4 Space-Borne Measurement of the Polarizational Characteristics of Earthlight: The POLDER Instrument

The POLDER (**POL**arization and **D**irectionality of the **E**arth's **R**eflectance) space-borne sequential imaging polarimeter aboard the Japanese ADEOS (**AD**vanced **E**arth **O**bserving **S**atellite) over a three year period (1996-1998) was designed to measure the directionality and polarization of the earthlight, that is, the sunlight reflected from the earth´s surface and scattered by the atmosphere (Deschamps et al. 1994). The inclination of the optical axis and the altitude of the instrument were 98.6^o from the horizontal and 796 km from the sea level, respectively. The instrument was composed of a CCD detector (with pixel resolution = 242×274; from the ADEOS one pixel corresponds to an area of 6×7 km^2 on the earth´s surface at the nadir; spectral sensitivity = 400-1050 nm), a wide (114^o×114^o) field-of-view telecentric optics (focal length = 3.57 mm, f-number = 4.5) and a rotating filter wheel carrying the colour and linearly polarizing filters (Fig. 4.1A). It could observe a terrestrial target from different viewing angles during the same orbit. An air-borne simulator of the instrument has also been developed and experimental air-borne campaigns have been conducted too.

As opposed to single scattering, multiple scattering or reflection of light can induce elliptic polarization. Radiative transfer simulations showed that in the atmosphere of the earth the fourth component V of the Stokes vector (characterizing elliptical and circular polarization) of light is negligible compared to the other components. Thus, the polarization of earthlight is mostly linear for prevailing atmospheric conditions. Therefore the POLDER instrument sensed only the linearly polarized component of earthlight.

This was achieved by three subsequent measurements with the transmission axes of the linear polarizers turned by steps of 60^o at 443, 670 and 865 nm. A combination of the three measurements yielded the Stokes parameters I, Q, U, from which the total radiance $R = I$, the linearly polarized radiance (the product of the total radiance and the degree of linear polarization p) $R_p = pR = (Q^2+U^2)^{1/2}$, and the angle of polarization α were computed. The POLDER-team prefers to use R_p, which is nearly additive with respect to the contributions of molecules, aerosols and land surfaces, rather than p, in which the contributions of polarized and unpolarized light are mixed ambiguously. Thus, in the publications of the POLDER-team colour-coded maps of R and R_p have been used, like those in Figs. 4.1B-E and 4.2B,C.

The POLDER radiometric measurements yielded target reflectance and polarization properties as well as bi-directional reflectance and polarization distribution functions from one or several orbits. An alternative instrument to POLDER planned to measure polarized reflectance from space is the EOSP (**E**arth **O**bserving **S**canning **P**olarimeter), which was scheduled for launch in 2003. The POLDER observations are used in studies of the biogeochemical cycles as well as the global energy, water and mass budgets and took part in the World Climate Research Program and the International Geosphere Biosphere Program. The main scientific objectives of the POLDER mission were (Deschamps et al. 1994):

- mapping atmospheric aerosols, including their sources and transport, and studying their influence on the earth's radiation budget (e.g. Deuzé et al. 1993; Bréon et al. 1997; Herman et al. 1997; Leroy et al. 1997);
- assessing cloud properties, such as cloud top height, phase and type (e.g. Goloub et al. 1994; Descloitres et al. 1995);
- estimating total integrated water vapour amount (e.g. Leroy et al. 1997);
- improving earth radiation budget estimates (Deschamps et al. 1994);
- estimating ocean colour and its role in the carbon cycle (Deschamps et al. 1994);
- characterizing land surface properties and vegetation cover (e.g. Deuzé et al. 1993; Bréon et al. 1995; Herman et al. 1997; Leroy et al. 1997).

The POLDER system provides new opportunities for estimating atmospheric aerosol content over land surfaces. While radiances reflected from most land surfaces are only slightly polarized, radiances scattered by the molecules and aerosols in the atmosphere are highly polarized. Consequently, the polarization of earthlight measured from the space originates primarily from the atmosphere (Fig. 4.1C), and aerosol properties can be derived from polarized reflectance measurements. Computing theoretically the polarized reflectance expected for an aerosol-free atmosphere (Rayleigh scattering only), the difference between the computed and measured polarized radiances corresponds to polarized radiance scattered by the aerosols. Thus, the polarized reflectance measurements by POLDER at 443, 670 and 865 nm yield the aerosol spectral behaviour, which provides an indication of their type (i.e., size distribution and refractive index).

POLDER polarization measurements allow also an estimate of the cloud pressure level. The measured polarized radiance is related to the atmospheric molecular optical thickness above the cloud, assuming that the radiance originating from the cloud is negligibly polarized and spectrally neutral. This assumption is not true for particular directions, such as that of the rainbow, which are avoided. In other viewing directions the measured polarized reflectance is mainly generated by the atmosphere and is nearly proportional to the molecular optical thickness above the cloud. This relationship leads to estimate the pressure at the top of clouds. Since the polarization induced by molecular scattering is maximal at 90^{o} from the solar direction, this viewing direction is preferred. Although the aerosols above the cloud layer can also produce some perturbing polarized radiance, the bulk of atmospheric aerosols is contained in the boundary layer below the cloud layer. For this method polarization measurements at 443 nm are used because the molecular scattering contribution to the polarized reflectance is maximal relative to other contributions.

Cloud type determination and thermodynamic studies of the atmosphere require recognition of the cloud phase, a parameter that POLDER polarization measurements can access. Radiative transfer simulations have shown that the polarization of cloud-reflected radiance in specific directions (e.g. that of the rainbow) is very sensitive to the cloud phase, which can be either ice or liquid water (Fig. 4.2). Liquid cloud droplets are evidenced by the characteristic strong polarization of the rainbow (Fig. 4.2C) exhibited by spherical particles for scattering angles near 140^o from the solar direction. The rainbow characteristic disappears as soon as the scattering particles depart from spherical geometry. The lack of this characteristic feature in cloud polarization signature, therefore, is indicative of the presence of ice crystals. The method utilizes the polarizational data measured at 865 nm, since this spectral channel is the least polluted by molecular scattering among the other channels. These informations are very useful also for polarimetric cloud detection.

Leaf cuticle and wax specularly reflect part of the incident solar radiation on the canopy. Because this radiance does not interact with chlorophyll pigments, and hence cannot participate in photosynthesis, it should not be considered when the aim is to remotely sense the vegetation. Since specularly reflected radiance is partially linearly polarized, polarization measurements over land surfaces can be applied to correct for the specular component of the reflectance. POLDER polarization observations help also to characterize the vegetation cover, because they are sensitive to the microscale structure of the canopy (Curran 1982). However, since the polarized reflectance measured from the space originates mostly from the atmosphere, accurate atmospheric corrections (subtracting the contribution of atmospheric scattering) are necessary before space-borne polarized reflectance measurements can be used for vegetation monitoring applications.

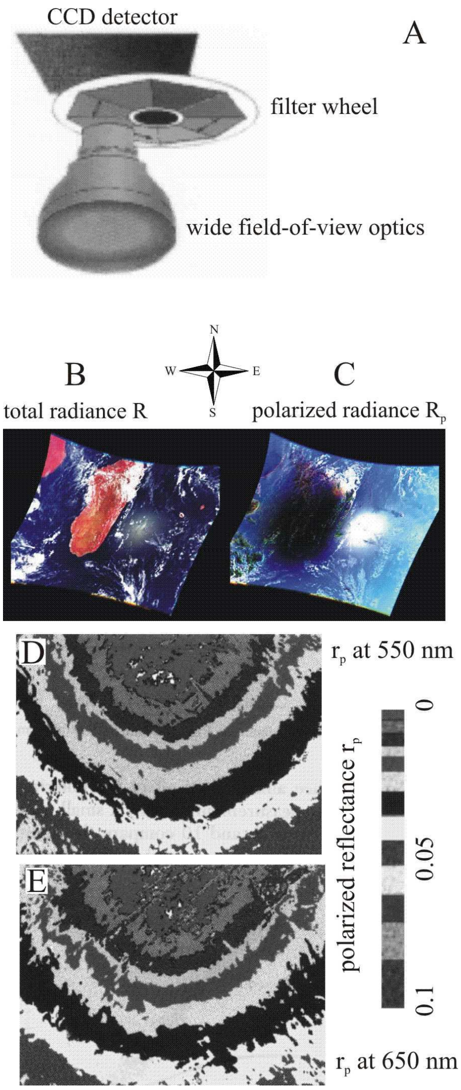

Fig. 4.1. A: Schematic picture of the POLDER sequential imaging polarimeter. (After Fig. 1 of Deschamps et al. 1994, p. 600). B, C: False-coloured patterns of the total radiance R and polarized radiance R_p of earthlight measured by the POLDER instrument above Madagascar. For both pictures red, green and blue codes the radiances measured at 865, 670 and 443 nm, respectively. The R_p-pattern is mainly blue because of the high linear polarization of molecular scattering at 443 nm. The ground surface has a very low contribution to the polarized signal, which depends mainly on the atmospheric light scattering. (After http://ceos.cnes.fr:8100/cdrom-00b2/ceos1/satellit/polder/index.html). D-F: Patterns of the dimensionless polarized reflectance r_p of earthlight measured by the air-born version of the POLDER instrument at 550 nm (D) and 650 nm (E). (After Fig. 6 of Deuzé et al. 1993, p. 145).

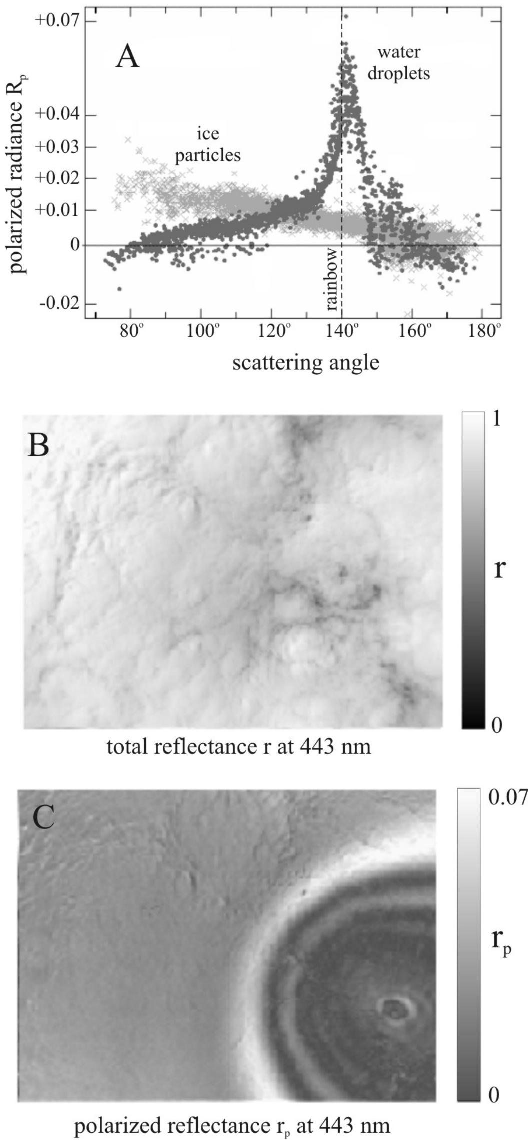

Fig. 4.2. A: The dimensionless polarized radiance R_p of clouds composed of either water droplets (dark grey dots) or ice particles (light grey ×) as a function of the scattering angle from the solar direction measured by the POLDER instrument at 865 nm. (After http://ceos.cnes.fr:8100/cdrom-00b2/ceos1/satellit/polder/index.html; similar graphs are seen in Figs. 4, 10, 11, 12 of Goloub et al. 1994, p. 81, 83, 84). B, C: Patterns of the total reflectance *r* and polarized reflectance r_p over stratocumulus clouds measured by the air-borne version of the POLDER instrument at 443 nm. In the r_p-pattern the strongly polarized primary and higher order rainbows are clearly discernible. (After Figs. 2 and 3 of Goloub et al. 1994, p. 80 and 81).