Monitoring dust particle orientation with measurements of sunlight dichroic extinction

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Abstract Alignment of irregularly shaped dust aerosols leading to linear dichroism has been reported in atmospheric layers. The present study intents to quantify the excess linear polarization of direct solar radiation propagating through atmospheric layers, when these contain oriented dust particles. In order to record the linear polarization, we have used the Solar Polarimeter (SolPol). SolPol is an instrument that measures the polarization of direct solar irradiance at 550nm. It is installed on an astronomical tracker in order target the solar disk. Using the measurements, the Stokes parameters are retrieved (I, Q/I, U/I and V/I) with an accuracy of ~1% and precision of 1 ppm. Collocated measurements of a sun-photometer (Aerosol Robotic Network; AERONET) and lidar are used to quantify the Aerosol Optical Depth (AOD) and identify the vertical distribution of dust layers, respectively. We will present indications of dust particle orientation recorded at the PANGEA station in the island of Antikythera, Greece, and at Nicosia, Cyprus during the preparatory phase for the ASKOS campaign in July 2021. The relation of the linear polarization of the solar irradiance to other optical properties of the dust layer is investigated.

1 Introduction

Mineral dust constitutes one of the most abundant atmospheric aerosols in terms of dry mass (Tegen et al. 1997) and, therefore, plays a significant role to the radiative forcing of the global climate (Miller and Tegen 1998, Miller et al. 2014) and can be the dominant source of aerosol forcing downwind of major dust sources such as the Sahara (Li et al. 1996; Chaibouet al. 2020). In atmospheric dust transport models, dust particles are assumed to be spherical due to computational limitations of the aerodynamic drag force on the gravitational settling schemes and therefore assumed randomly oriented. Although the effect of non-sphericity has been addressed previously (e.g. Ginoux 2003), only recent studies attempt to quantify this effect and take into account both particle orientation and asphericity to gravitational settling (Mallios et al. 2020). Similarly, in remote sensing aerosol retrievals, particle shape is an important factor for modelling the scattering properties of dust particles (e.g. Dubovik et al. 2006 and references therein). Polarimetric measurements can provide valuable information as they are sensitive to both parameters (Mishchenko et al. 2002, Gialitaki et al. 2020, Liu and Mishchenko 2020).

The dichroic extinction (i.e., the different extinction of the polarization components) of transmitted starlight through oriented dust particles is a well-documented phenomenon in the case of the interstellar medium, where dust particles are preferentially aligned along the galactic magnetic field lines (e.g. Dasgupta 1983, Siebenmorgen et al. 2014, Panopoulou et al. 2019, Skalidis and Tassis 2020). Atmospheric dust can provide similar polarization signatures, where vertically oriented particles lead to dichroic extinction of the transmitted starlight, which is predominantly horizontally polarized, as it was detected by Bailey et al. (2008) on La Palma, during a Saharan dust episode. A potential mechanism that is capable of aligning the lofted dust particles, and potentially counteracting gravitational settling, is the large scale electric field within the dust layer (Mallios et al. 2021, Ulanowski et al. 2007). Considering the seeming gap in literature concerning the effect of oriented dust to direct sun polarimetric measurements and motivated by previous passive polarimetric observations of the integrated sunlight, with sensitivities of the order of 10^{-6} which sets the detection order of magnitude for particle orientation (Kemp et al. 1987, Kemp and Barbour 1981), we utilize the direct Sun Polarimeter (SolPol) and report on signatures of dust particle orientation within the atmospheric column.

2 Data and Methodology

SolPol has been temporarily installed in the PANhellenic GEophysical observatory (PANGEA) at the remote island of Antikythera (35.861° N, 23.310° E, 193 m asl) since September 2018, housed in a specifically built astronomical dome and mounted on a simple EQ3 tracker which enables the instrument rotation and sun-tracking capabilities under various atmospheric conditions. Extensive measurement periods have been organized since, targeting both prominent dust events but also fair weather conditions. In the preparatory framework for the planned ASKOS 2021 (https://askos.space.noa.gr/) ESA Cal/Val activities, coordinated by the NOA-ReACT team (https://react.space.noa.gr/), such a scientific experiment was organized in Cyprus during November 2019. Considering the instrument’s light-weight and robust design, it was re-located in Nicosia (Cyprus Institute-CyI, 35°08'30.8" N 33°22'51.8" E) and measured direct sunlight polarization under different dust loads. Signatures of dust particle orientation were detected in several cases over Antikythera but, for the purposes of the specific study, we select the most distinct ones. Nonetheless, particle orientation was not clearly detected during the Cyprus field experiment.

2.1 The SolPol instrument

The design of SolPol is quite a venerable one and follows the design of its astronomical counterpart, the PlanetPol instrument (Bailey et al. 2008, Hough et al. 2006). SolPol measures the polarization fractions for linear and circular polarization from the whole solar disk plus a surrounding area of the sky depending on the choice of telescope and limiting field-of-view aperture, with an accuracy of ~1% and precision of 1 ppm. The polarimeter includes a classic Photo Elastic Modulator (PEM) (that modulates the incoming light, polarization, via controlled strain produced to the crystal by mechanical acoustic waves (Eq. 1) in a principal resonant frequency of 47 kHz), followed by a rotatable linear polarizer, a filter wheel with a mounted 550 nm neutral density filter, an imaging telescope and a large area photodiode detector (Martin et al. 2010). Equation 1 shows the intensity measured at the detector, written using the Bessel functions.

$$I(t) \sim \begin{cases} I + UJ_0(A) + VJ_1(A)\sin\omega t + UJ_2(A)\cos 2\omega t + O(3\omega t), \textit{assembly not rotated} \\ I - QJ_0(A) + VJ_1(A)\sin\omega t - QJ_2(A)\cos 2\omega t + O(3\omega t), \textit{assembly rotated to } 45^o \end{cases} \quad (1)$$

where A is the modulation amplitude, ω is the modulation frequency of the PEM, and $J_n(A)$ are the Bessel functions (for SolPol, $A = 2.4048$ so that $J_0(A) = 0$ and the PEM serves as a retarder with a phase shift of 0.382). Turning the linear polarizer at specific positions, we acquire the amplitude of the AC signal at the detector, which gives the magnitude of the V Stokes parameter (circular polarization) for odd ωt, and to the magnitude of Q and U (linear polarization) for even ωt. Measurement angles for I, Q, U are always direct sun. The DC signal gives the magnitude of the light intensity (I Stokes parameter). Higher order harmonic modulation frequency terms are considered negligible. The entire assembly is rotated about the PEM crystal optical axis over 45 degrees, so that biases and residual polarizations due to high frequency strain can be removed.

The Stokes vector of the light reaching the detector can be expressed using Mueller formulation as:

$$\begin{cases} \boldsymbol{I}'_{\alpha^o} = \boldsymbol{M}_{\boldsymbol{Pol.,a^\circ}}\boldsymbol{M}_{\boldsymbol{PEM}}\boldsymbol{I}, \textit{when the assemnbly is not rotated} \\ \boldsymbol{I}'_{\boldsymbol{rot},\alpha^o} = \boldsymbol{M}_{\boldsymbol{Pol.,a^\circ}}\boldsymbol{M}_{\boldsymbol{PEM}}\boldsymbol{I}_{\boldsymbol{rot}}, \textit{when the assembly is rotated to } 45° \end{cases} \quad (2)$$

where $\boldsymbol{I}$ is the Stokes vector of the input light $[I\ Q\ U\ V]^T$, $\boldsymbol{M}_{\boldsymbol{Pol.,a^\circ}}$ is the linear polarizer Mueller matrix at each position a^o and $\boldsymbol{M}_{\boldsymbol{PEM}}$ is the PEM Mueller matrix, respectively (Martin et al. 2010). Each full measurement sequence has a duration of 8 mins in total and comprises two distinct sets. The first set is of five measurements of solar irradiance on four positions of the linear polarizer (41°, 131°, 221° and 311°) with the assembly being on 0°, and the second over five measurements for the same positions of the linear polarizer, but the whole assembly rotated by 45° (Fig.1). SolPol measures simultaneously three of the four Stokes parameters, i. e. when the instrument assembly is at 0° for a full polarizer rotation, Q, V and I parameters are measured, while when at 45° U, V and I are measured.

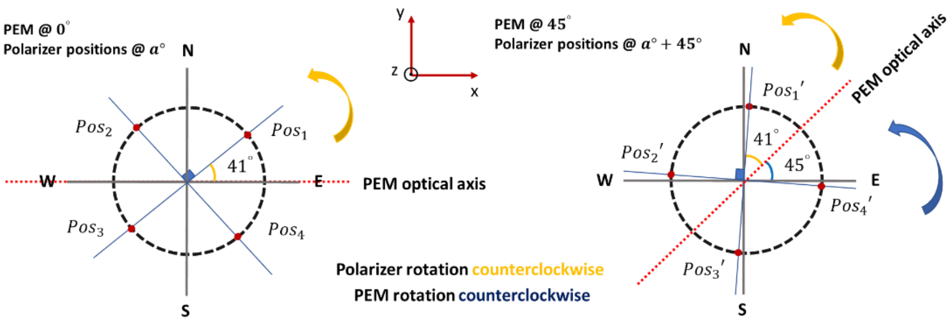

Fig. 1. Schematic representation of the instrument rotation over 45 degrees. The PEM and linear polarizer have the same zero-reference optical plane and the polarizer rotates over logged positions.

Equations 3 and 4 are used to derive the Q/I and U/I normalized values from the AC signal of the instrument divided by the DC signal (I), so as to remove the biases in the measurements, following a similar methodology as in Kemp et al. (1981):

$$Q = -\left(-flux(Pos_1) + flux(Pos_2) - flux(Pos_3) + flux(Pos_4)\right)/4 \quad (3)$$

$$U = -\left(-flux(Pos_1') + flux(Pos_2') - flux(Pos_3') + flux(Pos_4')\right)/4 \quad (4)$$

Pos1 to Pos4 are the positions of the linear polarizer at 41, 131, 221, 311 degrees, and the Pos1' to Pos4' denote the same positions of the linear polarizer, after the rotation of the whole assembly by 45 degrees.

- The degree of linear polarization (DOLP) is given as: $DOLP = \sqrt{\left(\frac{Q}{I}\right)^2 + \left(\frac{U}{I}\right)^2}$ (5)

DOLP is expected to increase over large solar zenith angles (SZA) as i. the sunlight travels through larger airmasses and, therefore, more particles could be preferentially aligned to the line of sight of the instrument and ii. the alignment angle changes with respect to the direction of observation. For the Antikythera case, bias readings in the form of dark measurements, are interspersed between all integration sequences for the quantification of biases on the measured DC flux (I), detector temperature-dependent offsets and PEM residual polarizations. Dark signal intensity I_{dark} is subtracted from the measured intensity (i.e., the DC flux). Moreover, the mean noise level is set at 50 ppm.

3 Results

In the specific study, we report on SolPol full day measurements on the 11th of November 2019 in Nicosia, Cyprus and the 2nd of September 2020 in Antikythera, under dust driven conditions. The dust events exhibit mean AOD values of 0.316 and 0.203 at 500 nm, as monitored by the two co-located at either location Cimel sun-photometers of AERONET (https://aeronet.gsfc.nasa.gov/, last access: 3 February 2021). Figure 2 shows the vertical distribution of the elevated dust layers, as given by the co-located micro pulse lidar data of Laboratoire d' Optique Atmosphérique (LOA) in Cyprus (https://loa-ptfi.univ-lille1.fr/lidar/calendars/cal_2019_cyprus.php, last access: 3 February 2021) and the Polly^{XT} Raman polarization lidar (Engelmann et al. 2016) of the National Observatory of Athens (NOA) in Antikythera, which is part of the European Aerosol Research Lidar Network (EARLINET).

We present the light polarization state as recorded by SolPol in parts per million during the two monitored dust events (Fig. 2), along with the time-height plots from both lidars signals. To verify the presence of large particle concentrations during these two dust events, we exploit the range corrected signal from the micro pulse lidar that shows concentration within the planetary boundary layer and up to 4 km. In Antikythera (Fig. 2, lower panel), attenuated backscatter values of up to ~2 $Mm^{-1}sr^{-1}$, are characteristic of the presence of lofted dust and the injection of dust particles in lower altitudes. Increased linear polarization starting at ~ 13:00 UTC (Cyprus) and at ~ 14:00 UTC (Antikythera) reaching up to 16 x 10^{-5} is observed (Fig. 2, top panel) clearly on the case of Antikythera and partially in the case of Cyprus. The polarization increase trend in Cyprus was less prominent but could have potentially been greater later, since the SolPol measurements stopped earlier on that day.

4 Conclusions

This study focuses on the first detection of atmospheric dust orientation with the use of a direct sun polarimeter over two locations, Nicosia at Cyprus and at PANGEA observatory in Antikythera, by quantifying the linear polarization of the direct solar light, that propagates through atmospheric dust layers. Our measurements indicate that the linear polarization of the direct sunlight increases with increasing solar zenith angle, mainly at early afternoon hours. This coincides with the presence of significant dust loads in altitudes between 2 and 4 km as seen in the lidar profiles and, therefore, can be explained by the dichroic extinction of the sunlight due to vertically-oriented dust particles. Future work will aim at identifying the relation between the varying dust layers' optical depth and associate it with the intensity of the orientation signature at large zenith angles. More sophisticated lidar retrievals through the novel NOA lidar systems, Wall-e and EVE (Tsekeri et al. 2021, Paschou et al. 2021), complemented by the operation of SolPol, will provide the complete characterization of the properties of oriented dust particles in imminent planned scientific experiments.

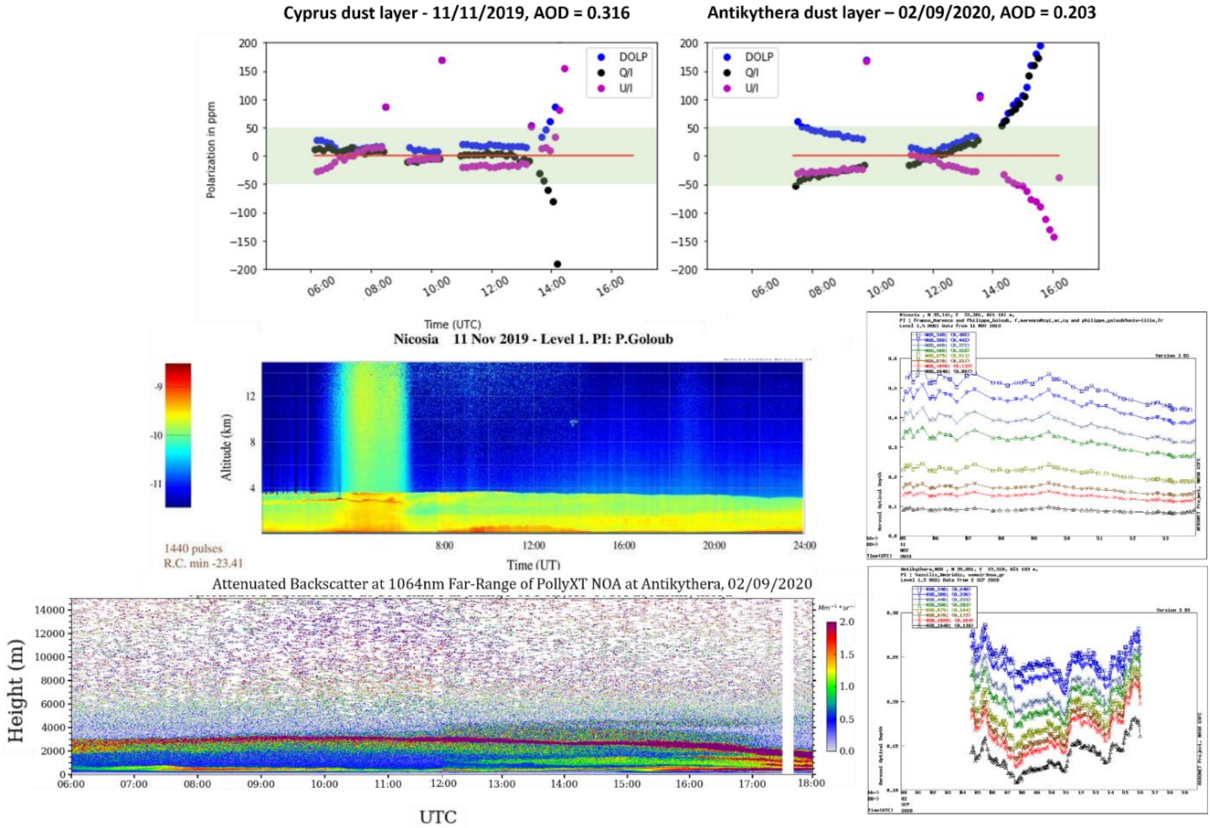

Fig. 2. Top panel: SolPol measurements of Q/I, U/I and degree of linear polarization (DOLP) for the 11 November 2019 and 2 September 2020 dust layers. The shaded area distinguishes the noise level. Mid panel: range corrected signal from the LOA micro pulse lidar in Nicosia, large aerosol loads are depicted in reddish tones and the AOD progression within the day from AERONET. Lower panel: attenuated backscatter at 1064 nm from the PollyXT lidar in Antikythera, large dust concentration is depicted in purple, along the AOD progression within the day from AERONET.

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