Modelling the Effect of Cirrus on Microwave Limb Sounding Radiances

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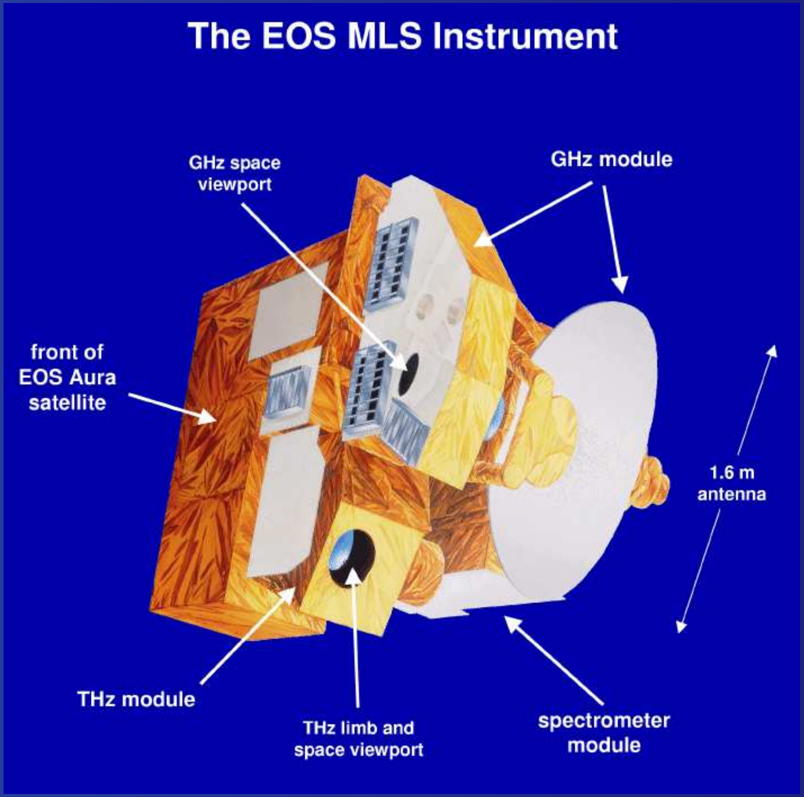
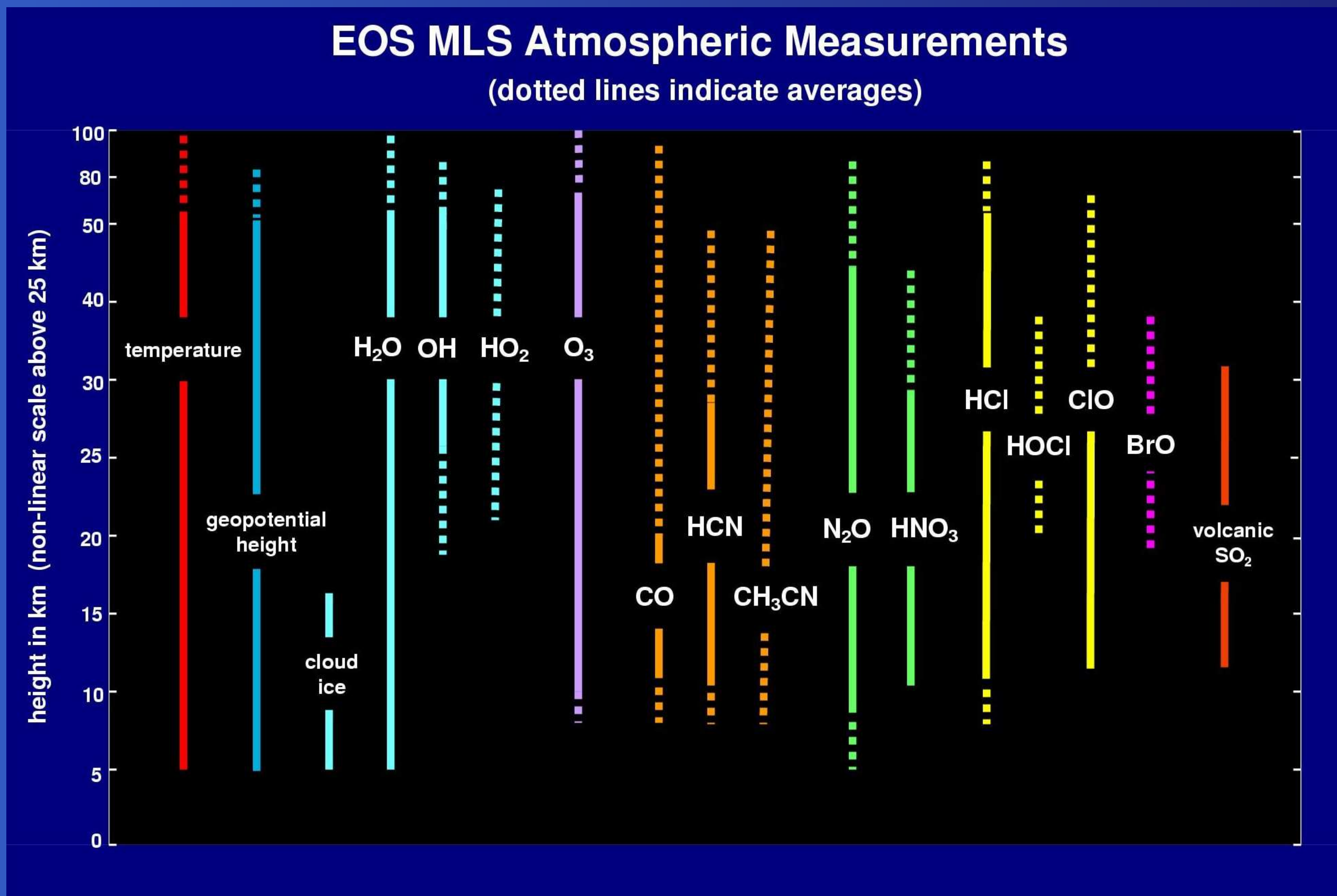
Motivation - EOS-MLS

- Sequel to UARS-MLS
- on AURA satellite - due for launch ~~January~~ June 2004
- mm and sub-mm wavelength heterodyne radiometers in 5 broad bands – 118 GHz, 190 GHz, 240 GHz, 640 GHz, 2.5 THz



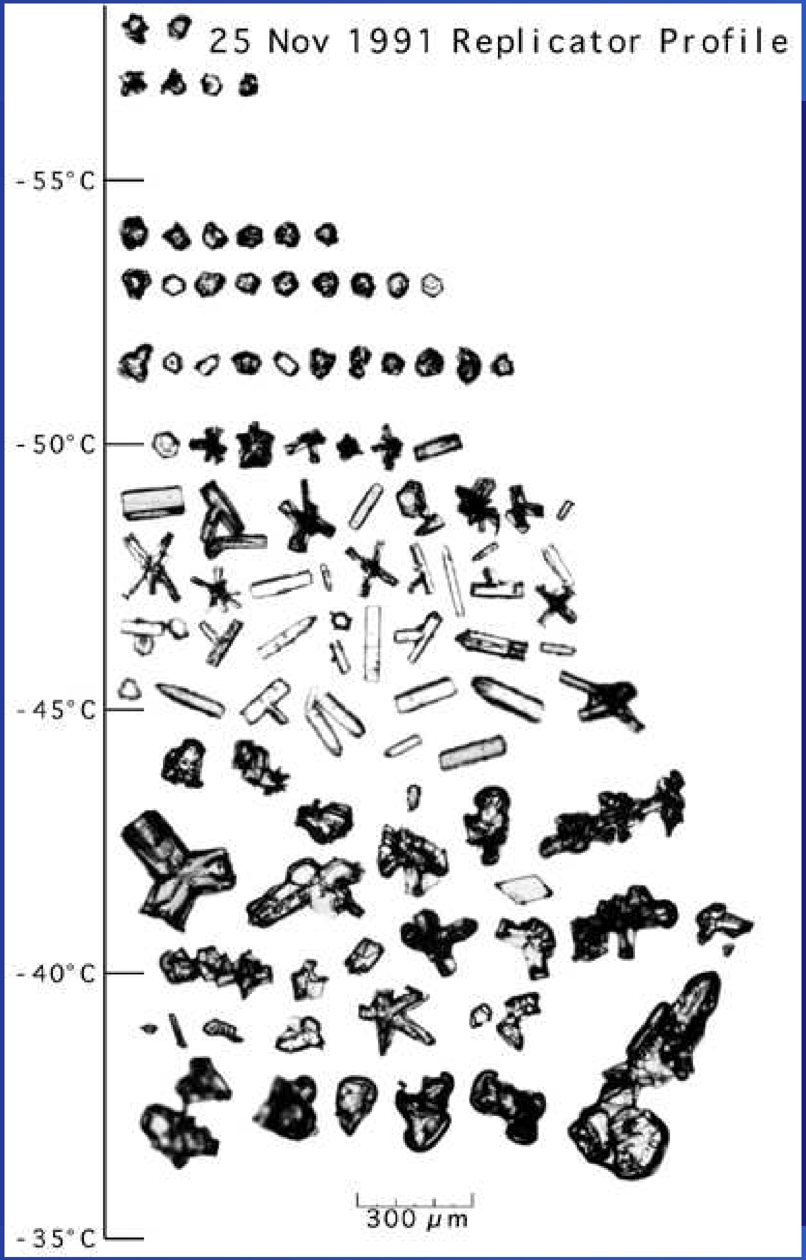

EOS MLS Atmospheric Measurements
(dotted lines indicate averages)
height in km (non-linear scale above 25 km)
100
80
50
40
30
25
20
15
10
5
0
temperature
geopotential height
cloud ice
H_2O
OH
HO_2
O_3
CO
HCN
CH_3CN
N_2O
HNO_3
HCl
HOCl
ClO
BrO
volcanic SO_2

Clouds and EOS-MLS

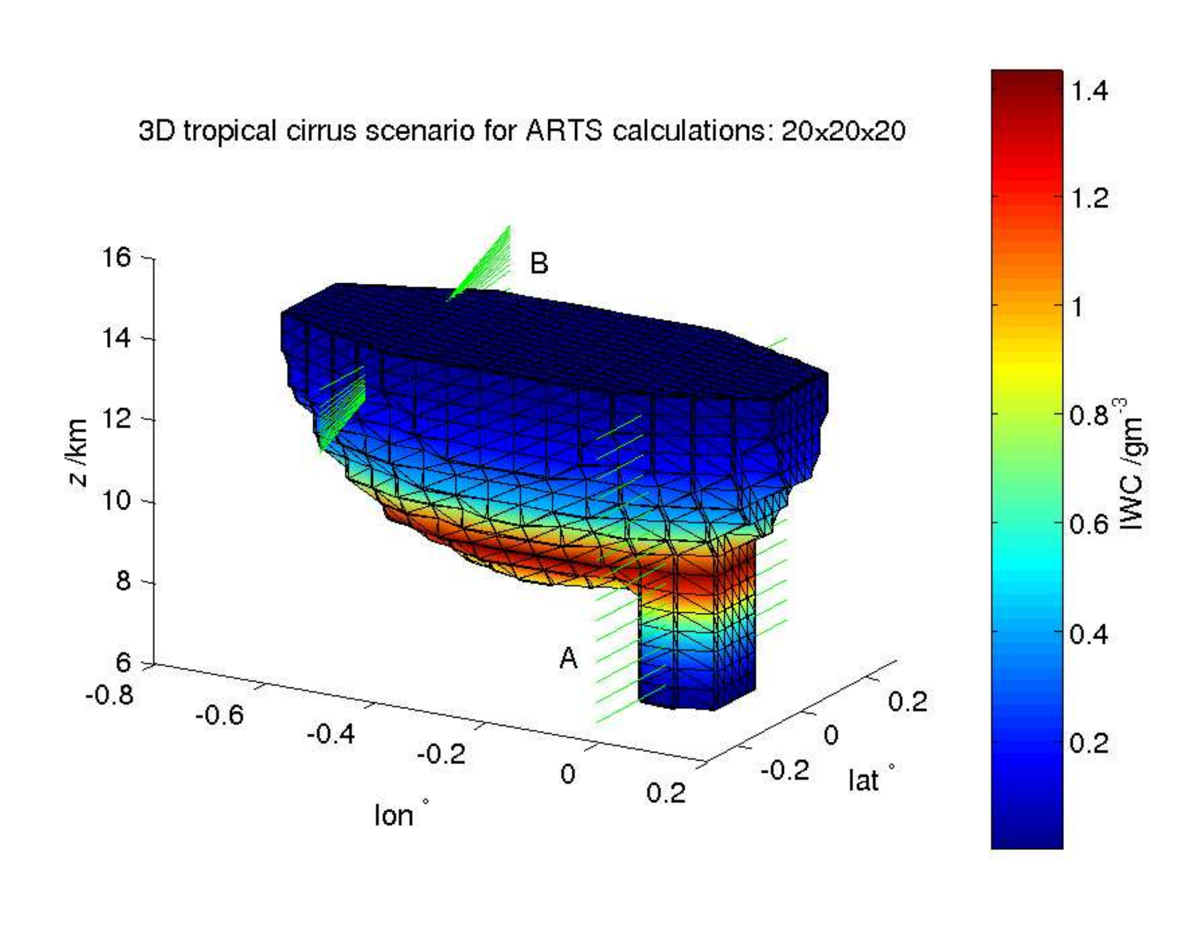
- Some tropospheric measurements will be influenced by cirrus.
- trace gas measurements degraded BUT some cloud information can be retrieved
- want maximise scientific return from EOS-MLS instrument
- Need Radiative Transfer Model to understand cloud effects

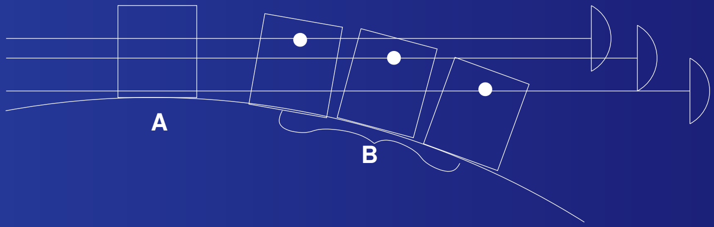
Requirements

- Existing EOSMLS RT models have been 1D and used Mie theory.
- Finite horizontal extent?, inhomogeneity?, non-spherical hydrometeors?
- Require 3D polarized radiative transfer model with spherical geometry



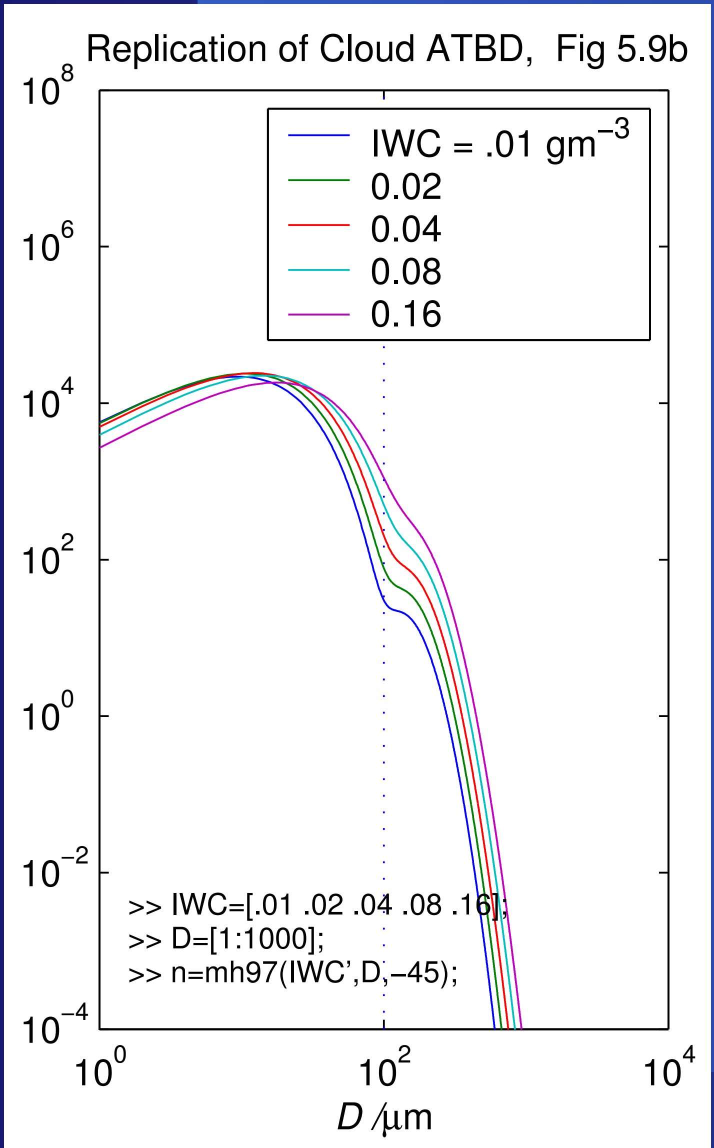
Example simulations





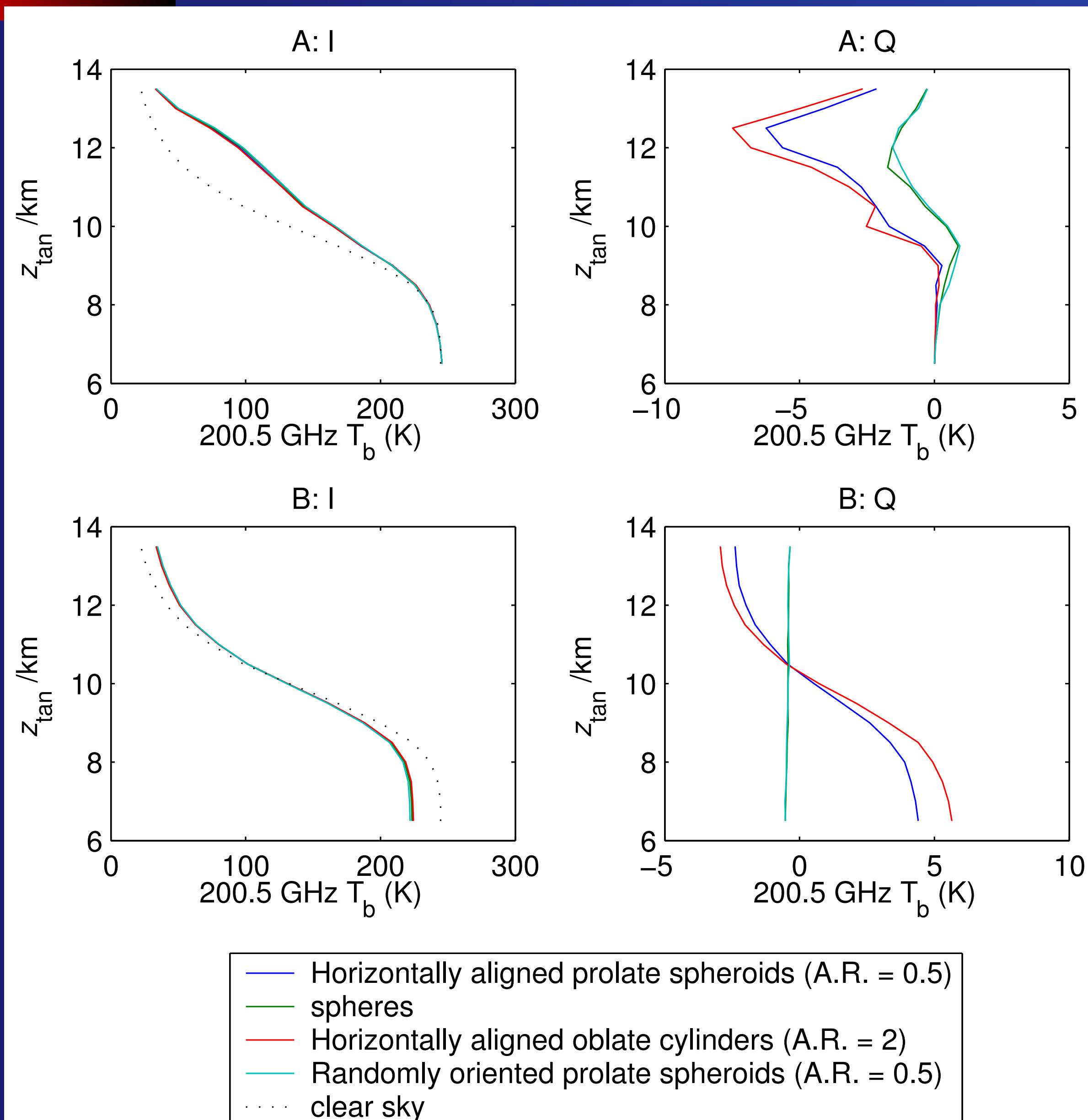
- 1D tropical atmospheric profile (with cloud)
- ice water content profile superimposed on an 'invented' 3D anvil cloud shape
- two schemes for placing sensor relative to the cloud

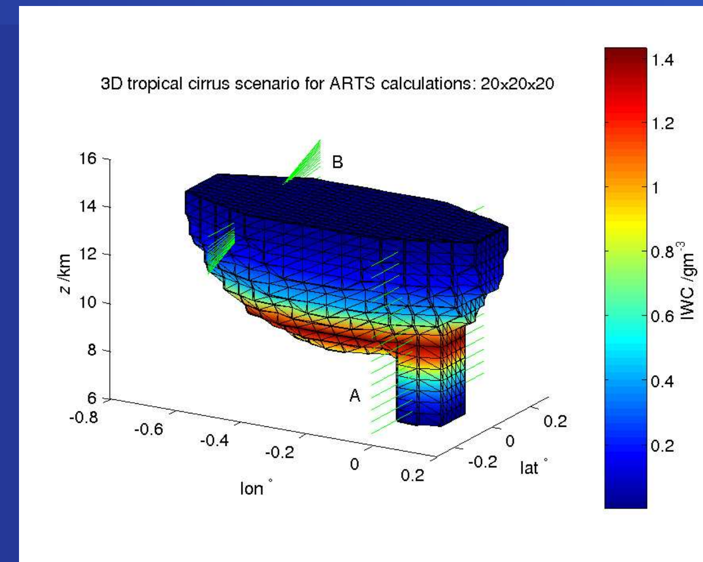
Microphysics



- Size distribution originates from measurement campaign in tropical outflows
- Consider 4 different particle shapes and orientation combinations:
  - Horizontally aligned prolate spheroids (AR = 0.5)
  - spheres
  - Horizontally aligned oblate cylinders (AR = 2)
  - Randomly oriented prolate spheroids (AR = 0.5)
- cloud is composed entirely of one of these - not realistic, but ...

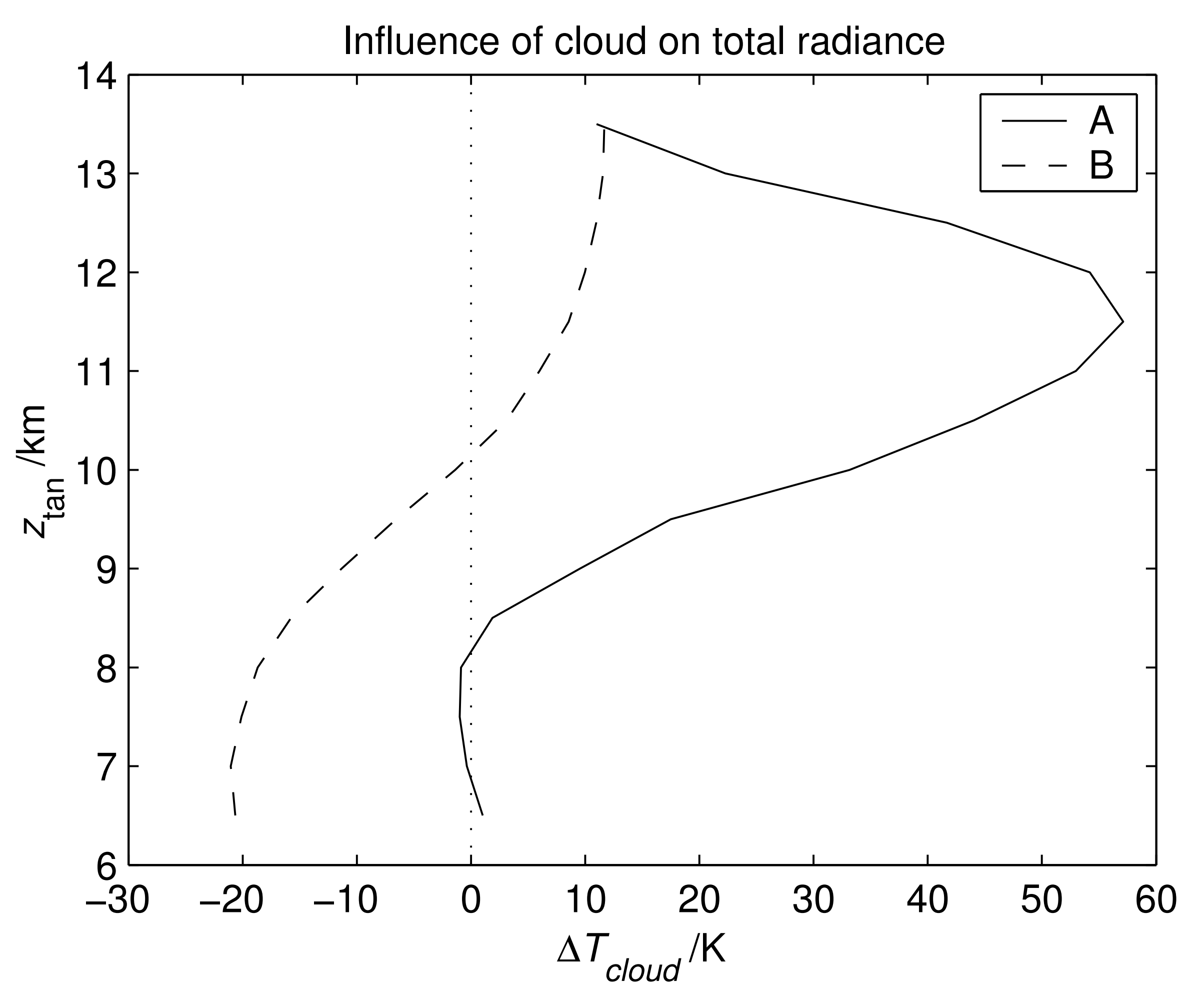
Results

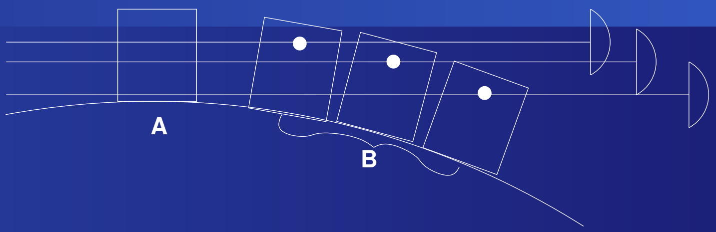




- $I = I_h + I_v, Q = I_v - I_h$
- different particles - not much effect on total radiance
- But significant polarization effect for horizontally aligned particles.
- sensor positioning scheme affects both I and Q.

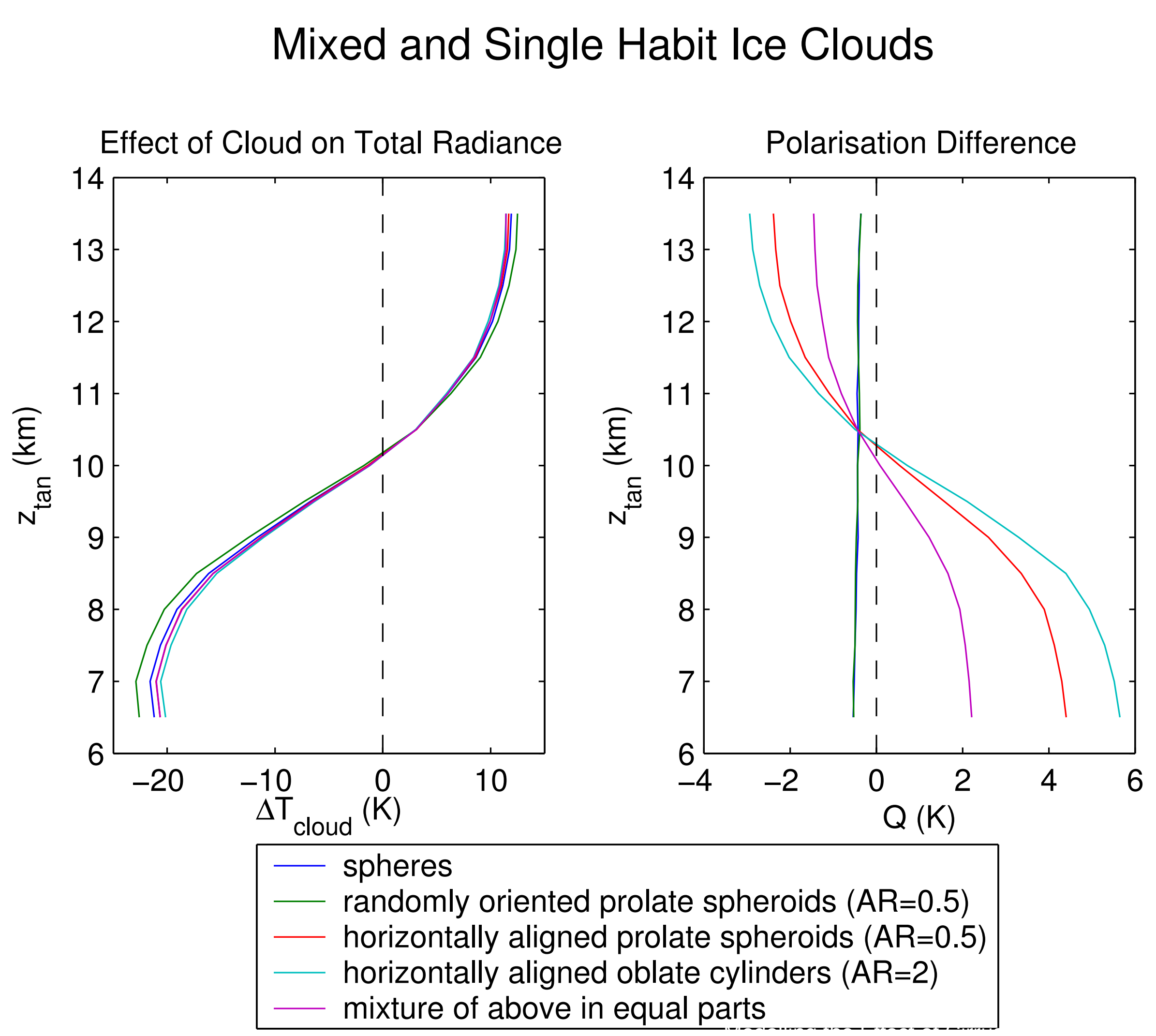
Cloud signal





- $\Delta T_{cloud} = I_{cloudy} - I_{clear}$
- different lines of sight hugely influencial on cloud signal
- ice water path and optical depth between cloud and sensor are the main factors.
- difference between A and B would be missed by a 1D RT model.

Mixed Habits



Tools

- PyARTS: a package of ARTS related Python modules. Preparation of atmospheric fields, calculation of hydrometeor scattering properties, and execution of cloudy sky ARTS simulations.
- ARTS: Reversed Monte Carlo RT module.

PyARTS

a package of ARTS related Python modules
Almost all you need for the preparation of atmospheric fields, scattering properties, and execution of cloudy sky ARTS simulations.
Main (high level) modules:

- arts_scat.py: Calculation of single scattering properties for ice and liquid water particles. Generation of scattering data files in ARTS XML format
- clouds.py: Higher level classes and functions dealing with 3D cloud structure and particle size distributions. Link between arts_scat and ARTS.
- PyARTS.py: Front-end for ARTS.

arts_scat.py : the SingleScatteringData class

- Analagous to arts class of the same name – optproperties.h
- but with member functions for the calculation of single scattering properties and generation of ARTS XML output – pydoc documentation
- an example
- Whats under the hood?
  - Compiled fortran extensions: tmatrix.so, tmd.so, REFICE.so, scatsubs.so
  - Also uses other python modules: artsXML, arts_math, arts_types,...

The clouds module

Two main classes:

- Cloud: main purpose is to generate 3D cloud fields and single scattering data files for ARTS simulations. Easily sub-classed (so far Anvil, Tower, Cumulonimbus)
- Hydrometeor: ice or liquid particles used to populate Cloud objects.

An example... pydoc documentation,

and what it looks like...

ARTS Reversed Monte Carlo module

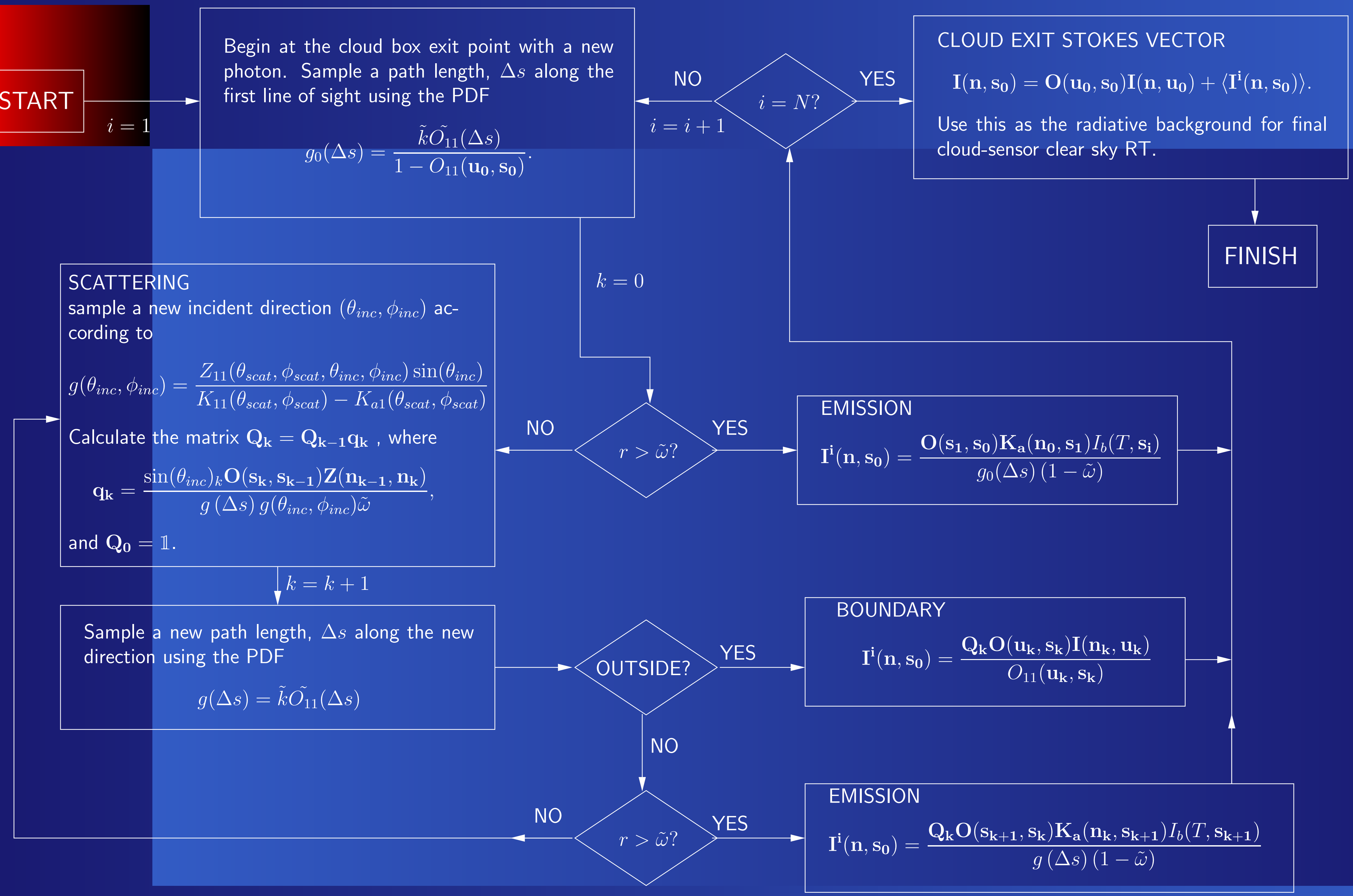
- Monte Carlo Integration with importance sampling

$$\int f dV = \int \frac{f}{g} g dV \approx \left\langle \frac{f}{g} \right\rangle \pm \sqrt{\frac{\langle f^2/g^2 \rangle - \langle f/g \rangle^2}{N}}$$

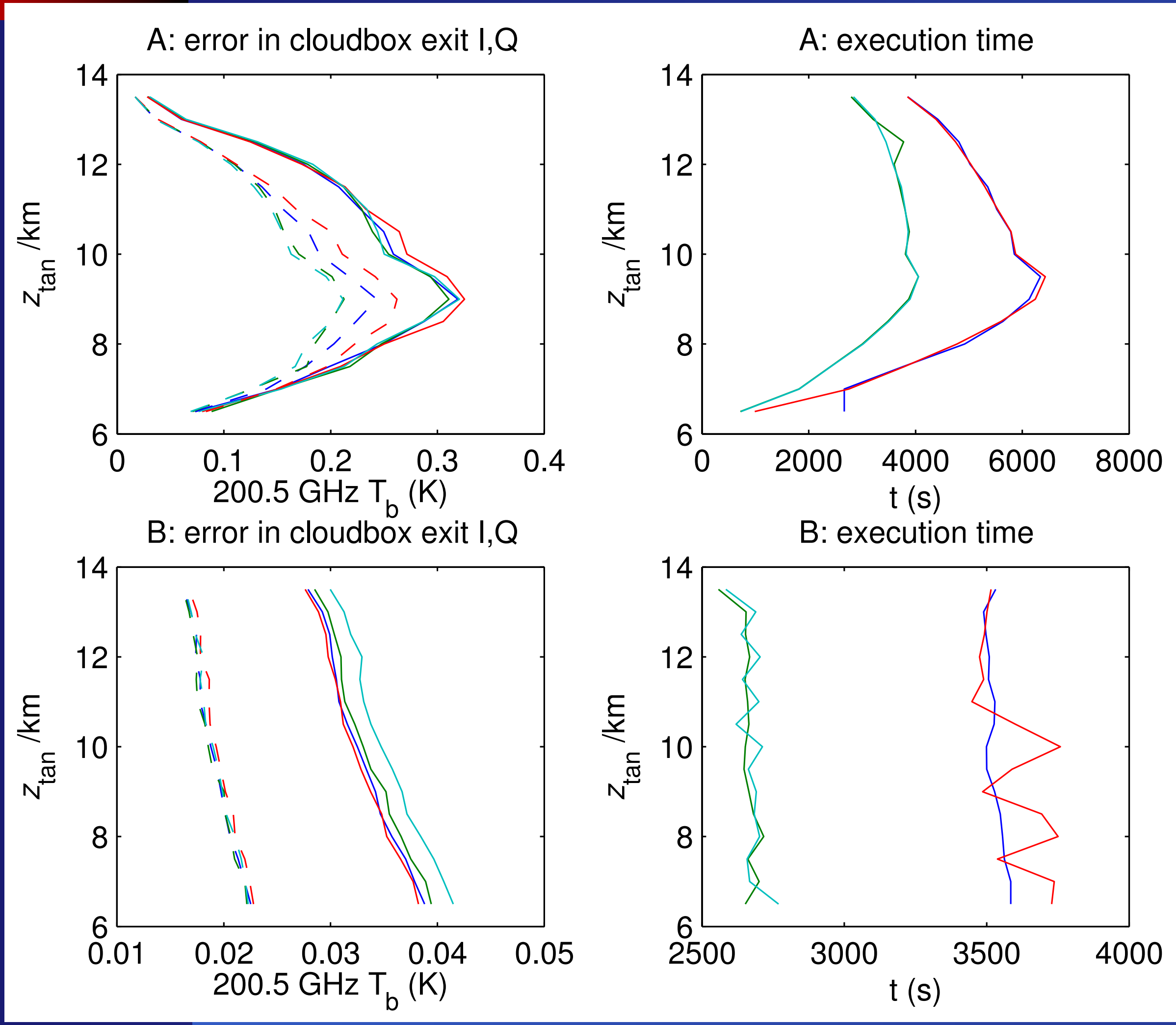
- Put VRTE in integral form

$$\mathbf{I}(\mathbf{n}, \mathbf{s_0}) = \mathbf{O}(\mathbf{u_0}, \mathbf{s_0})\mathbf{I}(\mathbf{n}, \mathbf{u_0}) + \int_{u_0}^{s_0} \mathbf{O}(\mathbf{s}', \mathbf{s_0}) \left(\mathbf{K_a}(\mathbf{n}) I_b(T) + \int_{4\pi} \mathbf{Z}(\mathbf{n}, \mathbf{n}')\mathbf{I}(\mathbf{n}')d\mathbf{n}' \right) ds'$$

- apply Monte Carlo integration to 2nd term.


START
$i = 1$
Begin at the cloud box exit point with a new photon. Sample a path length, Δs along the first line of sight using the PDF
$g_0(\Delta s) = \frac{\tilde{k}\tilde{O}_{11}(\Delta s)}{1 - O_{11}(\mathbf{u_0}, \mathbf{s_0})}.$
NO
$i = N?$
YES
$i = i + 1$
CLOUD EXIT STOKES VECTOR
$\mathbf{I}(\mathbf{n}, \mathbf{s_0}) = \mathbf{O}(\mathbf{u_0}, \mathbf{s_0})\mathbf{I}(\mathbf{n}, \mathbf{u_0}) + \langle \mathbf{I^i}(\mathbf{n}, \mathbf{s_0}) \rangle.$
Use this as the radiative background for final cloud-sensor clear sky RT.
FINISH
$k = 0$
SCATTERING
sample a new incident direction $(\theta_{inc}, \phi_{inc})$ according to
$g(\theta_{inc}, \phi_{inc}) = \frac{Z_{11}(\theta_{scat}, \phi_{scat}, \theta_{inc}, \phi_{inc}) \sin(\theta_{inc})}{K_{11}(\theta_{scat}, \phi_{scat}) - K_{a1}(\theta_{scat}, \phi_{scat})}$
Calculate the matrix $\mathbf{Q_k} = \mathbf{Q_{k-1}} \mathbf{q_k}$, where
$\mathbf{q_k} = \frac{\sin(\theta_{inc})_k \mathbf{O}(\mathbf{s_k}, \mathbf{s_{k-1}}) \mathbf{Z}(\mathbf{n_{k-1}}, \mathbf{n_k})}{g\,(\Delta s)\; g(\theta_{inc}, \phi_{inc})\tilde{\omega}},$
and $\mathbf{Q_0} = \mathbb{1}$.
NO
$r > \tilde{\omega}?$
YES
EMISSION
$\mathbf{I^i}(\mathbf{n}, \mathbf{s_0}) = \frac{\mathbf{O}(\mathbf{s_1}, \mathbf{s_0}) \mathbf{K_a}(\mathbf{n_0}, \mathbf{s_1}) I_b(T, \mathbf{s_i})}{g_0(\Delta s)\,(1 - \tilde{\omega})}$
$k = k + 1$
Sample a new path length, Δs along the new direction using the PDF
$g(\Delta s) = \tilde{k}\tilde{O}_{11}(\Delta s)$
OUTSIDE?
YES
BOUNDARY
$\mathbf{I^i}(\mathbf{n}, \mathbf{s_0}) = \frac{\mathbf{Q_k} \mathbf{O}(\mathbf{u_k}, \mathbf{s_k}) \mathbf{I}(\mathbf{n_k}, \mathbf{u_k})}{O_{11}(\mathbf{u_k}, \mathbf{s_k})}$
NO
NO
$r > \tilde{\omega}?$
YES
EMISSION
$\mathbf{I^i}(\mathbf{n}, \mathbf{s_0}) = \frac{\mathbf{Q_k} \mathbf{O}(\mathbf{s_{k+1}}, \mathbf{s_k}) \mathbf{K_a}(\mathbf{n_k}, \mathbf{s_{k+1}}) I_b(T, \mathbf{s_{k+1}})}{g\,(\Delta s)\,(1 - \tilde{\omega})}$

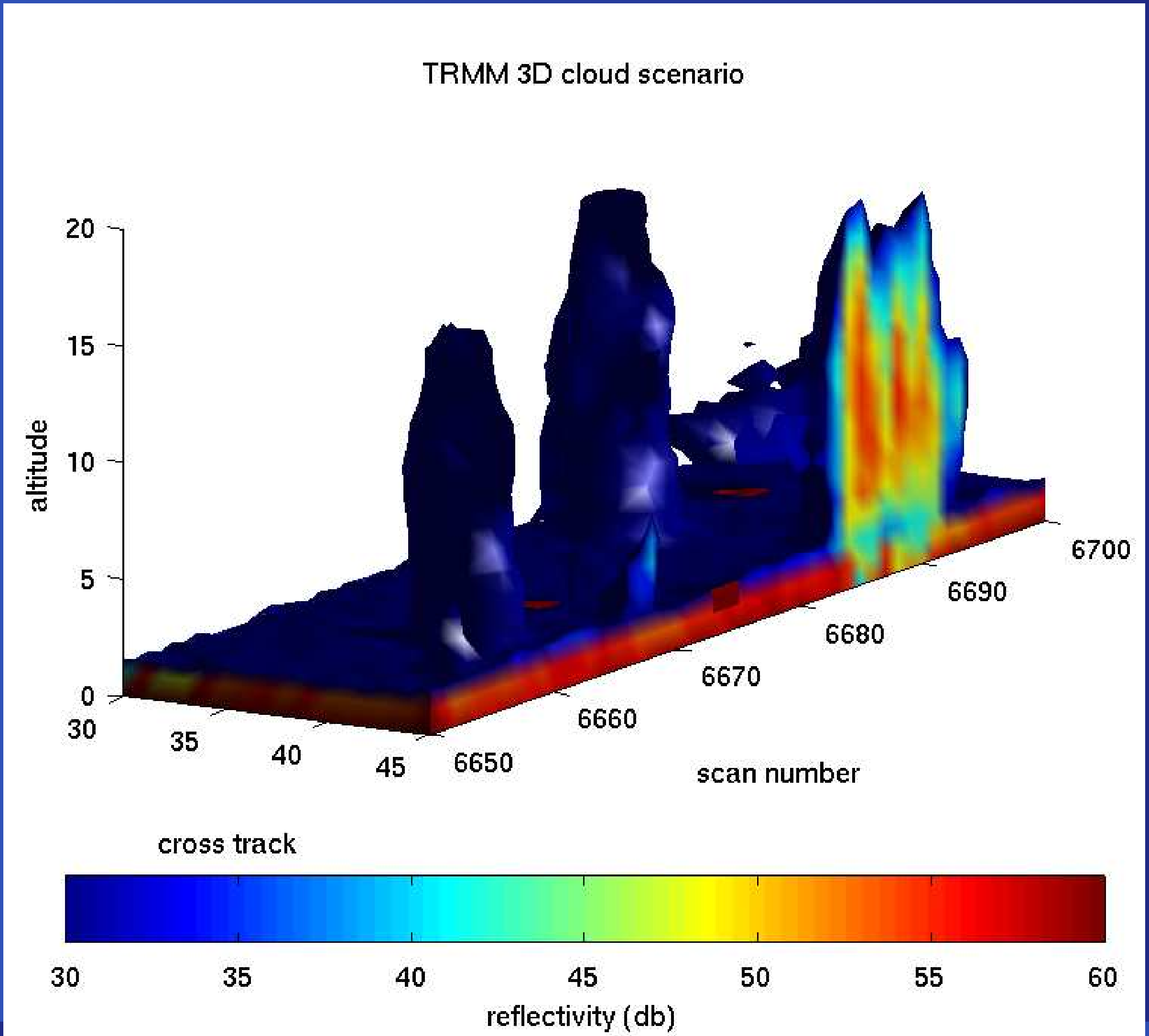
Performance



- 3D polarized radiative transfer is expensive - How expensive?
- error and CPU time depend on ice water path
- polarization difference has a higher relative error
- oriented particles cost more (non-diagonal extinction matrices and scattering properties have extra angular dependencies)

Summary

- software is capable of simulating microwave radiation in detailed 3D cloud fields, with non spherical particles
- have shown that significant effects will be missed by a 1D unpolarized RT model.
- have shown that MLS is particularly sensitive to horizontally oriented particles
- still need to implement sensor characteristics (FOV, antenna function)
- Waiting for some better 3D scenarios: ESA RT study, A–train, in the mean time ...


TRMM 3D cloud scenario
altitude
20
15
10
5
0
30
35
40
45
cross track
6650
6660
6670
6680
6690
6700
scan number
30
35
40
45
50
55
60
reflectivity (db)