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RESEARCH LETTER

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Key Points:

- The iSPEX add-on turns smartphones into aerosol measurement devices
- Thousands of iSPEX measurements across the Netherlands form AOT maps
- The iSPEX AOT data match MODIS and AERONET data and have 2 km resolution

Supporting Information:

- Readme
- Supporting Text and Figures S1–S6

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Mapping atmospheric aerosols with a citizen science network of smartphone spectropolarimeters

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Abstract To assess the impact of atmospheric aerosols on health, climate, and air traffic, aerosol properties must be measured with fine spatial and temporal sampling. This can be achieved by actively involving citizens and the technology they own to form an atmospheric measurement network. We establish this new measurement strategy by developing and deploying iSPEX, a low-cost, mass-producible optical add-on for smartphones with a corresponding app. The aerosol optical thickness (AOT) maps derived from iSPEX spectropolarimetric measurements of the daytime cloud-free sky by thousands of citizen scientists throughout the Netherlands are in good agreement with the spatial AOT structure derived from satellite imagery and temporal AOT variations derived from ground-based precision photometry. These maps show structures at scales of kilometers that are typical for urban air pollution, indicating the potential of iSPEX to provide information about aerosol properties at locations and at times that are not covered by current monitoring efforts.

1. Introduction

Atmospheric aerosols impact our lives in many ways. They reduce our life expectancy by causing and exacerbating lung and cardiovascular diseases [Beelen et al., 2014; Krall et al., 2013; Chen et al., 2013; Pope et al., 2002], influence the Earth's climate [Intergovernmental Panel on Climate Change, 2013; Rosenfeld et al., 2014; Quaas et al., 2008; Haywood and Boucher, 2000; Bréon et al., 2002], and impede air traffic in the form of volcanic ash clouds [Alexander, 2013]. Current measurement approaches provide insufficient information to understand and permit mitigation of these aerosol effects. In many populated areas, measurements are lacking or too sparse to provide the type of spatial and temporal monitoring required to evaluate aerosol-related health hazards. Furthermore, such measurements should measure not only the amount of aerosol but also the microphysical properties of the constituting particles, including their size distribution and chemical composition. Indeed, the smallest, insoluble particles cause the most detrimental health effects [Churg and Brauer, 2000]. Similar measurements are required on a global scale to understand the impact of the scattering and absorption of sunlight by aerosols on the atmospheric radiative balance and their influence on cloud formation and the Earth's hydrological cycle [Rosenfeld et al., 2014; Mishchenko et al., 2004].

Professional ground-based aerosol measurement stations are limited in spatial coverage. Satellite observations often lack temporal resolution (typically, a single measurement per location per day as geostationary satellites cannot perform the multiangle measurements required to retrieve microphysical aerosol parameters) and provide limited information on aerosol particle characteristics. Therefore, additional measurements based on a different strategy are needed to achieve a sufficiently high spatiotemporal resolution and to obtain information on the microphysical properties of aerosol particles.

Over the last years, citizen science approaches have transformed scientific data collection [e.g., Boersma and De Vroom, 2006; D'Hondt et al., 2013] and analysis [e.g., Fischer et al., 2012; Cooper et al., 2010] in some areas, mostly due to technological advances and the increased willingness of the general public to be involved in the scientific practice [Bonney et al., 2014; Freitag and Pfeffer, 2013; Raddick et al., 2013]. Mobile phone

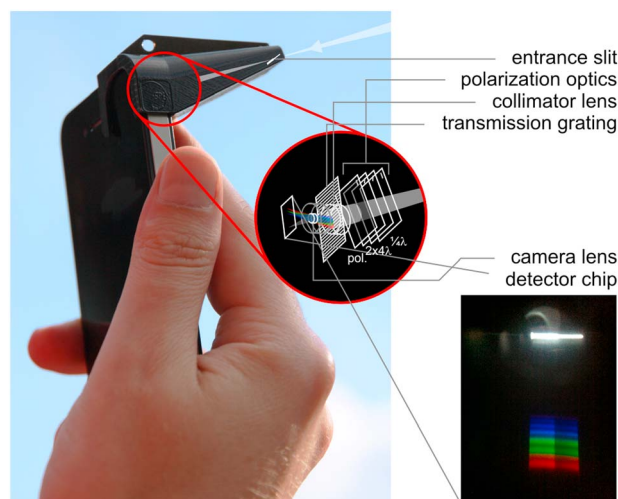


Figure 1. The iSPEX add-on for the iPhone and a typical image from blue sky observations. The optical design of iSPEX uses the smartphone camera as the detector, and the iSPEX add-on produces a spectrum of the light that entered the slit with sinusoidal bands created by the spectral polarization modulation optics. These bands provide a direct measure of the sky polarization.

technology now enables the collection of atmospheric quantities such as pressure [Mass and Madaus, 2014] and temperature [Overeem *et al.*, 2013]. Up to now, this data collection has been largely passive: the citizens' equipment automatically submits data to a database without any specific user actions necessary to acquire the data. Aerosol remote sensing, on the other hand, requires an active participation in the measurement process where participants follow a formal procedure.

2. The iSPEX Smartphone Add-On

We developed iSPEX, a low-cost, mass-producible add-on that a citizen scientist attaches in front of the smartphone camera to transform the phone into a spectropolarimetric instrument (see Figure 1). With the iSPEX add-on, the degree of linear polarization (DoLP) of the cloud-free sky can be measured as a

function of wavelength and, by pointing the phone at different directions in the sky, as a function of scattering angle. The DoLP as a function of both wavelength and scattering angle yields unique information on fundamental aerosol properties [Hansen and Travis, 1974; Mishchenko *et al.*, 2004; Boesche *et al.*, 2006; Hasekamp, 2010; Dubovik *et al.*, 2011]. The corresponding iSPEX app guides the participant through the measurement procedure from the orientation with respect to the principal scattering plane (Sun in the back) to the measurement series, which consist of a sequence of images from just above the horizon to the zenith and beyond. For data quality assessment, the app asks the participant to perform the measurement twice. The combination of the iSPEX add-on and the app makes optimum use of the high-tech smartphone capabilities: to record data, to add metadata including location, time, and pointing information, and to upload all information to an online database. iSPEX therefore enables the creation of a citizen science network that provides distributed, high spatial and high temporal resolution aerosol data.

The iSPEX add-on contains a stack of plastic optical components (see Figure 1) that imprints the polarization content of the incident light onto the intensity spectrum as a sinusoidal modulation; the relative amplitude of this modulation is proportional to the DoLP [Snik *et al.*, 2009]. In this study we extract the DoLP in the green channel of the spectrum (480–580 nm) from each image. The DoLP measurement accuracy is only limited by production tolerances and issues related to the smartphone camera system, since the iSPEX polarimetric technique does not suffer from differential effects or instrumental polarization [Tyo *et al.*, 2006; Snik and Keller, 2013]. The DoLP measurements are calibrated through a comparison with cospatial data from a professional and highly accurate, stand-alone SPEX instrument [Van Harten *et al.*, 2011, 2014].

The most basic aerosol property is the aerosol optical thickness (AOT), which we derive from the DoLP at 90° from the direction to the Sun. We fit a parabolic curve to the DoLP data points as a function of scattering angle to obtain DoLP(90°) and convert that to AOT using a formula that is obtained from the average of an ensemble of atmospheric modeling results (see Figure S3 in the supporting information). The DoLP is inversely related to the AOT: the more aerosol particles, the more depolarized the skylight is. The inherent accuracy of this straight-forward conversion of DoLP(90°) to AOT is highest for low AOT (i.e., high DoLP(90°)), as both the inherent scatter due to other atmospheric parameters and the dependence of AOT on DoLP(90°) is lowest there. This implies that the interpretation of iSPEX data presented here is most accurate in cases of patches of pollution or, e.g., volcanic ash in an otherwise clear sky. Figure S3 also shows that the DoLP(90°) signal starts to saturate for AOT > 0.8, which renders it insensitive in cases of heavy pollution. Classical AOT determinations require absolute photometric measurements with well-calibrated

instruments. Recent studies [Igoe *et al.*, 2014; Cao and Thompson, 2014] show that smartphone cameras can be used to determine AOT through direct Sun photometry with accuracies of 0.01–0.1. However, the equipment is relatively expensive, and every phone type and probably every phone needs to be calibrated in an absolute sense. The iSPEX polarization measurement of the diffuse sky is a relative measurement and does not require an absolute calibration of the smartphone camera and the iSPEX add-on.

A single iSPEX measurement is not accurate enough to yield quantitative aerosol information, because the DoLP measurements have an absolute 1σ error of 0.03 (Figures S6 and S2), which is insufficient to retrieve quantitative data on particle size and composition [Mishchenko *et al.*, 2004]. However, the widespread usage of smartphones and the low production costs of the iSPEX add-on enable crowdsourced measurements, which reduces polarimetric errors by averaging over measurements with many devices.

3. Results From Citizen Science Experiments

We distributed more than 8000 iSPEX add-ons to participants throughout the Netherlands with the goal of making maps of aerosol properties with unprecedented spatiotemporal resolution. We organized a national measurement day once the weather forecast predicted mostly cloud-free skies above the entire country (8 July 2013), which resulted in 6007 measurement submissions to our database. Two additional, less publicized, measurement days were held on 9 July and 5 September 2013, yielding 1546 and 2444 submissions, respectively. These citizen science experiments provided crucial and sufficient data to assess the information content of crowdsourced iSPEX measurements.

Figure 2a shows the AOT maps derived from the iSPEX measurements during the measurement days (indicated with black dots; see also Figure S3). At every location in the Netherlands, the nearest 50 iSPEX DoLP measurements within the indicated time window were averaged and converted to AOT, and the resulting map was smoothed to 2 km resolution. The AOT maps from the Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua and Terra satellites [Remer *et al.*, 2005] with the best spatial resolution on those days are presented in Figure 2b. Qualitative inspection of the iSPEX maps in Figure 2 shows that they are in good agreement with the MODIS data, taking into account the 7 h temporal smearing of the iSPEX maps versus the near-instantaneous snapshots from the satellite. The correlation analysis between iSPEX-derived AOT and MODIS-retrieved AOT presented in Figure S5 demonstrates a good agreement, although significant scatter is present. This scatter is of the same magnitude, as is observed in comparisons of MODIS AOT data with Aerosol Robotic Network (AERONET) AOT data [e.g., Cheng *et al.*, 2012; Grosso and Paronis, 2012], and is therefore partially attributed to limited accuracy of the MODIS retrievals over urban areas, which were the only locations that yielded sufficient iSPEX measurement density around the time of the MODIS overpass. This result therefore already demonstrates the potential of iSPEX measurements to support satellite data with on-ground correlative measurements for complex but important ground targets. A variogram analysis (Figure S6) shows that iSPEX maps exhibit spatial features as small as 2 km, which is indeed better than the satellite view (with 10–20 km resolution for the MODIS data). The spatial resolution of the iSPEX data obviously depends on the spatial measurement density per unit time but also on the three-dimensional distribution of aerosols as the AOT is a column-integrated value and the measured DoLP is determined by combining observations under different angles through the atmosphere. Moreover, there is an obvious correlation in Figure 2 between the iSPEX measurement density and the population density, which automatically leads to a finer measurement grid and/or higher time resolution in locations where it matters most.

Figure 3 presents time-resolved iSPEX AOT data within 20 km from Cabauw, the location of the CESAR ground station for atmospheric measurements [Apituley *et al.*, 2008]. The average iSPEX data are in good agreement with the AOT data derived from Sun photometry by the AERONET ground station at Cabauw [Dubovik *et al.*, 2000]. The typical standard errors and the typical offsets from the highly accurate AERONET data are <0.1 , which is probably limited by the inherent scatter in Figure S3. Still, these iSPEX AOT data are competitive with respect to smartphone Sun photometry [Igoe *et al.*, 2014; Cao and Thompson, 2014]. As most of the iSPEX measurements plotted in Figure 3 are obtained in the city of Utrecht, some 20 km north of rural Cabauw, the match between iSPEX and AERONET likely becomes better for a fully colocated situation. Remote aerosol measurements as a function of time can therefore be successfully obtained anywhere by anyone with an iSPEX add-on during (mostly) cloud-free conditions, given a sufficient measurement density, as exemplified in Figure 4 for the Dutch cities of Amsterdam, Rotterdam, Eindhoven,

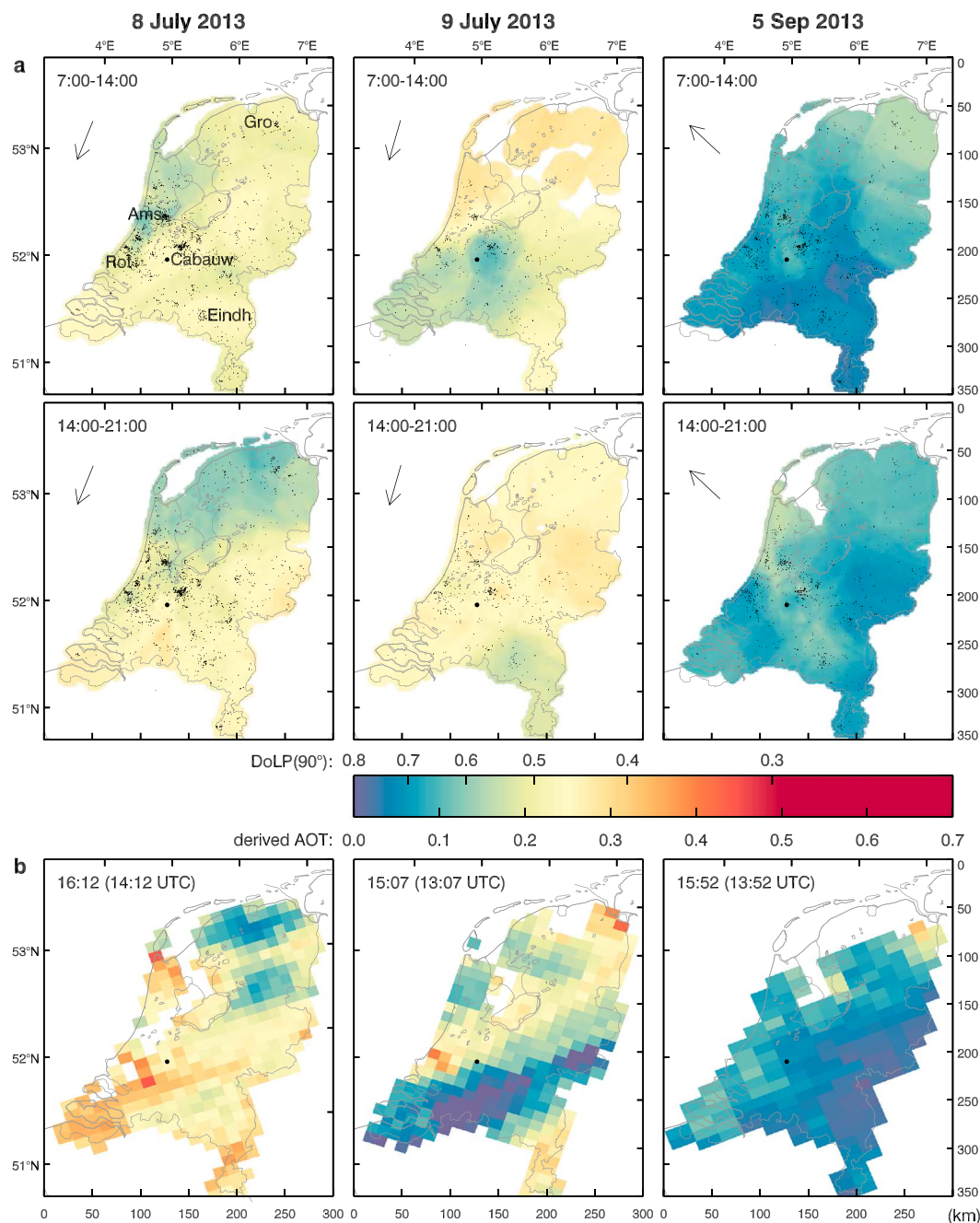


Figure 2. (a) AOT (550 nm) maps for the Netherlands derived from iSPEX DoLP data for 8 and 9 July and 5 September 2013. Note that the contrast in spatial aerosol features is decreased by spatial and temporal averaging, particularly on 9 July, when the measurement density was low and the spatiotemporal gradients in the AOT were large. The locations of all underlying iSPEX measurements are superimposed on the map. The daily averaged wind direction at Cabauw is indicated with an arrow. (b) MODIS AOT (550 nm) maps for the same dates: 8 July Aqua, 9 July Terra, and 5 September Aqua.

and Groningen. Thus, iSPEX measurements can complement professional aerosol measurement equipment both on the ground and in space and have the potential to surpass their spatiotemporal resolution.

4. Aerosol Sources

The iSPEX data, supplemented with groundSPEX and lidar measurements, provide a comprehensive overview of aerosol dynamics across the Netherlands during the measurement days. On 8 July 2013 aerosol

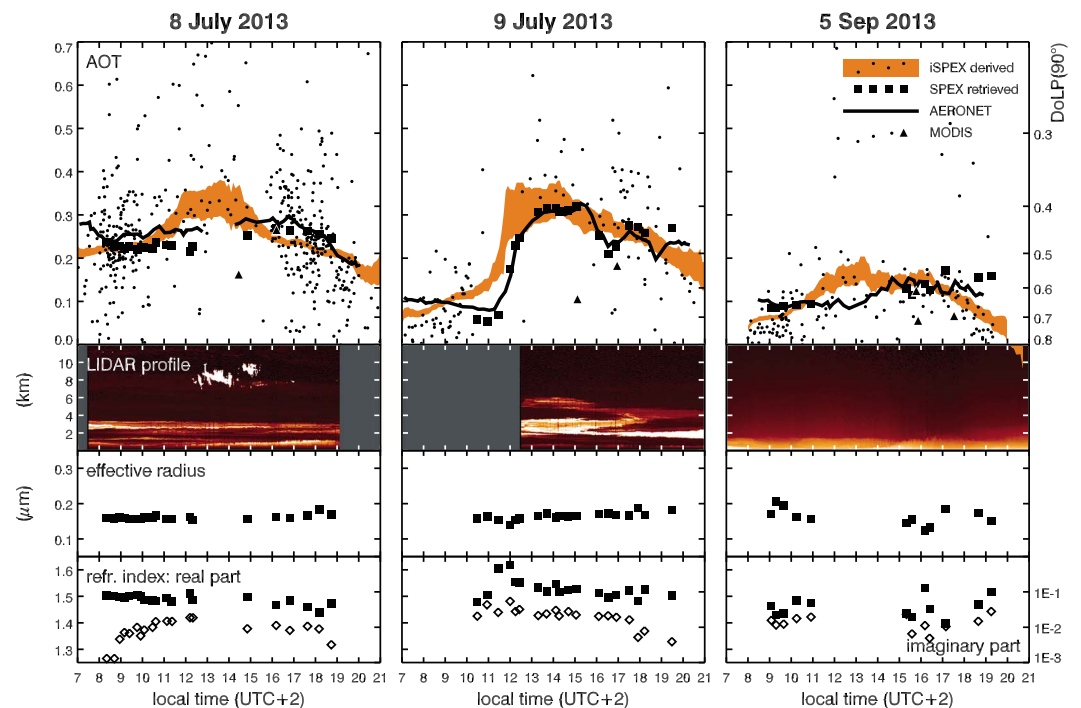


Figure 3. iSPEX AOT (550 nm) time series from measurements within 20 km from Cabauw, the Netherlands (51.97°N, 4.93°E) on 8 and 9 July and 5 September 2013 in comparison with AERONET AOT (550 nm), MODIS AOT (550 nm), and retrieved AOT (550 nm) from the groundSPEX instrument at Cabauw. The shaded area represents the standard error around the average iSPEX DoLP(90°) converted to AOT for a running 3 h time window. Note that the averaging takes place on the DoLP scale that is represented in a nonlinear fashion on the right side of the plot, corresponding to the conversion to the linear AOT scale, cf. the formula in Figure S3. Additional aerosol information: lidar vertical profiles at Cabauw [Apituley *et al.*, 2009] in July and Leosphere ALS450 LIDAR in September), and effective radius of the fine-mode particle size distribution and the refractive index (real part: squares, imaginary part: diamonds), from groundSPEX measurement retrievals [Van Harten *et al.*, 2014].

layers with a combined AOT of ~ 0.25 were present over most of the Netherlands. Most aerosols were located at altitudes of 0.5–3.5 km as derived from lidar observations. These aerosol layers originated from forest fires in North America. High cirrus clouds formed around noon over the Netherlands, which temporarily increased the iSPEX-derived AOT measurements. During the course of the day, wind moved cleaner air

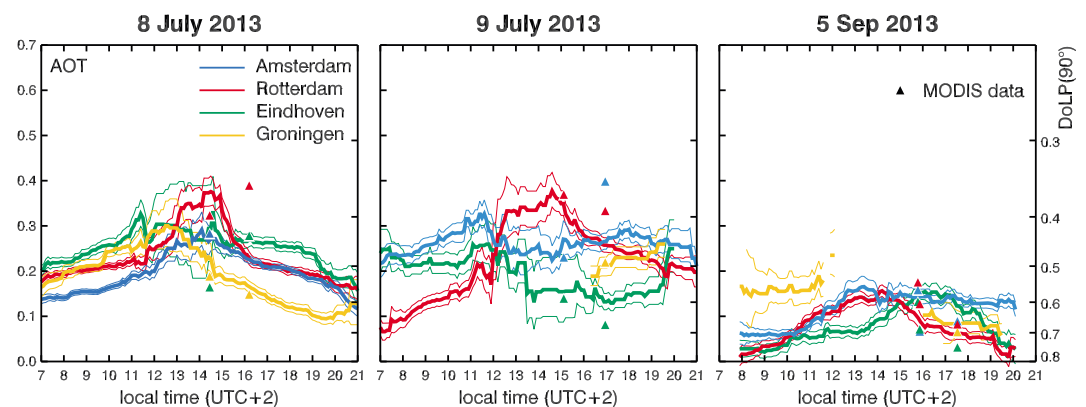


Figure 4. iSPEX-derived AOT time series for the cities of Amsterdam, Rotterdam, Eindhoven, and Groningen (20 km radius), indicated on the map in Figure 2. The corresponding thin lines indicate the range of the standard error for each area. MODIS data are overplotted. Note that MODIS retrievals for urban areas can be subject to severe inaccuracies (see also Figure S5), which is evident from the large scatter in the results for the near-simultaneous overpasses of Aqua and Terra on 5 September.

from the sea to the northern provinces. In the morning of 9 July, high-altitude aerosol layers were present again, except for a clear patch over the middle of the Netherlands, which included Cabauw. The aerosol plumes advected southward, leading to large temporal AOT gradients like the ones measured at Cabauw in Figure 3 and Rotterdam and Eindhoven in Figure 4. The iSPEX-derived AOT for Cabauw increased before the other measurements because most contributing measurements were performed in the city of Utrecht, north of Cabauw. On 5 September the aerosol situation was different with a lower overall AOT (~ 0.1) from an aerosol layer that was confined to the boundary layer, as confirmed by lidar. The iSPEX maps show the wind blowing in patches of aerosol with an additional AOT of ~ 0.1 from sources southeast of the Netherlands.

5. Outlook

We conclude that through averaging of ~ 50 iSPEX measurements, subpercent polarimetric accuracy can be achieved, which is required for quantitative aerosol remote sensing. Obviously, these measurements will need to sample the same atmospheric conditions, which generally vary in time and space. A sufficiently dense iSPEX measurement network can deliver a spatial resolution of ~ 2 km, which is crucial to address urban and regional sources of aerosol pollution. Multiangle spectropolarimetric measurements as provided by iSPEX allow for a more detailed determination of AOT and can yield more aerosol parameters than just the AOT. Because of their large measurement dimensionality, the data can also be interpreted unambiguously in terms of the particle size distribution and chemical composition through the complex refractive index [Mishchenko *et al.* 2004; Hasekamp, 2010; Dubovik *et al.* 2011; Boesche *et al.* 2006; Hansen and Travis, 1974], which also further constrains the AOT. Such retrievals (based on Hasekamp [2010]) are presented in Figure 3 for the well-calibrated groundSPEX instrument [Van Harten *et al.*, 2011, 2014], which performed measurements at Cabauw during the iSPEX measurement days. SPEX retrievals during the measurement days showed that spectropolarimetric data are sensitive to submicron particles and can distinguish them from water droplets ($n = 1.33$). The imaginary value (i.e., the absorptive component) of the refractive index can distinguish nonabsorbing from absorbing aerosols such as soot particles that are particularly harmful to health. Figure S2 shows the excellent match between averaged iSPEX DoLP and SPEX DoLP data as a function of scattering angle. Hence, iSPEX has the potential to deliver the same microphysical aerosol parameters as groundSPEX does. These parameters are difficult to obtain from other (remote sensing) measurements. So far, additional data would need to be added to the iSPEX DoLP measurements, like the accurate radiometry of the SPEX instrument, to better constrain aerosol parameters. If smartphone cameras can be controlled well enough, the iSPEX measurements can yield *relative* radiometry [Igoe *et al.*, 2014], which by itself provides a complementary measure of AOT through the relative sky brightness above the horizon [Vlemmix *et al.*, 2010; Poduri *et al.*, 2010] and particle size through the shape of the solar aureole [Deepak *et al.*, 1982]. The current measurement procedure in the iSPEX app would need to be updated to include viewing directions closer to the Sun. The averaged iSPEX radiometry data could also be converted into absolute values using calibrated instruments as references at a number of locations. Therefore, the combined measurement of diffuse sky DoLP and brightness as a function of wavelength and scattering angle can provide input to a retrieval algorithm that provides a better constrained AOT and could yield additional information on microphysical aerosol parameters like size and composition. Moreover, iSPEX measurements could provide a three-dimensional view of aerosol clouds by adopting a tomographic measurement and data analysis strategy [Aides *et al.*, 2013].

The iSPEX citizen science experiment shows that iSPEX can deliver, in quasi-real-time, crucial information on atmospheric aerosols that is complementary to data from professional instrumentation both in spatiotemporal resolution and coverage and in terms of aerosol parameters. A flexible iSPEX-network of active participants may even provide targeted observations during particular aerosol events and long-term monitoring at many locations.

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