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SPEX: A HIGHLY ACCURATE SPECTROPOLARIMETER FOR ATMOSPHERIC AEROSOL CHARACTERIZATION

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I. INTRODUCTION

Global characterization of atmospheric aerosol in terms of the microphysical properties of the particles is essential for understanding the role aerosols in Earth climate [1]. For more accurate predictions of future climate the uncertainties of the net radiative forcing of aerosols in the Earth's atmosphere must be reduced [2]. Essential parameters that are needed as input in climate models are not only the aerosol optical thickness (AOT), but also particle specific properties such as the aerosol mean size, the single scattering albedo (SSA) and the complex refractive index. The latter can be used to discriminate between absorbing and non-absorbing aerosol types, and between natural and anthropogenic aerosol. Classification of aerosol types is also very important for air-quality and health-related issues [3].

Remote sensing from an orbiting satellite platform is the only way to globally characterize atmospheric aerosol at a relevant timescale of ~ 1 day [4]. One of the few methods that can be employed for measuring the microphysical properties of aerosols is to observe both radiance and degree of linear polarization of sunlight scattered in the Earth atmosphere under different viewing directions [5][6][7]. The requirement on the absolute accuracy of the degree of linear polarization P_L is very stringent: the absolute error in P_L must be smaller then $0.001+0.005 \cdot P_L$ in order to retrieve aerosol parameters with sufficient accuracy to advance climate modelling and to enable discrimination of aerosol types based on their refractive index for air-quality studies [6][7].

In this paper we present the SPEX instrument, which is a multi-angle spectropolarimeter that can comply with the polarimetric accuracy needed for characterizing aerosols in the Earth's atmosphere. We describe the implementation of spectral polarization modulation in a prototype instrument of SPEX and show results of ground based measurements from which aerosol microphysical properties are retrieved.

II. SPEX INSTRUMENT

A. Instrument concept

The SPEX prototype instrument is a spectropolarimeter that is designed for a generic space mission with the goal of demonstrating the performance of a relatively new concept for spectropolarimetry and its implementation into a compact, robust instrument [8]. This concept is spectral polarization modulation, which has the key characteristic that the degree and angle of linear polarization are encoded in a modulation of the radiance spectrum [9]. This is achieved by placing a set of dedicated optical crystals, an achromatic quarter-wave retarder (QWR), an a-thermal multiple order retarder (MOR) and a polarizing beam splitter, in front of the telescope. The QWR and MOR ensure that incident linearly polarized light is modulated in the spectral domain. The polarizing beam splitter transforms the spectral polarization modulation into two spectrally modulated intensities $S_+(\lambda)$ and $S_-(\lambda)$, such that amplitude and phase of the modulation are proportional to the degree and angle (ϕ_L) of linear polarization respectively, according to

$$S_{\pm}(\lambda) = \frac{I_0}{2}\left(1 \pm P_L(\lambda)\cos\left(\frac{2\pi\delta(\lambda)}{\lambda} + 2\phi_L(\lambda)\right)\right). \tag{1}$$

Here, I_0 is the incident (unmodulated) radiance spectrum, and δ the retardance of the MOR.

In the SPEX prototype, a dual beam version is implemented such that both S_+ and S_- are recorded. This enables the reconstruction of the unmodulated radiance spectrum at the intrinsic spectral resolution of the spectrometer and allows for a dynamic transmission correction of S_+ and S_-, which in turn enables highly accurate polarimetry. Also, this concept allows polarimetry at the intrinsic spectral resolution, enabling e.g. line polarimetry, albeit at a lower accuracy and a spectrally varying efficiency proportional to $\cos\left(2\pi\delta(\lambda)/\lambda + 2\phi_L(\lambda)\right)$ [12].

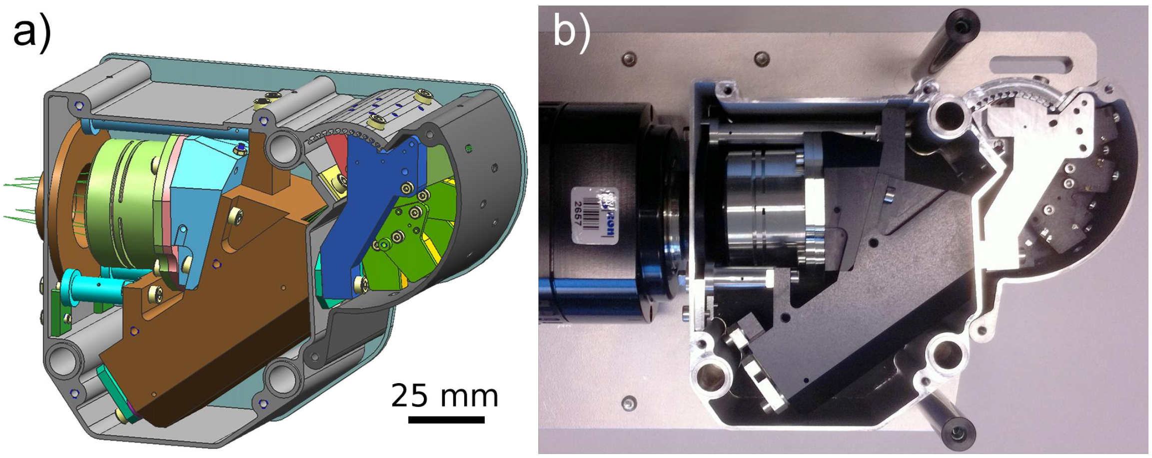

Fig. 1. a) Mechanical design drawing of the opto-mechanical unit of SPEX. The nine viewports are the green units on the right, the grating is mounted in the cyan compartment and the imaging lenses are embedded in the light green housing. The focal plane lies just outside the structure. b) Picture of the realization of SPEX showing the black anodised viewports on the right and the detector mounted to the structure on the left.

B. Instrument design

The mechanical design and realization of the SPEX prototype are shown in Fig. 1. In the SPEX prototype the QWR is implemented as a Fresnel rhomb, while the MOR consists of an a-thermal combination of two birefringent crystals, sapphire and magnesium fluoride with thicknesses of 1.2 mm and 2.88 mm respectively. This results in an average retardance of 24.4 μm over the spectral range from 400 to 750 nm and ~30 modulation periods. The modulation period, which is roughly the polarimetric spectral resolution, increases from 6.6 nm at 400 nm to 26 nm at 800 nm. The polarizing beam splitter is an alpha-BBO Wollaston prism, which is placed at the focal plane of a small suprasil lenslet such that two images of a 1°×7° field-of-view (FoV) are focused on a slit plate.

Spectral modulators are realized nine times at fixed viewing angles of 0, ±14°, ±28°, ±42° and ±53°. For the results presented in this paper, three of the nine modulators were equipped with optics. Two images per modulator are thus imaged on a common slit plate, which serves as the entrance slit of a spectrograph. A volume phase holographic transmission grating is used as the dispersive element and three lenses image the 18 spectra on a focal plane. A commercial QImaging Retiga4000R with 2048×2048 square pixels with 7.4 μm width is attached to the opto-mechanical unit of the prototype.

C. Instrument performance

The polarimetric performance of the SPEX prototype has been assessed using a dedicated stimulus that provides light with a well-known state of linear polarization in the range of $0 < P_L < 0.5$ [10], see Fig. 2. It consists of a Xenon light source which output is coupled to an integrating sphere using a fiber. Two rotatable P-SF57 glass plates are used to repolarize the almost unpolarized output of the integrating sphere. The glass plates have an anti-reflection coating on one side and are tilted in opposite directions in order to minimize beam wobble and sensitivity to tilt-errors. The glass plates are placed in a rotating cradle in order to vary the angle of linear polarization. The entrance pupil of the system in the integrating sphere is imaged by a lens in order to create a field of view of ~10° at an exit pupil of 3.3 mm, both of which are larger than the 7° FOV and 1.2 mm entrance pupil of SPEX. The output of the stimulus was measured with a verification polarimeter that consist of a rotating polarizer in front of a fiber collimator and fiber that transmits the incident light to a fiber-spectrometer.

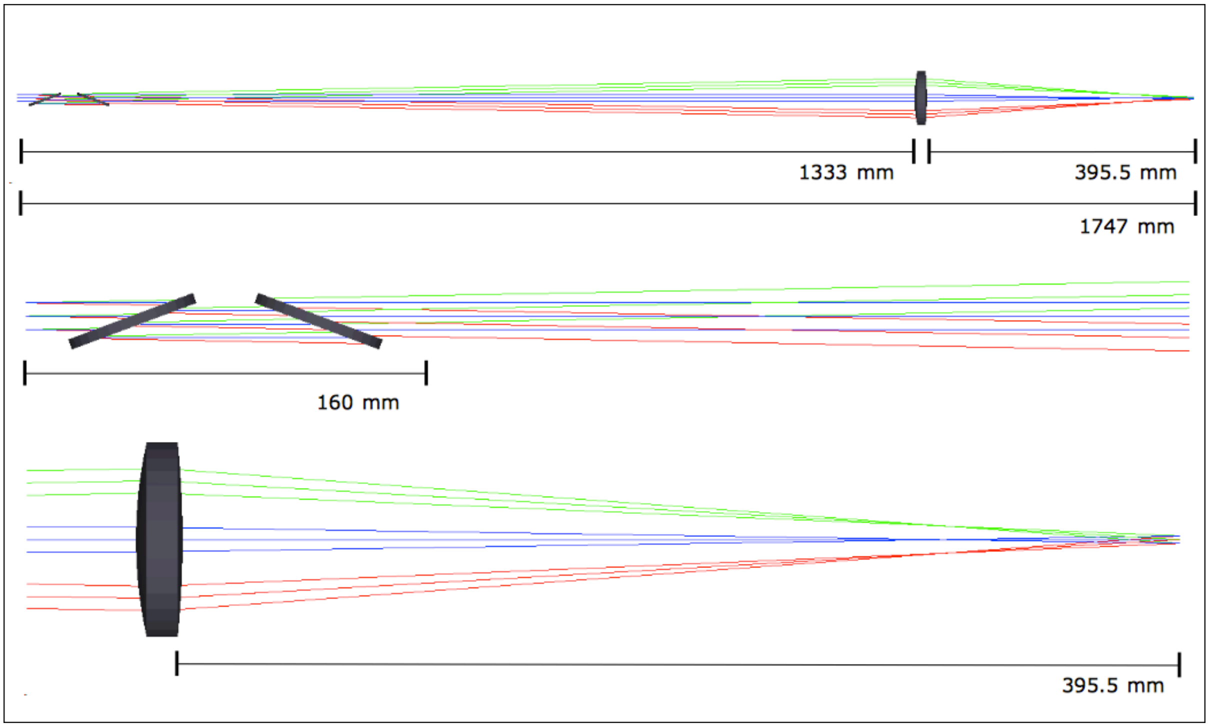

Fig. 2. ZEMAX model of the calibration stimulus. The light travels from left to right. The schematic starts with the entrance pupil, which is the integrating sphere's 1 cm diameter exit hole, and it ends with the 3.3 mm diameter exit pupil. Different colors correspond to different angles, which roughly correspond with SPEX' field-of-view of ±3.5°. The glass plates (shown at ±70°) are Schott P-SF57 with AR coating on the inner sides of the V-shape (sides for the glass-plates 'facing' each other).

Measurement results obtained with the verification polarimeter are plotted in Fig. 3. The increase in P_L with increasing tilt angle of the glass plates is evident from Fig. 3a, while the spectral variation due to the AR-coating clearly shows up in Fig. 3b. This spectral variation in P_L at a given glass plate tilt angle shows the necessity to characterize the output of the stimulus, since calculations with the required accuracy using the Fresnel equations cannot be performed due to the lack of knowledge of the details of the AR-coating.

Comparison of measurements performed with SPEX and with the verification polarimeter show an agreement better than $0.002+0.01{\cdot}P_L$ over the FoV of all three viewports, and for most parts of the spectral range [10]. The observed differences across the spectrum and as a function of P_L of the stimulus are reproducible and systematic in all measurements to within $0.001+0.005{\cdot}P_L$. In case SPEX is closer to the truth than the verification polarimeter, this is the polarimetric accuracy that SPEX can achieve. In case the verification polarimeter is

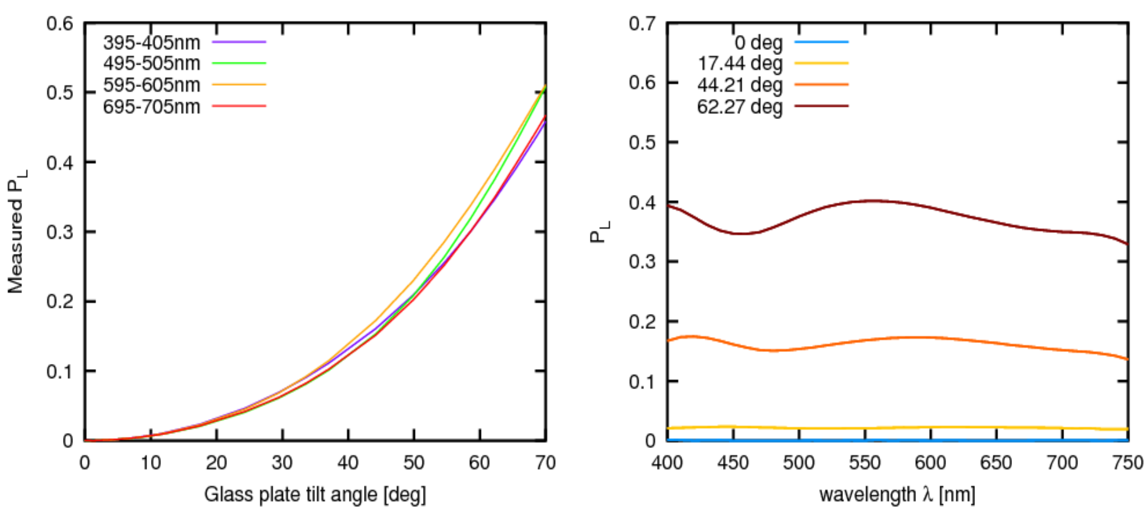

Fig. 3. a) Measured P_L of the stimulus plotted as a function of glass plate tilt angle for four different wavelength. b) Spectral variation of P_L plotted for four different glass plate tilt angle.

closer to the truth, the average observed difference between SPEX and the verification polarimeter can be used to obtain calibration factors as a function of wavelength and stimulus P_L. After applying the calibrations factors, the difference between SPEX and the verification polarimeter is reduced to $0.001+0.005 \cdot P_L$, which is thus a measure for the consistency and obtainable absolute polarimetric accuracy with SPEX. Note that this polarimetric accuracy is compliant with the accuracy requirement stated for an aerosol characterization mission, which shows that the SPEX concept is a promising concept for such a mission.

III. GROUND-BASED MEASUREMENTS

As mentioned in the introduction, the high polarimetric accuracy of $0.001+0.005 \cdot P_L$ is needed in order to reliably retrieve aerosol microphysical properties from multi-angle photo-polarimetric measurements. We have performed ground-based clear sky measurements with the SPEX prototype at the Cabauw Experimental Site for Atmospheric Research (CESAR) in the Netherlands in May 2012 in order to demonstrate the ability to retrieve aerosol microphysical properties using SPEX data.

For this purpose, the SPEX prototype was placed on a telescope mount, which allowed pointing to the sky with an estimated accuracy of 1° based on several measurement of the position of the sun during the observing days. SPEX images were acquired while scanning the clear sky in steps of 10°. Data from a full scan are processed to radiance and degree of linear polarization spectra as a function of scattering angle. Radiance spectra are obtained by adding S_+ and S_- spectra after applying a transmission correction algorithm that minimizes residual modulations in the sum spectrum. The sum spectrum is radiometrically calibrated by comparing the total binary units inside a wavelength bin with data from three band pass filters employed by the CIMEL sunphotometer at Cabauw, which is part of AERONET. The estimated accuracy of the radiance spectrum thus obtained is of the order of 5%. The degree and angle of linear orientation are obtained using a demodulation algorithm [10]. This algorithm takes a normalized spectrum $S_N = S_+/I_0$ and fits each modulation

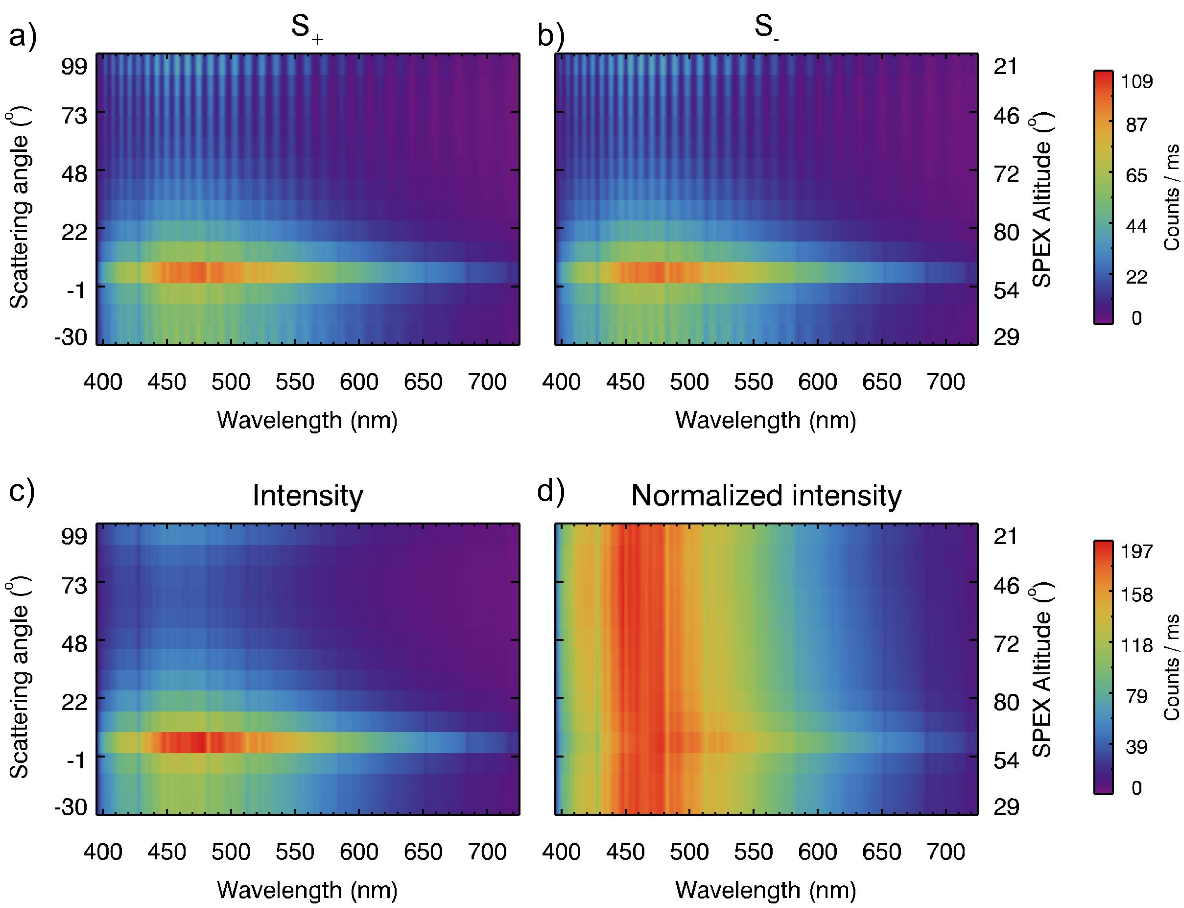

Fig. 4. a,b) Transmission corrected SPEX S_+ and S_- spectra of a principle plane scan of the clear sky. c) Intensity spectra of the principle plane scan obtained by summing S_+ and S_- spectra. d) Normalized intensity spectra of c) showing more reddish skylight near the sun.

period centered around a certain spectral pixel corresponding to wavelength λ_0 to

$$S_N(\lambda) = O \pm \frac{A(\lambda)}{2}\cos\left(\frac{2\pi\delta(\lambda)}{\lambda} + 2\phi_L\right). \tag{1}$$

Here the offset O is around ~0.5 and constant over a spectral window, while $A(\lambda) = A_0 + A_1(\lambda - \lambda_0)$ to allow for a linear variation of the degree of linear polarization over a spectral window, $\delta(\lambda)$ the spectral retardance determined from a reference measurement, and ϕ_L the angle of linear polarization that is assumed constant over a spectral window.

An example of a measurement sequence, taken across the principle plane, is plotted in Fig. 4. Transmission corrected spectra $S_+(\lambda)$ and $S_-(\lambda)$ extracted from SPEX measurements at each viewing angle are plotted as a function of scattering angle. Clearly, the sky light is almost unpolarized near the Sun (scattering angles close to 0°). Non-zero polarization shows up as a modulated intensity, with maximum contrast and thus maximum degree of linear polarization reached at a scattering angle of 90°. A maximum P_L at 90° is expected for pure Rayleigh single scattering. Radiance spectra are visualized in Fig. 4c and 4d, which show increased brightness near the Sun as well as a shift towards the red part of the spectrum.

The P_L and ϕ_L extracted from the data of this measurement sequence are plotted in Fig. 5a and 5b respectively. Indeed, P_L is very close to zero at zero scattering angles, and reaches a maximum of 0.66 at 90° scattering angle. Since all measurement are taken close to the principle plane, the angle of linear polarization ϕ_L is close to 0, except near the Sun, when a deviation from the principle plane leads to large changes in ϕ_L as a result of the changing scattering geometry. Also, at low P_L it is more difficult to extract ϕ_L with high accuracy.

IV. AEROSOL RETRIEVAL

Radiance and polarization spectra as a function of scattering angle serve as input for an aerosol retrieval algorithm. This algorithm is a modified version of the algorithm developed for the retrieval of aerosol properties from data from the PARASOL satellite [11], with the main difference that the geometry is changed for the inversion of ground-based measurements. In short, the algorithm retrieves a set of aerosol parameters using a scheme based on Phillips-Tikhonov regularization, in which nonlinear cost function – depending on the discrepancy between observed and simulated intensities and degrees of polarization at multiple wavelengths and viewing angles – is iteratively minimized, starting from a first guess provided by a loop-up table. Simulated intensities are determined using a full-Stokes radiative transfer model. Aerosol is parameterized with a bi-modal (coarse and fine mode) log-normal aerosol size distribution with mean aerosol size and variance. Other retrieved parameter per aerosol mode are the AOT, a wavelength independent complex refractive index, and sphericity, thus 12 parameters in total. From these parameters, the SSA can be calculated.

Adopted wavelengths in this work correspond to wavelength bands in the visible part of the spectrum of the CIMEL sun photometer at CESAR, namely 440, 490 and 670 nm. The fitted P_L's at these wavelength are plotted together with the measured spectra in Fig. 6a, which shows that a very good fit result is obtained. The three important aerosol parameters that are obtained with such a retrieval from the presented measurement sequence as well as from 5 other measurements sequences taken on three different days, are plotted in Fig. 6b-d.

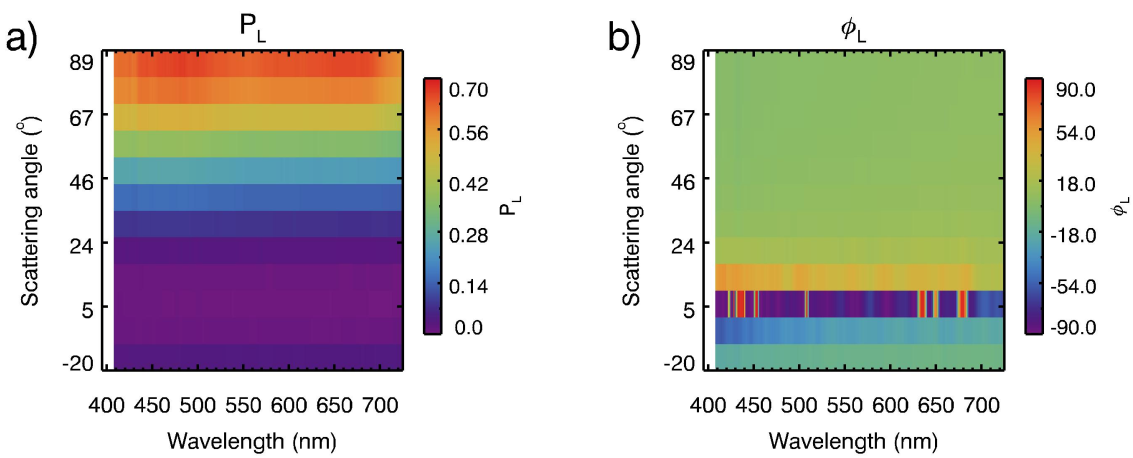

Fig. 5. P_L (a) and ϕ_L (b) extracted from the data of Fig. 4 plotted as a function of wavelength and scattering angle.

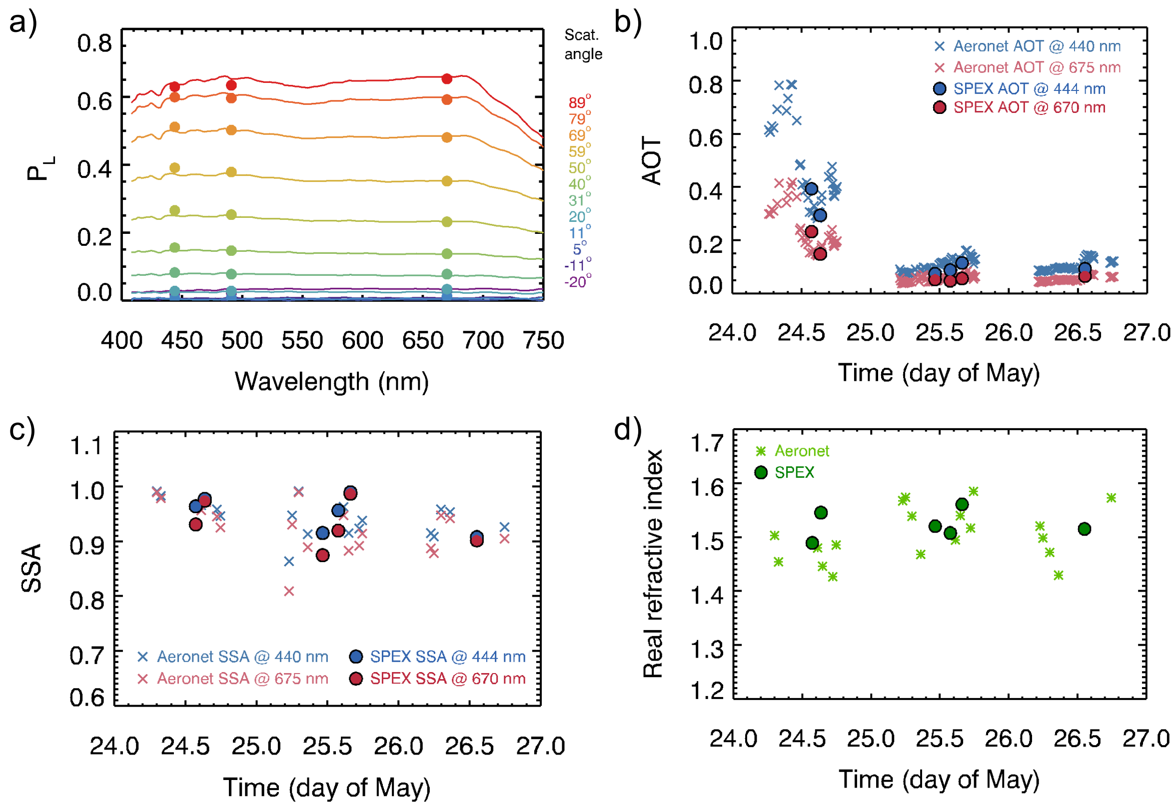

Fig. 6. a) Measured P_L spectra for a range of scattering angles and fitted P_L (filled circles) at 440, 490 and 670 nm. b) Retrieved aerosol optical thickness from SPEX (filled circles) and from AERONET (crosses) plotted for two wavelengths. c) Retrieved single scattering albedo from SPEX (filled circles) and from AERONET (crosses) plotted for two wavelength. d) Retrieved real refractive index from SPEX (filled circles) and from AERONET (crosses).

These aerosol parameters are the aerosol optical depth, single scattering albedo and the real part of the refractive index. Also plotted are the same parameters obtained with the AERONET sun photometer at CESAR, the AOT using direct sun measurements [13], and the level 1.5 SSA and real refractive index results from sky radiance measurements [14]. Although the SPEX results form a limited dataset, a good agreement exist between the retrieved parameter values from the SPEX data and those from AERONET, especially for the AOT, showing the potential of aerosol characterization with SPEX. Recent results obtained with a dedicated ground-based SPEX instrument form a more extended data set that allow a more in-depth comparison of retrieved aerosol parameters from SPEX and AERONET as well as an error analysis [15].

V. CONCLUSIONS AND OUTLOOK

We have presented the SPEX instrument that employs spectral polarization modulation for achieving very high polarimetric accuracy. The instrument has been polarimetrically calibrated using a dedicated optical stimulus. When the average systematic (and reproducible) difference between SPEX and the verification polarimeter is used as a calibration, the accuracy of SPEX can become better then $0.001 + 0.005 \cdot P_L$, which is required, among others, for aerosol characterization instruments. The potential of aerosol characterization with SPEX is demonstrated by retrieval results from ground-based measurement of the SPEX prototype at CESAR. These results show a good agreement of AOT, SSA and real refractive index retrieved using SPEX data and retrieval results from AERONET. This paper therefore shows that multi-angle spectral polarization modulation has the potential to enable instruments that are suited for aerosol related climate and air quality research. SPEX-like instruments could especially contribute to aerosol characterization initiatives either from the ground or from a space based platform.

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