# The SPEX Instrument: Science, requirements and instrument concept

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# Outline

- Science Goals
- Sensitivity studies
- Instrument requirements
- Instrument concept
- Prototototype / airborne instrument: accuracy and sensitivity
- Ground based measurements and retrievals

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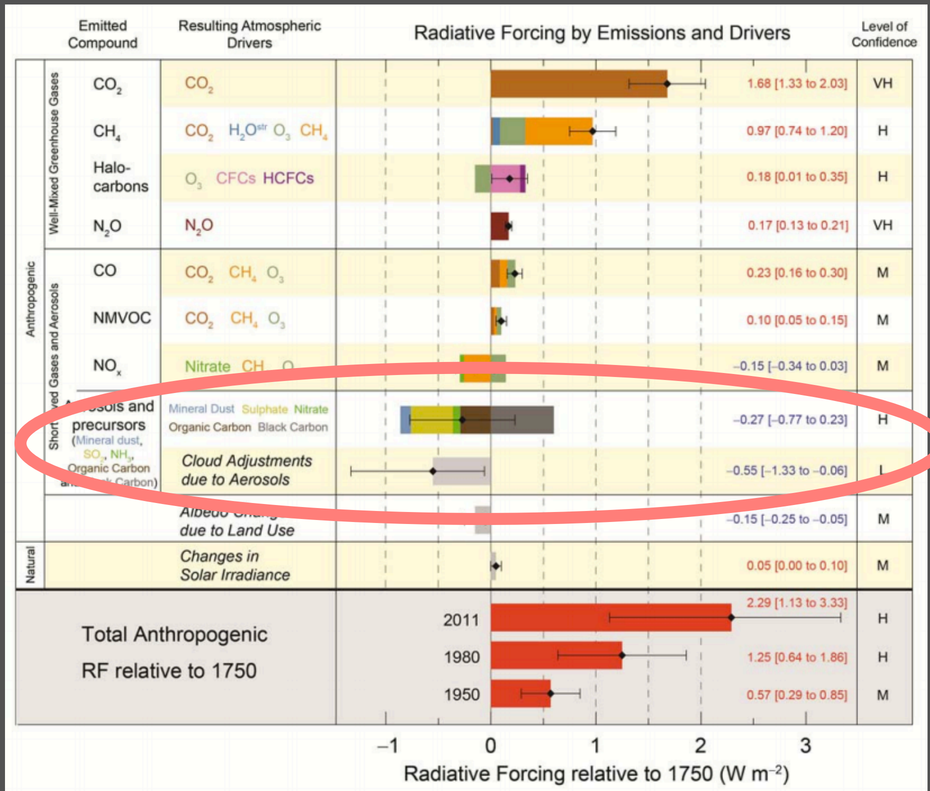
# IPCC, Radiative Forcing, Future Climate Change




IPCC, AR5, 2013

## Steps to be taken

- **Quantifying** present day aerosol radiative forcing
- **Understanding** present day aerosol radiative forcing
- **Predicting** future changes in aerosol radiative forcing.

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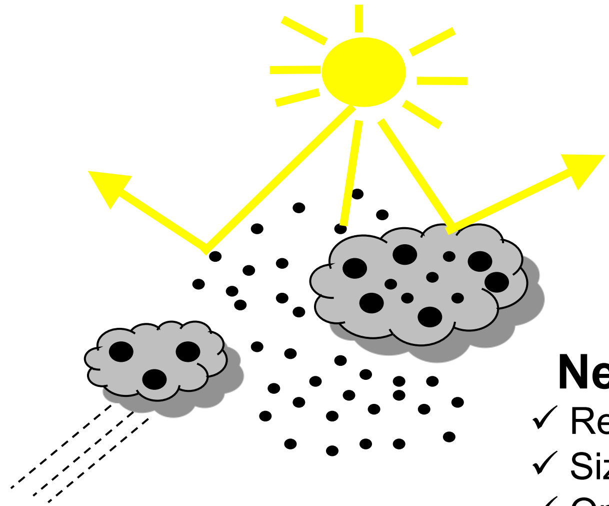
# Aerosols & Climate



**Needed** (globally):

- ✓ Refractive index (composition, water uptake).
- ✓ Size, shape, and concentration.
- ✓ Optical properties (AOT, SSA, phase function)
- ✓ Measurements close to and above clouds

Multi-angle photo-polarimetry essential to retrieve the relevant aerosol properties [Mishchenko and Travis, JGR, 2007; Hasekamp and Landgraf, Appl. Opt., 2007; Kokhanovsky et al, AMT, 2010]

# Science Goals and Level 2 products

## Science Goals

Aerosol Direct Radiative Forcing

Aerosol effect on cloud formation

Quantification of aerosol sources for air quality forecast

## SPEX Products

**Aerosols (fine and coarse mode)**:
Single Scattering Albedo (+/- 0.02)
Effective radius (+/- 10%)
refractive index (+/- 0.02)
Aerosol Optical Thickness (+/- 0.03 or 10%)
Aerosol layer height (2 km)
Particle shape

**Clouds**
Optical thickness (+/- 10%)
Effective radius (+/- 10%)
Effective variance (+/- 50%)
Cloud height (+/- 300 m)
Cloud phase

**Aerosols near and above clouds**

# Sensitivity Studies

- Based on linear error propagation
  (Hasekamp and Landgraf, Appl. Opt.,2007; Hasekamp, AMT, 2010)

$$\mathbf{S}_x = (\mathbf{K}^T \mathbf{S}_y^{-1} \mathbf{K})^{-1}$$

or

$$\mathbf{S}_x = (\mathbf{K}^T \mathbf{S}_y^{-1} \mathbf{K} + \mathbf{S}_a^{-1})^{-1}$$

- Full iterative retrieval for an ensemble of synthetic measurements (Wu et al., AMTD, 2015).

- Retrieval from airbore RSP measurements (Wu et al., AMTD, 2015)

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# Fit Parameters

## Aerosols:

| | $r_{eff}$ | $v_{eff}$ | $m_r$ | $m_i$ | N | $f_{sph}$ |
|---|---|---|---|---|---|---|
| fine mode | ✔ | ✔ | ✔ | ✔ | ✔ | ✗ |
| coarse mode | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |

Derived optical properties: AOT, SSA, phase matrix

**Ocean**

- Chlorophyll-*a* concentration.
- Foam coverage.
- Wind speed (2 components).

**Land Surface**

- Total reflectance **at each wavelength**
- Directional parameters (RPV parameters or kernel coefficients).
- Polarization scaling and variance of facet distribution

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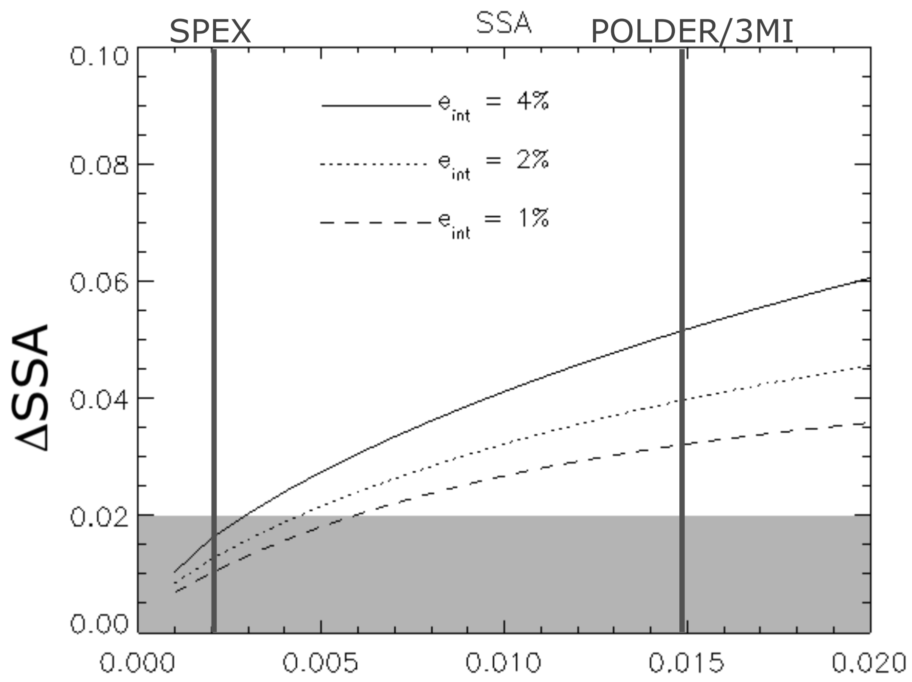
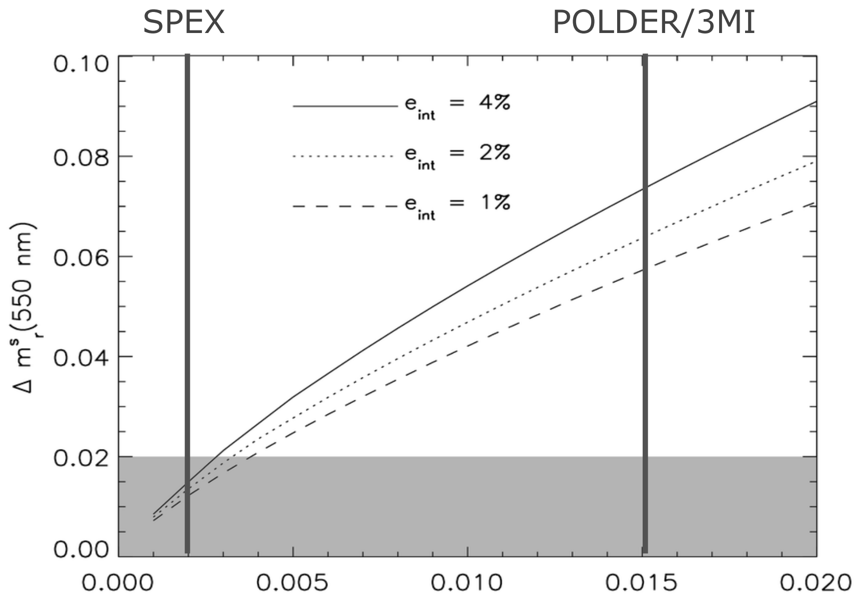
# Polarimetric Accuracy is the key to success!

Single Scattering Albedo (SSA)




polarimetric error

Real Refractive Index (RRI)




polarimetric error

Single Scattering Albedo (aerosol absorption) and refractive index (chemical composition) are key aerosol parameters. The polarimetric accuracy of SPEX is essential to retrieve these parameters with the required accuracy [Mishchenko et al., 2004; Hasekamp and Landgraf 2007; Loeb and Su 2010].

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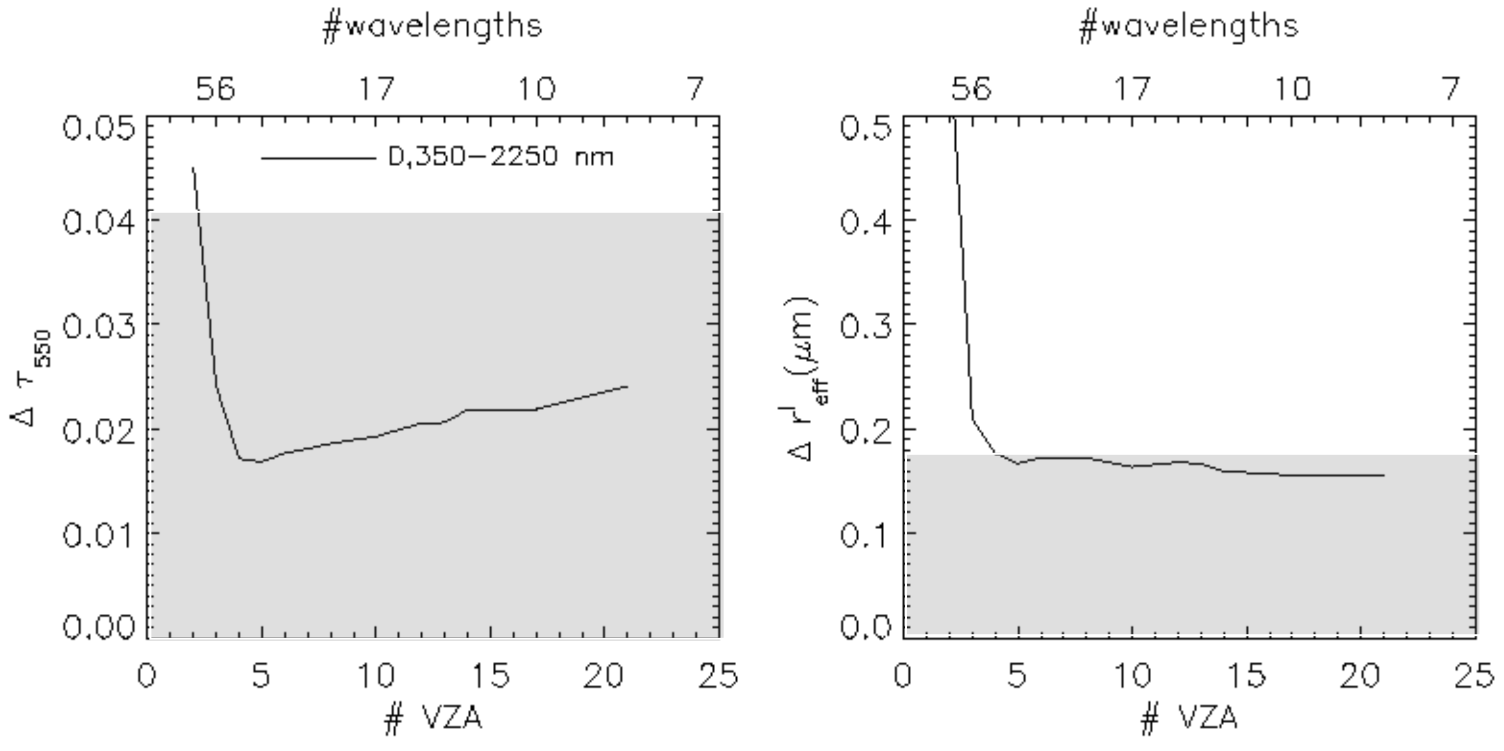
# Spectral Vs. Angular Information




Total number of measurements is kept constant

Hasekamp and Landgraf, Appl. Opt., 2007

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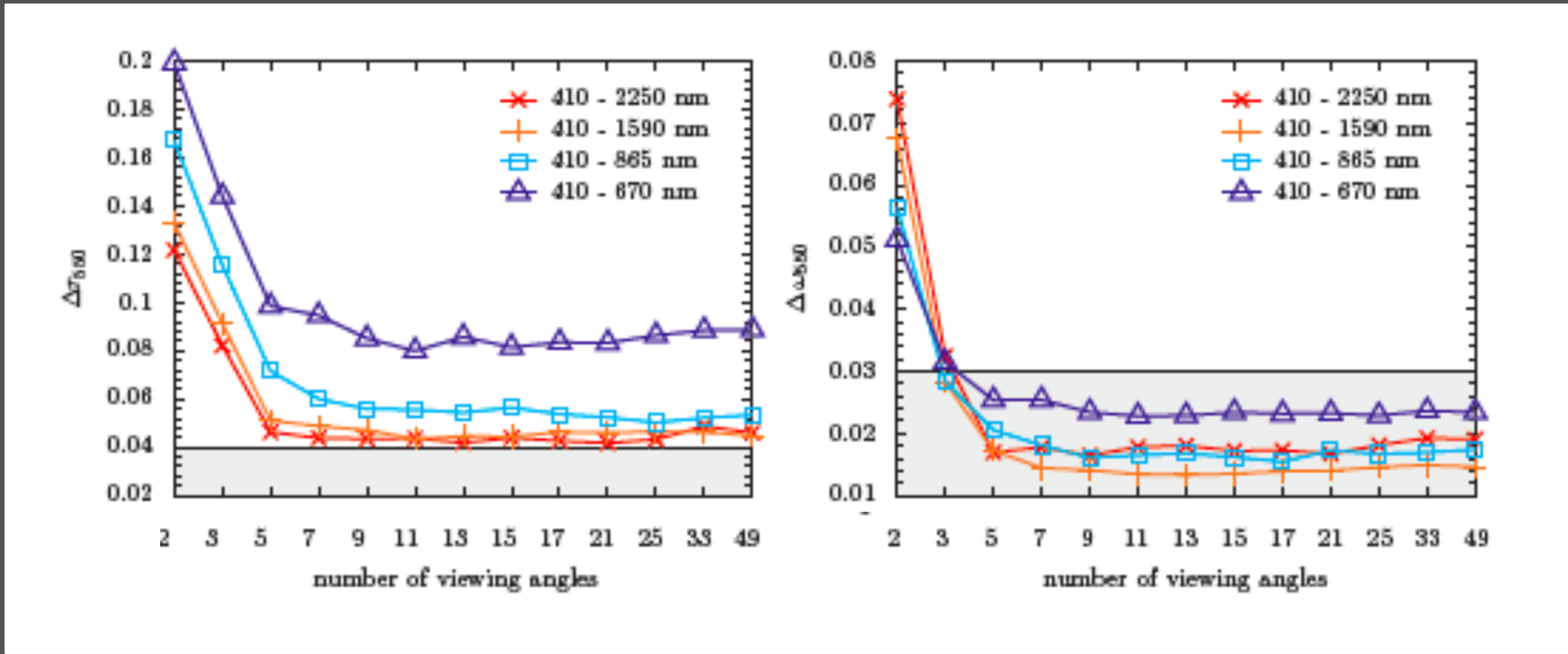
# Spectral range and viewing angles: iterative retrieval on synthetic APS measurements.




Wu et al., AMTD, 2015

- Retrieval (full iteration) on 1000 synthetic measurements.
- Confirms that 5 viewing angles is sufficient for aerosol retrieval.
- Including SWIR band at ~1600 nm is important.
- 2250 nm band not essential

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## Retrievals from RSP (Research Scanning Polarimeter)

- 9 spectral channels:
  410, 470, 550, 670, 865, 960,  1590, 1880, and 2250 nm

- 152 viewing angles (-40$^{o}$ to 60$^{o}$)

- Accuracy: polarimetric  0.5%, radiometric  2%.

- Used campaigns:
  - PODEX (Polarimeter Denition Experiment ), 2013.
  - SEAC4RS  (Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys), 2013.

- ER-2 high-altitude aircraft (altitude  20 km, speed  200 m/s).

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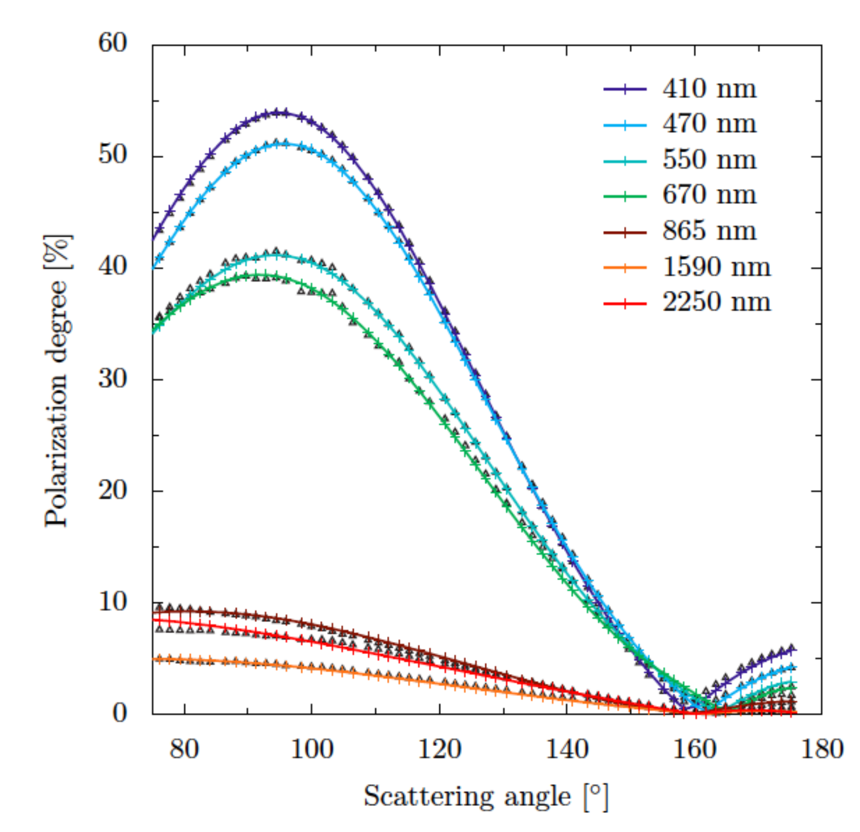
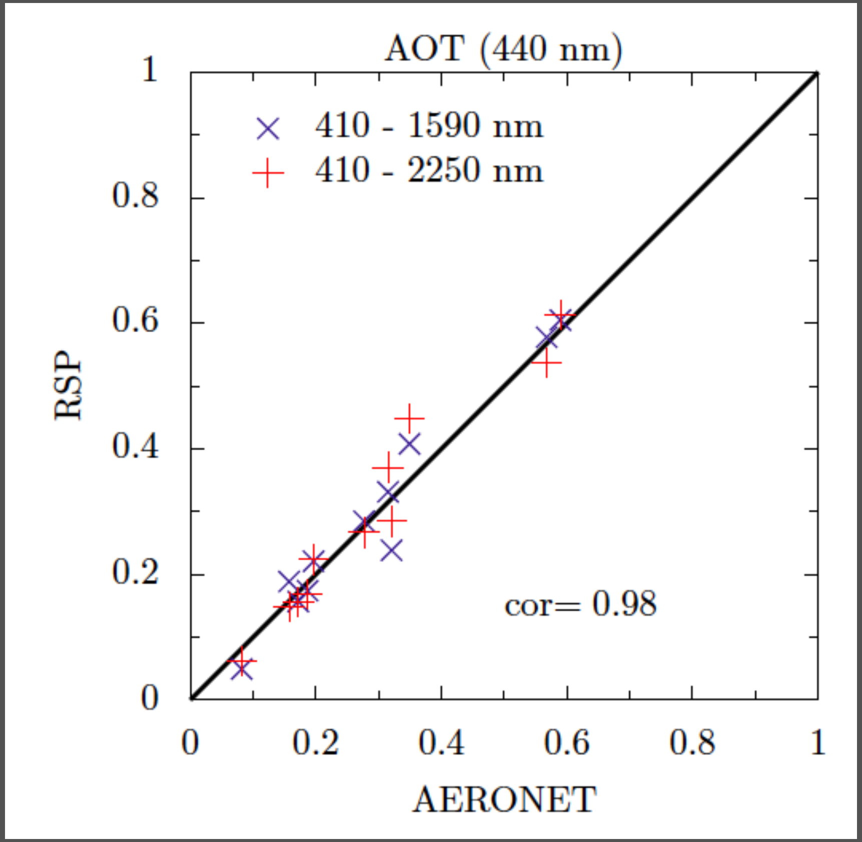
# Retrievals from RSP




Wu et al., AMTD, 2793-2822, 2015

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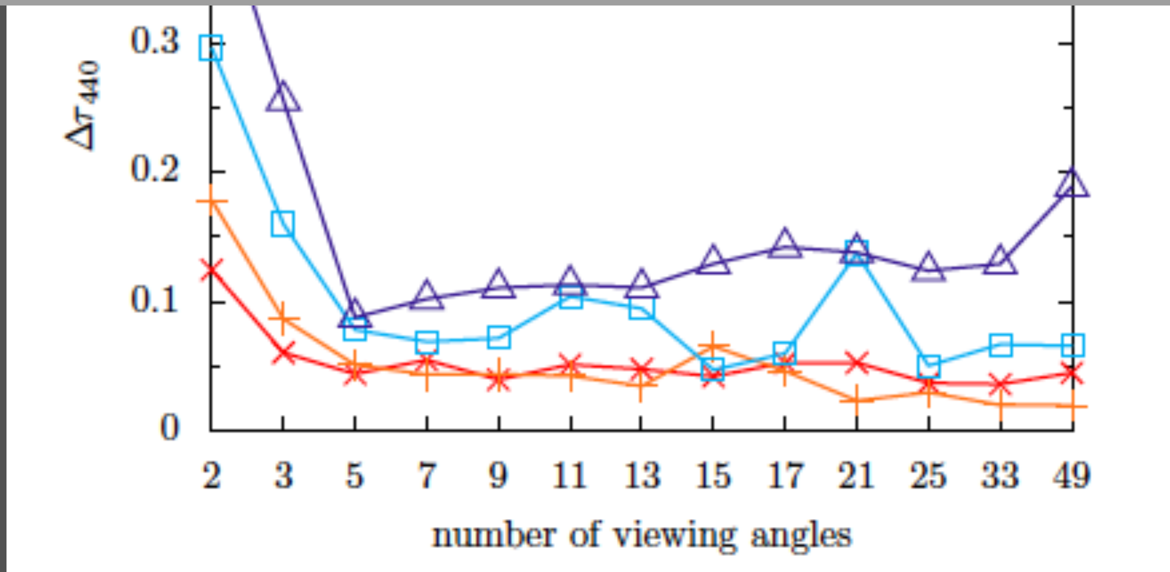
# Viewing angles and spectral range: Study with RSP

- Confirms that 5 viewing angles is sufficient for aerosol characterization
- Demonstrates importance of SWIR band at ~1600 nm for aerosol retrieval over land.
- Shows that further extension of spectral range (to 2200 nm) is NOT essential




Wu et al., AMTD, 2793-2822, 2015

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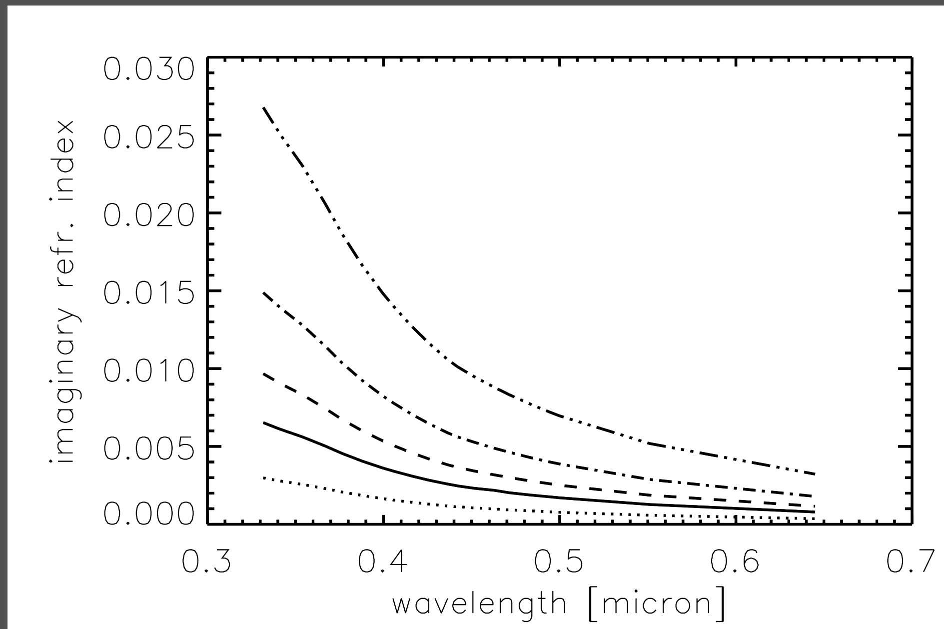
# UV Absorbing Aerosols

- Absorption by mineral dust increases significantly towards the UV.
- For ocean color remote sensing this needs to be quantified and corrected.
- This also holds for Brown Carbon.

Mineral Dust Im. refr. index

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# Aerosol height

- Polarimetry in near UV: elevated aerosol layer ‘shields’ partly molecular (Rayleigh) scattering → spectral polarization measurements provide aerosol height information.

- Intensity in O2 a band: At least one ‘absorbing’ and one ‘continuum’ wavelength

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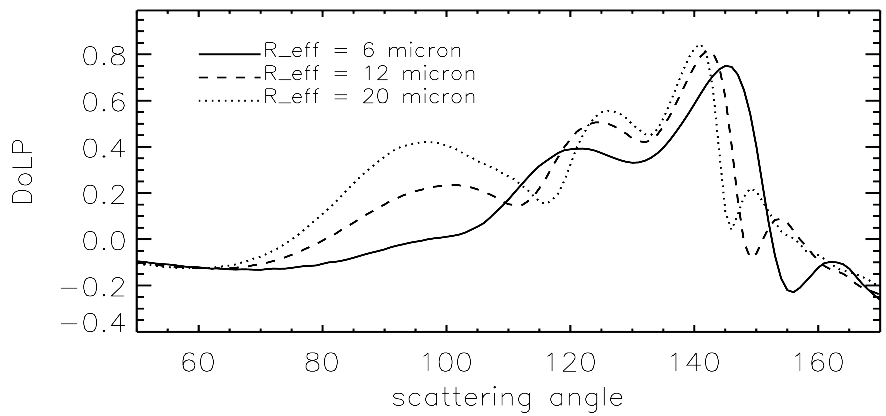
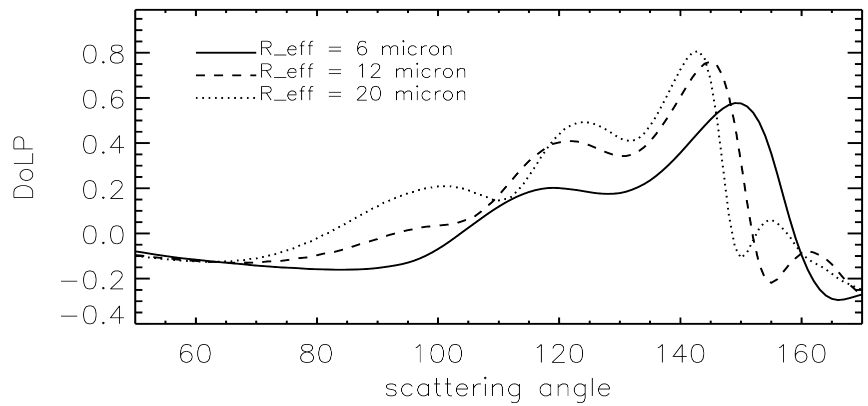
# Cloud Retrievals: Cloud Bow




- Cloud bow in polarization powerful tool for droplet size retrieval (e.g. Breon, GRL, 1998; Alexandrov et al., RSE, 2012).
- Combination with 'Nakajima-King' retrievals may give height dependent droplet size (e.g. 670 and 1600 nm), as polarization more sensitive to cloud top and intensity more deeper into cloud.
- Polarization signature very different from aerosols → distinguish cloud droplets from aerosols in partially cloudy scenes (Hasekamp, AMT, 2010)

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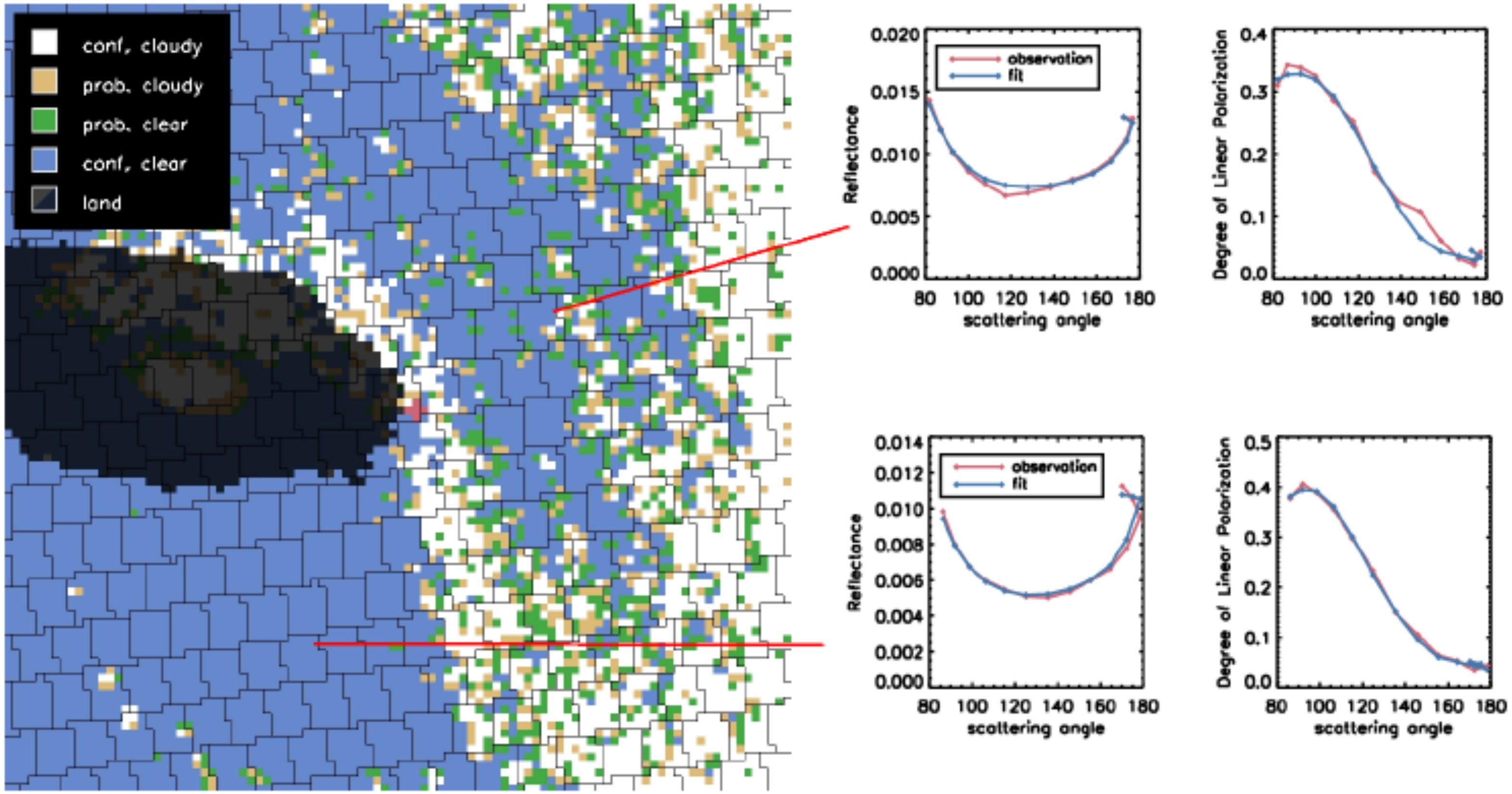
# Signatures of cloud contamination in POLDER




Stap et al., AMT, 2015

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# Summary: What is important?

| | |
|---|---|
| polarimetric accuracy | - aerosol SSA<br>- refractive index<br>- All aerosol properties |
| near UV measurements | -Aerosol height<br>- Absorption |
| SWIR band | -AOT<br>-Cloud retrieval |
| O2 a-band | - Aerosol height<br>- Cloud height |
| angular resolution | Cloud retrieval and aerosol/cloud retrieval |

# High Level Instrument Requirements

| parameter | VNIR | SWIR |
|---|---|---|
| Swath | 60° | 60° |
| polarimetric method | spectral modulation | filter based |
| angular range | +/- 55 deg | +/- 55 deg |
| # viewing angles VIS | 5 | 50 (threshold) - 100 (goal) |
| spectral range | 375-850 nm | (1360-1390 nm), 1620-1660 nm |
| spectral resolution intensity | 4–8 nm ($\lambda/\Delta\lambda$ = 100) | |
| spectral resolution DoLP continuum | 20–40 nm ($\lambda/\Delta\lambda$ = 20) | 1620-1660 nm |
| spatial resolution (for all angles) | ≤4X4 km2 | ≤4X4 km2 |
| ground pixel size | 2X2km2 at nadir | 2X2km2 at nadir<br>4X4km2 at fore/aft angles |
| polarimetric accuracy | 0.001+0.005*DoLP | 0.005+0.01*DoLP |
| radiometric accuracy | 2% (goal) - 4% (threshold) | 2% (goal) - 4% (threshold) |
| Signal to Noise Ration (SNR) | 300 @ 850 nm, LER=0.03, SZA=70 | 200 @ 1600 nm, LER=0.05, SZA=70 |

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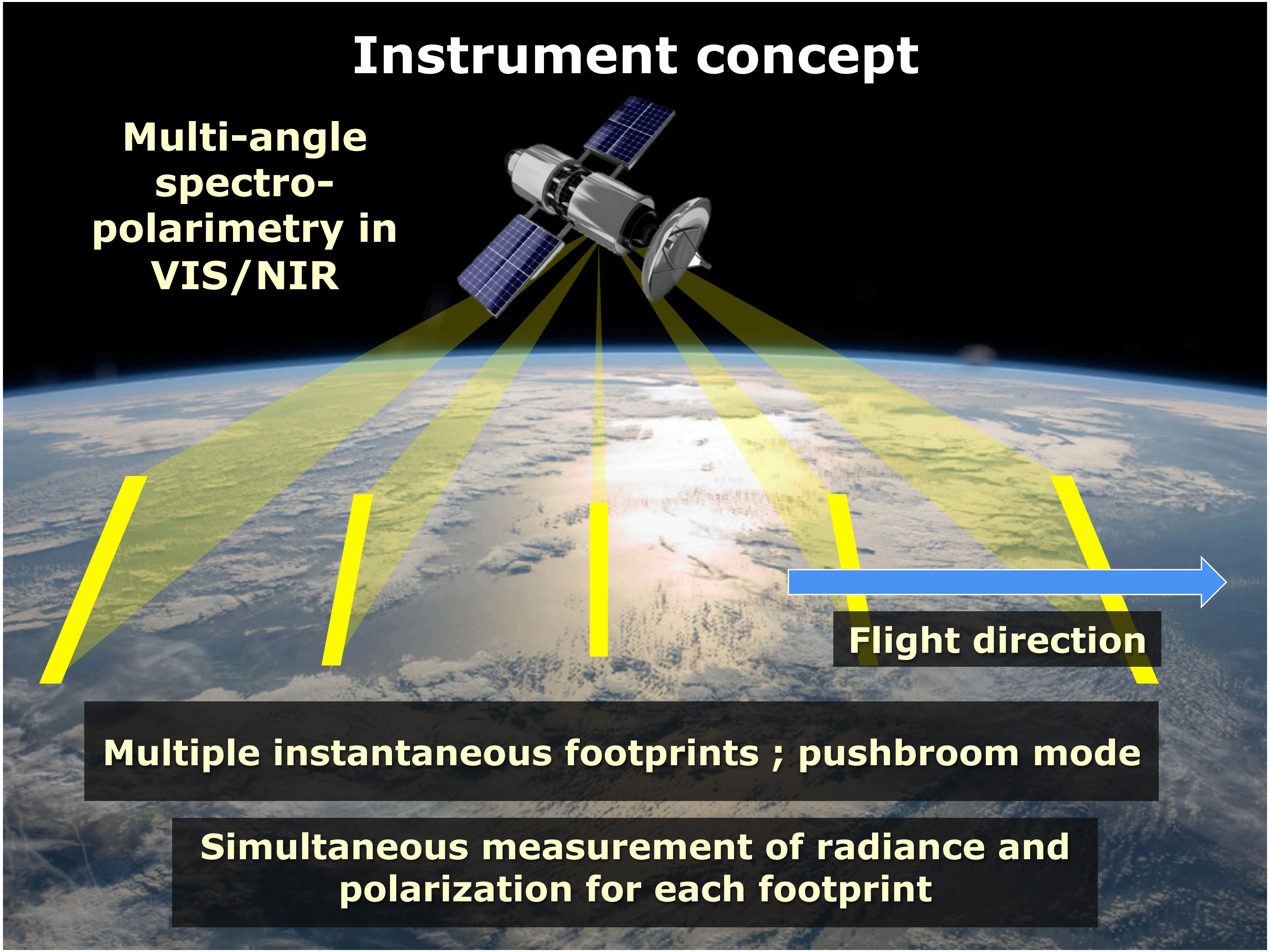
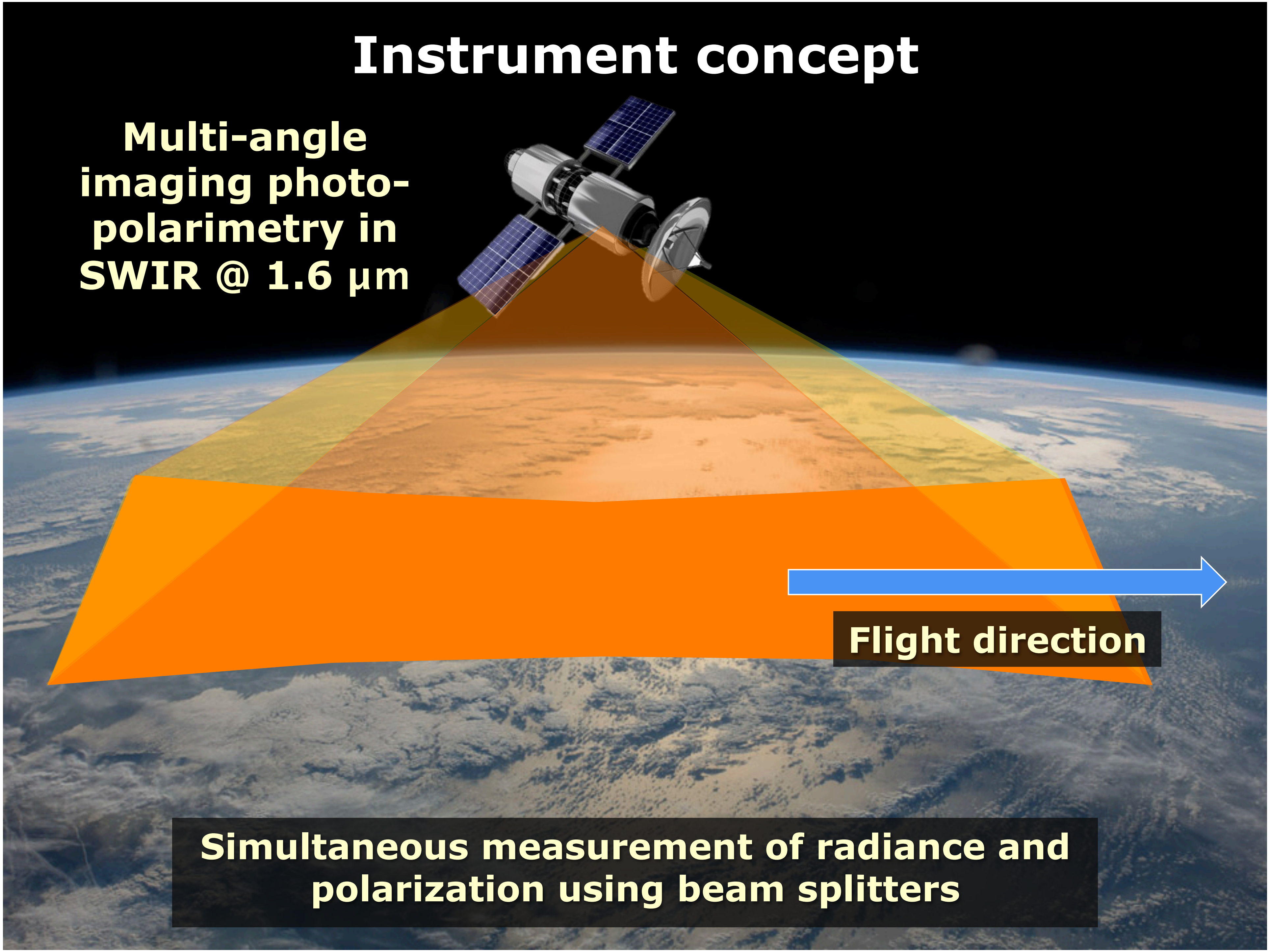
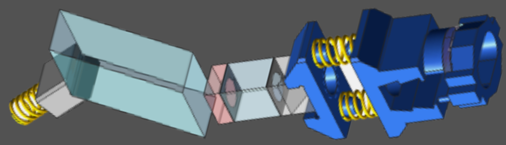
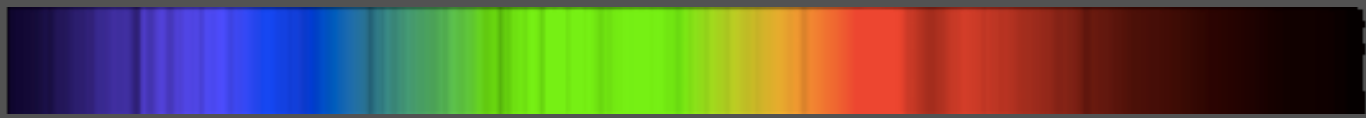


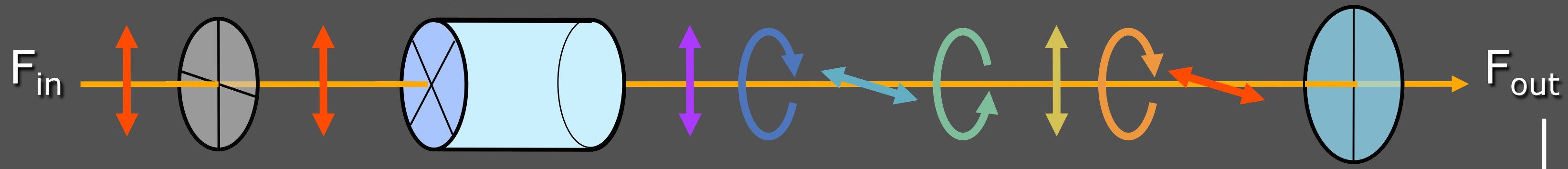
Instrument concept
Multi-angle spectro-polarimetry in VIS/NIR
Flight direction
Multiple instantaneous footprints ; pushbroom mode
Simultaneous measurement of radiance and polarization for each footprint


Instrument concept
Multi-angle imaging photo-polarimetry in SWIR @ 1.6 μm
Flight direction
Simultaneous measurement of radiance and polarization using beam splitters

# VNIR Measurement principle: Spectral modulation

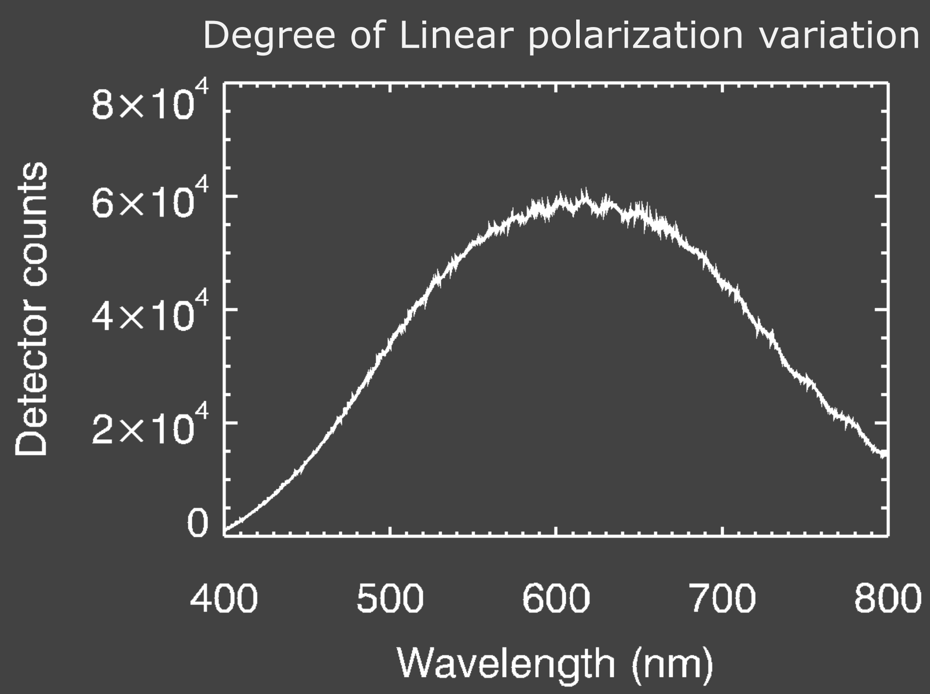


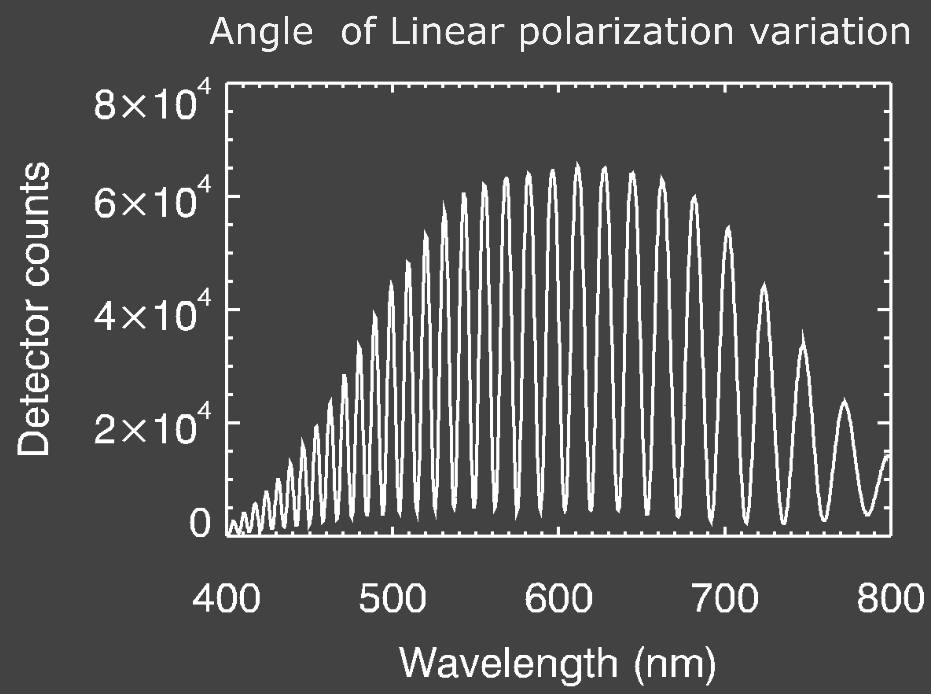





$$I(\lambda) = \frac{I_0}{2}\left(1 \pm P(\lambda)\cos\left(\frac{2\pi\delta(\lambda)}{\lambda} + 2X(\lambda)\right)\right)$$

# Spectral polarization modulation




$$I(\lambda) = \frac{I_0}{2}\left(1 \pm P_L(\lambda)\cos\left(\frac{2\pi\delta(\lambda)}{\lambda} + 2\varphi_L(\lambda)\right)\right)$$

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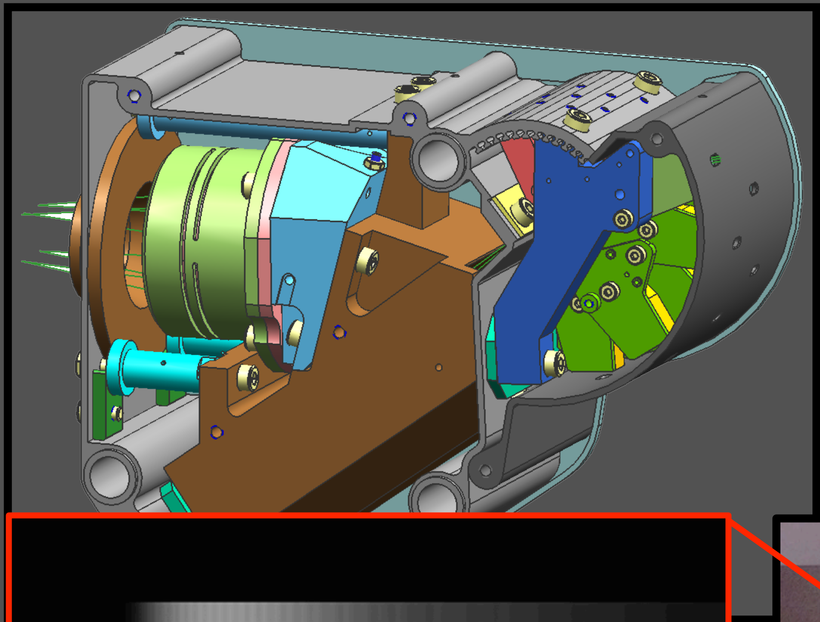
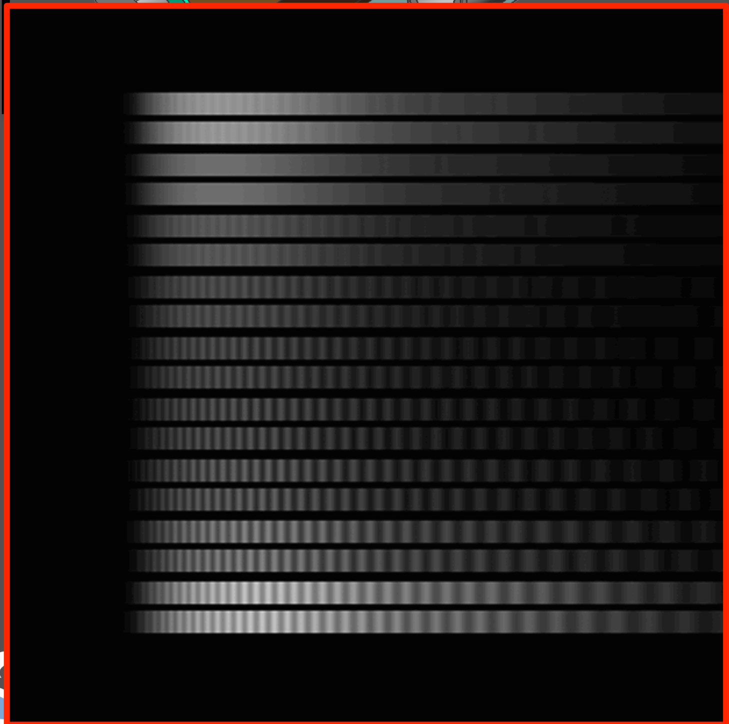
# SPEX Prototype / Airborne Instrument

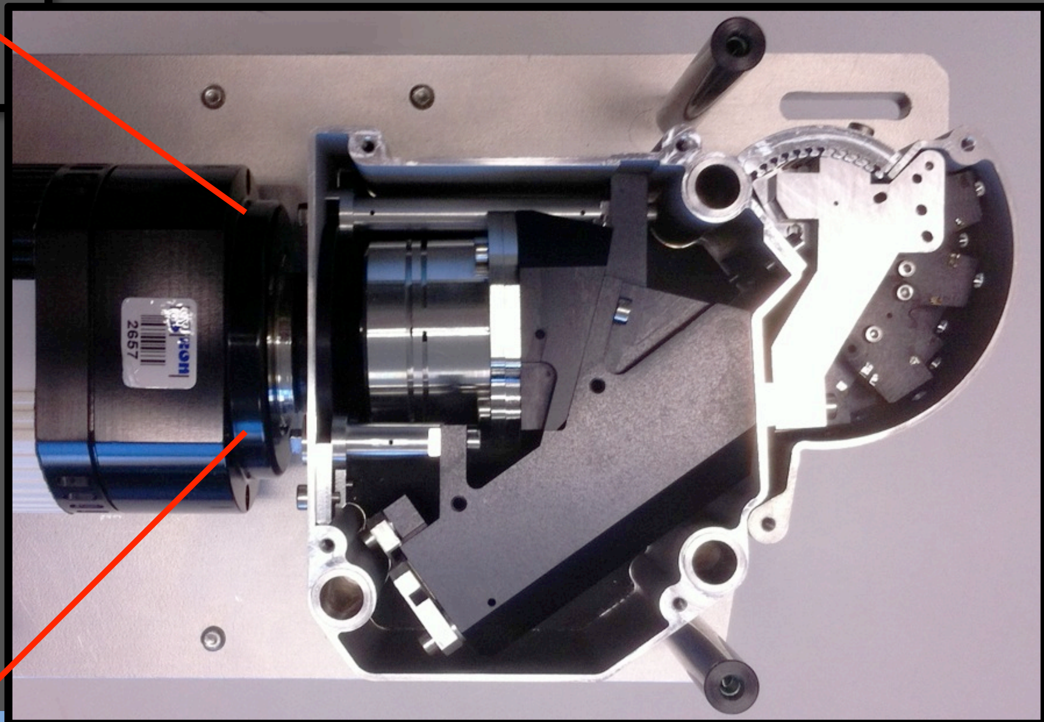


- 9 viewing directions ; 1°×7°
- Single spectrograph
- 400-800 nm

Optics module

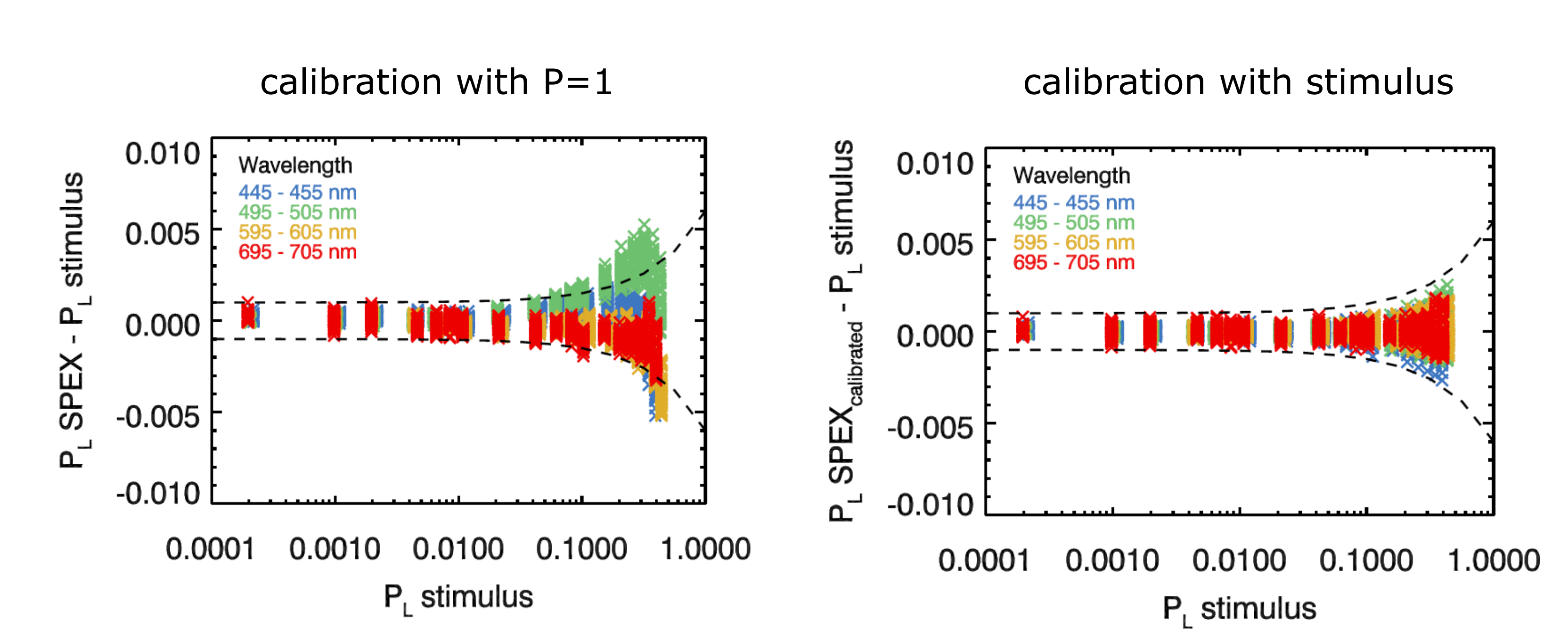
- Volume 2 $dm^3$
- Mass 2 kg
- Commercial detector



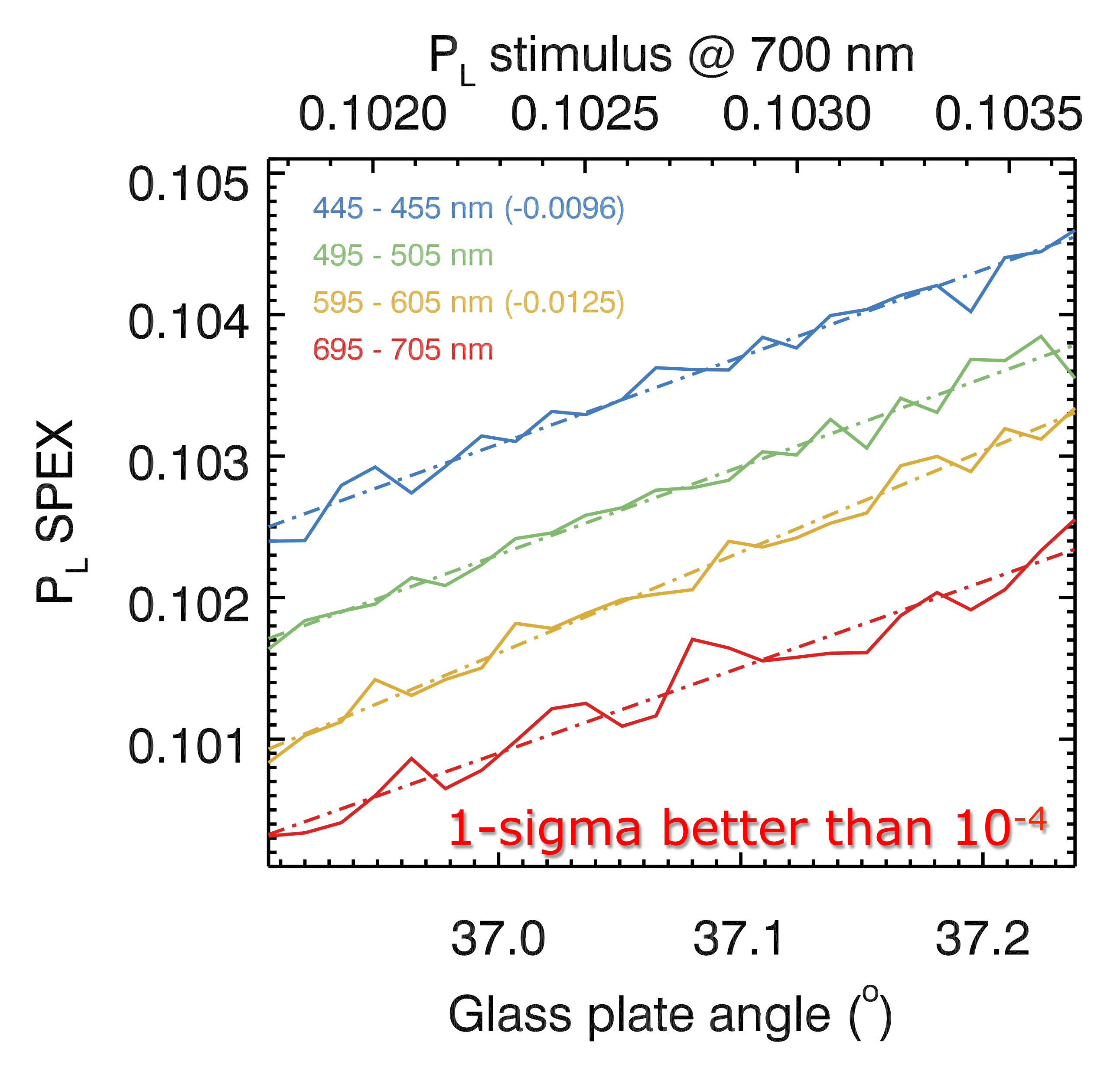


# Polarization accuracy

- SPEX absolute DoLP Calibration with Polarization Stimulus.
- Design requirement (Mars): 0.01 + 0.05*DoLP
- Earth requirement: 0.001 + 0.005*DoLP
- SPEX prototype meets Earth requirement (in laboratory)
- Sensitivity for degree of polarization better than 0.0001!



# Polarization calibration: DoLP sensitivity

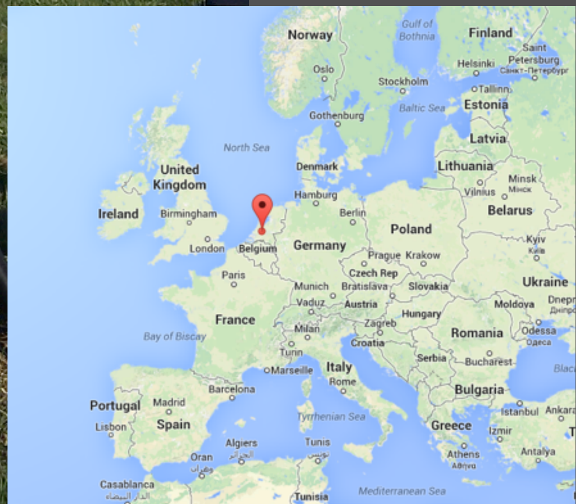


# SPEX Measurements at "CESAR" Meteorological site in the Netherlands

Two SPEX realizations
- SPEX prototype
- *ground*SPEX

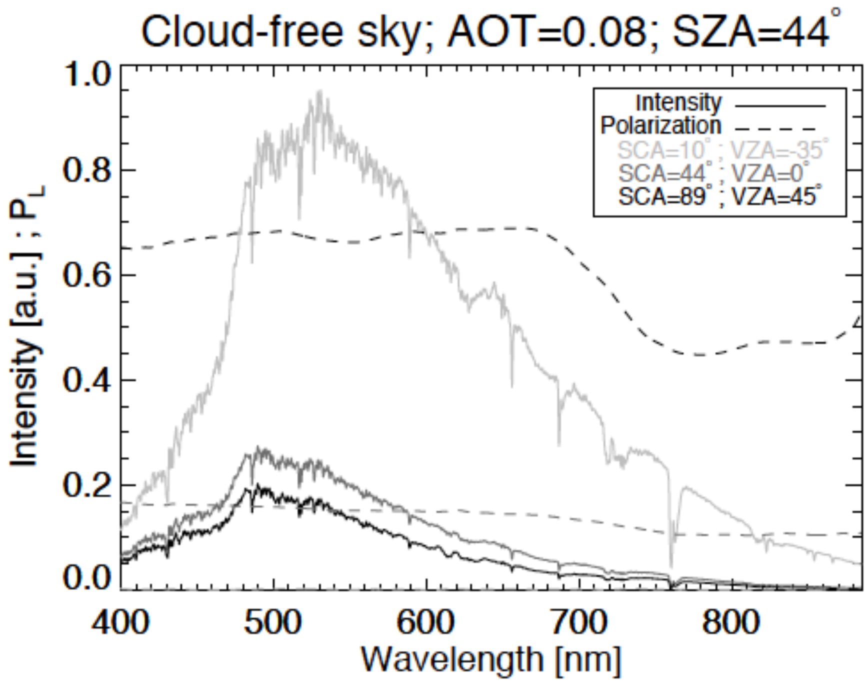
Sky-sweeps to obtain multi-angle measurements

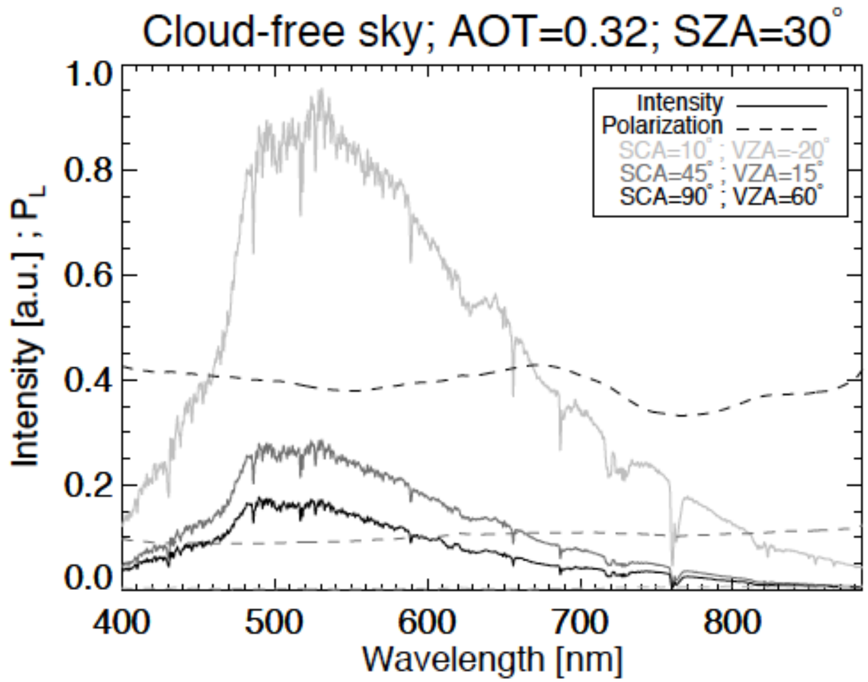
Comparison with AERONET




CIMEL Sun Photometer
AERONET

# groundSPEX measurements




PhD thesis Gerard van Harten

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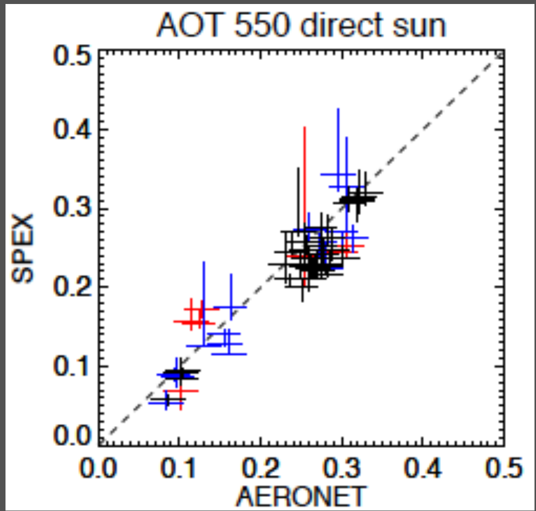
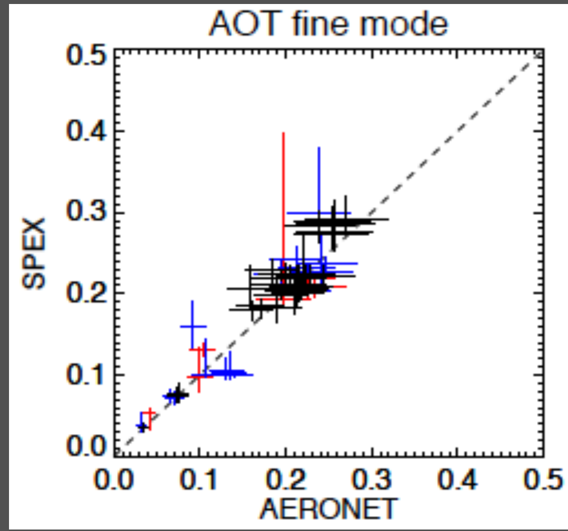
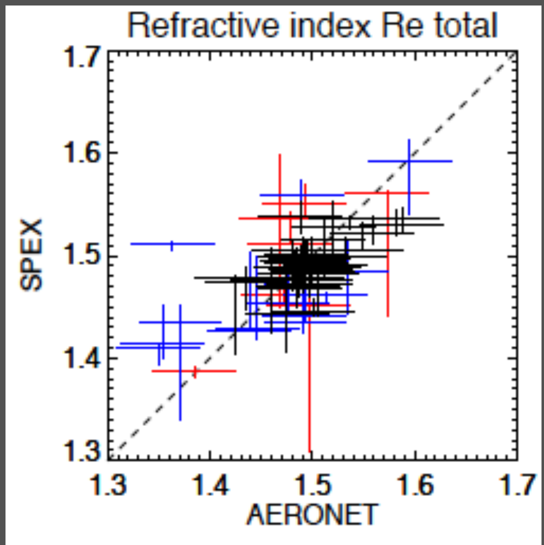
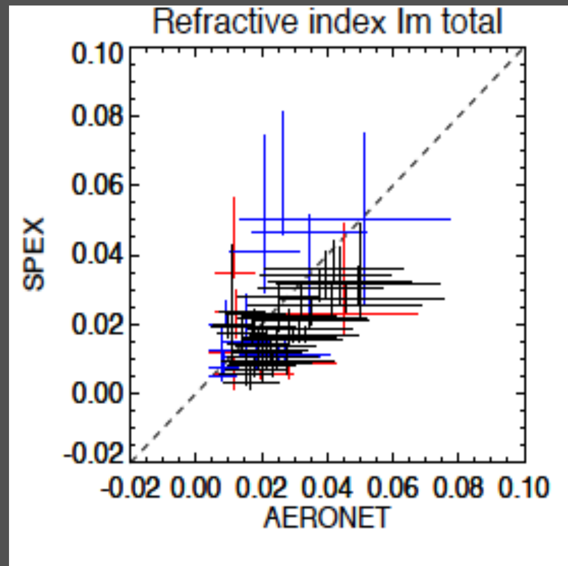
# *Ground*SPEX aerosol parameters versus AERONET




van Harten et al., AMT, 2014
Di Noia et al., AMT, 2015

# Outlook: airSPEX on the NASA ER-2 aircraft

- SRON is now building airSPEX  to fly on the NASA ER2.
- First flight expected Fall 2015.
- Flights together with Research Scanning Polarimeter (RSP) of NASA-GISS PRISM and AVIRIS hyperspectral imagers, LIDAR(?), airMSPI(?).
- Goals:
  - Comparison of DoLP with RSP.
  - End-to-end demonstration of measurement principle.
  - Characterize microphysical and optical properties of different aerosol types.
  - Polarimetric O2 a-band measurements
  - Synergistic retrievals with LIDAR?
  - Ocean applications?

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# Summary: SPEX

- Original science goals: aerosol direct and indirect forcing

- VNIR:
  spectral modulation, spectrometer, 375-850 nm, resolution
  4-8 nm for I, 20-40 nm for DoLP, 5 viewing angles
  (1 module per angle)
- SWIR: Focus on many viewing angles → cloud bow
  Filter based, polarimetric imager, 1 band 1620-1660 nm,
  50-100 viewing angles.
- Swath +/- 30 degrees
- Spatial resolution 4X4 $km^2$, pixel size 2X2 $km^2$