AEROSOL REMOTE SENSING FROM MOVING PLATFORMS WITH THE FUBISS RADIOMETERS

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1. INTRODUCTION

Aerosol particles have an important impact on the surface net radiation budget by direct scattering and absorption (direct aerosol effect) of solar radiation, and also by influencing cloud formation processes (semi-direct and indirect aerosol effects). To study the former, a multispectral multiangle spectrometer system for flexible use on moving platforms has been developed at the Institute for Space Sciences. It enables simultaneous measurements of the direct solar irradiance, the solar aureole radiance, and the zenith sky radiance in the UV, visible and NIR spectral region. It has been used on various international campaigns, either mounted on a Cessna 207T, on the German research icebreaker FS Polarstern, or based on the ground.

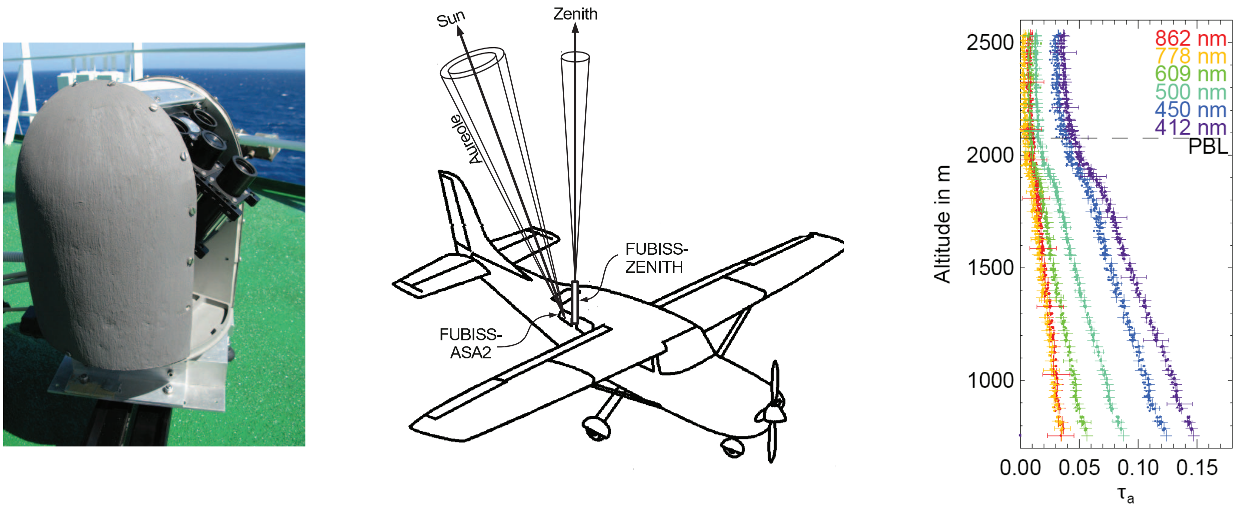

Fig. 1. FUBISS-ASA2 (left), the instrument viewing angles on the Cessna 207T (middle), and measured aerosol optical depths during FUBEX 2008 (right).

2. INSTRUMENTATION

Most of the common sunphotometers for aerosol remote sensing, such as the CIMEL instruments used in the AERONET network, are based on a filter wheel technique, and therefore don't allow for simultaneous measurements of different spectral components of the solar radiance. Under varying atmospheric conditions, and especially on moving platforms, a delay between the measurement of different spectral components introduces noise, and significantly reduces the accuracy of derived aerosol properties.

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Different approaches were made in the past century to develop airborne sunphotometers capable of high multispectral measurement rates. The NASA Ames Airborne Tracking Sun Photometer, for instance, provides 14 separate sensors and interference filters at 354-2139 nm for simultaneous measurements [1]. The FUBISS (Free University Berlin Integrated Spectrographic System) Instruments discussed here uses grating spectrometers for the UV, Visible, and NIR with a spectral resolution better than 10nm. The first airborne radiometer from this series, FUBISS-ASA1 (Aureole and Sun Adapter 1), provided two baffles for the simultaneous measurement of the direct solar irradiance and the the scattered radiance from the solar aureole; the latter providing additional information about scattering properties of the aerosol particles [2].

Further miniaturization of the components led to the construction of the airborne dual aureole- and sunphotometer FUBISS-ASA2 (Aureole and Sun Adapter 2), where all optical components, including the optical fibres and the spectrometers, are mounted inside the Sun tracking head [3]. Various ring shaped apertures in the aureole baffles shield the direct sunlight and only allow radiation from the $4°$ and $6°$ scattering angle regions to pass. The monolithic miniature spectrometers used for the sun- as well as the aureolephotometers provide 256 evenly spaced channels from 300 to 1000 nm. For the sunphotometer additional 512 channels in the NIR between 1000 and 1690 nm are provided by an extra temperature controlled spectrometer. Broadband color and gray filters in the tubes of the sunphotometer optimize the incoming radiation for the dynamic range of the sensor at an integration time of about 100 ms. Sun tracking is achieved by the real-time evaluation of signals from a four-quadrant-diode to generate commands for two DC-motors, enabling the rotation of the head around two orthogonal axis, and is independent of the aircraft roll, pitch and yaw. Since 2008, the system is accompanied by the zenith radiometer FUBISS-ZENITH, which has a static upward viewing optical entrance tube with an opening angle of $1.8°$ [4]. Control and data logging of all spectrometers, the motion control, and all additional sensors (for GPS position, air pressure, temperature and relative humidity) is performed on a standard 19 inch PC that can be accessed and controlled via LAN with a laptop.

The sunphotometers are calibrated using the Langley-plot technique. In this case the calibration coefficients are the exoatmospheric detector voltages E_0 for every spectrometer pixel, extrapolated from sunrise or sunset measurements. To meet the requirements of stable atmospheric conditions during the calibration measurements, they are performed above the planetary boundary layer, if possible. FUBISS-ASA2 calibrations in the past years were either performed on the UFS Zugspitze (a research platform on the highest German mountain), at the European Southern Observatory (ESO) in Chile, or airborne during campaigns on a Cessna207T. In a next step, calibration of the sunphotometer relative to the two aureole photometers and the zenith radiometer using a halogen light source and an integrating sphere, yields exoatmospheric voltages for the latter. Since no narrow band interference filters are used, whose transmissivity often are subject to degradation, the development of the calibration coefficients in the past years shows no significant trend.

3. SOUNDING TECHNIQUES

Scattering and absorption by air molecules, cloud droplets and aerosols lead to the extinction of solar radiation entering the atmosphere. Under cloud free conditions the integrated extinction from the instrument to the top of the atmosphere due to aerosol particles, the so called aerosol optical depth, can be derived from the measured direct solar irradiance E_d using the rearranged Beer-Lambertian Law[1]:

$$\tau_a = \frac{\ln(E_0) - \ln(E_d)}{m} - \tau_r - \tau_g. \quad (1)$$

In case of altitude resolved airborne measurements, the extinction in an atmospheric layer can be calculated as the derivative of $\tau_a(alt)$. The relative airmass $m \approx 1/\cos\theta$ normalizes the optical depth to the zenith direction (zenith angle $\theta = 0$). The calculation of optical thicknesses due to Rayleigh scattering by air molecules (τ_r) is described in [5]. In case of a priori assumptions about the spectral behavior of τ_a the optical thickness of absorbing trace gases can be derived from the sunphotometer measurements by minimizing the residual to computed curves of τ_g for different trace gas concentrations [6]. The spectral variation of τ_a contains information about the size distribution of the aerosol particles. A smoother decrease with rising wavelength corresponds to bigger particles and vice versa. The parameter used to quantify the latter is called Ångström exponent α and can be derived from the fit of a power law, called the Ångström formula, to the spectral decrease of $\tau_a(\lambda)$:

$$\tau_a(\lambda) \sim \lambda^{-\alpha}. \quad (2)$$

The product of τ_a, the aerosol phase function P_a (describing the angular dependence of the scattered light) and the single scattering albedo ω_0, the so called volume scattering function $\tilde{\beta}_a$, can be derived from the measured direct solar irradiances E_d

[1]The Beer-Lamber Law is strictly valid only for monochromatic irradiance in this form, but may also be applied for channels with a small bandwidth in spectral regions without fine structured absorption by water vapor or other gases.

and the aureole radiances I_a for the $4°$ and $6°$ degree angle regions using an equation suggested by Bullrich [7][2]:

$$\tilde{\beta}_a = \omega_0 P_a \tau_a = \frac{I_A}{E_d m} - P_r \tau_r. \quad (3)$$

Zieger et al. suggested to define a new parameter called aureole index, being the ratio of the obtained volume scattering functions for the $4°$ and $6°$ scattering angle [3]. The comparison of this parameter to values computed by Mie calculations for different aerosol models allows conclusions about the observed aerosol type and the microphysical properties.

An inversion algorithm, using measured altitude dependent extinction coefficients as input for radiative transfer simulations to create a look-up-table of zenith radiances, allows further conclusions about the aerosol mixture and the single scattering albedo of the particles using the FUBISS-ZENITH measurements [4]. As a second result from radiative transfer simulations, the influence of the observed aerosol layers on the net radiation budget can be derived.

4. CAMPAIGNS

From the various campaigns that the instruments took part in, including profiling flights of the ash cloud from the Eyjafjallajkull eruption in April 2010, two from the past two years, in which the instruments were mounted on moving platforms, are introduced here.

4.1. FUBEX 2008

FUBEX in July 2008 was the first airborne campaign with FUBISS-ASA2, FUBISS-ZENITH and a nadir viewing engineering model of the new airborne polarimeter AMSSP [8] simultaneously mounted on the Cessna 207T of the Institute for Space Sciences based in Berlin. A first flight for the calibration of the sunphotometer and a first test of AMSSP over a cloud cover was performed on July 23, followed by another flight on July 28 mainly for vertical profiling of the planetary boundary layer (PBL) in the vicinity of Berlin with FUBISS-ASA2 and FUBISS-ZENITH.

The measured vertical resolved extinction coefficients were nearly constant in the PBL ($(0.050 \pm 0.001) km^{-1}$) and near zero above the boundary to the free troposphere at 2065m (see figure 1). The aureole index and the Ångström coefficients suggested a polluted continental aerosol type within the PBL. The data sets from ascends and descends through the PBL on July 28 were the first to be additionally processed with the inversion algorithm mentioned in the last section, indicating very low values for the single scattering albedo of 0.82 ± 0.5 for 500nm and a high relative soot concentration in the observed aerosol. These results agree with values from the nearest ground based AERONET station south of Hamburg (Germany), though a direct comparison may not be reasonable due to the spacial distance of more than 100 km.

4.2. FS Polarstern Cruise ANT-XXVI/1

In contrast to the ground based remote sensing of aerosols over land, by stationary Sun photometers as the AERONET stations, there is a lack of stationary platforms for comparable measurements on the oceans. Mounting aerosol remote sensing instruments on moving ships and using satellite measurements are the main approaches to fill this gap. The FUBISS-ASA2 and -ZENITH radiometers were originally designed for airborne remote sensing of aerosols and are therefore able to continuously correct their attitude when mounted on a moving ship unlike most of the sunphotometers designed for ground based use.

During the cruise ANT-XXVI/1 of the German research icebreaker FS Polarstern from Bremerhaven (Germany) to Punta Arena (Chile) in Oktober and November 2009 the instruments were mounted on the lookout platform of the ship, the so called crow's nest. Over all, more than 150 hours of multispectral Sun and sky radiances could be recorded on 22 days spread over the whole cruise leg from Bremerhaven to Punta Arenas, of which measurements with direct sunlight were processed. The data was recorded on days with a variety of different atmospheric conditions, as a Saharan dust outbreak over Cape Verde, typical marine conditions with salt particles in the marine boundary layer and pristine conditions in the southern Atlantic [9]. Access to the data of the various other instruments aboard the ship, as a Raman-Lidar, a cloud camera and a weather station, provided valuable a priori information for processing and error correction of the measurements. The results may be especially interesting for the validation of satellite aerosol products.

[2] The equation is only valid for single scattered radiation. This assumption, however, is appropriate for the forward scattered radiation from the solar aureole in this case.

5. REFERENCES

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