The SPEXone Instrument for the NASA PACE Mission
SPEXONE SCIENCE CASE
Atmospheric Aerosol
Aerosols: Small Particles in the Air
Aerosol Sources
The Earth Energy Budget

In the diagram, the incoming solar radiation (340.4 W/m²) is split into absorbed by atmosphere (77.1 W/m²), reflected by clouds & atmosphere (77.0 W/m²), and absorbed by surface (163.3 W/m²). The reflected by surface (22.9 W/m²) is added to the total reflected solar radiation (99.9 W/m²). The emitted by atmosphere (169.9 W/m²) and emitted by clouds (29.2 W/m²) contribute to the total outgoing infrared radiation (239.9 W/m²). The net absorbed (398.2 W/m²) is the difference between the absorbed by surface and the total reflected solar radiation. The back radiation (340.3 W/m²) and latent heat (change of state) (86.4 W/m²) contribute to the energy budget. Evapotranspiration (18.4 W/m²) is also depicted.

All values are fluxes in W/m² and are average values based on ten years of data.
Aerosol Effects on Climate

- Scattering & absorption of radiation
- Unperturbed cloud
- Increased CDNC (constant LWC) (Twomey, 1974)
- Drizzle suppression. Increased LWC
- Increased cloud height (Pincus & Baker, 1994)
- Increased cloud lifetime (Albrecht, 1989)
- Heating causes cloud burn-off (Ackerman et al., 2000)

Direct effects:

Cloud albedo effect/ 1st indirect effect/ Twomey effect

Cloud lifetime effect/ 2nd indirect effect/ Albrecht effect

Semi-direct effect

Top of the atmosphere

Surface

Indirect effect on ice clouds and contrails
Contributions to Climate Change

- Aerosols represent the largest uncertainty on the effective radiative Forcing.
- SPEXone is designed to provide improved aerosol observations.
- In synergy with the other instruments of PACE it is expected that the radiative forcing can be better quantified.
Strong present-day aerosol cooling implies a hot future

Meinrat O. Andreae¹, Chris D. Jones² & Peter M. Cox³

Climate sensitivity

\[ \lambda = \frac{\Delta T}{\Delta F_{ghg} + \Delta F_{aer}} \] (past \( \Delta T \))

The more negative \( \Delta F_{aer} \) the larger \( \lambda \).

\( \Delta T = \lambda \times (\Delta F_{ghg} + \Delta F_{aer}) \) (future \( \Delta T \))
Aerosol Properties

Microphysical properties:
✓ Size distribution
✓ Shape
✓ Composition (refractive index)

Optical properties:
✓ Aerosol Optical Depth (AOD) → total extinction (scattering+absorption)
✓ Single Scattering Albedo (SSA) → scattering / (scattering+absorption)
✓ Scattering Phase Matrix

Optical Model (Mie / T-Matrix)
Why is Aerosol Radiative Forcing so Uncertain?

We do not know how aerosols affect clouds (how much brighter, do they live longer, do they contain more or less water?) --> main uncertainty

- SPEXone will provide a better characterisation of aerosol properties that determine the suitability to act as Cloud Condensation Nuclei (CCN)
- In combination with improved cloud properties from HARP-2 and OCI this will help to better understand the effect of aerosol on clouds

We do not know what the balance is between scattering and absorption of solar radiation by aerosols.

- SPEXone will measure scattering and absorption properties of aerosol

We do not know present and pre-industrial aerosol properties and emission sources.

- SPEXone will measure properties that relate to aerosol composition (e.g. refractive index or derived quantities). This will help to quantify aerosol emission sources (in a data assimilation system) and link them to radiative forcing
AEROSOL POLARIMETRY WITH SPEXONE
How to Best Measure Aerosol Properties with a satellite?

Measure the intensity and Degree of Polarization of scattered light as a function of scattering angle and wavelength.

![Diagram showing incident light and scattered light](image-url)

![Graphs showing phase function and degree of polarization](image-url)
# Polarimeters in Space

<table>
<thead>
<tr>
<th>Year</th>
<th>Polarimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>POLDER-3</td>
</tr>
<tr>
<td>2013</td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td>PACE</td>
</tr>
<tr>
<td>2025</td>
<td>3MI</td>
</tr>
<tr>
<td>2026</td>
<td>MAP/CO2M</td>
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</tbody>
</table>

>10 year GAP!

**SPEXone – PACE**

**HARP2 – PACE**

**SRON**
## SPEXone Characteristics

Multi-angle spectropolarimetry between 385 – 770 nm

5 instantaneous footprints; Simultaneous pushbroom measurement of radiance and polarization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>5X5 km²</td>
</tr>
<tr>
<td>Spectral resolution (radiance)</td>
<td>400 bands, 2nm FWHM</td>
</tr>
<tr>
<td>Spectral resolution (polarization)</td>
<td>50 bands 15-35 nm FWHM</td>
</tr>
<tr>
<td>Radiometric uncertainty</td>
<td>&lt; 2%</td>
</tr>
<tr>
<td>Polarimetric uncertainty</td>
<td>&lt; 0.003</td>
</tr>
</tbody>
</table>
Combining Viewing Angles
Polarization Accuracy is Important
Incident spectrum

Telescope assembly
Polarization modulation optics
Spectrometer
Detector module
ICU

Modulated spectrum

\[ S_+(\lambda) = \left(\frac{1}{2}\right)(1 + P(\lambda) \cos\left[\frac{2\pi \delta(\lambda)}{\lambda} + 2\phi(\lambda)\right]) \]

\[ S_-(\lambda) = \left(\frac{1}{2}\right)(1 - P(\lambda) \cos\left[\frac{2\pi \delta(\lambda)}{\lambda} + 2\phi(\lambda)\right]) \]

\[ S_{mod} = \frac{(S_+(\lambda) - S_-(\lambda))}{(S_+(\lambda) + S_-(\lambda))} = P(\lambda) \cos\left[\frac{2\pi \delta(\lambda)}{\lambda} + 2\phi(\lambda)\right] \]

→ amplitude proportional to P

\[ S_{mod} \]

reflectance

DoLP

wavelength (nm)
Modulated Spectra

![Graph 1](image1.png)

![Graph 2](image2.png)
SPEXone Calibration Campaign
L1A-L1B processor

Data preparation
Detector calibration
Stray light correction
Field of view calibration
Spectral calibration
Radiometric calibration
Polarimetric calibration
Geolocation
Transformation to local meridian plane

Processor architecture
Calibration Setup @SRON

- Reference mirror
- Flow box
- Feedthrough EGSE harness + cover sheets
- Flow regulator box
- Ambient test enclosure
- SPEXone
- Theodolites on rail
- Chiller
Polarimetric Calibration and Verification

polarization angle 0°, glass-plate angle 60.872°
Spectral Calibration

- Full spectral range is covered
- 375 – 785 nm can be downlinked in-flight
- Uniform behavior over viewing angles and swath
Retrieving Aerosol Properties from SPEXone Measurements

State vector: aerosol and surface properties

Forward Model: Simulate the measurement

Measurement: radiance and DoLP

Update till optimal agreement
Using aerosol properties from an aerosol-climate model → more complex aerosol description than used in retrieval.

Land and ocean properties from satellite climatology.

Coverage, solar-, and viewing geometry from PACE orbit simulator.

Simulate SPEXone measurements: radiance and DoLP as function of wavelength for 5 viewing angles. Include noise on measurements.

Apply retrieval algorithm to synthetic measurements and compare retrieved values to the truth.
Validate uncertainty estimate:

Distribution of
(retrieved – truth) / uncertainty

should be a normal distribution.
Testing the Retrieval Algorithm with Simulated Measurements (3)

Retrieved vs true values for effective radius and refractive index

SPEXone is expected to provide aerosol microphysical and optical aerosol properties with unprecedented accuracy
SPEX airborne

- Airborne Precursor for SPEXone
- Using the same spectral modulation method.
- 9 viewing angles (instead of 5 for SPEXone)
- Spectral range 400-800nm (385-770nm for SPEXone)
- Several improvements in SPEXone (optical, spatial sampling)
NASA and SRON collaborated in the ACEPOL field campaign to acquire data with advanced active and passive remote sensors. These data will be used to develop and assess algorithms for retrieving profiles of aerosol optical and microphysical properties for various atmospheric applications. The measurements and algorithms are applicable to future satellite missions such as ACE, PACE, METOP-SG, and EarthCare.

**Mission Scientists:** Richard A. Ferrare (LaRC); Kirk Knobelspiesse (GSFC), Otto Hasekamp (SRON); Felix Seidel (HQ)

**NASA support:** Hal Maring, Felix Seidel (HQ); Arlindo da Silva (GSFC)
ACEPOL: 9 flights, 41.3 hours

ACEPOL field campaign
9 flights, Oct. 19 - Nov 9, 2017
Validation of DoLP and Radiance measurements with RSP

RSP is considered a reference polarimeter (> 20 years proven performance)

- Very good agreement in DoLP (RMSE = 0.003) at mid-visible wavelengths
- Larger differences towards shorter wavelengths. Reduced sensitivity, has been improved for SPEXone.
- At 410 nm the spectral response of RSP is different than for SPEX → no accurate comparison
Validation against AERONET for SPEX, RSP, airMSPI

(a) SPEX airborne

(b) RSP

(c) airMSPI

(d) 

(e) 

(f)
SPEX airborne aerosol retrievals: Comparison to HSRL2

Fu et al., 2020, AMT

Fan et al., 2019, Remote Sensing,
Forest fires in Arizona (1)
As seen from the ER-2 cockpit  As seen by SPEX airborne
Forest Fires in Arizona (2)

For 32 points:
RMSE: 0.1042
bias: -0.0262
corr: 0.9600

$\tau_{532}$ (case: 20171109)
Synergy SPEXone with OCI and HARP-2

- Hyperspectral, multi (5)-angle, radiance and polarization measurements for 385-770 nm
- Hyper-angular radiance and polarization measurements at 4 spectral bands (440-870 nm)
- Hyperspectral single viewing angle measurements 340-890 nm + 6 SWIR bands

Study relationships between aerosols and clouds

Hasekamp et al., NatComm., 2019