

### 3.7 AEROSOL RETRIEVALS OVER LAND SURFACES (THE ADVANTAGES OF POLARIZATION)

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#### 1. INTRODUCTION

The principal difficulties in retrieving aerosol loadings and microphysical properties using passive remote sensing measurements over land surfaces are the significant spectral and spatial variations in the observed intensities that are caused by the land surface. Indeed the unique and highly variable spectral signatures of land surfaces and their rapid spatial variations are of considerable value in geological prospecting and crop identification and evaluation [Asner 1998]

The polarized light reflected by surfaces may also be of use in remote sensing of the surface, being indicative of its roughness, or in the case of vegetation its leaf inclination distribution [Rondeaux and Herman 1991]. It is believed that this polarization is generated at the surface interface and this hypothesis has been used to develop theoretical models [Bréon et. al. 1995] for the polarized reflectance of vegetation and of bare soils. The fact that most surface polarization is generated at the surface interface and that the refractive index of natural targets varies little within the spectral domain of interest suggests that surface polarized reflectance will be spectrally neutral.

If this is the case, then the use of a measurement at a sufficiently long wavelength that the aerosol load is negligible could be used to characterize and correct for surface polarization effects at the shorter wavelengths. Such an approach has also been suggested for use with intensity measurements [Kaufman et. al. 1997] based on the observation that surface reflectances at 450 and 670nm are correlated with reflectances at 2250nm for many surface types. The shorter wavelengths can then be used to estimate the aerosol load and microphysical properties, for example size and refractive index. A theoretical examination of such an approach based on the assumption that the surface polarized reflectance is spectrally neutral has been performed elsewhere [Cairns et. al. 1997]. In this paper we examine the validity of assuming that surface polarized reflectance is spectrally neutral and the capabilities of polarization measurements for remote sensing of aerosols over land surfaces using data from the Research Scanning Polarimeter. We also indicate how these measurements relate to the type of empirical surface models that have been developed for use in retrieving aerosol properties over land surfaces from POLDER measurements.

#### 2. DESCRIPTION OF INSTRUMENTATION AND METHODS

The Research Scanning Polarimeter (RSP) makes polarization measurements in nine spectral bands. In the visible/near infrared (VNIR) blue enhanced silicon photodiodes are used to make measurements in six spectral bands at 410, 470, 555, 670, 865 and 960nm. In the short wave infrared (SWIR) HgCdTe detectors cooled to 150K are used to make measurements in three spectral bands at 1590, 1880 and 2250nm. The optical system consists of six boresighted refractive telescopes. Each telescope makes measurements in three spectral bands of two orthogonal polarization states which are spatially separated using a Wollaston prism. Telescopes that measure the same three spectral bands are paired so that the orientation of the polarization measurement in one is rotated 45° with respect to the other. This means that the Stokes parameters Q and U are measured simultaneously, Q in one telescope and U in the other. The instantaneous field of view (14mrad) of each telescope is scanned continuously with data being taken over a range of 120° ( $\pm 60^\circ$  from nadir) using a polarization-insensitive system. This system consists of two mirrors each used at 45° angle of incidence and with their planes of incidence oriented orthogonally to each other. During the course of a scan 152 samples are taken plus ten dark samples with a sample dwell time of 1.875msec. The polarimetric accuracy is better than 0.2% and the radiometric accuracy is 3.5% [Cairns et al. 1999]. This is based on pre- and post-flight reflectance calibrations using a spectralon reflectance standard and nearby Multi-Filter Rotating Shadowband Radiometer (MFRSR) data for an atmospheric transmission estimate. The MFRSR measures the intensity of the direct beam of the sun and diffuse skylight at six bands: 410, 500, 610, 670, 865 and 945nm. These measurements allow for a robust estimate of the column ozone, aerosol optical depth and size of the accumulation mode and column water vapor.

The RSP instrument was deployed in a Cessna 210 aircraft which allowed along-track measurements over a range of  $\pm 45^\circ$  from nadir to be obtained before the aircraft skin vigneted the scan. By having the RSP scan along the groundtrack, as the aircraft moves forward, the same point at the ground is seen from multiple view angles. The aircraft altitude was 3000m and the speed was 50m/s. An MFRSR instrument was deployed on the ground near Oxnard CA., and the aircraft data that we show here was obtained simultaneously with that from

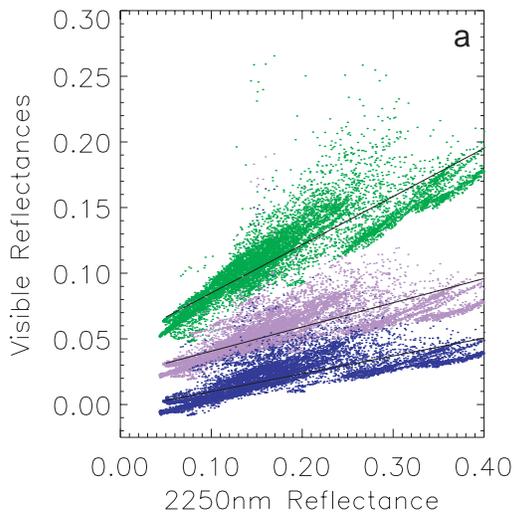
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the sunphotometer and is located within 2km of it. The measurements were all taken on 10/14/1999.

### 3. DATA ANALYSIS AND DISCUSSION

The RSP instrument counts were corrected for dark current and reduced to calibrated reflectances. These reflectance measurements contain contributions from both the surface and the atmosphere. The atmospheric contribution is well characterized by the MFRSR measurements, which provide accurate estimates of aerosol optical depth and allow a plausible aerosol microphysical model to be inferred. The atmospheric reflectance was then calculated using a vector adding/doubling code [Cairns et. al. 1997]. The model atmosphere that is used consists of a two layer atmosphere with a pure molecular layer above the aircraft and an aerosol layer mixed with the remaining molecular contribution below the aircraft. The vertical distribution of scattering properties is reasonable for the suppressed boundary layer that was observed and the aerosol properties were defined by the MFRSR measurements. The calculated atmospheric reflectance was then used to correct the RSP measured reflectances so that they provide a reasonable estimate of the surface reflectance [Hu et. al. 1999], particularly for the low aerosol load (optical depth of 0.14 at 550nm) on 10/14/1999.



In Fig. 1 we show scatter plots of these atmospherically corrected RSP reflectances. The measurements come from a 4km segment of flight track and represent a range of scattering geometries and surface types with approximately 20,000 measurements for each wavelength. In Fig. 1a we show 2250 nm reflectances plotted against the 410, 470 and 670 nm reflectances. The solid lines are based on robust regressions of the 2250 nm reflectance against the visible reflectances.

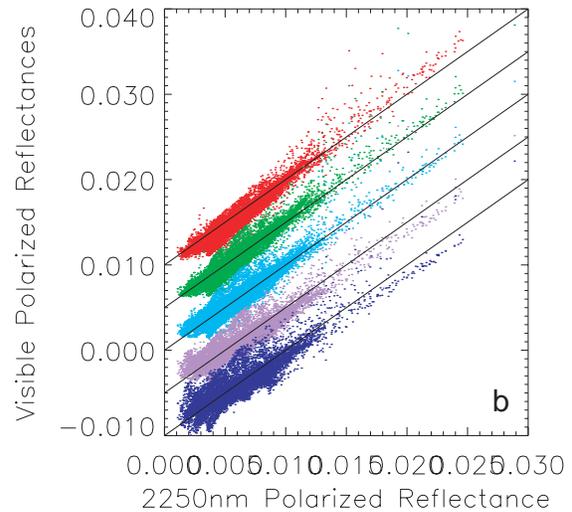


Figure 1. RSP measurements that have been atmospherically corrected based on simultaneous MFRSR measurements. Symbols and lines are offset to allow different bands to be distinguished. a) Reflectance at 2250nm versus reflectance measurements at 410, 470 and 670 nm (ordered from bottom to top). b) Polarized reflectance at 2250nm versus polarized reflectance measurements at 410, 470, 555, 670 and 865 nm (ordered from bottom to top).

Although the measurements are grouped about these regression lines there is a considerable spread and it appears that the measurements might represent two different populations. Fig. 1b shows the polarized reflectance at 2250nm plotted against the polarized reflectance at 410, 470, 555, 670 and 865 nm, with solid lines showing the 1:1 line. As can be seen the measurements are strongly clustered about the theoretically predicted lines. It should be emphasized that these lines are not empirical regressions, but are based on our understanding that most of the polarized reflectance from surfaces is generated at the surface air interface and is therefore determined mostly by the real refractive index of the material. Since the real refractive indices of soils and leaves show only weak spectral variation the polarized reflectance also shows weak spectral variation as demonstrated by Fig. 1b which shows little variation in polarized surface reflectance between 410 and 2250nm.

We will now examine how well the atmospheric reflectance signal can be estimated using the regression relations shown in Fig. 1a and how well the polarized atmospheric reflectance signal can be estimated using the physically based relations shown in Fig. 1b. Fig. 2a shows how well the atmospheric reflectance calculated based on MFRSR measurements agrees with the atmospheric reflectance measured by the RSP when the surface contribution is removed using a regression relation between the reflectance at 2250nm and that at 410, 470 and 670nm [Kaufman et. al. 1997]. As can be seen the agreement is poor. It is certainly possible to find surface types for which this approach is valid, but it appears to depend on surface type (i.e. particularly

vegetation type and coverage) and would therefore tend to however uncontrollable seasonal and regional biases.

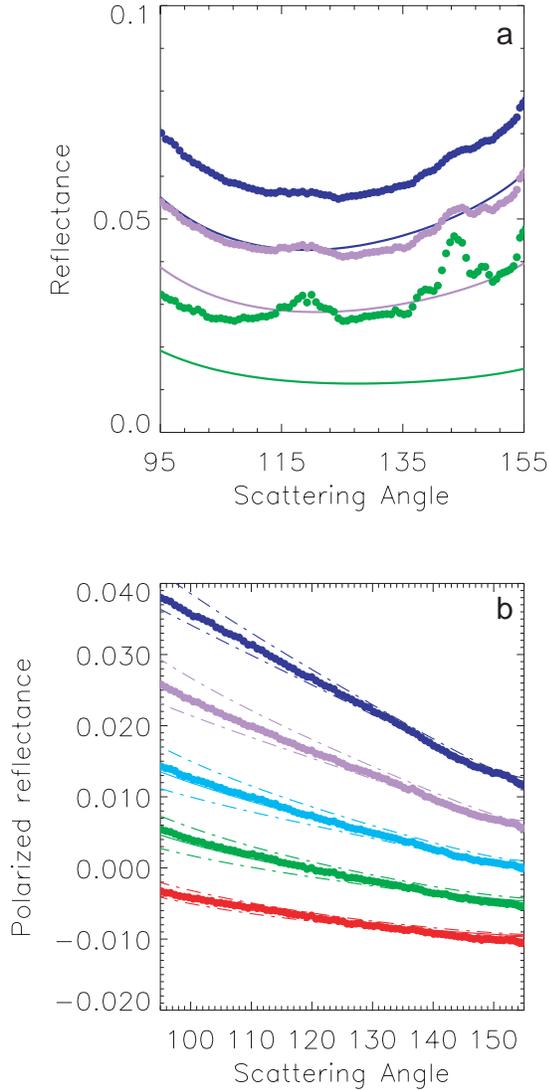


Figure 2. RSP measurements that have been corrected for surface reflectance: a) Atmospheric reflectances that have been corrected based on the empirical regression model of surface reflectance (symbols) compared with model calculations based on MFRSR measurements (solid lines). b) Polarized atmospheric reflectances that have been corrected for the surface contribution based on polarized reflectance measurements at 2250nm (symbols) compared with model calculations based on MFRSR measurements (solid lines).

In contrast the agreement in Fig. 2b between the simulated polarized reflectances (solid lines) and the RSP measurements corrected for surface polarization, using the 2250nm measurements as a proxy for the actual surface polarized reflectance, is excellent. This agreement is true at a pixel level for each pixel (not shown). The dot-dashed lines shown in Fig. 2b are simulations of the atmospheric polarized reflectance when the effective radius of the aerosol model is

perturbed by  $\pm 0.05\mu\text{m}$  from its best estimate value of  $0.185\mu\text{m}$ . Comparing these perturbed values with the RSP measurements indicates a sensitivity to aerosol size, at least for accumulation mode particles, of  $\pm 0.05\mu\text{m}$  for downward looking polarization measurements over land.

### 3. SIMPLE SURFACE POLARIZATION MODELS

Although the results shown above indicate that the assumption that surfaces generate polarization mostly at the surface-air interface is valid, a separate and important question is whether simple models that have been developed to link Fresnel reflection coefficients with the surface polarized reflectance are valid. When a measurement at 2250nm is not available to characterize surface polarization it becomes necessary to have reliable surface polarization models that are parameterized based on the surface type and its vegetation cover, or some other appropriate measure [e.g. Normalized Difference Vegetation Index (NDVI)]. These models can then be used to correct observed polarized reflectances for the surface contribution and therefore allow aerosol properties to be estimated. Such an approach has been developed, with encouraging results, for the analysis of POLDER measurements [Nadal and Bréon 1999]. They found that the original simple physical models that had been developed [Bréon et. al. 1995] were not valid and indeed found that near the backscatter direction the observed polarized reflectance was four times larger than that predicted by a simple physical model. Their empirical model (I) for the polarized reflectance  $R_P$  is defined by the expression

$$R_P(\Omega_v, \Omega_s, \varphi) = r \left[ 1 - \exp\left(-\beta \frac{F_P(\Omega_v, \Omega_s, \varphi)}{\mu_v + \mu_s}\right) \right] \quad (1)$$

where  $F_P$  is simply the polarized Fresnel reflection coefficient for the given viewing geometry,  $\Omega_v$  is the viewing zenith [ $\mu_v = \cos(\Omega_v)$ ] and  $\Omega_s$  is the solar zenith angle.  $r$  and  $\beta$  are the empirical coefficients that are tuned to provide a good match to observations and that can then be predicted based on surface type and NDVI.

$$R_P(\Omega_v, \Omega_s, \varphi) = r \left[ \frac{S(\beta, \Omega_v) S(\beta, \Omega_s) F_P(\Omega_v, \Omega_s, \varphi)}{\mu_v + \mu_s} \right] \quad (2)$$

Above is shown an alternative empirical model (II) for a vegetated surface where the  $S$  functions allow for shadowing with  $\beta$  being an empirical coefficient that is indicative of surface roughness and  $r$  is an empirically tunable coefficient, which based on simple theory should be  $1/4$ . The empirical model I of Nadal and Breon, which is shown as a dashed line in Fig.3, is based on the empirical coefficients for a "low vegetation, high NDVI" case (3a) and on the empirical coefficients for a "desert" case (3b). Based on the preceding analysis the 2250nm polarized reflectance measurements are a reasonable approximation to the surface polarized reflectance. The empirical model I provides a reasonable fit for vegetation (3a) and a somewhat worse fit for bare soil (3b). This may simply be because a desert model is not appropriate for a bare soil field. The empirical model II (solid line) fits the data extremely well in both cases.

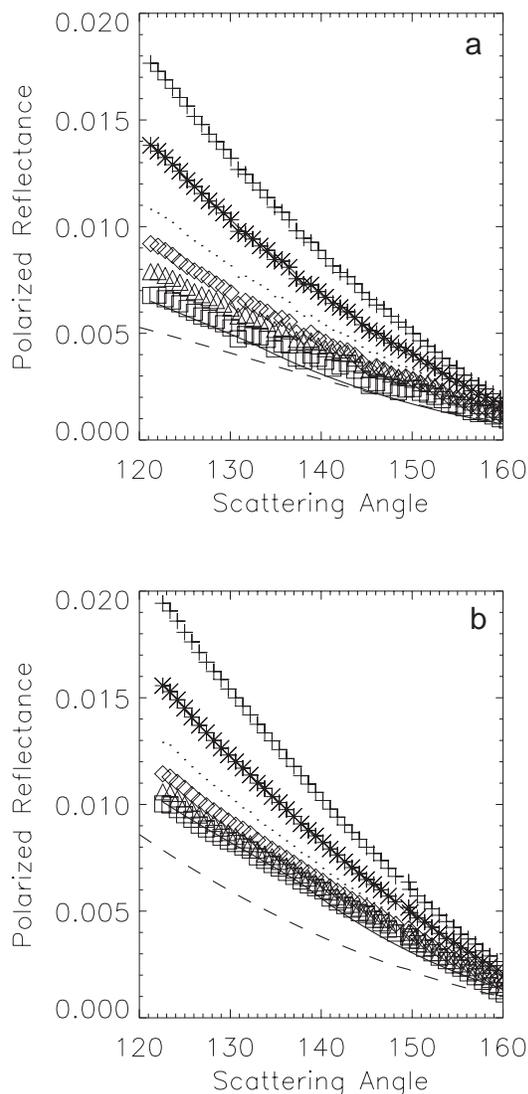


Figure 3. Polarized reflectance measurements at 410 (cross), 470 (star), 555 (dot), 670 (diamond), 865 (triangle) and 2250 (square) nm of a) a vegetated field and b) a bare soil field. The dashed line (I) and solid line (II) are the empirical models.

This is not an indication that it is a better model than that of Nadal and Bréon [1999] since it was tuned to this data, but simply that it is an acceptable model that may explain some of the observed features of surface polarized reflectance using simple physical mechanisms e.g. shadowing [Saunders 1967].

#### 4. CONCLUSIONS

The hypothesis that the polarized reflectance of surfaces is generated by front facet reflections and is therefore spectrally neutral is born out by the data presented here. This phenomena allows polarized reflectance measurements at 2250nm to be used as a

reliable proxy for the surface polarized reflectance over a wide spectral range. The agreement between simulated and measured atmospheric polarized reflectance indicates that aerosol retrievals over land surfaces should be possible using such polarized reflectance measurements and may have the ability to retrieve the effective radius of accumulation mode particles with an accuracy of  $\pm 0.05\mu\text{m}$ . The regression models that link the surface reflectance at 2250nm with that at shorter wavelengths to allow the retrieval of aerosol properties over land from intensity measurements do not appear to be as robust.

The larger magnitude of observed surface polarized reflectance near the backscatter direction compared with simple physical models, that was observed by Nadal and Bréon [1999], is also found in the data presented here. An examination of the effects of higher orders of scattering that may be responsible for this feature and that have been used to explain negative polarization features in the backscatter direction [Wolff 1980] will be the subject of future work.

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