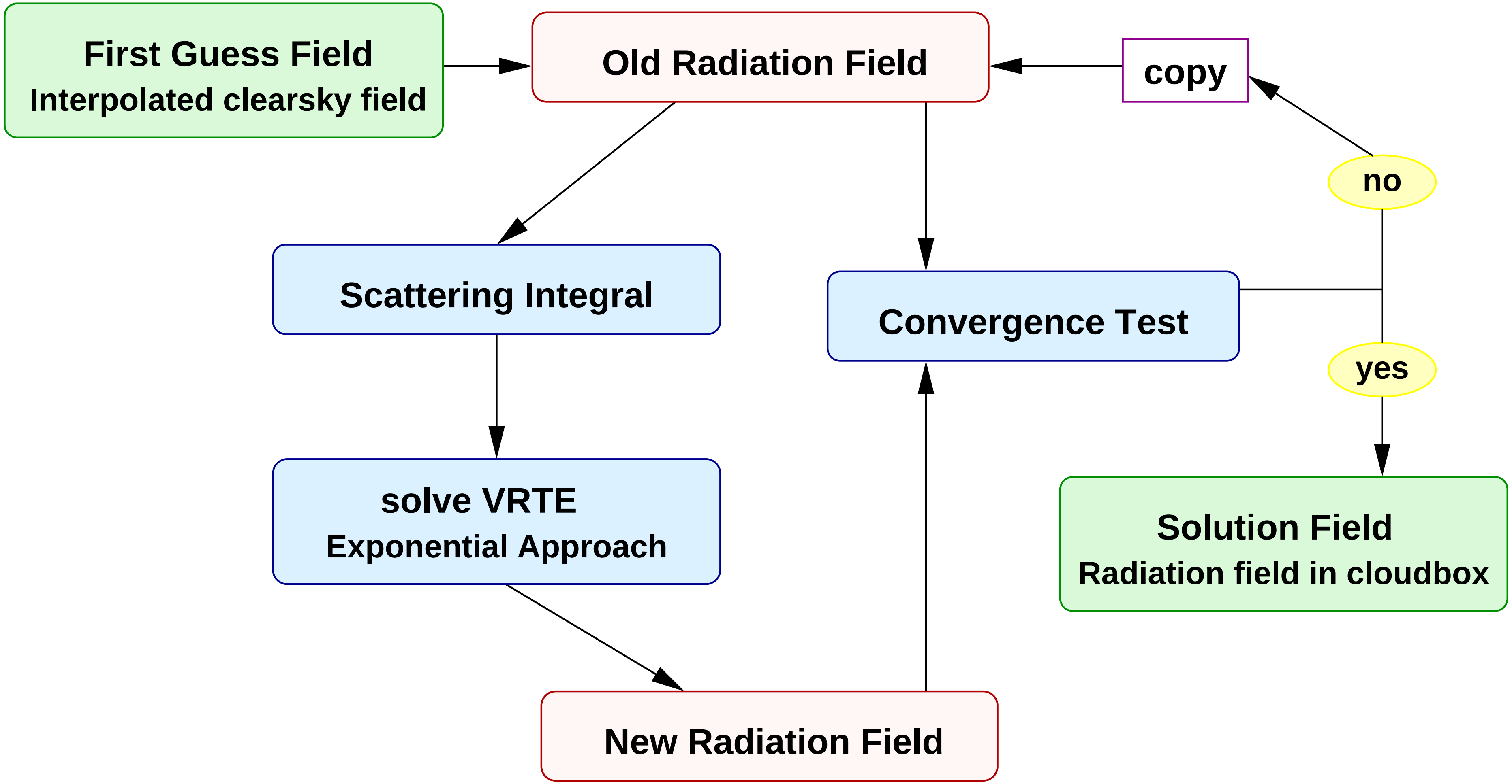
Definition of numerical grids:

$$\begin{aligned}
\vec{p} &= \{p_1, p_2, ..., p_{N_p}\} \\
\vec{\alpha} &= \{\alpha_1, \alpha_2, ..., \alpha_{N_\alpha}\} \\
\vec{\beta} &= \left\{\beta_1, \beta_2, ..., \beta_{N_\beta}\right\} \\
\vec{\theta} &= \{\theta_1, \theta_2, ..., \theta_{N_\theta}\} \\
\vec{\phi} &= \left\{\phi_1, \phi_2, ..., \phi_{N_\phi}\right\}
\end{aligned}$$

Radiation field → set of Stokes vectors for all combinations of positions and directions:

$$\begin{aligned}
\mathcal{I} = \{&\mathbf{I}_1(p_1, \alpha_1, \beta_1, \theta_1, \phi_1), \mathbf{I}_2(p_2, \alpha_1, \beta_1, \theta_1, \phi_1), ..., \\
&\mathbf{I}_{N_p \times N_\alpha \times N_\beta \times N_\theta \times N_\theta}(p_{N_p}, \alpha_{N_\alpha}, \beta_{N_\beta}, \theta_{N_\theta}, \phi_{N_\phi})\}
\end{aligned}$$

DOIT - Schematic of the iterative method



First Guess Field
Interpolated clearsky field

Old Radiation Field

copy

no

Scattering Integral

Convergence Test

yes

solve VRTE
Exponential Approach

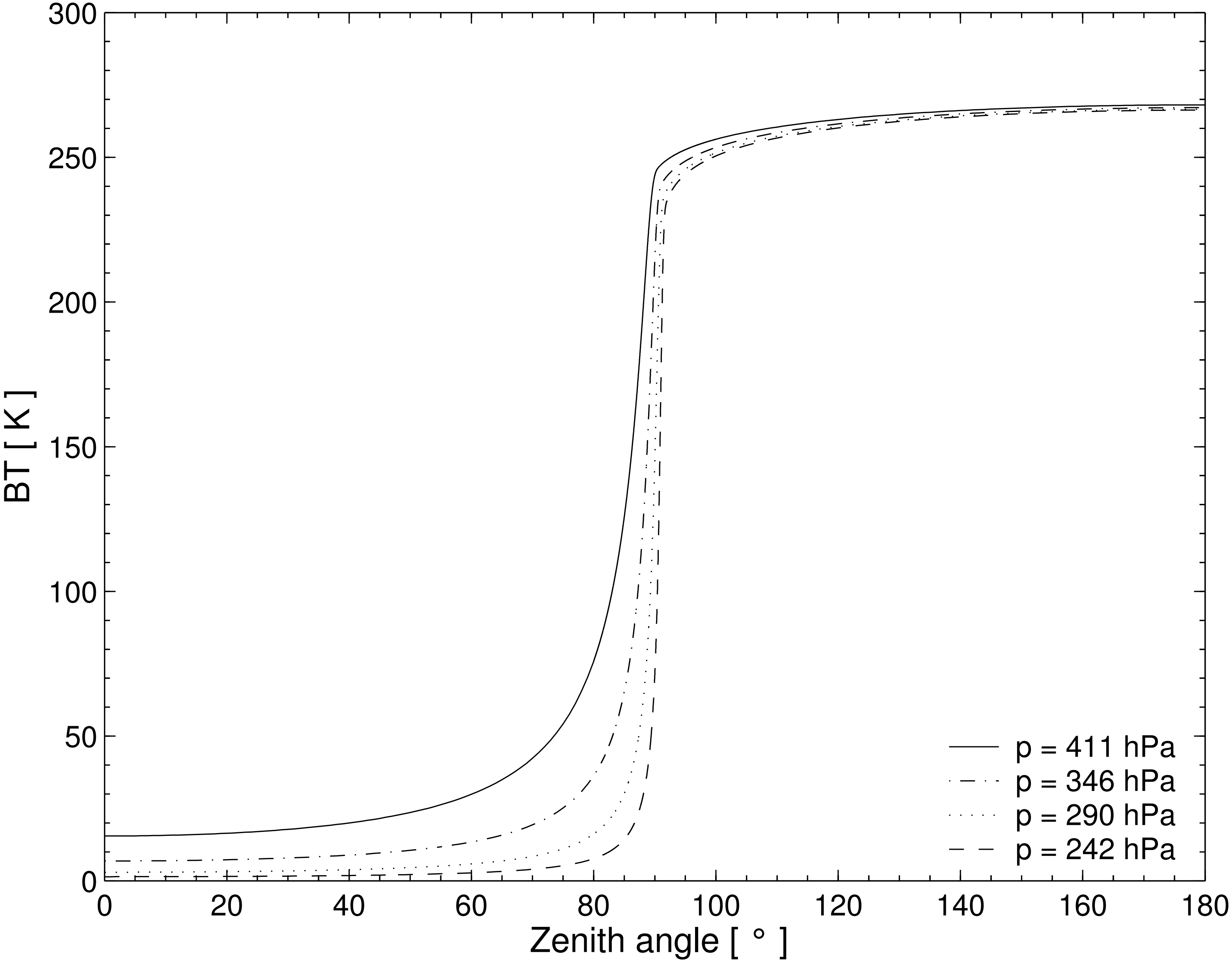
Solution Field
Radiation field in cloudbox

New Radiation Field

DOIT - Numerical issues

1. Sequential update of radiation field
   - # iterations in simple DOIT method depends on # pressure levels
   - Intelligent loop order → scattering effect can propagate throughout the cloudbox during 1 iteration
2. Zenith angle grid optimization

Intensity field



DOIT - Numerical issues

1. Sequential update of radiation field
    - # iterations in simple DOIT method depends on # pressure levels
    - Intelligent loop order → scattering effect can propagate throughout the cloudbox during 1 iteration

2. Zenith angle grid optimization
    - Radiation field strongly increases at about 90°
    - Very fine zenith angle grid resolution required to minimize interpolation errors
    - Find optimal number of zenith angle grid points

3. Interpolation methods
    - Linear interpolation: simple and fast
    - Cubic interpolation: more expensive, but more accurate and requires less grid points

Model intercomparisons

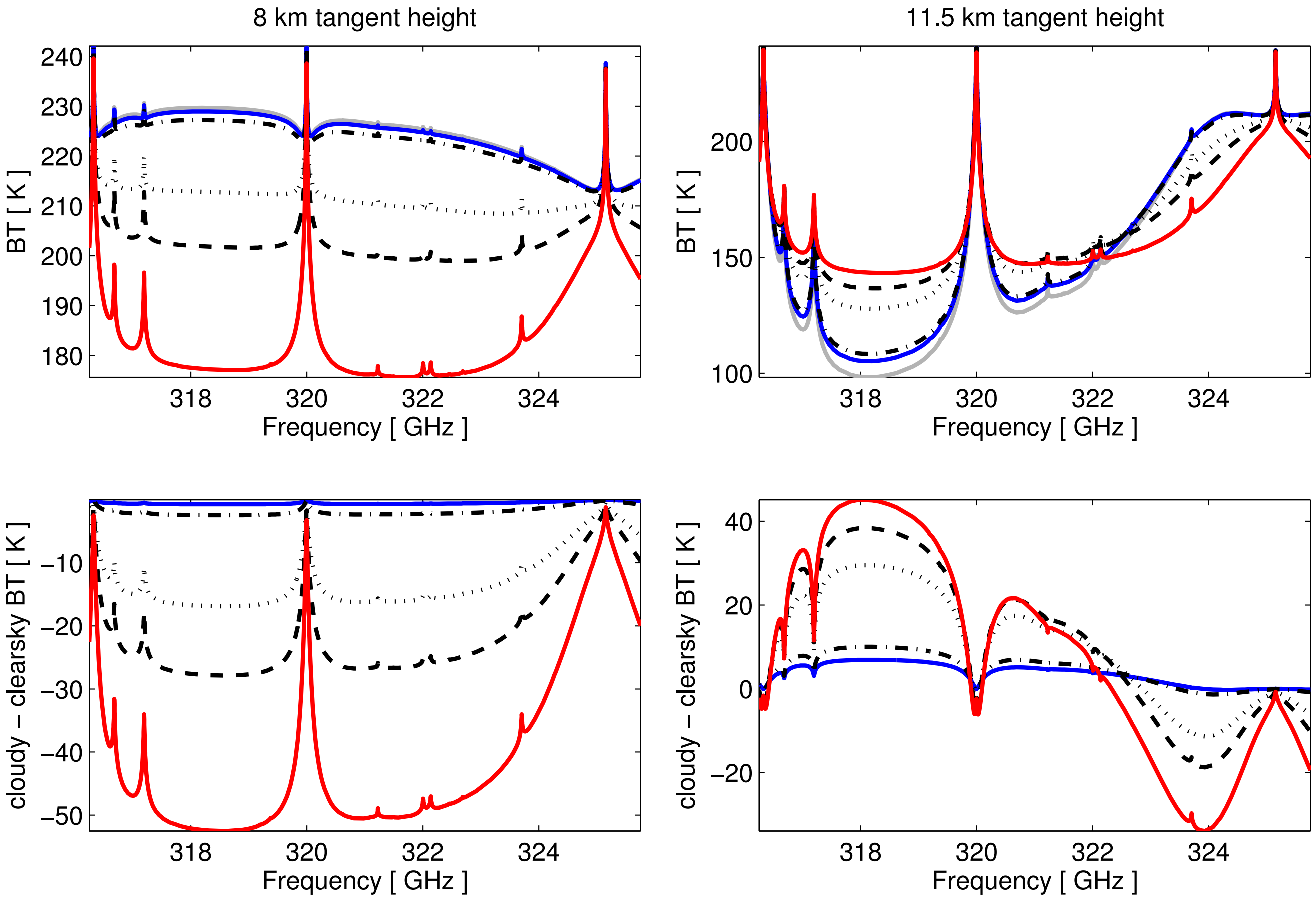
1. ARTS-1D vs. RAL-FM-1D (MASTER-C Band)
    - excellent agreement for cases with spherical particles
    - less than 1 K deviation for most cloud cases
2. ARTS-1D vs. KOPRA (infrared)
    - Good agreement in single scattering regime

Setup for 1D simulations

Table 1: Definition of test cases

	IMC [g/m^3]	$R_{\rm eff}$ [microns]	cloud alt. [km]	band	aspect ratio
1	$1.6{\cdot}10^{-3}$	21.5, 34.0, 68.5 85.5, 128.5	10-12	C	-
2	$1.6{\cdot}10^{-3}$	34.0	6-8, 8-10, 10-12	C	-
3	$1.6{\cdot}10^{-3}$	68.5	10-12	C	0.3, 0.5, 1.0 2.0, 4.0
4	$4{\cdot}10^{-5}$ $1.6{\cdot}10^{-3}$ $8{\cdot}10^{-3}$ 0.016 0.04	21.5 34.0 68.5 85.5 128.5	10-12	C	-
5	$1.6{\cdot}10^{-3}$	34.0	10-12	B, C, D, E	-

1D simulations - Effect of particle size (limb)

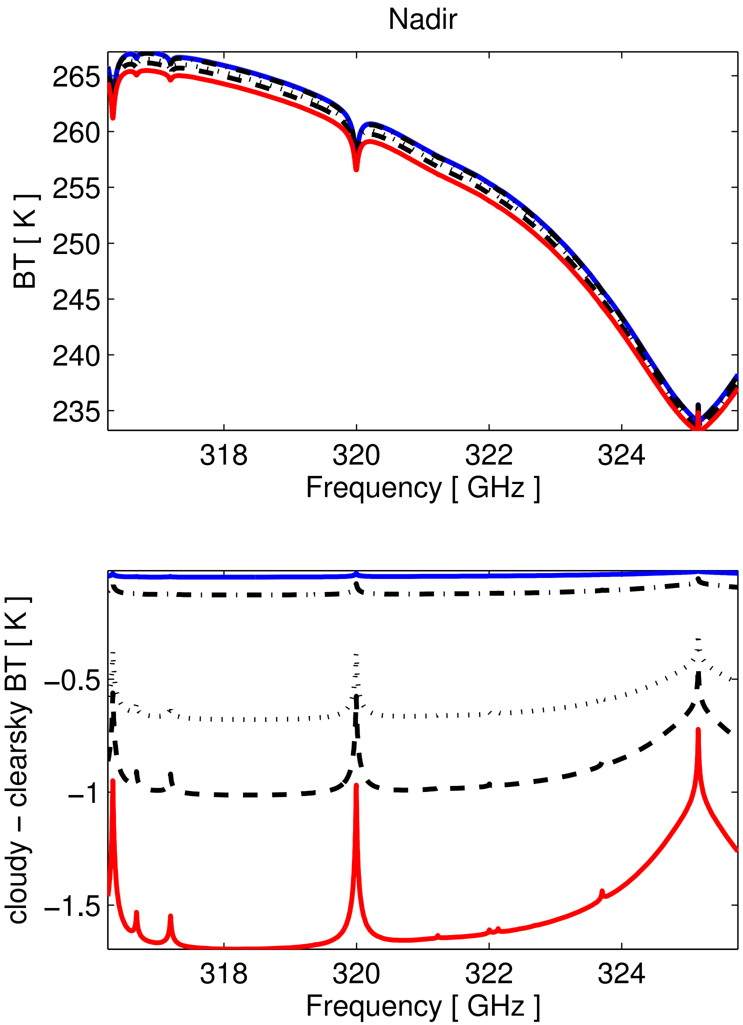


clearsky (grey)

particle sizes:
21.5 μm (blue)
34.0 μm (- -)
68.5 μm $(\cdots)$
85.5 μm (-·-)
128.5 μm (red)

IMC const:
$1.6{\cdot}10^{-3}$ g/m^3
cloud altitude:
10 - 12 km

1D simulations - Effect of particle size (nadir)

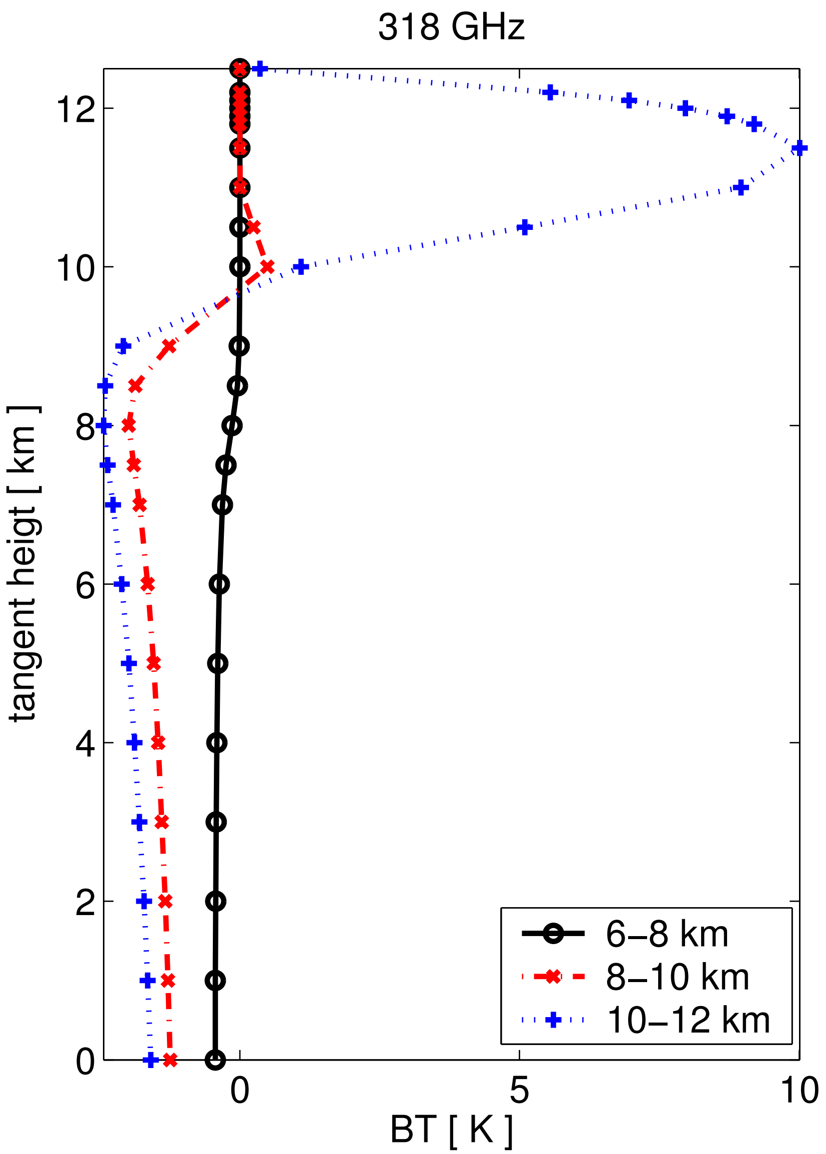


clearsky (grey)

particle sizes:
21.5 μm (blue)
34.0 μm (- -)
68.5 μm ($\cdots$)
85.5 μm (-·-)
128.5 μm (red)

IMC const:
$1.6{\cdot}10^{-3}$ g/m^3
cloud altitude:
10 - 12 km

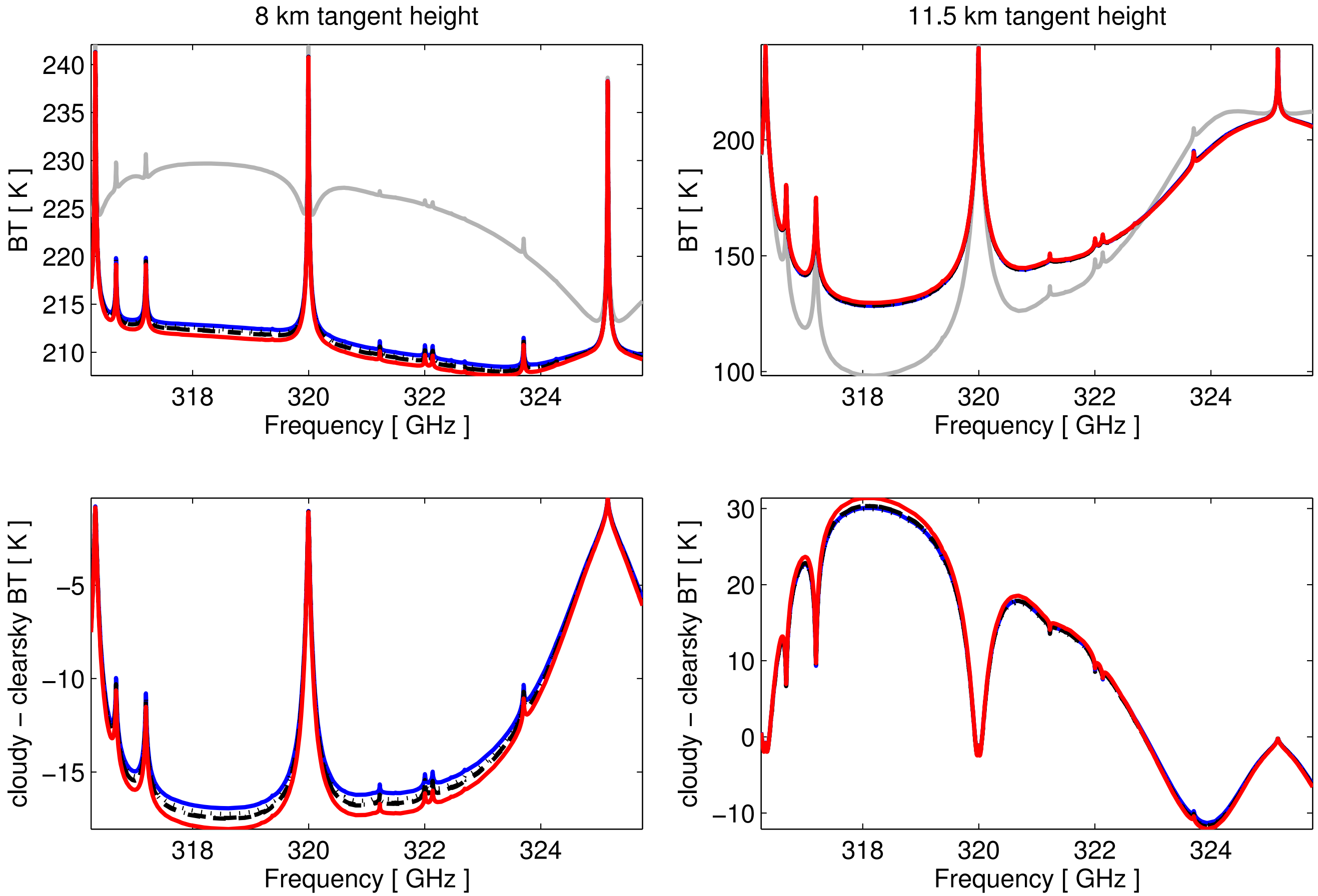
1D simulations - Effect of cloud height



particle size:
34.0 μm

IMC const:
$1.6{\cdot}10^{-3}$ g/m^3

1D simulations - Effect of particle shape

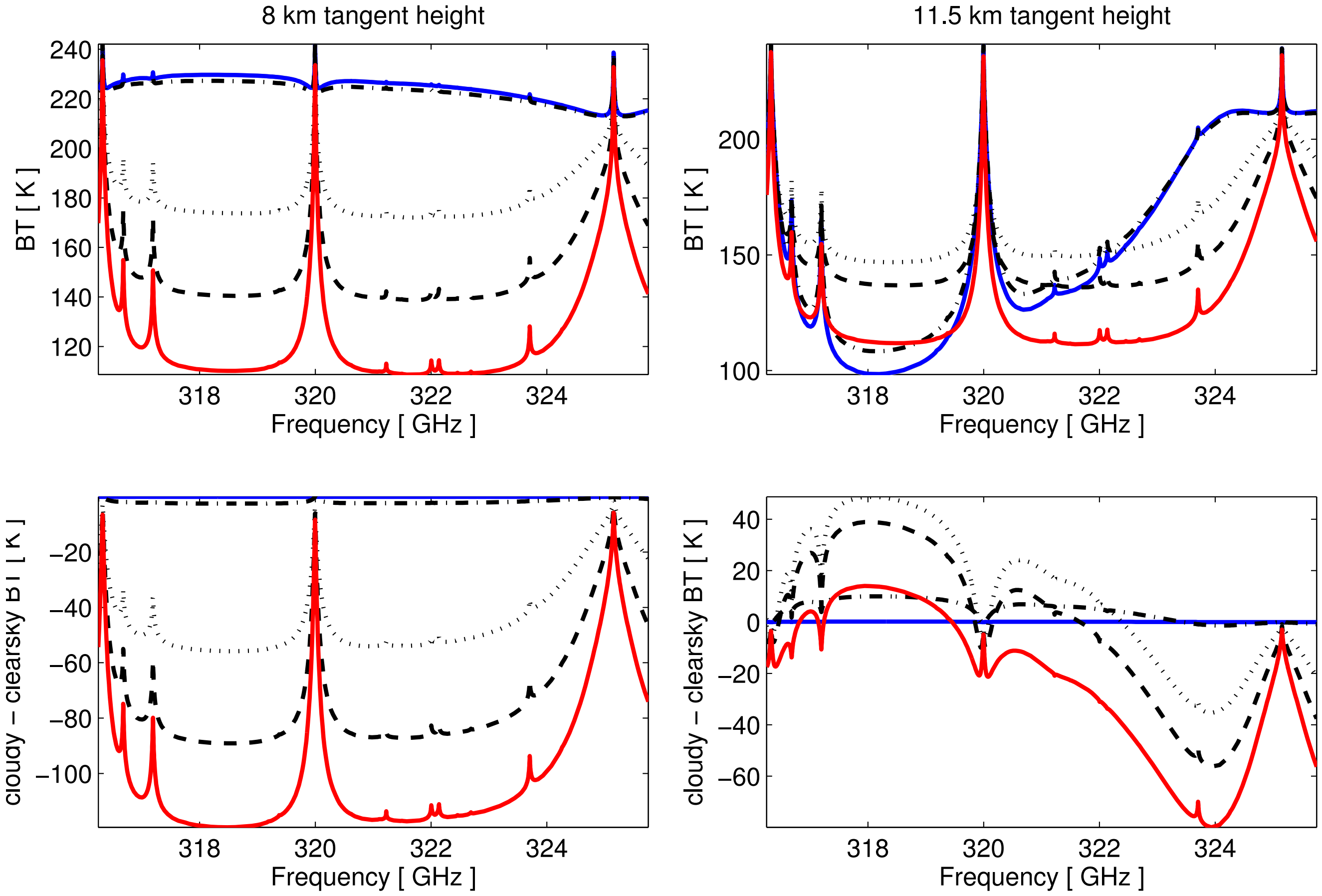


clearsky (grey)

aspect ratios:
0.3 (blue)
0.5 (- -)
1.0 $(\cdots)$
2.0 (-·-)
4.0 (red)

IMC const:
$1.6{\cdot}10^{-3}$ g/m^3
cloud altitude:
10 - 12 km

1D simulations - Cloud scenarios from FIRE measurements

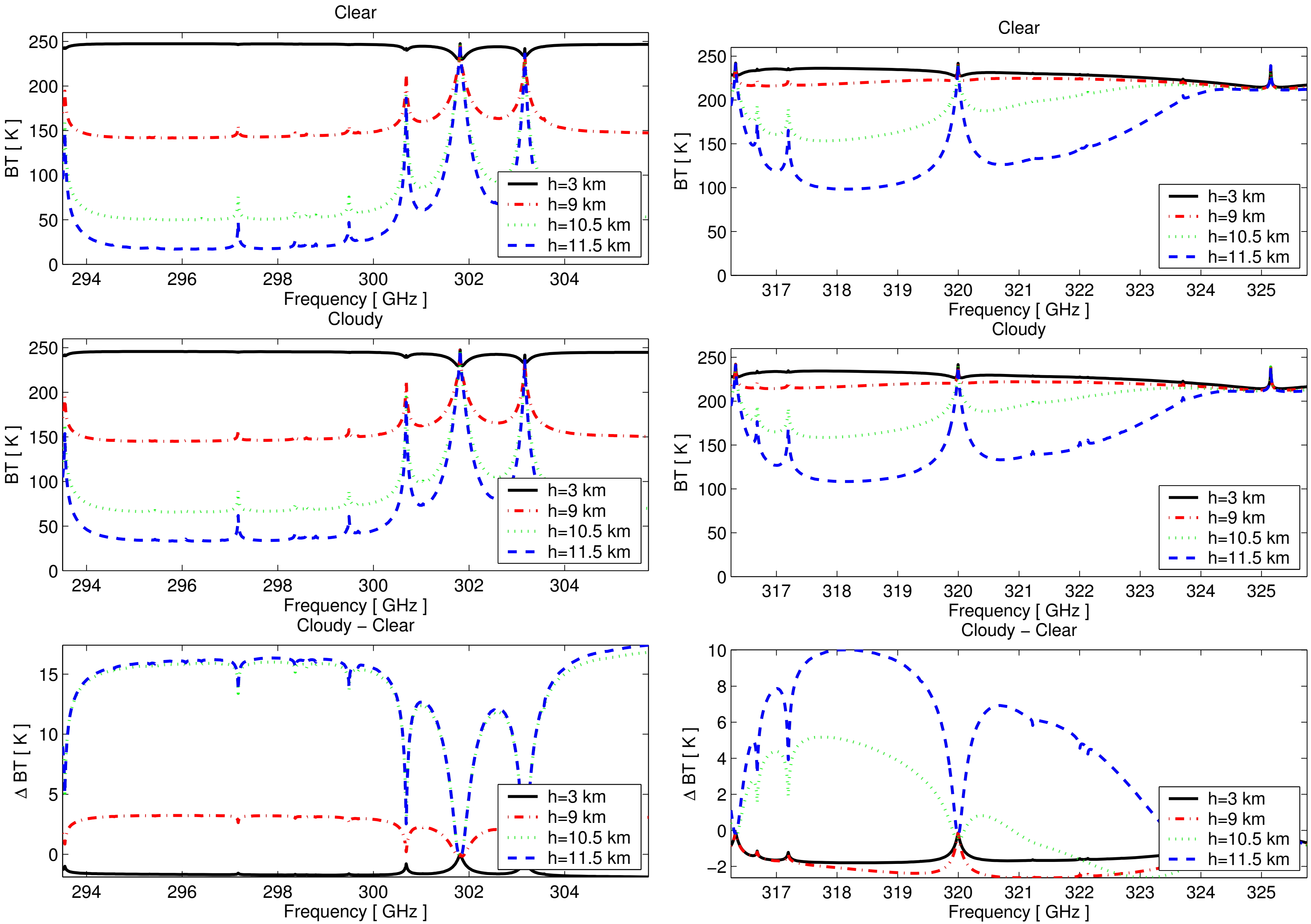


clearsky (grey)

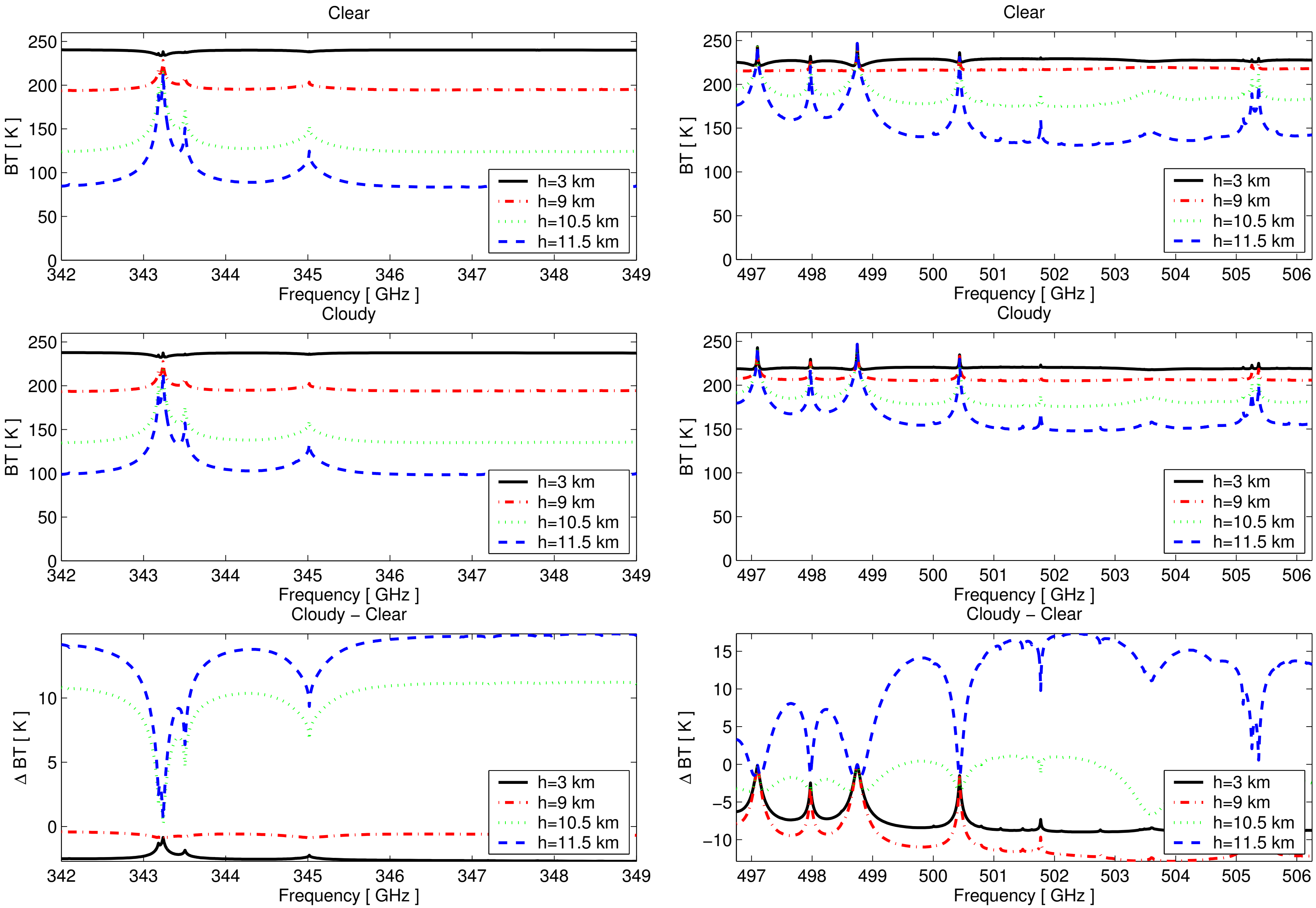
size (μm)	IMC (g/m^3)	line
21.5	$4{\cdot}10^{-5}$	(blue)
34.0	$1.6{\cdot}10^{-3}$	(- -)
68.5	$8{\cdot}10^{-3}$	($\cdots$)
85.5	0.016	(-·-)
128.5	0.04	(red)

cloud altitude:
10 - 12 km

1D simulations - MASTER bands B and C



1D simulations - MASTER bands D and E



Clear

Cloudy

Cloudy – Clear

Setup for 3D simulation

- Finite cloud in 1D atmosphere
- Cloud extent: 32×64 km
- IMC: 0.016 g/m^3
- R_{eff}: 85.5 μm
- cloud altitude: 10 - 12 km
- spherical particles

3D simulations - LOS

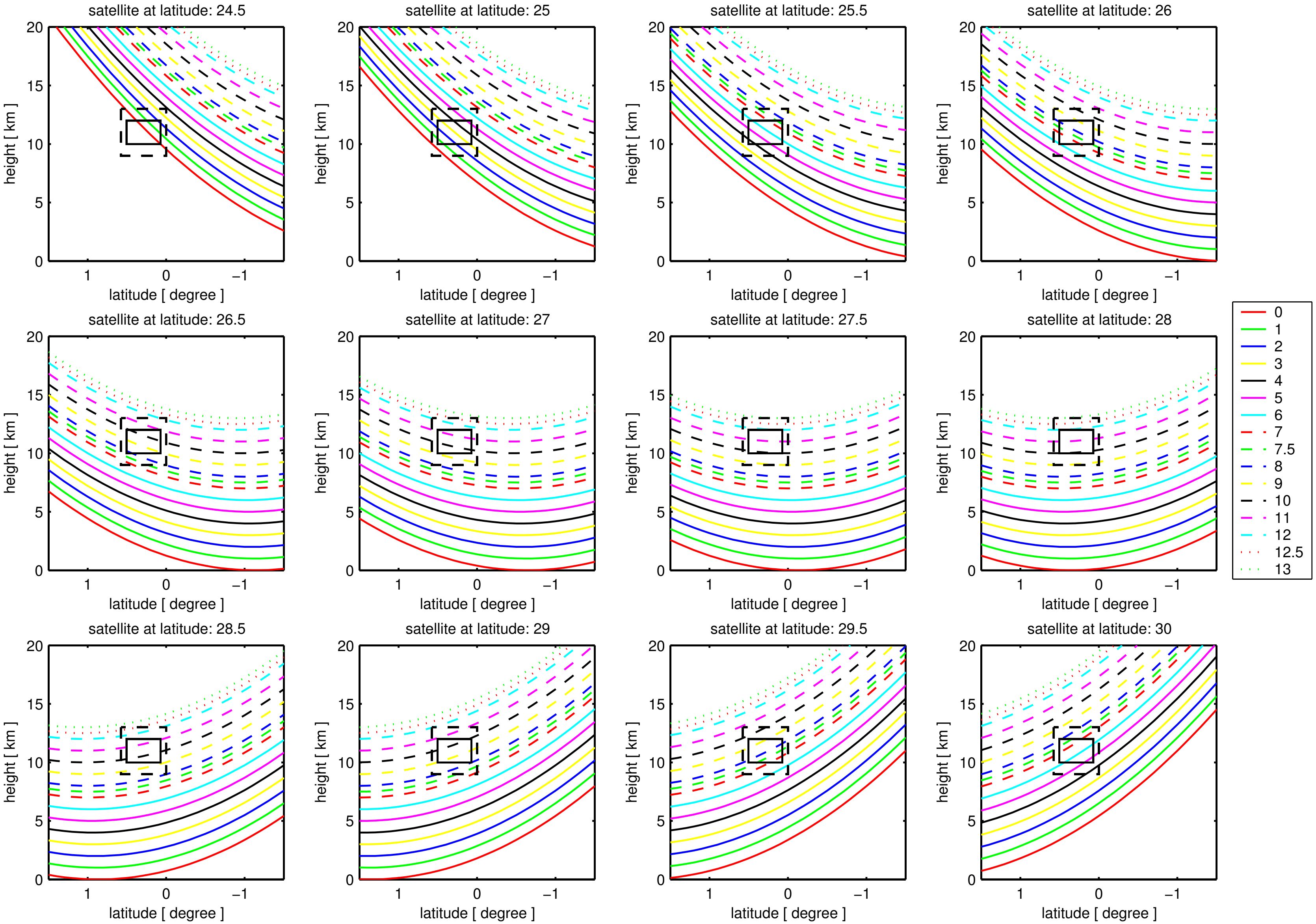
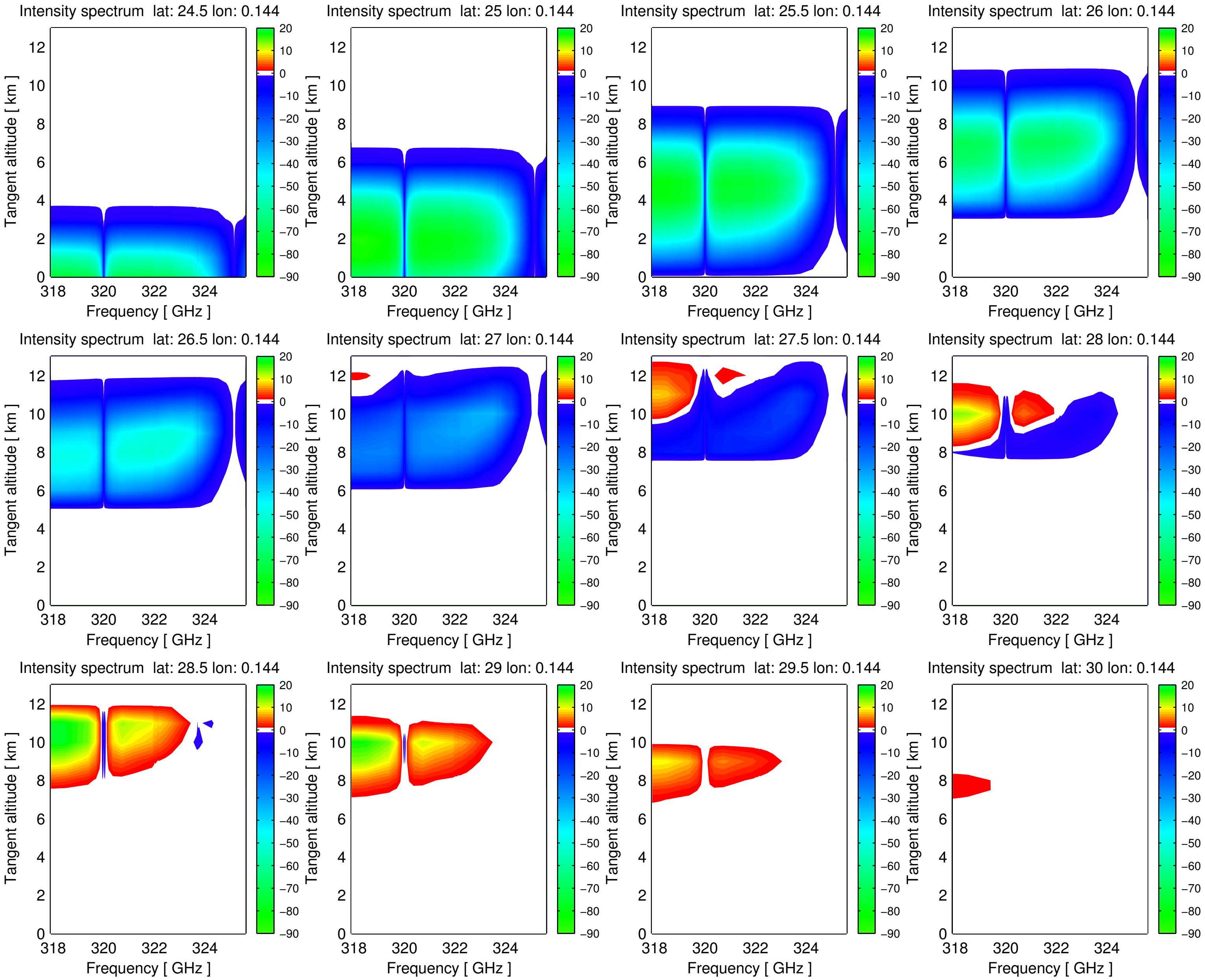
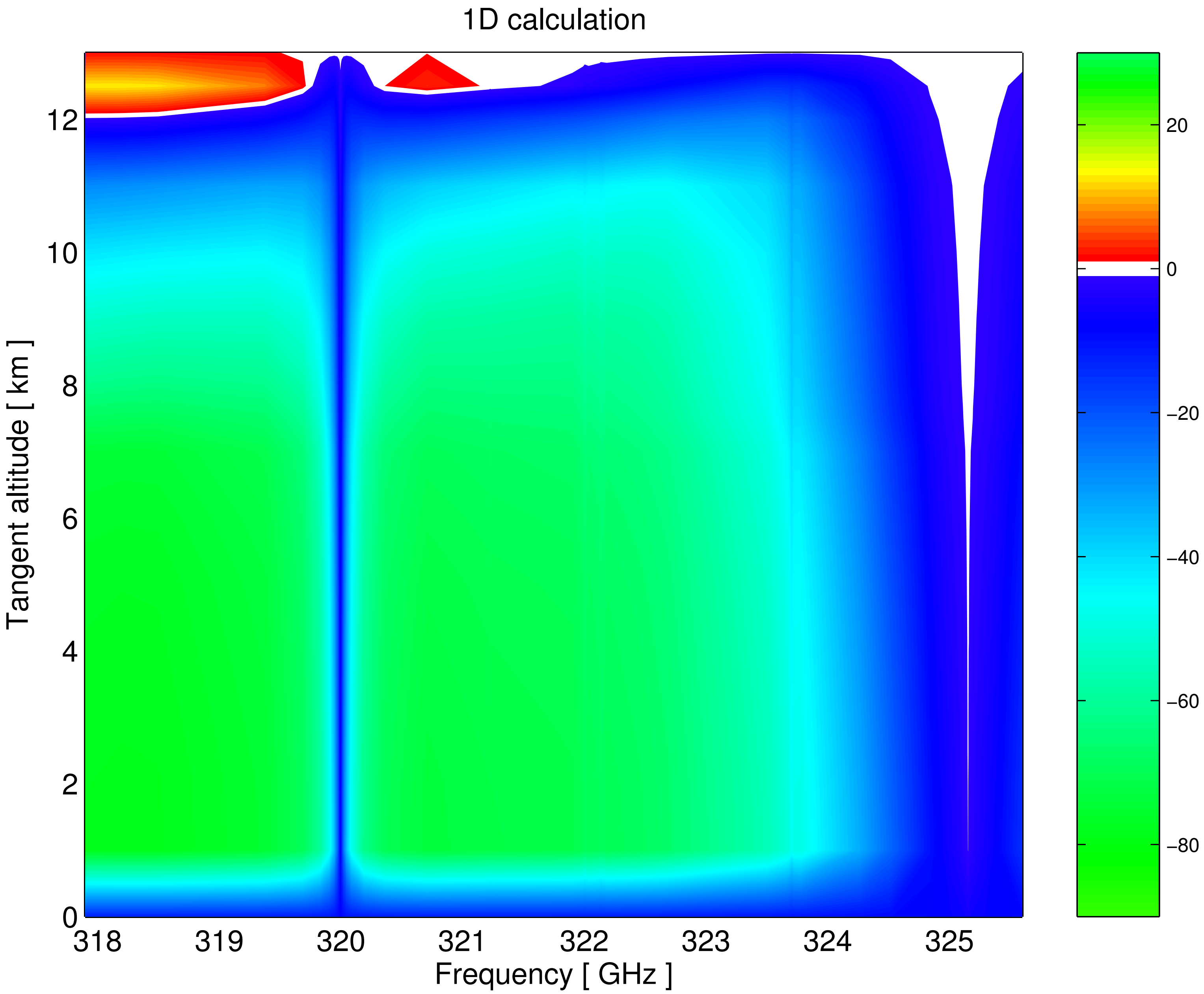


Figure by Claas Teichmann

3D simulations - Radiances



Equivalent 1D result



Conclusions

- Particle size and IMC strongly influence cloud effect
- Particle shape less important, but further study required to investigate
  - particle orientation
  - more extreme aspect ratios
- Frequency: largest effect in microwave window regions
- Cloud altitude: largest effect for high clouds
- 3D simulations: great differences between 3D and 1D for cloud of finite extent

Publications

- C. Emde, S. A. Buehler, P. Eriksson and Sreerekha T. R.
  The effect of cirrus clouds on microwave limb radiances
  Journal of Atmospheric Research, *in press 2004*

- C. Emde, S. A. Buehler, C. Davis, P. Eriksson, Sreerekha T. R. and C. Teichmann
  A polarized discrete ordinate scattering model for simulations of limb and nadir longwave measurements in 1D/3D atmospheres
  Journal of Geophysical Research, *submitted 2004*

- M. Höpfner and C. Emde
  Comparison of single and multiple scattering approaches for the simulation of limb-emission observations in the mid-IR
  Journal of Quantitative Spectroscopy and Radiative Transfer, *in press 2004*