Simulation and Study of the Stokes Vector in a Precipitating Atmosphere

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Outline

• Part I: Background
  • Passive Microwave Remote Sensing
  • Wave Polarization
  • Scattering Theory and Radiative Transfer
    • The T-Matrix

• Part II: Radiative Transfer Model
  • Precipitation Profiles
  • Gas Absorption
  • Scattering Calculations

• Part III: Results
Part I
Microwave Radiometry

- Passively measure microwave energy
  - Absorption, emission, and reflection
- Application in geophysical retrievals
  - e.g., Precipitation, wind
- Use range of frequencies
  - Simultaneously solve interdependent variables
- Strong heritage
  - SMMR, SSM/I
- WindSat
  - 6.8, 23.8 GHz v & h
  - 10.7, 18.7, 37.0 GHz fully polarimetric
Geophysical Retrievals

- **Gas**
  - Unpolarized absorption/emission in microwave region
  - Primarily water vapor
- **Hydrometeors**
  - Non-spherical particles
  - Absorption/emission and scattering frequency dependent
  - Polarizing
- **Sea surface temperature**
  - Low frequency effects
- **Ocean surface wind vector**
  - Speed and direction dependence
    - Small directional signal
  - Polarized emission and reflection
Precipitation Interference

- **Emission**
  - Large compared to other ocean parameters
  - Polarized

- **Scattering**
  - Reduces measured surface emission signal
  - Alters incident polarization

- **Absorption**
  - Related to emission
  - Reduces measured surface emission signal

- **Surface perturbations**
  - Changes small scale surface structure
  - Little information available
Geophysical Models

- **Empirical models**
  - Requires large sets of training data
  - Only conditioned for cases included in training data
    - Can lack physical insight
  - Relatively simple to implement

- **Physics-based models**
  - Broad application
  - More difficult to implement
Wave Polarization

- Orientation of electric (and magnetic) fields
- Effected by particle shape or surface structure
  - Drop shape
  - Wind direction
- Defined by Stokes vector
- Polarization
- Orientation
- Ellipticity
Stokes Vector

\[ \mathbf{I} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \frac{1}{2} \sqrt{\frac{\epsilon}{\mu}} \begin{bmatrix} E_{0v} E_{0v}^* + E_{0h} E_{0h}^* \\ E_{0v} E_{0v}^* - E_{0h} E_{0h}^* \\ -E_{0v} E_{0h}^* - E_{0h} E_{0v}^* \\ j(E_{0h} E_{0v}^* - E_{0v} E_{0h}^*) \end{bmatrix} = \frac{1}{2} \sqrt{\frac{\epsilon}{\mu}} \begin{bmatrix} E_{0v} E_{0v}^* + E_{0h} E_{0h}^* \\ E_{0v} E_{0v}^* - E_{0h} E_{0h}^* \\ -2\text{Re}(E_{0v} E_{0h}^*) \\ 2\text{Im}(E_{0v} E_{0h}^*) \end{bmatrix}. \]
Coordinate System
Orientation

\[ \tan 2\gamma = -\frac{U}{Q} \]

Ellipticity

\[ \tan 2\psi = -\frac{V}{\sqrt{Q^2 + U^2}}. \]
• **Amplitude scattering matrix**

\[
\begin{bmatrix}
E_v^s(r\hat{n}) \\
E_h^s(r\hat{n})
\end{bmatrix} = \frac{e^{jk_1r}}{r} \begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}
\begin{bmatrix}
E_{0v}^i \\
E_{0h}^i
\end{bmatrix}
\]

• **4 x 4 scattering matrix**
  • Intensity and polarization of scattered wave

• **4 x 4 extinction matrix**
  • Intensity and polarization loss of wave

• **Absorption vector**
  • Difference of extinction and scattering
Planck Emission

- Emission due to heat
  - All real bodies absorb and emit
- Emission of body directly related to absorption
  - Body temperature times emissivity
  - Interface between two media
Radiative Transfer Equation

• Describes flow of energy through media
• Collection of particles considered homogeneous medium
• Includes emission, extinction and scattering

\[
\frac{d}{ds} I(r, \hat{n}, \omega) = - N_0(r) \langle K(r, \hat{n}, \omega) \rangle I(r, \hat{n}, \omega) \quad \text{extinction}
\]
\[
+ N_0(r) \langle K_a(r, \hat{n}, \omega) \rangle I_{T_b}(T, \omega) \quad \text{emission}
\]
\[
+ N_0(r) \int_{4\pi} d\hat{n}' \langle Z(r, \hat{n}, \hat{n}', \omega) \rangle I(r, \hat{n}, \omega) \quad \text{scattering}
\]
• Analytical relationship between incident and scattered energy
• Solved using extended boundary condition method
  • Internal field excited by incident radiation
  • Scattered field resultant of internal field
• Ideally suited for rotationally symmetric particles
• Efficient FORTRAN algorithms developed by Michael Mishchenko
Randomly oriented particles

- Isotropic, mirror symmetric medium
- Extinction matrix diagonal
  - No polarization
- Scattering matrix block diagonal
  - I and Q separate from U and V
- Scalar emission
- Spherical particles
  - Special case
  - Diagonal scattering matrix
Horizontally Aligned Particles

- Not isotropic
- Some symmetries
  - No azimuthal dependence
- Extinction block diagonal
- I and Q separate from U and V along incidence direction
- Off-angle scattering breaks separation between I/Q and U/V
- Polarized emission
Goddard Cumulus Ensemble

- Simulates evolution of convective systems
  - 3 spatial dimensions
  - Time evolution
- Water content profiles
  - Rain
  - Snow
  - Graupel
  - Cloud Liquid
  - Cloud Ice
- Temperature, pressure and humidity information
- Does not represent melting layer
- TOGA-COARE array event
  - 22 February 1993
- Courtesy of Chris Kummerow and Jody Crook
3D Rain Profiles
3D Snow Profiles
Water Content

- Convert water content to particle number density
  - Falling hydrometeors described by Marshall-Palmer type (inverse exponential) distribution

  \[ N(D) = N_0 e^{-\lambda D} \]

  where
  - \( D \) = Drop diameter
  - \( N_0 \) = Intercept
  - \( \lambda \) = Slope
  - \( N(D) \) = Number density over \( D + dD \)

- Modified gamma used for cloud liquid
- McFarquhar and Heymsfield for cloud ice
Aspect Ratio

- Rain drops flatten due to drag
  - Closely approximated by oblate spheroid
  - Horizontally Aligned
- Snow particle shape related to size and formation
  - Oblate spheroid “1st order” approximation
  - Horizontally aligned in average
  - Intricate structure $\ll$ incident microwave wavelength

$$\frac{1}{R_A} = c_0 + c_1 D - c_2 D^2 + c_3 D^3 - c_4 D^4$$

$D = \text{Equivalent-volume-sphere radius}$
Complex Permittivity

- Liquid water
  - Double-Debye equation
    - Empirical fit
  - Real and Imaginary frequency and temperature dependent
- Ice
  - Empirical Fit
  - Real constant
  - Imaginary frequency and temperature dependent
  - Maxwell-Garnett mixing for inclusion of air
Scattering Parameters

- Mishchenko T-matrix code
  - Public domain scattering code
- Computationally efficient
- Aspect ratio limited
  - Computational accuracy
    - Only able to process in double precision
  - Particle size
    - Limit for rain beyond largest physical drop size
  - Imaginary component of refractive index
- Separate codes for randomly oriented and aligned particles
  - Spheres considered randomly oriented particles
Gas Absorption

• Water vapor line at 22.235 GHz
  • Noticeable effect at 18.7 GHz
  • Small at 10.7 and 37 GHz
  • Rosencranz PWR 98 Model
  • Present in trace amounts (< 3%)

• Oxygen continuum
  • Second most abundant constituent of air (~21%)
  • Most noticeable at 37 GHz
  • Small at 18.7 GHz
  • Rosencranz PWR 93 Model

• Nitrogen
  • Negligible at simulated frequencies
  • Most abundant constituent (~78%)
Volume Mixing Ratio

- Ratio of constituent partial pressure to air
- Constant for nitrogen (0.781) and oxygen (0.209)
- Related to water vapor saturation pressure (Flatau) and humidity

\[ p_s = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5 + a_6 T^6 \]

where

\[ T = \text{Temperature [Celcius]} \]

\[ p_{H_2O} = p_s \times RH \]
• Radiative transfer calculations
  • 3D curved atmosphere
  • Scattering
• Separate gas absorption calculations
  • Generate lookup table
    • Does not account for varying humidity
    • Must generate for each profile
• Monte Carlo scattering
• Customizable surface
• User defined instrument characteristics
• Open source
• Photon tracing from instrument to photon origin
  • Random path lengths and directions
  • Calculate contributions
    • Across path
    • At end of path step
  • Decision at end of path step
    • Scatter (repeat random path length and direction)
    • Absorb (start with new photon)
• Only in specified cloud box
• 3D capable
• Accuracy depends on number of photons
  • High water content requires more photons
• Python interface to ARTS
  • General control of ARTS and ARTS scattering
• Template for ARTS handling of scattering parameters
• Contains distributions for clouds
• Includes Mishchenko’s T-matrix FORTRAN code
  • Compiled as Python module
• Open source
Part III
Related Work

• Roberti and Kummerow
  • Polarization due to precipitation
  • Primarily V and H (I and Q)
  • Small 3rd Stokes
    • No data

• Kutuza et al.
  • Canted rain drops
  • Simplistic model
  • Large third stokes
Simulation Data

• Simulation Set 1
  • 2D Slice of 3D profile
    • Spatially correlated data set
  • Each 1D profile considered separately
  • 50 degree incidence angle
  • Frequency and water content dependence
  • 1 Profile for accuracy and timing analysis

• Simulation Set 2
  • 12 separate 1D profiles
  • Lighter water content
  • Incidence angle dependence
    • 40 to 60 degrees in 5 degree steps
  • 2 cases presented for 18.7 GHz
Simulation Set 1: Rain Profiles
Simulation Set 1: Graupel

![Graph showing the distribution of graupel in kilometers. The x-axis represents distance in kilometers (32 to 152), and the y-axis represents altitude in kilometers (0 to 18). The graph uses a color scale ranging from 0 to 0.8 g/m^3.](image-url)
Accuracy: Error

First Stokes Parameter, I

Second Stokes Parameter, Q

Third Stokes Parameter, U

Ph: 25,000 50,000 100,000 200,000 400,000 800,000 1600000

Tb (K)

0.4 0.6 0.8 0.9

10.7 18.7 37.0

0.0 0.1 0.2 0.3 0.4 0.5 0.6
Accuracy: Magnitude

First Stokes Parameter, I

Second Stokes Parameter, Q

Third Stokes Parameter, U

Photons
Accuracy: Time

The graph shows the relationship between runtime (in hours) and the number of photons. The curve indicates an increasing trend with the number of photons, suggesting that as the number of photons increases, the runtime also increases.
Set 1 Results: 10.7 GHz
Set 1 Results: 18.7 GHz
Set 1 Results: 37.0 GHz

First Stokes Parameter, I

Second Stokes Parameter, Q

Third Stokes Parameter, U

Distance (km)
Simulation Set 2: Case 1

Profile 7

Altitude (km)

Water Content (g/m³)

- rain
- snow
- graupel
Set 2, Case 1 Results

First Stokes Parameter, I

Second Stokes Parameter, Q

Third Stokes Parameter, U

Incidences (degrees)
Profile 12

- rain
- snow
- graupel
Set 2, Case 2 Results

First Stokes Parameter, $I$

Second Stokes Parameter, $Q$

Third Stokes Parameter, $U$

Incidence (degrees)
Conclusions

- V and H (Q) changes
  - Due to non-spherical drops
- No 3rd Stokes contribution
  - Off angle effects average out
  - No particle type discrimination
    - No possible retrievals
  - No contribution to surface
    - Must still account for extinction
  - Did not account for canting of rain
    - Probably small effect
- Incidence angle dependence
Current and Future Work

- **Current work using ARTS**
  - Examine radiometer calibration
  - Parameterize brightness temperatures vs. cloud, water vapor and sea surface temperature
  - Added polarimetric surface models
- **Future work for ARTS scattering**
  - Adjust code to accept canted rain drops
  - Examine degradation of surface signal
• **Journal Papers**


Publications

• Conference presentations/proceedings


