The Use of Circular Polarization in Space-Based Lidar systems: Considerations for the EarthCARE lidar.

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Abstract

The proposed Earth Clouds And Radiation Explorer (EarthCARE) satellite mission is at joint European and Japanese program. The EarthCARE mission is focused on investigating the interactions between clouds, aerosol and long and short-wave atmospheric radiation. The proposed platform instruments include a lidar and a cloud profiling radar along with various passive sensors. The use of circular polarization is being considered for the EarthCARE lidar. This consideration may turn out to have particular advantages with regards to the ability to discriminate water and ice layers on the basis of the depolarized return. In particular, for EarthCARE the use of circular depolarization would reduce the amount of depolarization signal induced by multiple-scattering processes in water clouds.

1 Introduction

The lidar depolarization ratio has long been used to discriminate between spherical (i.e. water droplets) and non-spherical (i.e. ice crystals) (Pal and Carswell (1977)). In general, light with a known polarization state is transmitted and the return signal is separated on the basis of its polarization state. In general, the polarization state of light is completely described by its associated Stokes vector

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \tag{1}$$

By passing the returned lidar signal through a suitable optical assembly both the linear (δ_l) and circular (δ_c) depolarization ratio may be measured

$$\delta_l = \frac{I-Q}{I+Q} \tag{2}$$

and

$$\delta_c = \frac{I-V}{I+V} \tag{3}$$

For spheres, $\delta_{c(l)}$ will be close to zero only if the multiple scattering contribution to the return signal is small compared to the single-scattering only signal. This is due to the fact that for spheres, scattering at angles other than directly forward or backward will give rise to other polarization components. In the case of space-borne lidars (Winker et al. (1996)), this multiple scattered contribution to the depolarization signal can be large and can complicate the interpretation of the depolarization signal.

Multiple scattering and depolarization In order to properly describe the behavior of the lidar depolarization signal it is necessary to specify the full scattering matrix. For rotationally symmetric or randomly oriented the relationship between the Stokes vectors of the scattered and incident electromagnetic fields (with respect to the scattering plane) can be written as

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{12} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & -P_{34} & P_{44} \end{pmatrix} \begin{pmatrix} I_o \\ Q_o \\ U_o \\ V_o \end{pmatrix} \tag{4}$$

The phase matrix is defined with respect to the scattering plane (i.e. the plane defined by the incoming and outgoing scattered photon paths). For the treatment of scattering at arbitrary angles, the Stokes vector of the incoming radiation and the resulting vector describing the scattered radiation must be rotated with respect to the scattering plane. The Stokes vector resulting from a photon scattered through an angle (θ, ϕ) is given by

$$\mathbf{S} = \mathbf{L}(\pi - i_2)\mathbf{P}(\theta)\mathbf{L}(-i_1)\mathbf{So} \tag{5}$$

where $\mathbf{So}$ is the incoming Stokes vector and $\mathbf{S}$ is the Stokes vector associated with the scattered radiation. $\mathbf{P}(\theta)$ is the scattering phase matrix and $\mathbf{L}$ is the transformation matrix for the Stokes parameters (Liou (2002))

$$\mathbf{L}(\chi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\chi) & \sin(2\chi) & 0 \\ 0 & -\sin(2\chi) & \cos(2\chi) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{6}$$

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where $\chi = \pi - i_2, -i_1$ is the orientation angle. The angles i_1 and i_2 in Equation 5 are given by

$$\cos(i_1) = \frac{-\mu + \mu_o \cos(\theta)}{\pm(1 - \cos(\theta)^2)^{1/2}(1 - \mu_o)^{1/2}} \tag{7}$$

where μ_o is the z component of the direction cosine of the incoming photon and μ is the z component of the direction cosine of the scattered photon. The plus sign is to be used when $\pi < \phi - \phi_o < 2\pi$ and the minus sign is to be used otherwise where the π's refer to the azimuth angles of the incoming and outgoing photon's respectively.

For direct backscatter $\mathbf{L}$ in Eqn. 5 is equal to the identify matrix and further for spheres P_{12} and P_{34} are equal to zero. Thus, if linearly polarized light is transmitted $\mathbf{So} = I_o(1, 1, 0, 0)$ $\delta_l = 0$ and if circularity polarized light is transmitted $\mathbf{So} = I_o(1, 0, 0, 1)$ then $\delta_c = 0$.

1.1 Simple 2nd order model

Using the above considerations a simple model can be constructed to illustrate how multiple-scattering can lead to a depolarization signal even where only scattering from spheres is involved.

The geometry of the 2nd order model is shown in Fig. 1. Here photons are forward scattered at an angle θ then backscattered at an angle of $180 - \theta$ degrees. The polarization ratio of the returned signals are then calculated as a function of θ using the repeated application of Eq. 5. An example is shown in Fig. 2 for a distribution of water spheres ($R_{eff} = 10$) microns. Here it can be seen that the δ_l ratio rises with increasing θ much faster than corresponding δ_c.

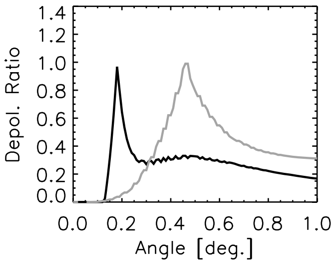

Figure 2: *Depolarization ratio for 2nd order scattering as a function of scattering angle (θ in Fig. 1. The linear depolarization ratio (with $\mathbf{S_o} = \mathbf{I_o(1, 1, 0, 0)}$) is shown in black while the circular depolarization ratio (with $\mathbf{S_o} = \mathbf{I_o(1, 0, 0, 1)}$) is shown in Grey.*

2 Application to the EarthCARE lidar

EarthCARE has been specifically designed with the scientific objectives of determining, in a radiatively consistent manner, the global distribution of vertical profiles of cloud and aerosol characteristics in order to better understand the role of clouds and aerosol in radiative transfer in the Earth's atmosphere. The mission configuration consists of:

- A High Spectral Resolution Cloud/Aerosol Lidar.
- A 94 GHz cloud profiling radar.
- A Multichannel Spectral Imager (MSI)
- Long and Short-wave Broad-Band Radiometers (BBRs)

It is envisaged that EarthCARE will shed light on many aspects of cloud-radiation climatology with special attention to aerosol-cloud interactions that influence Earth's hydrological and radiative budgets via cloud and precipitation life cycles and albedo. Likewise, the multitude of conditional distributions involving cloud structure and atmospheric state that will be drawn from EarthCARE data will provide tremendous opportunities to assess cloud and radiative parameterizations used in GCMs and numerical weather prediction (NWP) models. For more information on the EarthCARE mission please see http://www.esa.int/esaLP/LPearthcare.html.

2.1 The EarthCARE lidar

The proposed EarthCARE lidar is a High-Spectral Resolution (HSRL) lidar Shipley et al. (1983). This type of lidar transmits a spectrally narrow signal. The return signal consists of an elastic backscattered cloud-aerosol component as well as a broader Rayleigh-Brillouin component (Miles, Lempert and Forkey (2001)) due to molecular scattering (see Fig. 3). The separation of the elastic and inelastic backscatter is to be achieved using a Fabry-Perot Etalon assembly.

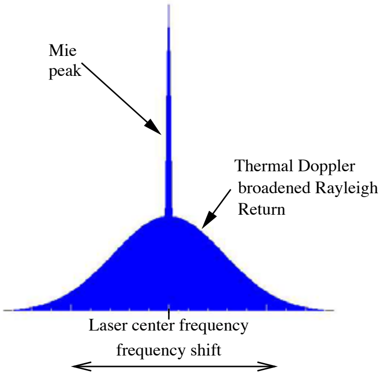

Figure 3: *Idealized view of spectral signature of a lidar return.*

As part of the design process, the use of circular polarization is being considered for the EarthCARE lidar. As may be expected from the simple model results described above the use of circular depolarization may have particular advantages with regards to the ability to discriminate water and ice layers on the basis of the depolarized return. In particular, for EarthCARE the use of circular depolarization would reduce the amount of depolarization signal induced by multiple-scattering processes in water clouds. This potential advantage of circular polarization for use in space-borne lidar systems was noted previously by Yong et al. (2003).

2.2 Monte-Carlo Simulations

As part of the EarthCARE development activities a simulator has been built. One of the components is a 3-D Monte-Carlo (MC) model which accounts for the spectral and polarization characteristics of the lidar signal. The lidar MC model typically is a semi-analytical type (i.e. after each scattering event the contribution to the return signal is calculated directly) and takes realistic instrument and shot noise levels into account. Typically 5-6 orders of scattering are calculated. A sample simulation is shown in Fig. 4. Here it can be seen that the return from the stratus water cloud is clearly visible while using circular polarization reduces the multiply scattered induced polarization in the cross-polar channel by about a factor of 5.

3 Conclusions

The use of circular polarization seems to offer an advantage for space-borne lidar. Simulations indicated that the amount of multiple scattering induced depolarization signal should be substantially reduced in water clouds. More investigation is necessary to judge the potential effects on the measurement of depolarization ratio in ice clouds and non-spherical aerosols,

4 References

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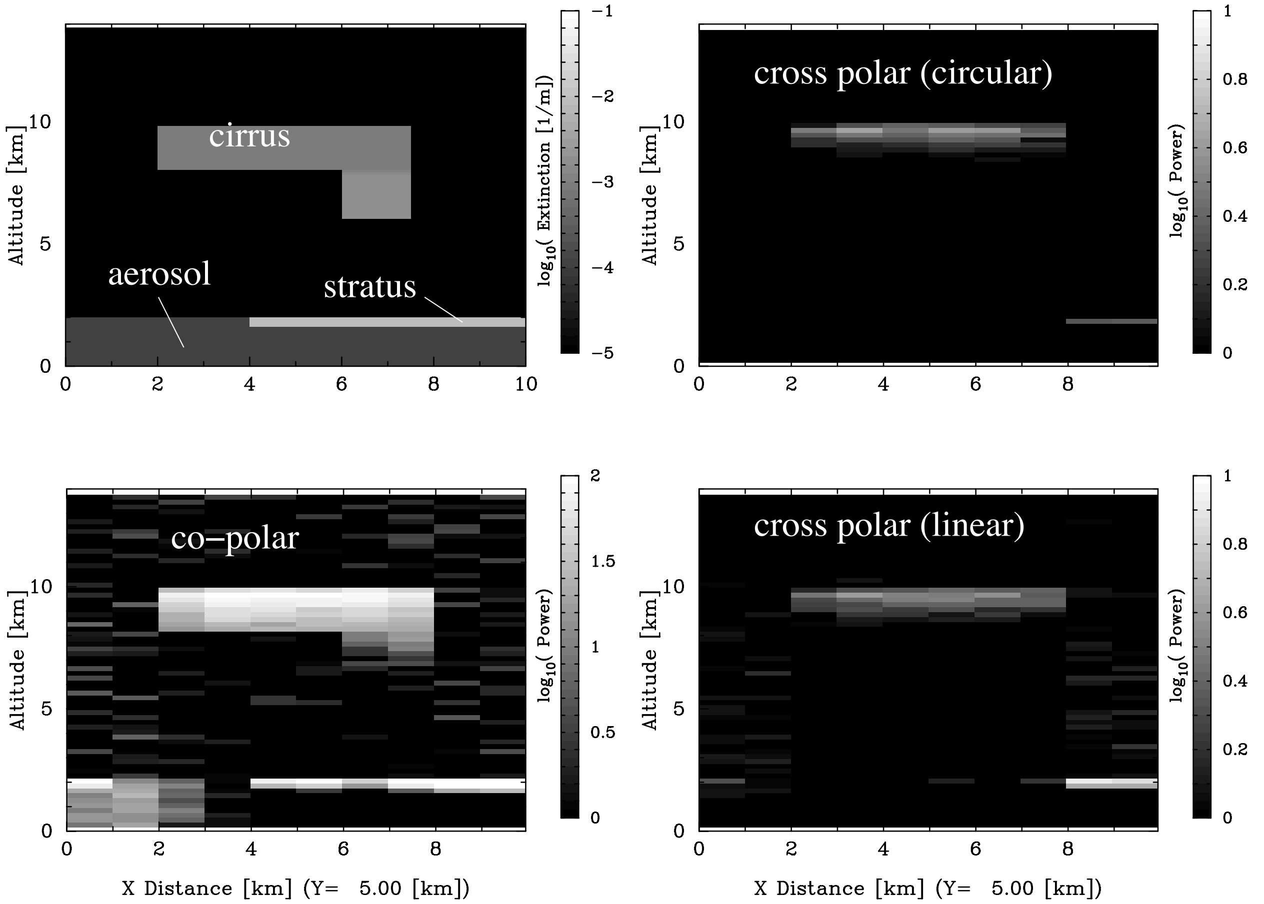

Figure 4: *Extinction field for Monte-Carlo simulation (Top–Left), simulated lidar return in the elastic co-polar channel (Bottom-Left) and simulated returns in the cross-polar channels using circular (Top–Right) and linear polarization (Bottom-Right).*