Polarized radiative transfer including multiple scattering – Methods and applications

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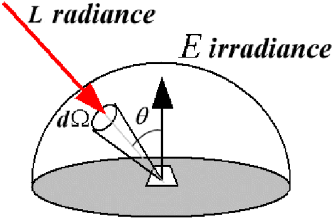
ARTS workshop, Kristineberg, Sweden, 7–10 June 2010

Outline

Radiation quantities



$$E = \int L \cos\theta \, d\Omega$$

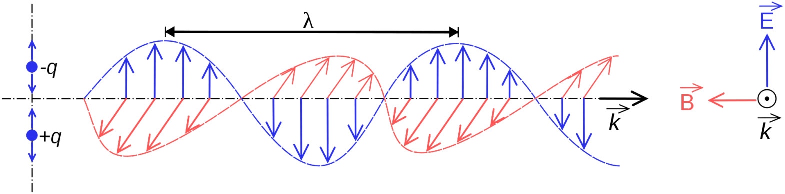
Adapted from http://escience.anu.edu.au

- Radiance
  - Unit: W/(m^2 nm sr) or W/(m^{2}s^{-1} sr)
  - Required for remote sensing application, instruments measure specific direction.
- Irradiance
  - Unit: W/(m^2 nm) or W/(m^{2}s^{-1})
  - Radiance integrated over half space, required to compute radiative forcing (climate models).

Polarisation in the atmosphere - rainbow

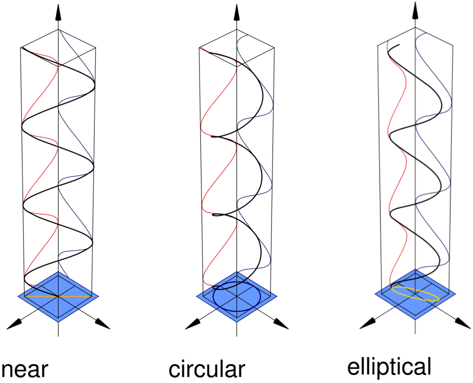
Polarisation in the atmsophere - rainbow

Description of polarization - The Stokes vector



Definition:

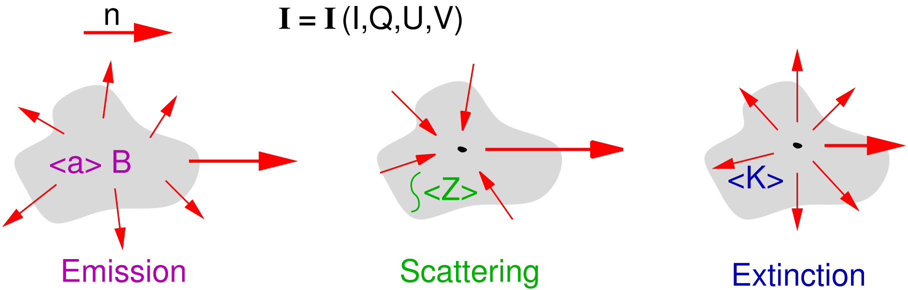
$$
\begin{aligned}
I &= \langle E_l E_l^* + E_r E_r^* \rangle \\
Q &= \langle E_l E_l^* - E_r E_r^* \rangle \\
U &= \langle E_l E_r^* + E_r E_l^* \rangle \\
V &= i \langle E_l E_r^* - E_r E_l^* \rangle
\end{aligned}
$$



The vector radiative transfer equation

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

$\Rightarrow$ Differential equation for Stokes vector $\mathbf{I}$



Cloud particles and trace gases

- **Single scattering properties** (SSP) of cloud particles: $\langle \mathbf{K^p} \rangle$, $\langle \mathbf{a^p} \rangle$, $\langle \mathbf{Z^p} \rangle$
- **Computation methods/theories** for SSP:
  - Rayleigh scattering (particle size (r) $\ll$ wavelength (λ))
  - Lorentz-Mie theory (spherical particles)
  - T-matrix method ($r \approx \lambda$, aspherical, rotationally symmetric particles) (*Mishchenko et. al.*, 2002)
  - Discrete dipole approximation ($r \approx \lambda$, arbitrarily shaped particles)
  - Geometrical optics approximation ($r \gg \lambda$)
- **Gas absorption coefficients**: $\langle \mathbf{K^g} \rangle$, $\langle \mathbf{a^g} \rangle$
  - Calculated based on HITRAN/JPL spectral line catalogs

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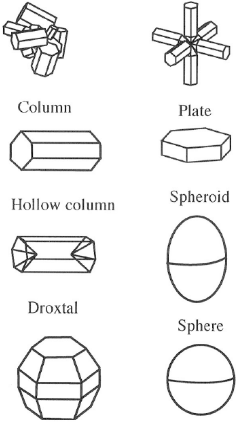
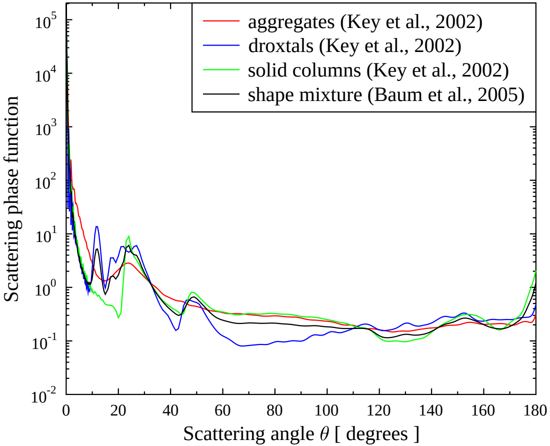
Ice particle scattering



Paricle shapes (Yang, 2005)



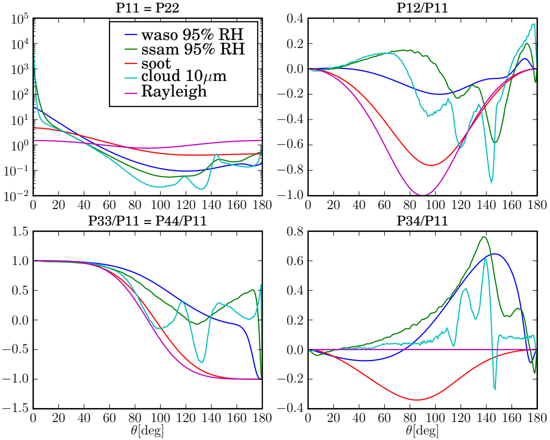
Halo at 22° scattering angle

22° halo and sundog

www.dewbow.co.uk

Scattering phase matrix

- Solar radiation and emitted radiation unpolarized (incoherent superposition of electromagnetic waves)
- Polarisation by scattering in the atmosphere (Molecules, clouds, aerosols)

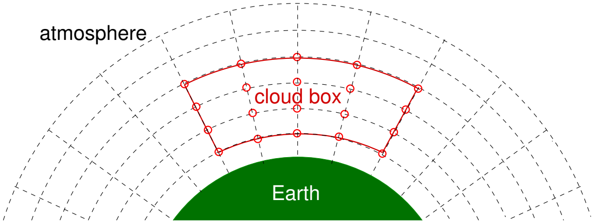


Discrete Ordinate ITerative Method (ARTS-DOIT)

- Multiple scattering model for thermal radiative transfer
- Special features
  - polarization
  - spherical geometry
  - oriented particles
- Applications:
  - Cloud remote sensing in down-looking and limb geometry
  - Calculate impact of clouds on occultation measurements

ARTS-DOIT: The cloud box

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

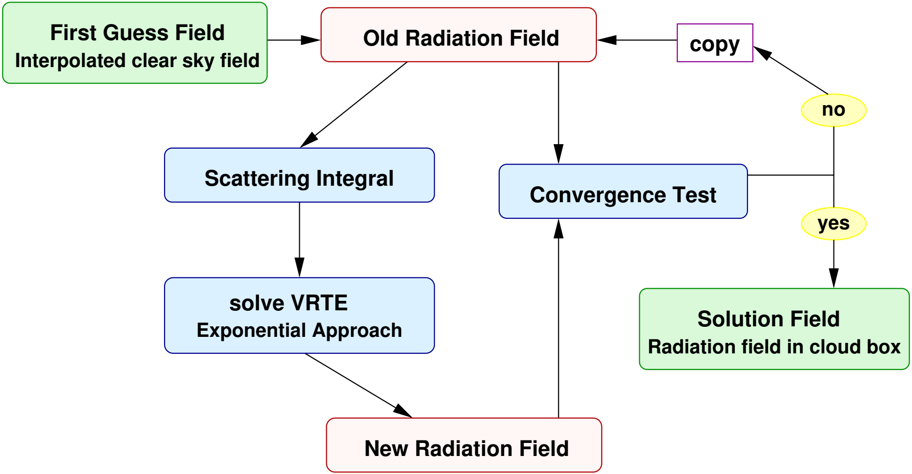


Radiation field:

Set of Stokes vectors for all combinations of positions and directions:

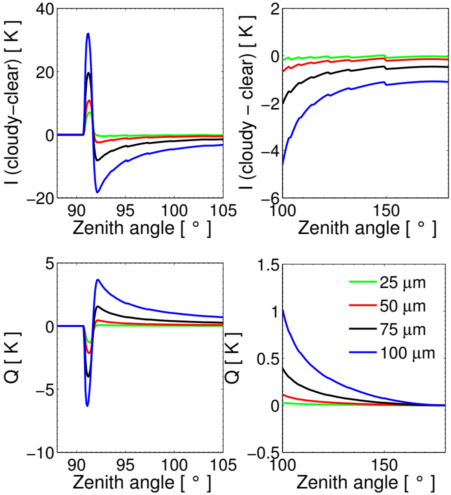
$$\mathbf{I} = \mathbf{I}(p, \alpha, \beta, \theta, \phi)$$

ARTS-DOIT: Schematic of iterative method



Details in *Emde et. al.*, JGR, 2004

Example - DOIT calculation

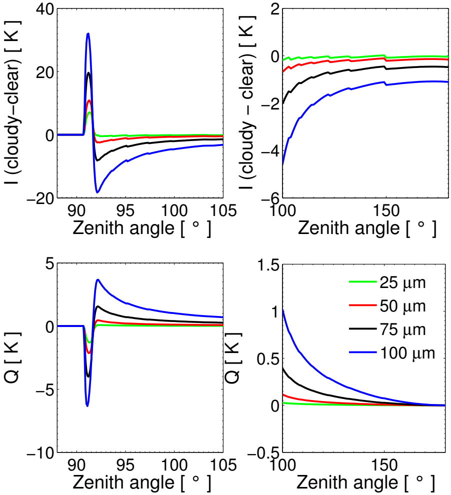


From *Emde et. al.*, JGR, 2004.

Setup:

- 1D atmosphere
- Cloud altitude: 10–12 km
- Prolate spheroids (aspect ratio 0.5)
- Horizontally aligned
- Sensor at 13 km altitude
- Frequency: 318 GHz

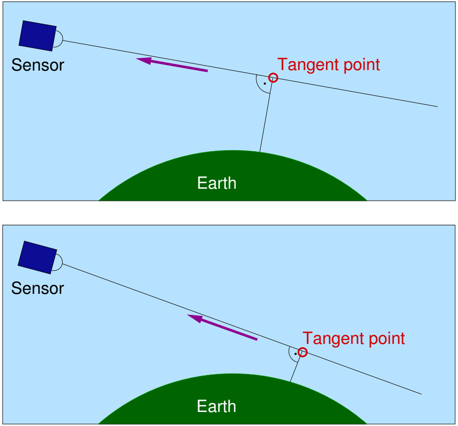
Example - DOIT calculation



From *Emde et. al.*, JGR, 2004.

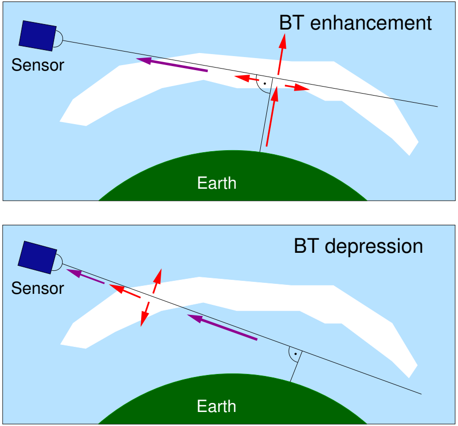
- Intensity I ($I_v + I_h$)
  - enhancement at angles close to 90°
  - otherwise depression
- Polarization difference Q ($I_v - I_h$)
  - negative close to 90°
  - otherwise positive
- Cloud effect on intensity and on polarization increases with particle size.

Cloud effect in limb geometry



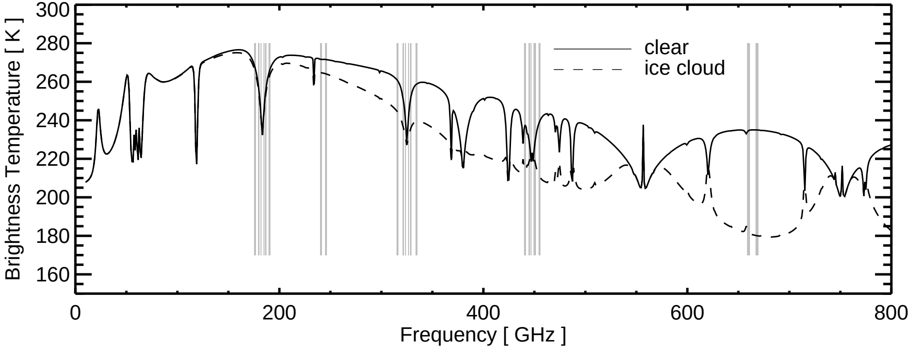
- Main source of radiation from tangent point.

Cloud effect in limb geometry



- Main source of radiation from tangent point.
- Two effects:
  - Tangent point inside cloud: Scattering into Line Of Sight (LOS) dominates
    $\Rightarrow$ BT enhancement.
  - Tangent point below cloud: Scattering away from LOS dominates
    $\Rightarrow$ BT depression.

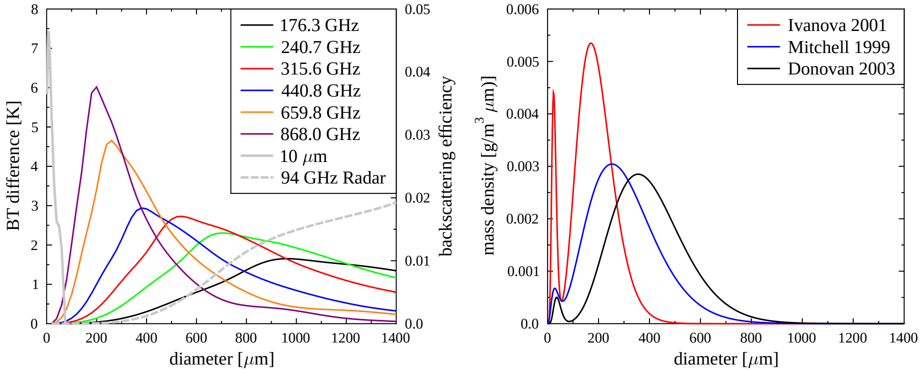
CloudIce – Submillimeter passive satellite radiometer



Channels selected for the CloudIce instrument

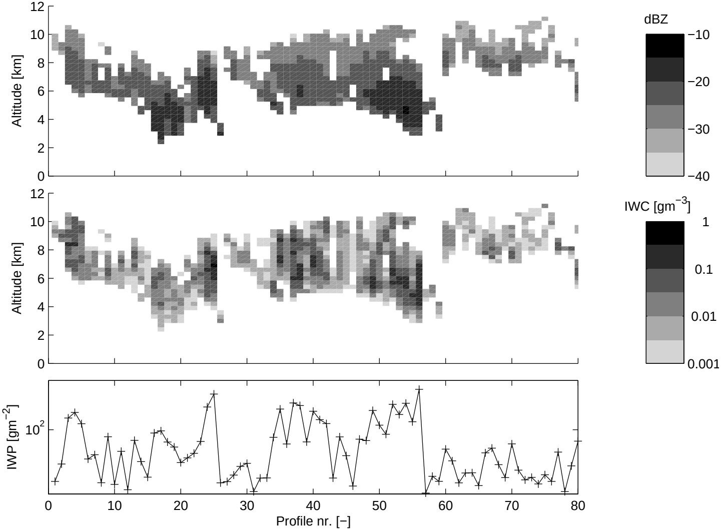
from Bühler et al., QJRMS, 2007

CloudIce – Sensitivity to particle size



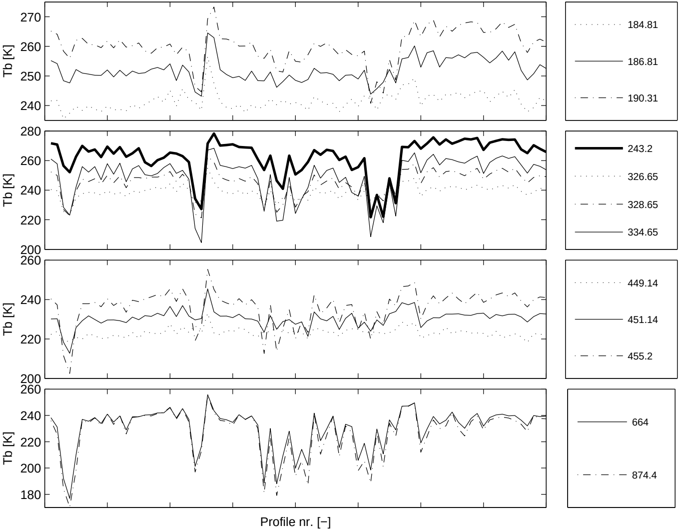
Left: Simulations for narrow gamma distributions.

Retrieval database



IWC and IWP profiles derived from radar and in-situ data
from Rydberg et al., QJRMS, 2007

CloudIce simulations



Independent pixel approximation

from Rydberg et al., QJRMS, 2007

Short overview of DISORT

- Multiple scattering model for solar and thermal radiative transfer (Stamnes et al., 1988)
- very well tested and validated
- Approximations:
  - 1D plane-parallel geometry
  - no polarization
  - randomly oriented particles
- Features:
  - second order intensity correction (needed to simulate rainbow or halo)
  - method is much faster than DOIT for thick clouds, because no iterations required
  - very accurate

Monte Carlo Methods

- Generation of random numbers ξ for a given probability density function $p(x)$
- Normalized cumulative distribution $F(x)$:

$$F(x) = \frac{\int_{x_{\min}}^{x} p(x')dx'}{\int_{x_{\min}}^{x_{\max}} p(x')dx'} \quad (1)$$

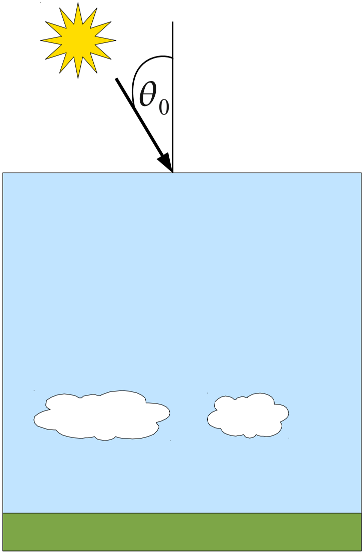
- Random number r, uniformly distributed between 0 and 1:

$$F(\xi) = r \quad (2)$$

- Random number ξ:

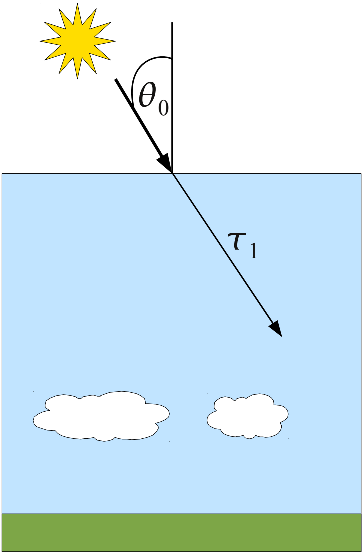
$$\xi = F^{-1}(r) \quad (3)$$

1. Generate photon



- Photon direction determined by sun position (solar zenith angle θ_0, solar azimuth angle ϕ_0)
- Starting position at top of atmosphere determined randomly

2. Sample the pathlength



- Absorption is included by photon weight

$$w_a = \exp(-\int \beta_{\rm abs} ds)$$

- Total absorption coefficient (molecules, aerosols, clouds)

$$\beta_{\rm abs} = \sum \beta_{\rm abs,i}$$

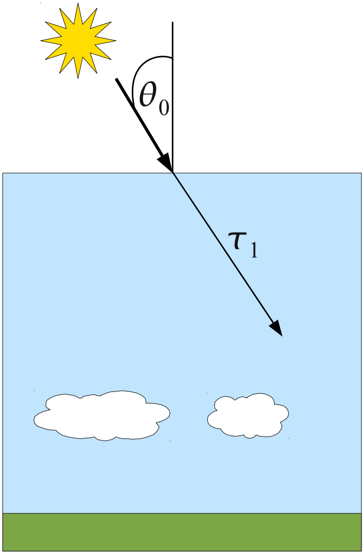
- PDF for free pathlength of photon

$$P_s = \exp(-\int_0^s \beta_{\rm sca} ds')$$

- Total scattering coefficient (molecules, aerosols, clouds)

$$\beta_{\rm sca} = \sum \beta_{\rm sca,i}$$

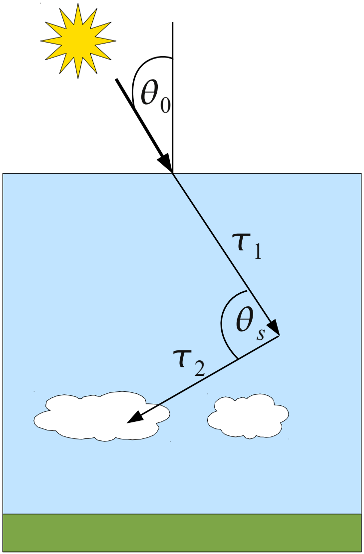
3. Interaction



- use random number $r \in [0, 1]$ to decide whether the photon interacts with a cloud droplet/particle, aerosol or molecule

$$\frac{\sum_{i=1}^{n_j-1} \beta_{\mathrm{sca,i}}}{\beta_{\mathrm{sca}}} < r \leq \frac{\sum_{i=1}^{n_j} \beta_{\mathrm{sca,i}}}{\beta_{\mathrm{sca}}}$$

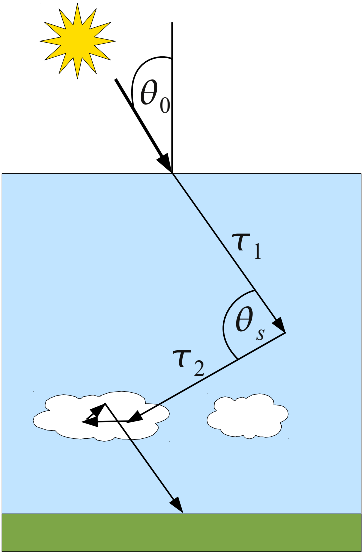
4. Scattering direction



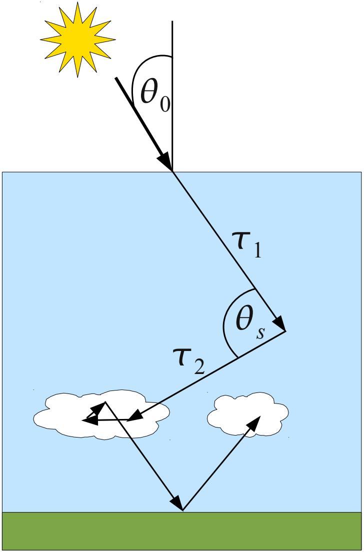
- Use phase function (P_{11}) as PDF for the scattering angle and a random angle between 0 and 2π for the azimuth direction
- Scattered Stokes weight vector (Importance sampling method)

$$\mathbf{I}^{\text{sca}} = P_{11}^{-1}\mathbf{L}(\sigma_2)\mathbf{P}\mathbf{L}(\sigma_1)\mathbf{I}^{\text{inc}} = P_{11}^{-1}\mathbf{Z}\mathbf{I}^{\text{inc}}$$

5. Multiple scattering

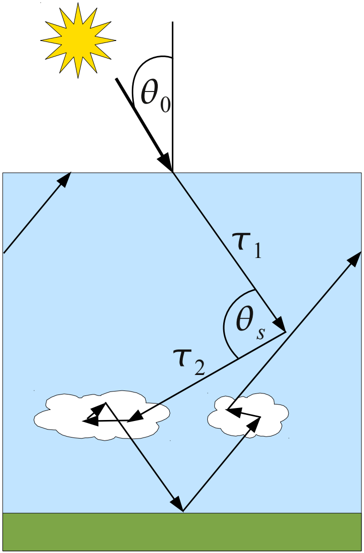


6. Surface reflection

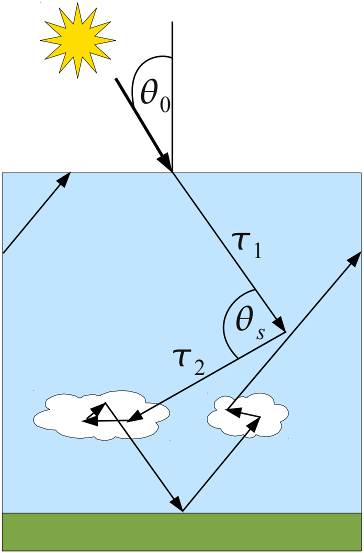


- Lambertian surface, PDF $P(\theta) = cos(\theta)$
- Bidirectional reflectance distribution function, BPDF($\theta_{\text{inc}}, \phi_{\text{inc}}, \theta_{\text{ref}}, \phi_{\text{ref}}$), matrix for polarized RT

7. Periodic boundary condition

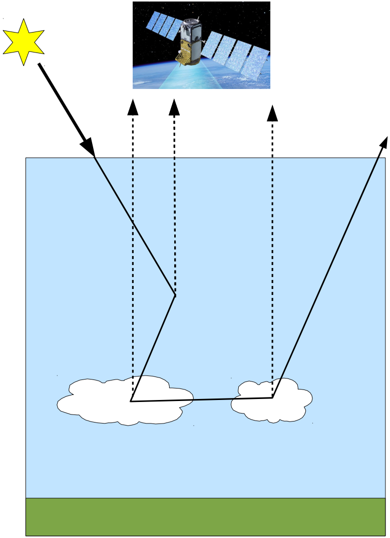


8. Count the photon



- Photon is counted when it reaches TOA or the surface
- Reflected irradiance: $R = N_{TOA}/N_{tot}$
- Transmitted irradiance $T = N_{BOA}/N_{tot}$
- How to compute radiances?

Directional (local) estimate method



- At each scattering point the probability that the photon is scattered into the direction of the sensor is calculated

$$w = w_0 P(\theta_p) \frac{\exp(-\tau_{\mathrm{ext}})}{\cos(\theta_d)}$$

- Sum of weights yields radiance in required direction
- Details in Marshak and Davis, 2005

Radiative transfer model MYSTIC

Monte carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres

Mayer [2009], *Emde and Mayer* [2007]

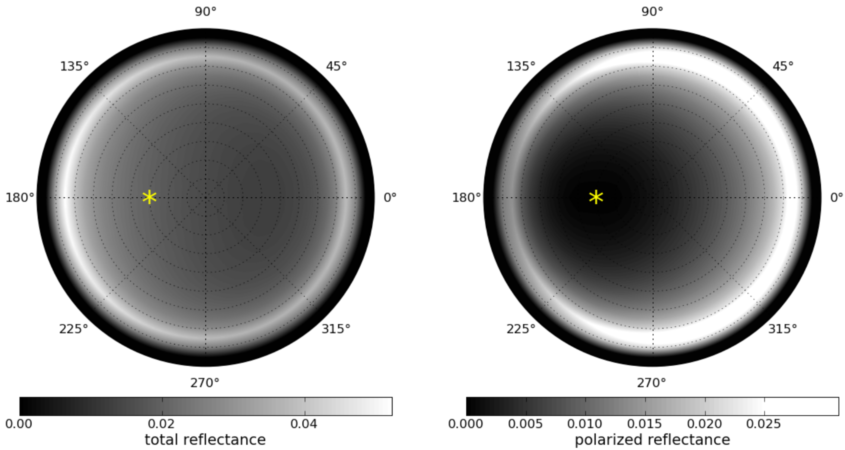
- Polarization fully integrated, Stokes vector may be calculated for arbitrary atmospheres with molecules, aerosols, and clouds (*Emde et al., 2010*)
- Combination of several methods to make code accurate and efficient:
  - Local estimate method + variance reduction
  - Importance sampling
  - Forward and backward mode
  - 1D or 3D simulations
  - spherical geometry in 1D mode
- Validation:
  - Benchmark results (*Coulson et al., 1960*; *Wauben and Hovenier, 1992*)
  - Polarized radiance measurements (*Blumthaler et al., 2008*)

libRadtran

Mayer and Kylling, ACP, 2005
http://www.libradtran.org

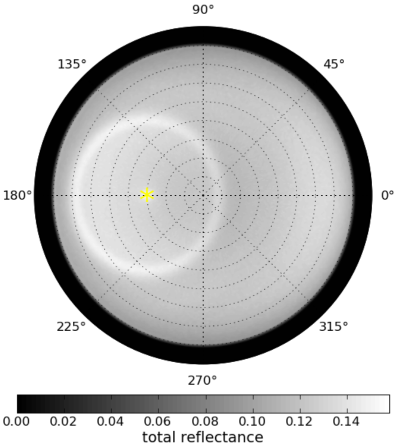
- Spectrally resolved in the UV/visible, line-by-line, quasi-spectral (LOWTRAN), and correlated-k in the solar and thermal infrared
- User-friendly flexible interface to various 1D and 3D solvers, including *disort*, *sdisort*, *twostr*, *polradtran* (Evans, 1991), (*MYSTIC*)
- Mostly open source
- Validated in various model-model and model-measurement intercomparisons
- Includes several parameterizations of cloud and aerosol optical properties

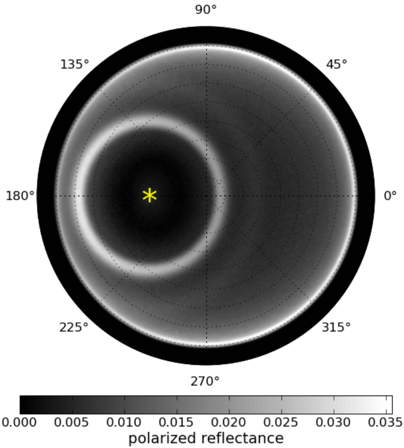
Clear sky reflectance



- Total and polarized reflectance at 500 nm (top of atmosphere)
- Spherical geometry, therefore reflectance is very small at angles above 80° (tangent point above ≈ 20 km)

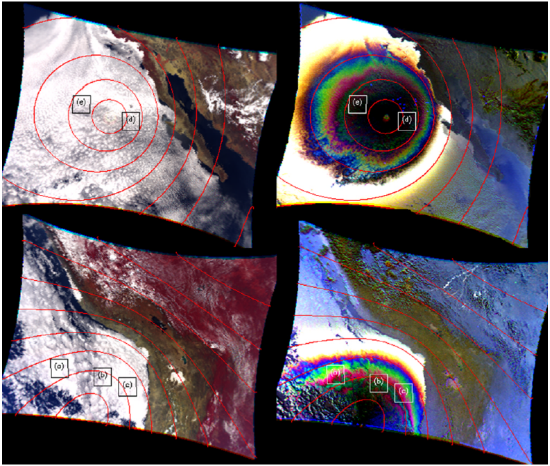
Cloud reflectance ($\tau = 10$)



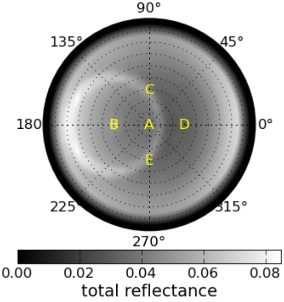


- Total and polarized reflectance at 500 nm (top of atmosphere)
- Rainbow shows large polarization

Satellite image - POLDER



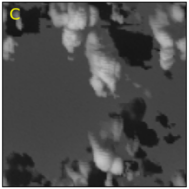
Left: radiance I, Right: polarized radiance Q
False color composite of 3 channels [0.87, 0.67, 0.49] μm, from Bréon (2005).



1D cloud layer

Cumulus Clouds

$\phi_v = 90^\circ$

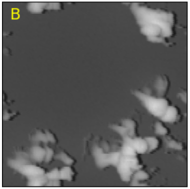


solar zenith angle: 30°

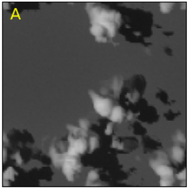
viewing zenith angle: 30°

wavelength: 500 nm

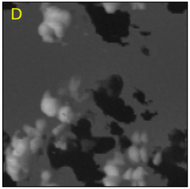
$\phi_v = 180^\circ$



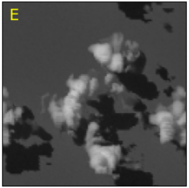
$\phi_v = 10^\circ$, $\theta_v = 0^\circ$



$\phi_v = 0^\circ$



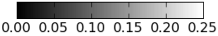
$\phi_v = 270^\circ$

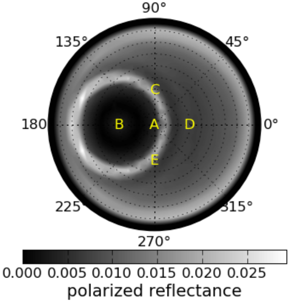


cloud resolution: 60 m

sample resolution: 47 m

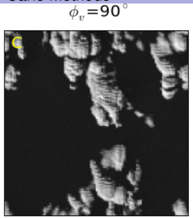
total reflectance





1D cloud layer

Cumulus Clouds



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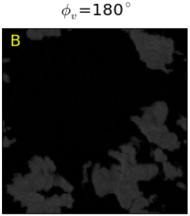
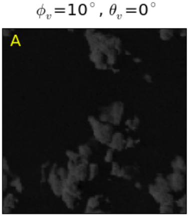
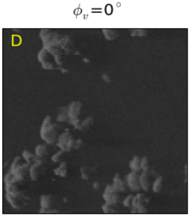
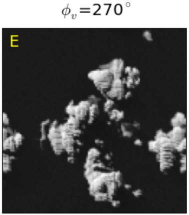
wavelength: 500 nm





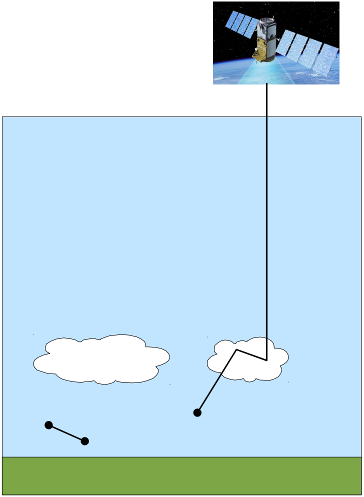




cloud resolution: 60 m

sample resolution: 47 m

Backward photon tracing

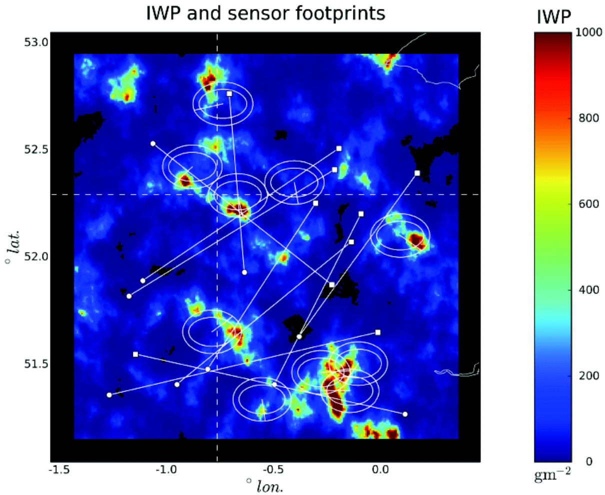


- Forward Monte Carlo extremely inefficient for thermal radiative transfer
- Reciprocity principle allows to trace photon backwards starting from the sensor until their point of emission

Monte Carlo Method - ARTS-MC

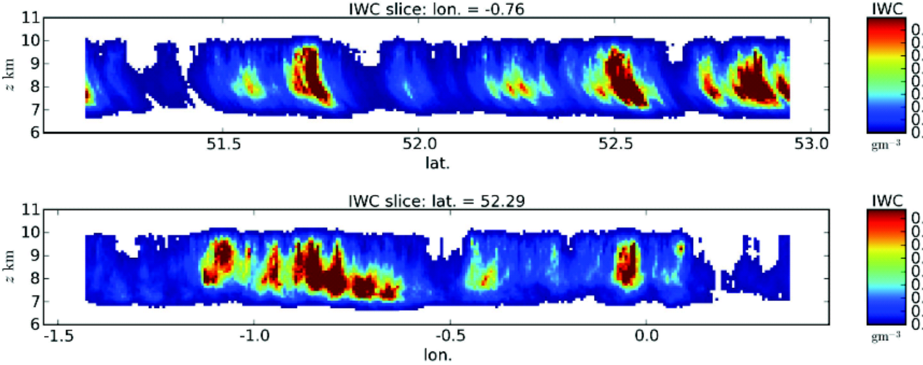
- 3D radiative transfer solver for the thermal spectral range (Davis et al., 2005)
- Specials:
  - oriented particles
  - polarisation
  - backward tracing method
  - spherical geometry
- Applications:
  - Investigate 3D effects in cloud remote sensing
  - Limb sounding (including inhomogeneous clouds)

3D cloud scenario



Scenario generated based on radar data and stochastical method.
Software by R. Hogan. [Davis et al., ACP 2007]

Ice water content slices from 3D scenario

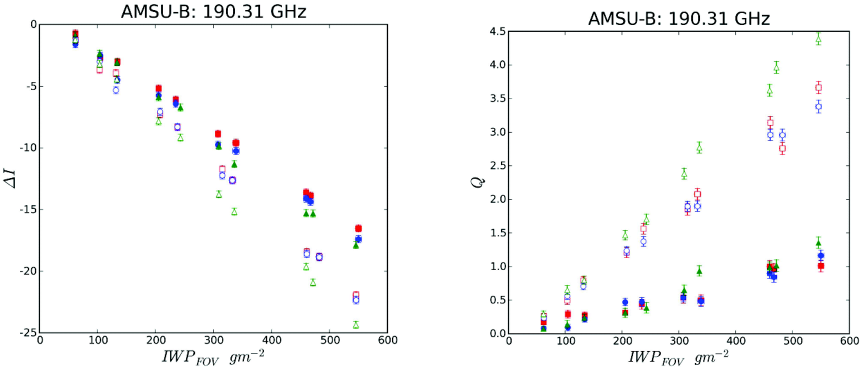


resolution: 780m $\times$ 780m $\times$ 110m

Grid size: 256 $\times$ 256 $\times$ 64

from Davis et al., ACP 2007

Results for AMSU-B Channel 20



3D – red squares, IPA – blue circles, 1D – green triangles
aspect ratio 1.3 – solid, aspect ratio 3.0 – hollow

from Davis et al., ACP 2007

Summary of ARTS scattering modules

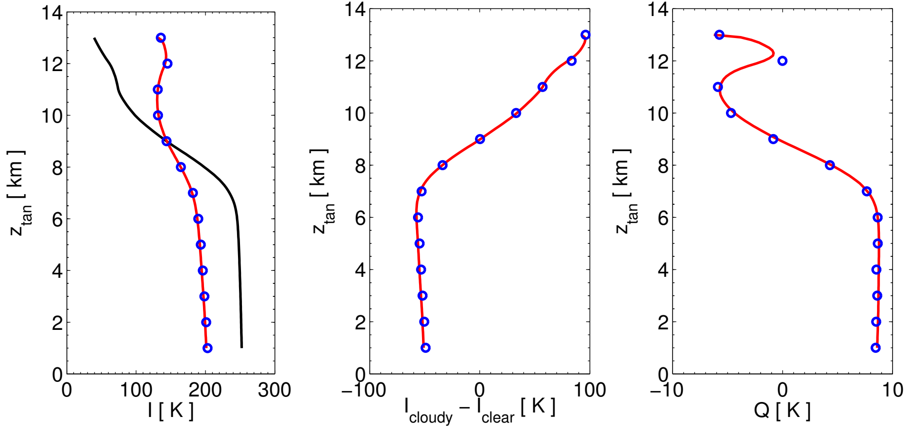
- Two modules: Discrete Ordinate and Monte Carlo
- Spherical model atmosphere: 1D and 3D
- Polarization included
- Particle shapes: rotationally symmetric (spheroids, cylinders, plates)
- Orientations: Horizontally aligned, random

ARTS
The Atmospheric Radiative Transfer Simulator

`http://www.sat.ltu.se/arts`

Additional tools: PyARTS, ATMLAB

Comparison between DOIT and MC



clear sky

DOIT

Monte Carlo

Frequency: 230 GHZ

Conclusions and discussion

- What is included in ARTS:
  - Two modules to calculate polarized RT with multiple scattering (MC and DOIT), unique methods because they work in spherical geometry and with oriented particles
  - Depending on the application, the user has to decide which method to use
- What is missing in ARTS?
  - Parameterization of cloud optical properties (e.g. Hong et al. (2008), pre-calculated optical properties))?
  - Fast solver for 1D plane-parallel atmosphere (to simulate CloudIce)?
  - Very fast (twostream) solver to compute OLR?