Polarimetric remote sensing of atmospheric aerosols: POLDER and beyond

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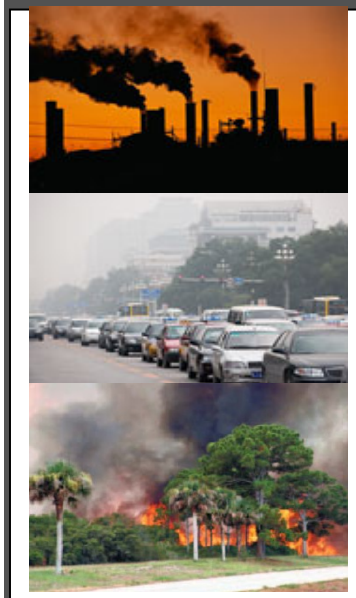
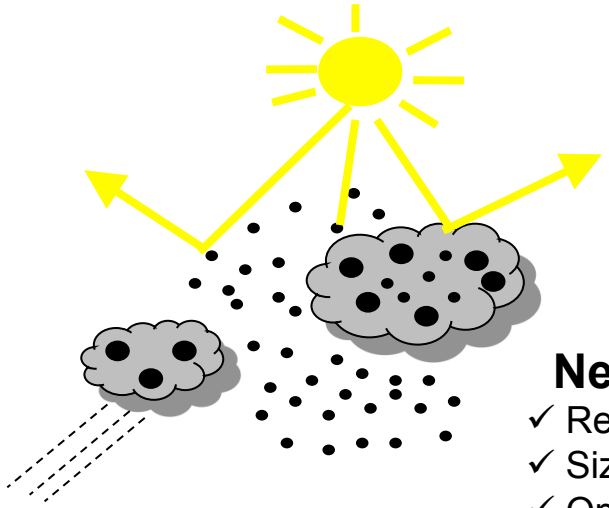
Netherlands Institute for Space Research

Netherlands Organisation for Scientific Research (NWO)

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]

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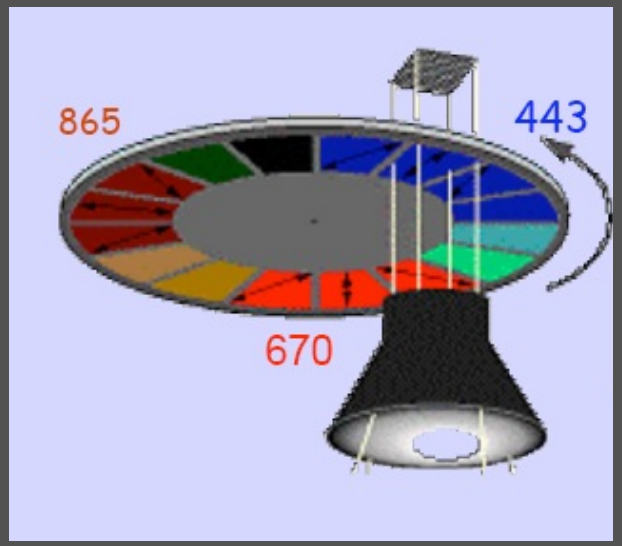
POLDER-3 on PARASOL

- 2004 - 2013
- Wide FOV CCD Camera with +/- 43 degrees cross track - +/- 51 degrees along track.
- Each ground pixel is viewed under multiple viewing angles (up to 16).
- 9 spectral bands between 443-1020 nm, polarization (Stokes parameters Q,U) at 490, 670, 865 nm.
- Polarimetric accuracy estimated between 0.01 (ocean)-0.02 (land)
- In this work 4 wavelengths are being used: 490, 670, 865 , 1020 nm.



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New Generation of Algorithms

Current standard retrieval approaches are not able to cope with (potential) capabilities of POLDER:

- Limited number of "standard" aerosol models.
- Simplified treatment of ocean / land reflectance.

New generation of algorithms is currently under development for POLDER (Dubovik et al., AMT, 2011; Hasekamp et al., JGR, 2011)

- No restriction to "standard" aerosol models (size distribution, refractive index, shape) but retrieve properties of aerosol models.
- Retrieve land / ocean properties simultaneously with aerosol.
- Fit full polarized RT model to multi-angle, multi-wavelength measurements of radiance and polarization

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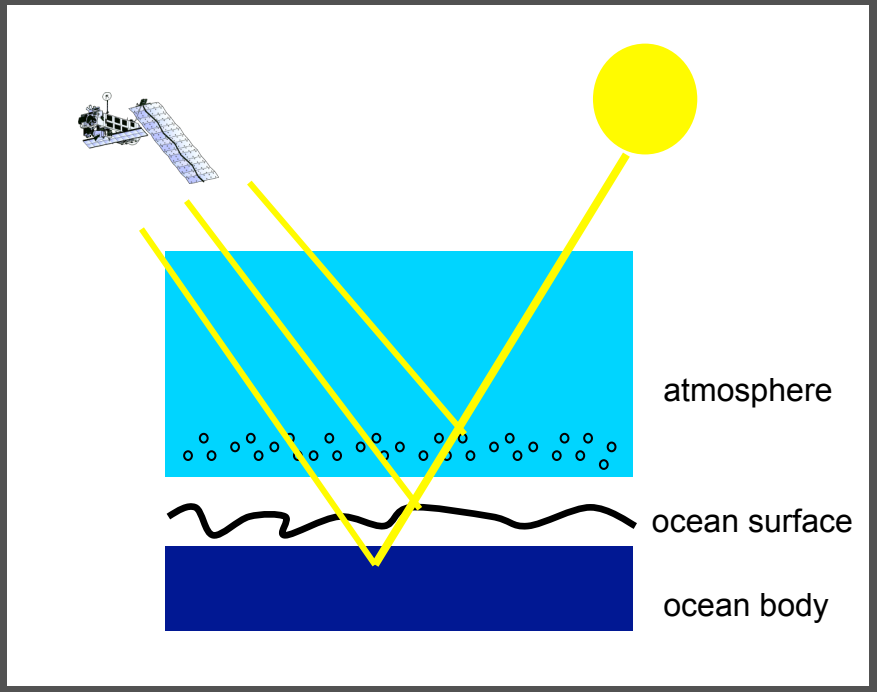
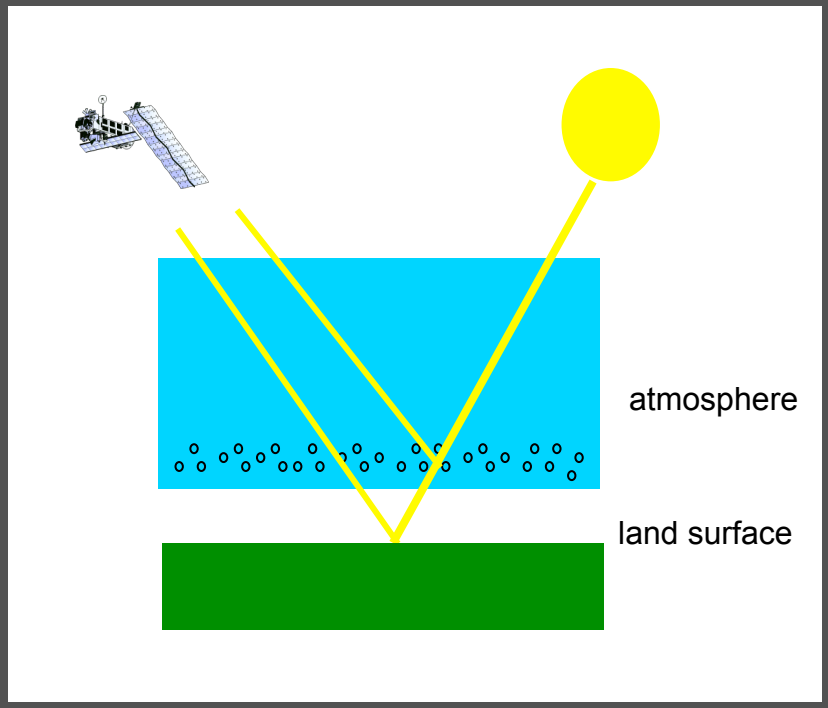
Forward Model





- **Ocean surface**: Cox & Munk, 1954
- **Ocean body**: optical properties as function of [Chl_a] (Morel, 2001; Chowdhary 2010)

- **Land BRDF**: Rahman-Pinkty-Verstraete or kernel based Ross-Roujean / Ross-Li
- Land BPDF: Surface facets + shadowing (Litvinov et al (RSE 2011))

Atmosphere

Landgraf et al. (JQSRT 2001; JGR 2002)
Hasekamp and Landgraf (JQSRT 2002; JGR 2005)
Hasekamp and Butz (JGR 2008)
Hasekamp et al (JGR 2011)

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Inversion Approach

Tikhonov regularization:

$$\hat{\mathbf{x}} = \min_{\mathbf{x}} \left(\| \mathbf{S}_e^{-1/2} (\mathbf{F}(\mathbf{x}) - \mathbf{y}) \|^2 + \gamma \| \mathbf{\Gamma}(\mathbf{x} - \mathbf{x}_a) \|^2 \right)$$

Initial guess and a priori:

- Use LUT with pre-calculated values of I, Q, and U for 192 aerosol models.

- Fit AOT (fine), AOT (coarse), Chlorophyll-a concentration, and wind speed using LUT as forward model (interpolation between node points).

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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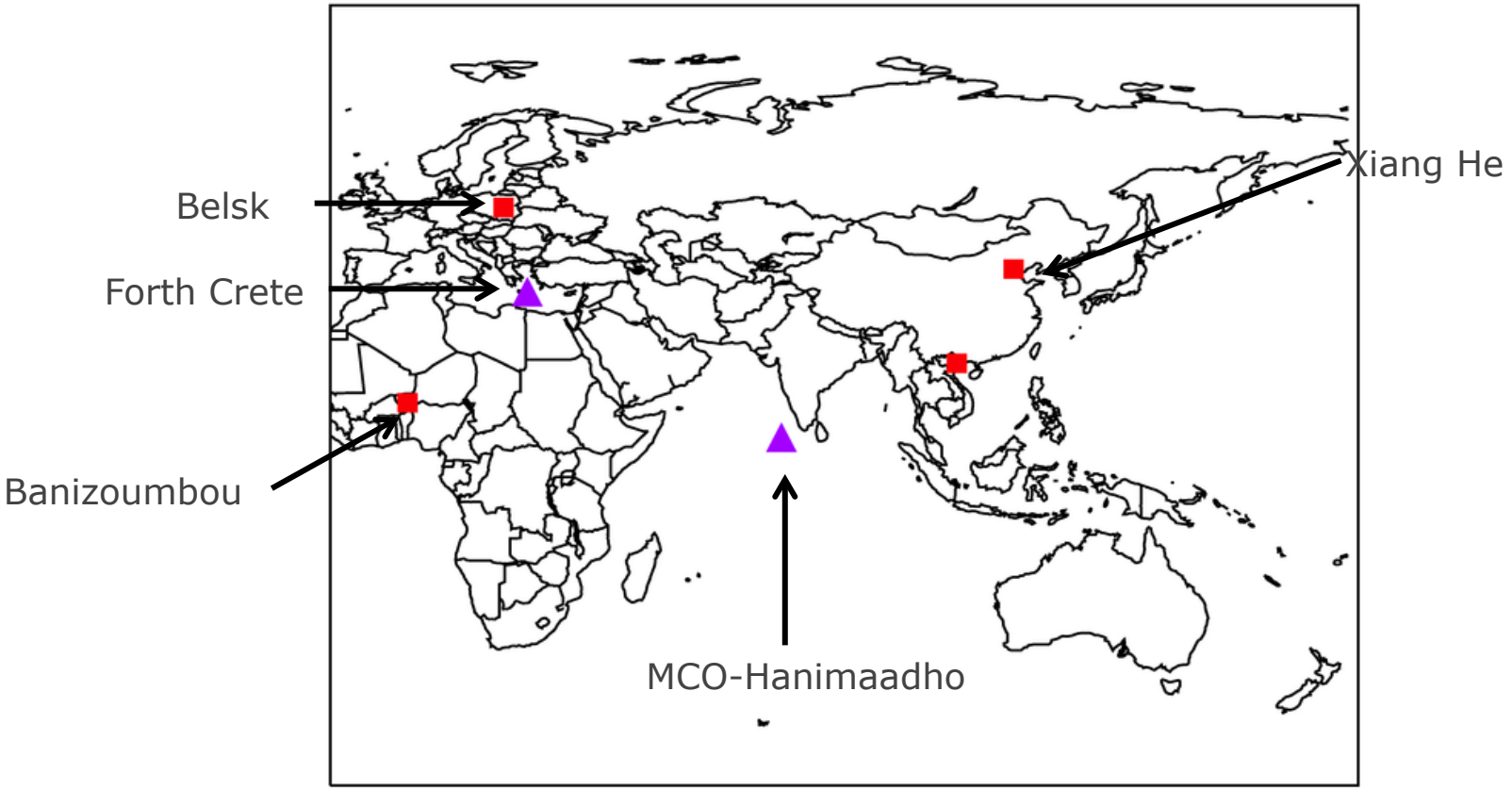
Validation with AERONET (2006)

Ocean (blue triangles):
distance < 40 km
ΔT < 1 hour

Land (red squares):
distance < 15 km
ΔT < 1 hour



Retrievals over Ocean

Hasekamp et al, JGR, 2011, with improvements:

- Use 490, 670, 865, 1020 nm bands instead of only 490 and 670 nm.
- Include non-spherical particles for coarse mode (Dubovik Kernels).
- Different iteration / regularization approach

Filtering:

- Clouds (PARASOL cloud mask)
- Goodness of fit
- Refractive index > 1.33

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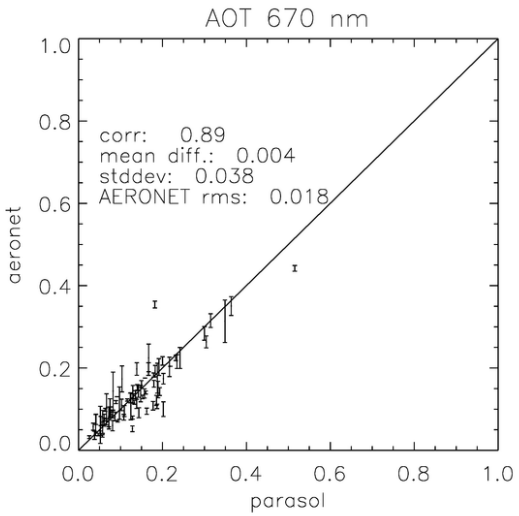
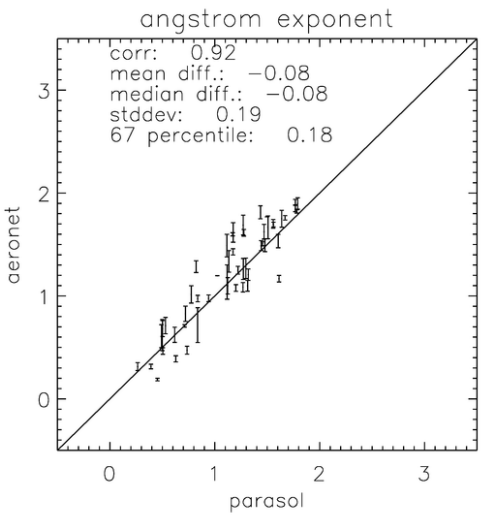
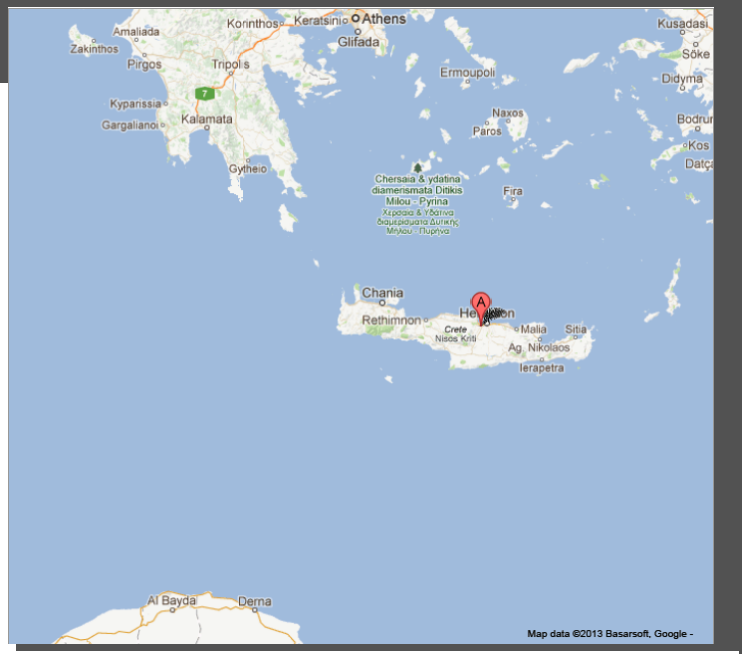
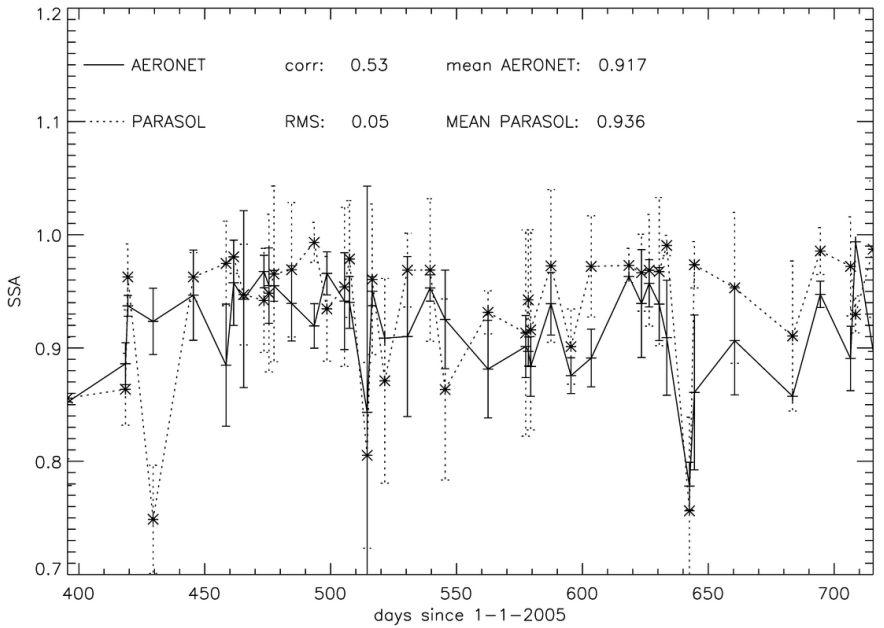
Forth Crete (Ocean)









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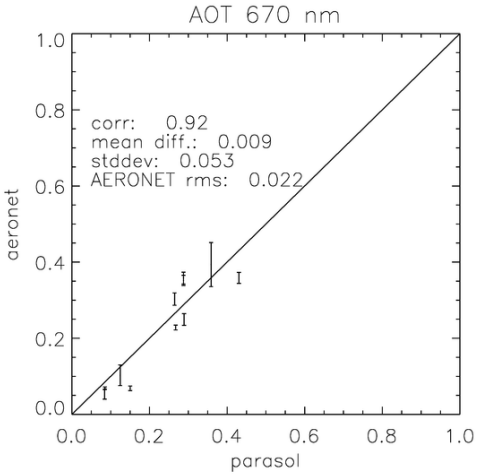
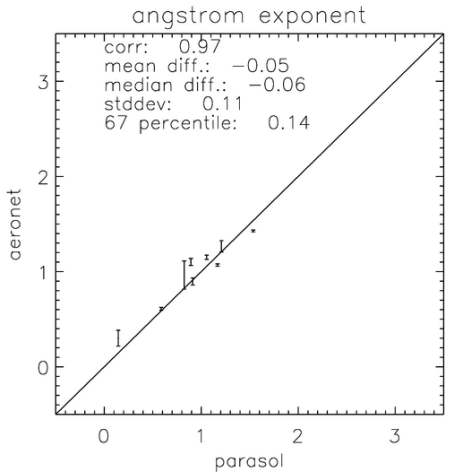
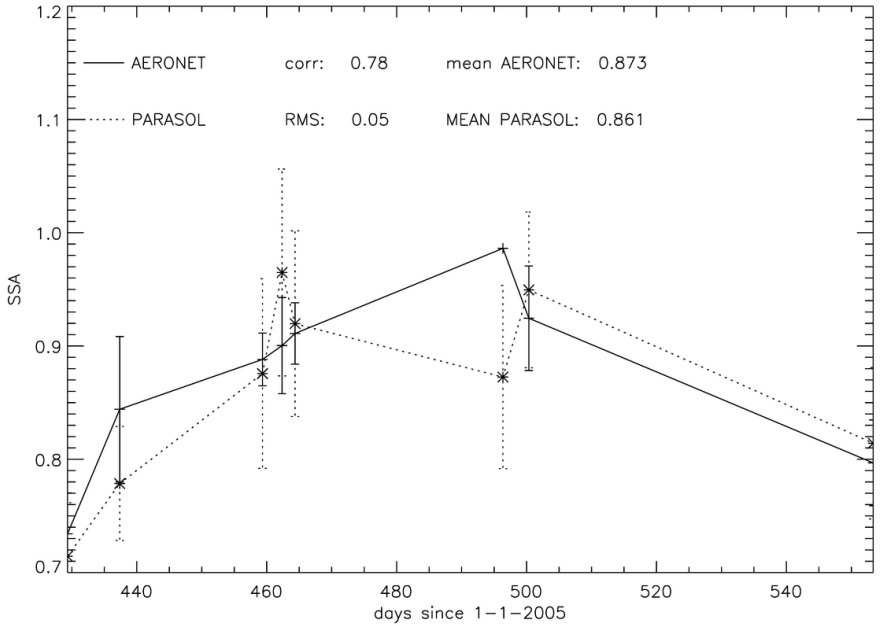
Hanimadhoo (ocean)







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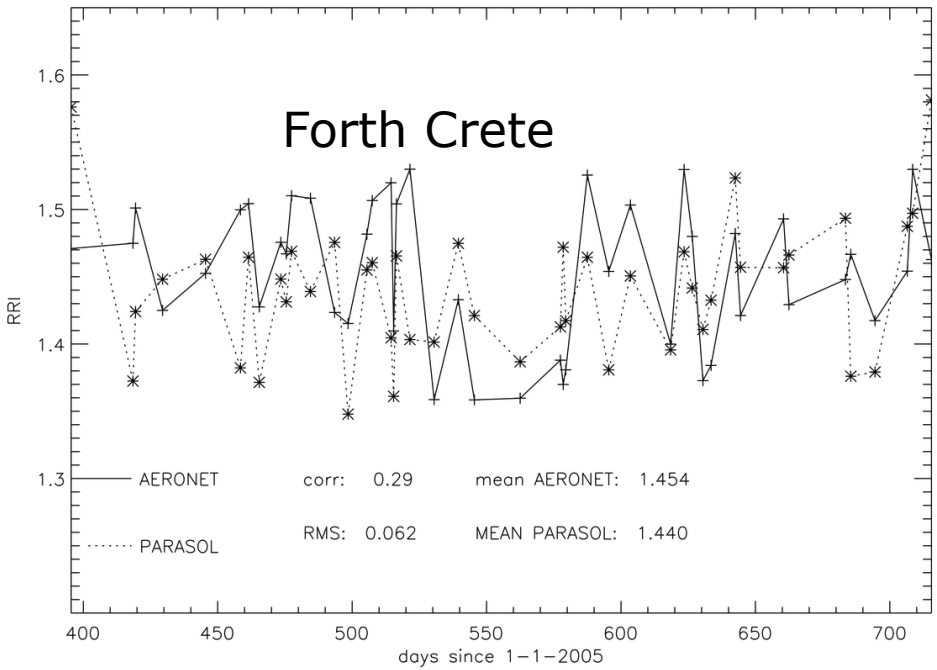
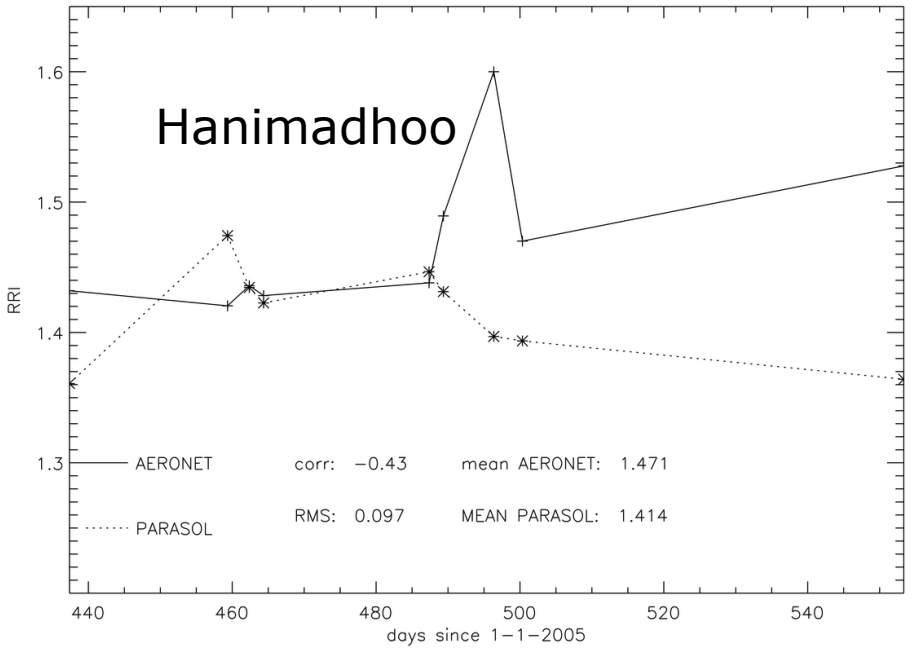
Refractive Index



Note:
AERONET does not retrieve the same quantity (size independent, wavelength dependent) as we do from PARASOL (size dependent, wavelength independent)

$$m_{comp} = \frac{V_{fine} m_{fine} + V_{coarse} m_{coarse}}{V_{fine} + V_{coarse}}$$



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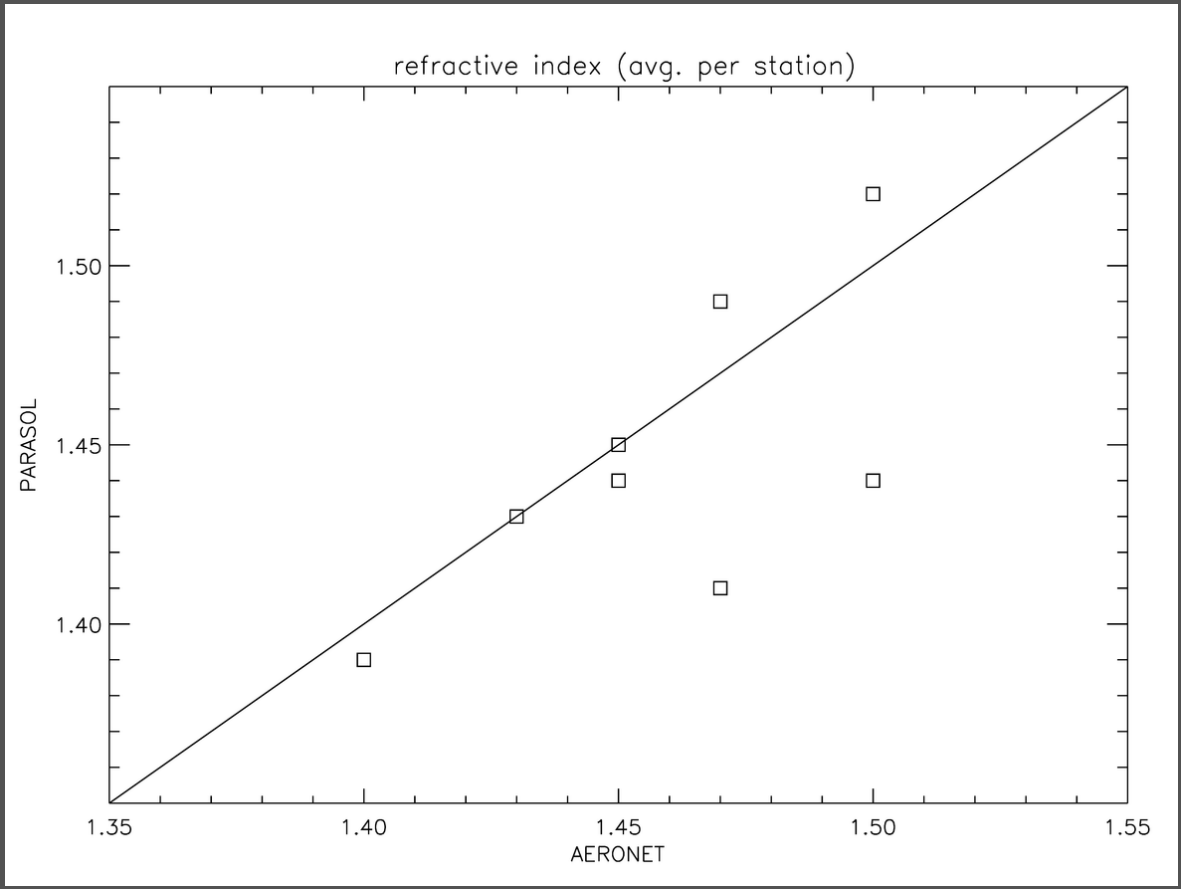
Refractive Index: Average per Station



Stations:
- Anmyon
- Cheng Kung
- Forth Crete
- Gosan Snu
- Guam
- IMS-METU-ERDEMLI
- Hanimaadhoo
- Sevastopol

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Under development: Retrievals over Land

- Retrievals performed for both RPV and Ross-Roujean surface models
- RPV gives best results
- Cloud filtering only based on χ^2 of fit (see talk Arjen Stap).

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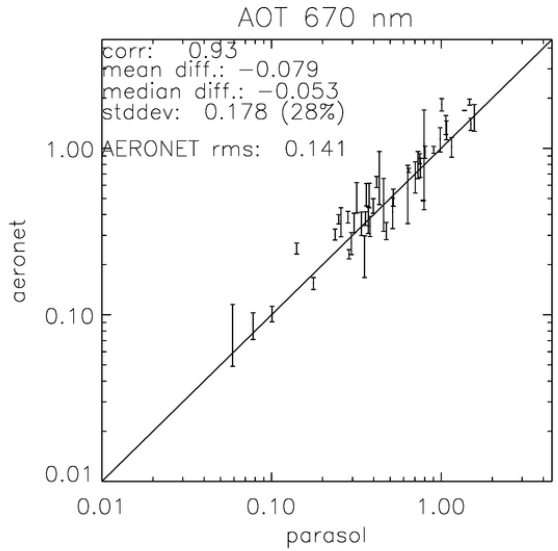
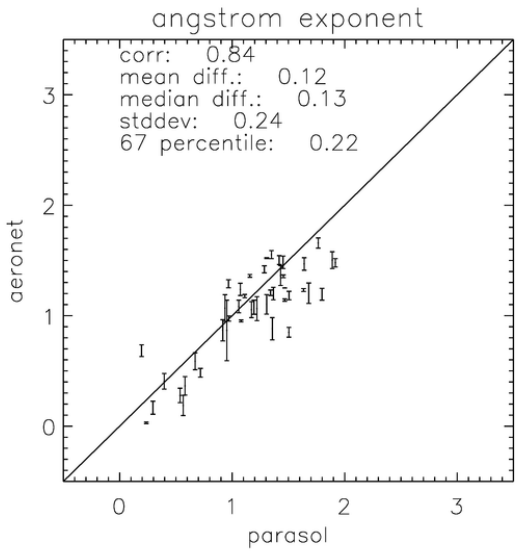
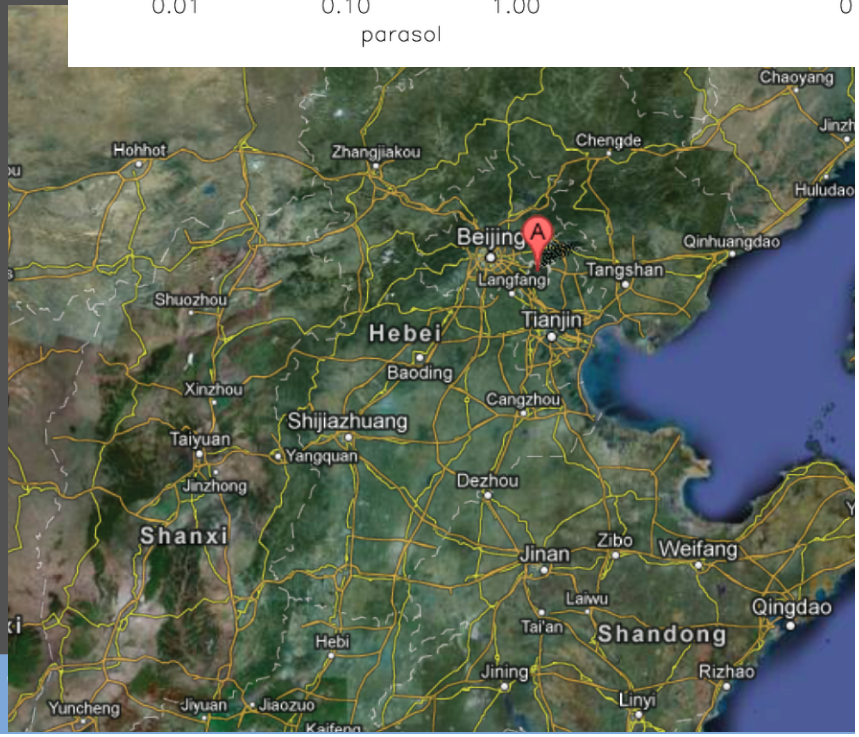
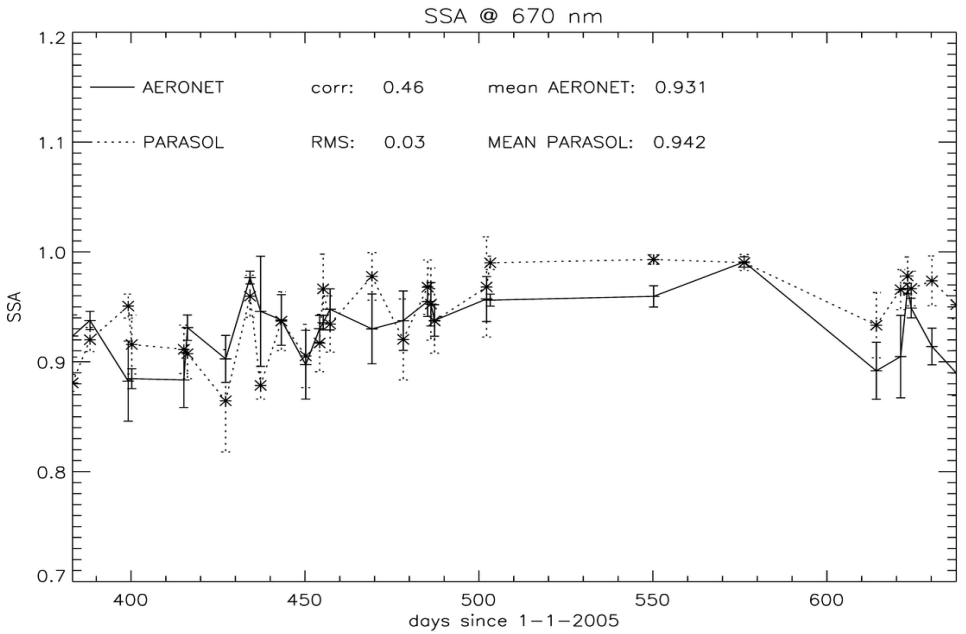
Xiang He (Land)

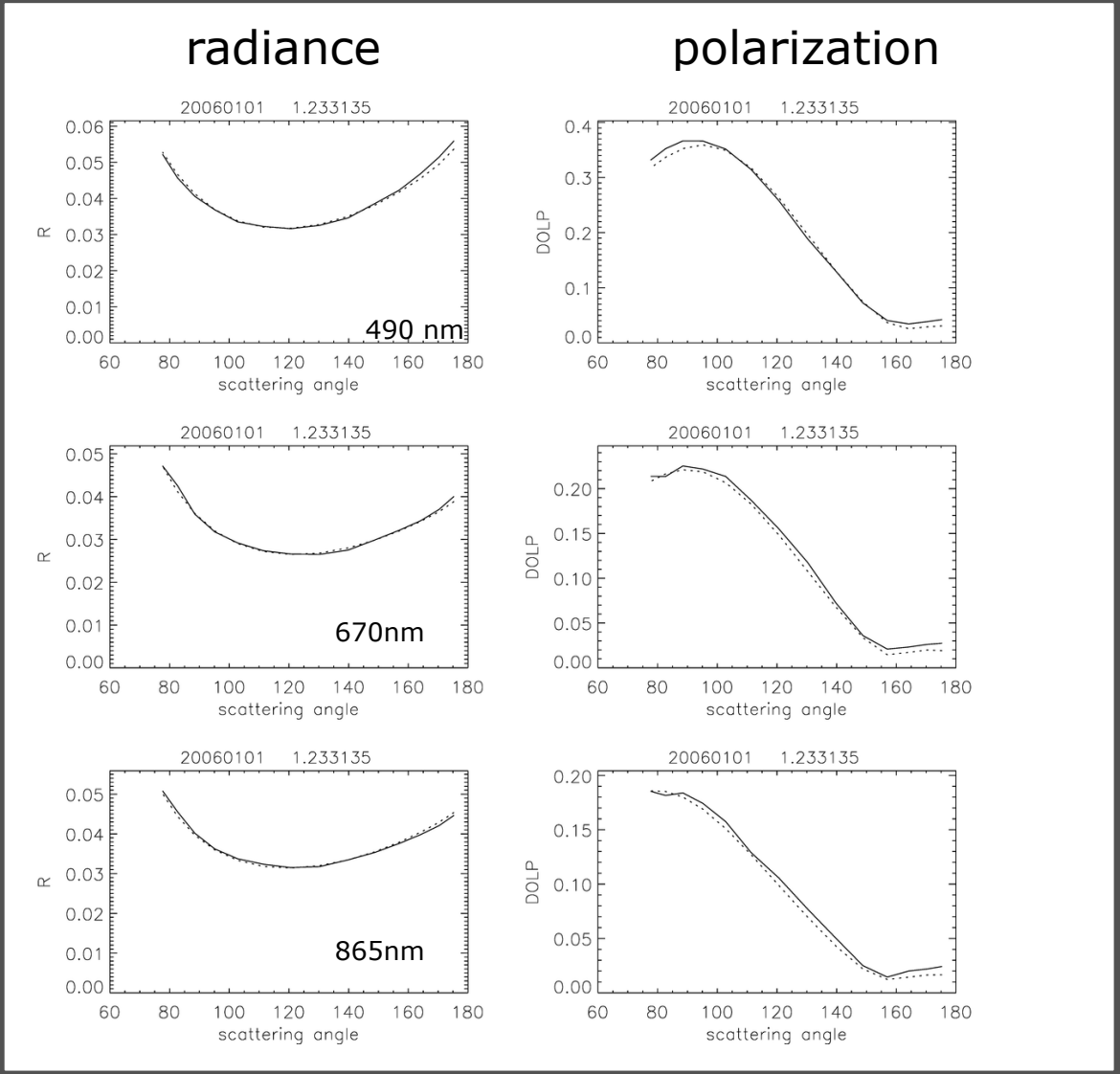




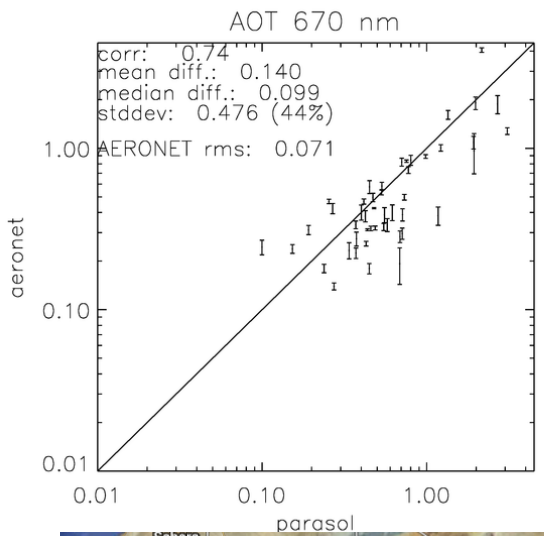


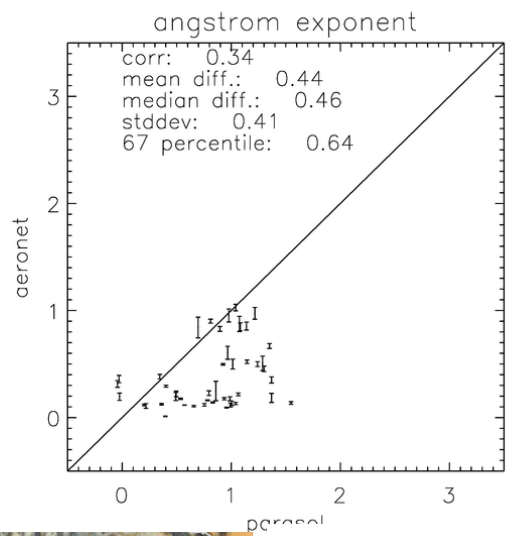


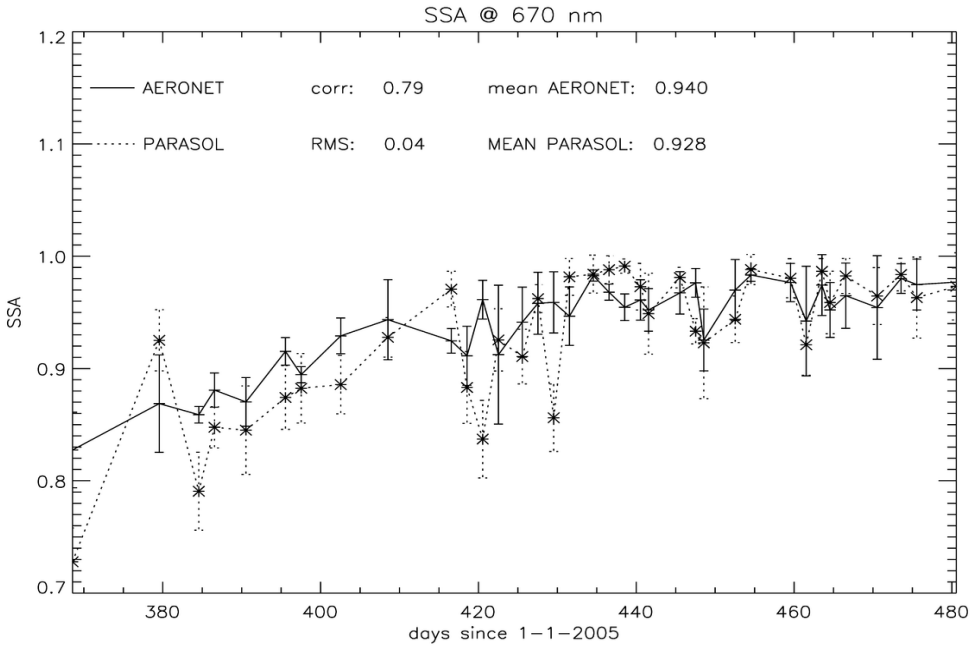
Land: Xiang He - Fits



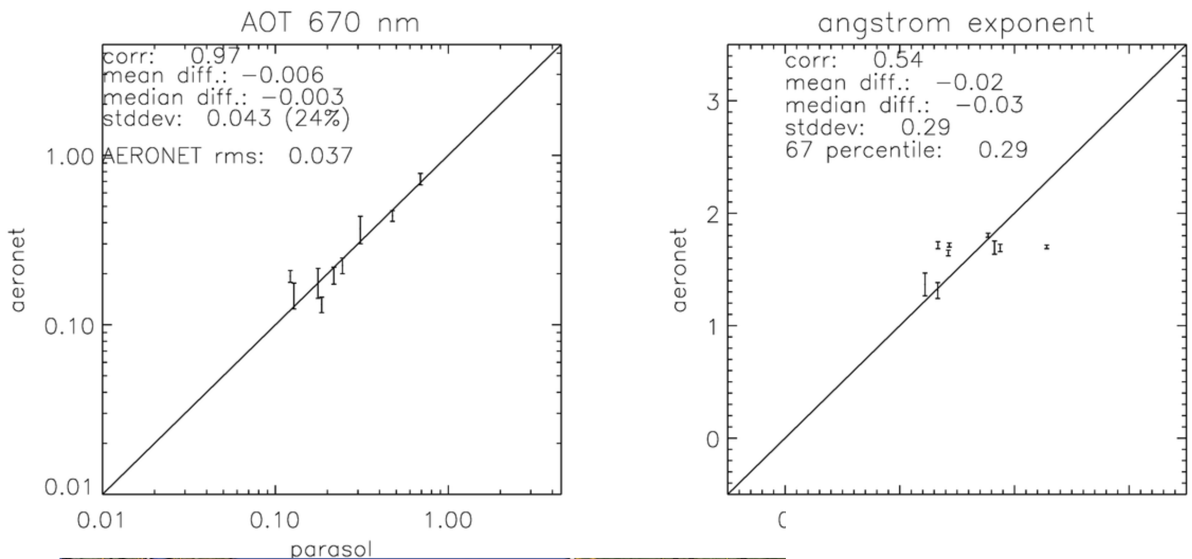
Banizoumbou (land)



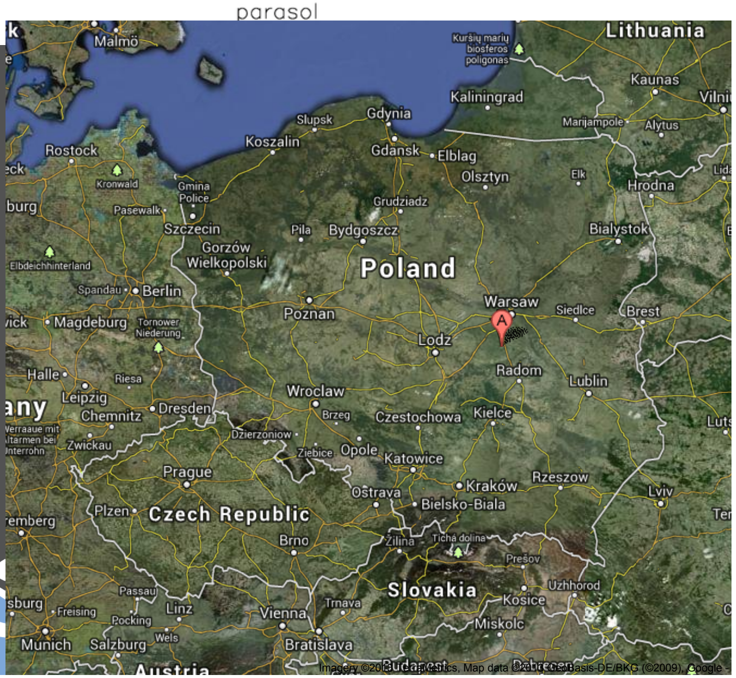




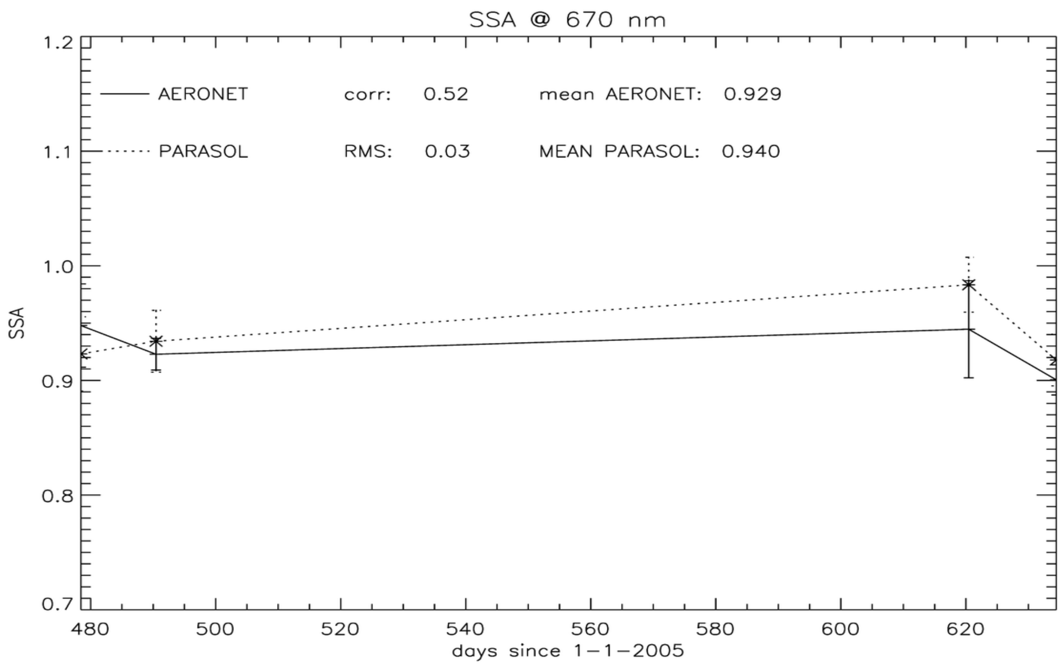
Belsk (Land)



AOT 670 nm
corr: 0.97
mean diff.: −0.006
median diff.: −0.003
stddev: 0.043 (24%)
AERONET rms: 0.037
1.00
0.10
0.01
aeronet
parasol
angstrom exponent
corr: 0.54
mean diff.: −0.02
median diff.: −0.03
stddev: 0.29
67 percentile: 0.29
3
2
1
0



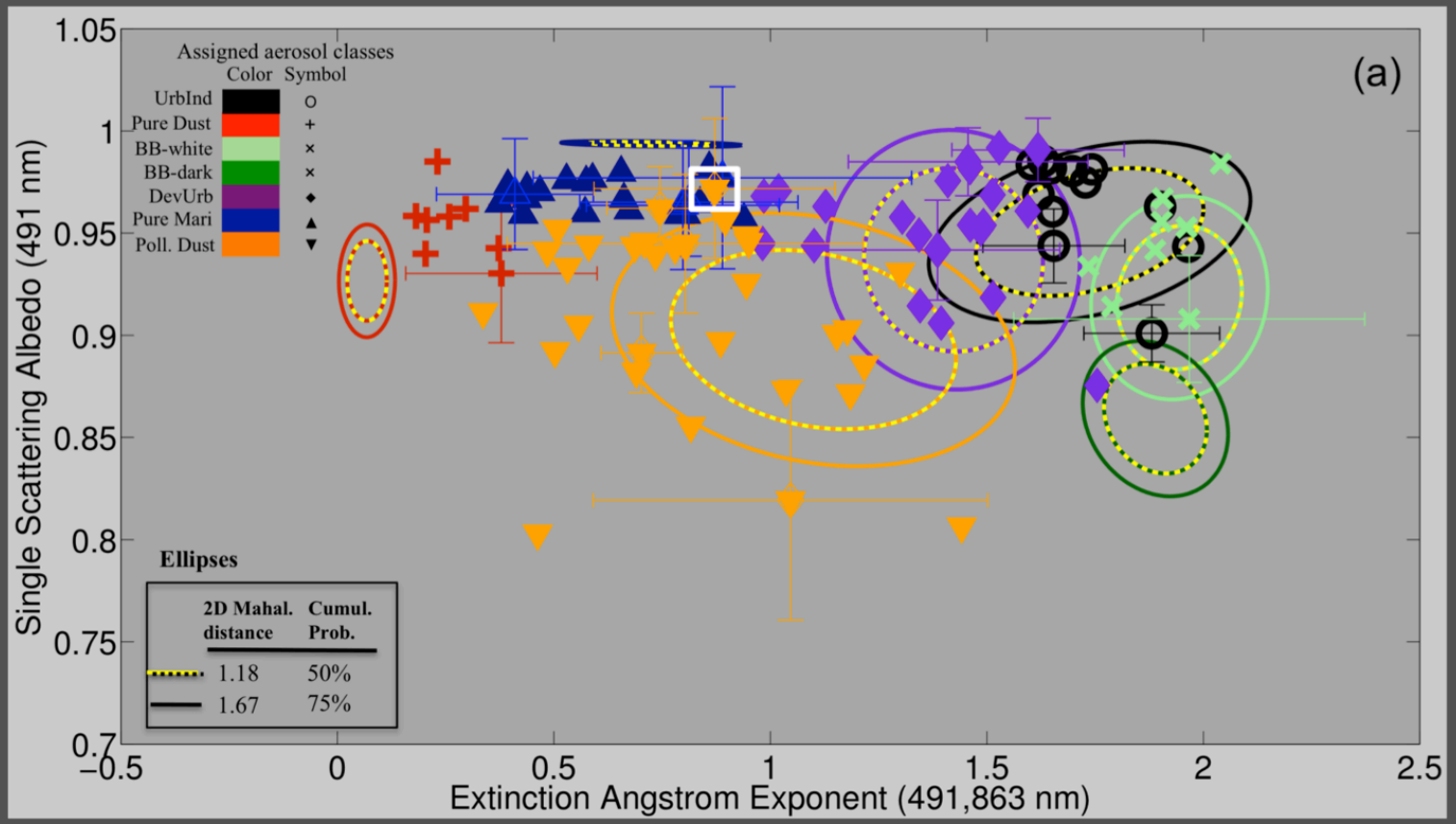
Lithuania
Kaliningrad
Gdynia
Gdansk
Elblag
Olsztyn
Koszalin
Slupsk
Rostock
Szczecin
Bydgoszcz
Poland
Warsaw
Poznan
Lodz
Radom
Lublin
Berlin
Magdeburg
Leipzig
Dresden
Wroclaw
Czestochowa
Kielce
Katowice
Opole
Kraków
Rzeszow
Prague
Czech Republic
Brno
Ostrava
Slovakia
Vienna
Bratislava
Budapest
Munich
Salzburg
Linz
Austria
Hrodna
Bialystok
Brest
Lviv
Kaunas
Kosice
Miskolc
Siedlce



SSA @ 670 nm
AERONET
corr: 0.52
mean AERONET: 0.929
PARASOL
RMS: 0.03
MEAN PARASOL: 0.940
SSA
1.2
1.1
1.0
0.9
0.8
0.7
480
500
520
540
560
580
600
620
days since 1−1−2005

Application:Aerosol Classification (@NASA-AMES)

Aerosol classification from POLDER over Forth Crete



Work by Phil Russell, Meloe Kacenelenbogen, et al.

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…. and beyond

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The Next Generation of Instruments

POLDER is at the forefront of aerosol satellite remote sensing, but has a number of shortcomings. The most important improvements needed for the next generation of polarimeters are:

- Improvement of polarimetric accuracy for refractive index and SSA.
- Increase number of viewing angles to distinguish clouds and aerosols.
- Increase spectral resolution to measure O2-A band (aerosol height)
- Extend spectral range to SWIR for coarse aerosol characterization
- Extend spectral range to blue/UV for aerosol absorption (+ fine mode)

POLDER's successor 3MI, with extended spectral coverage, will provide operational monitoring of aerosols with **daily global coverage** > 2020

In addition, a **high accuracy polarimeter** is needed to meet refractive index and SSA requirements, preferably in combination with LIDAR.

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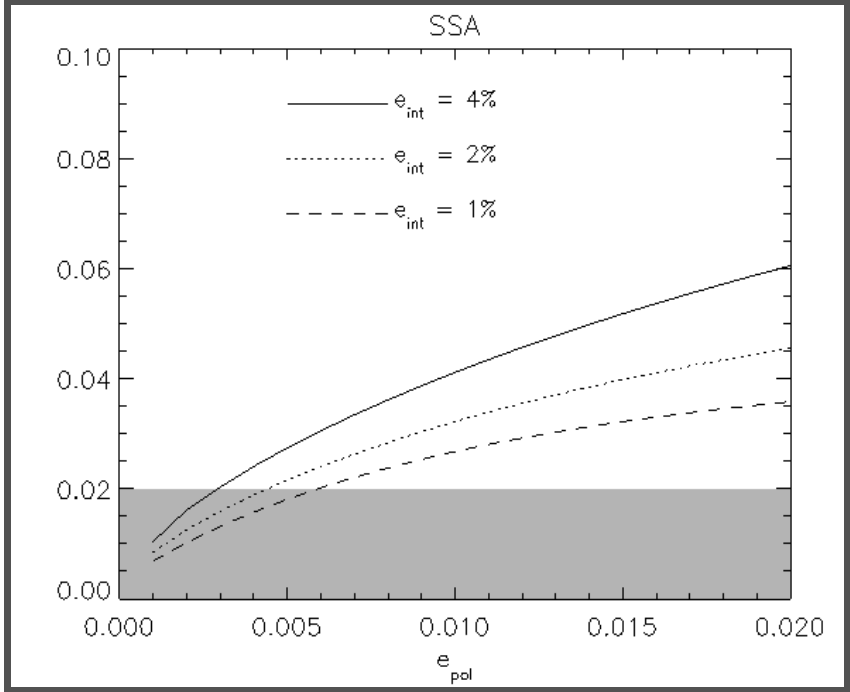
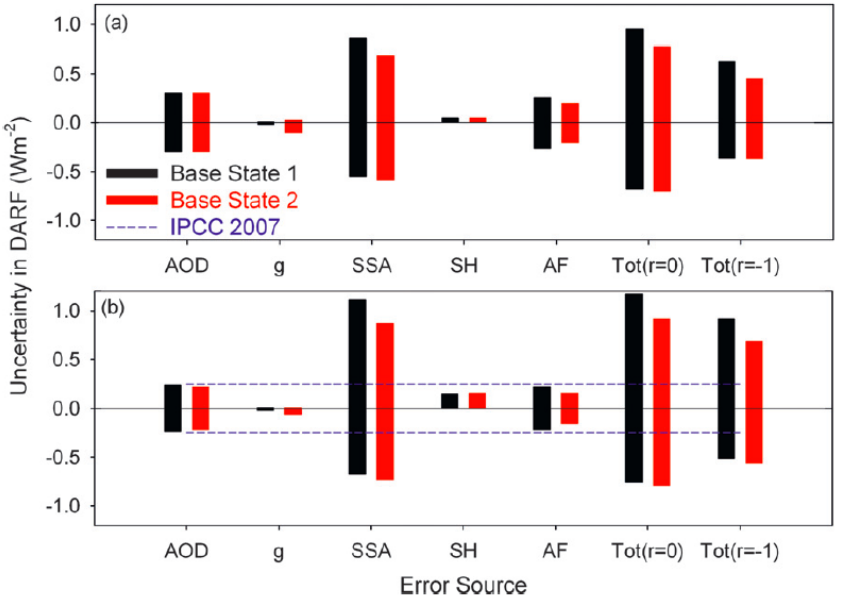
Polarimetric accuracy → SSA → DARF



The Direct Forcing uncertainties are mostly related to aerosol absorption (SSA)

With a polarimetric accuracy of 0.002 an SSA accuracy of 0.01-0.02 is achievable

Loeb and Su, 2010



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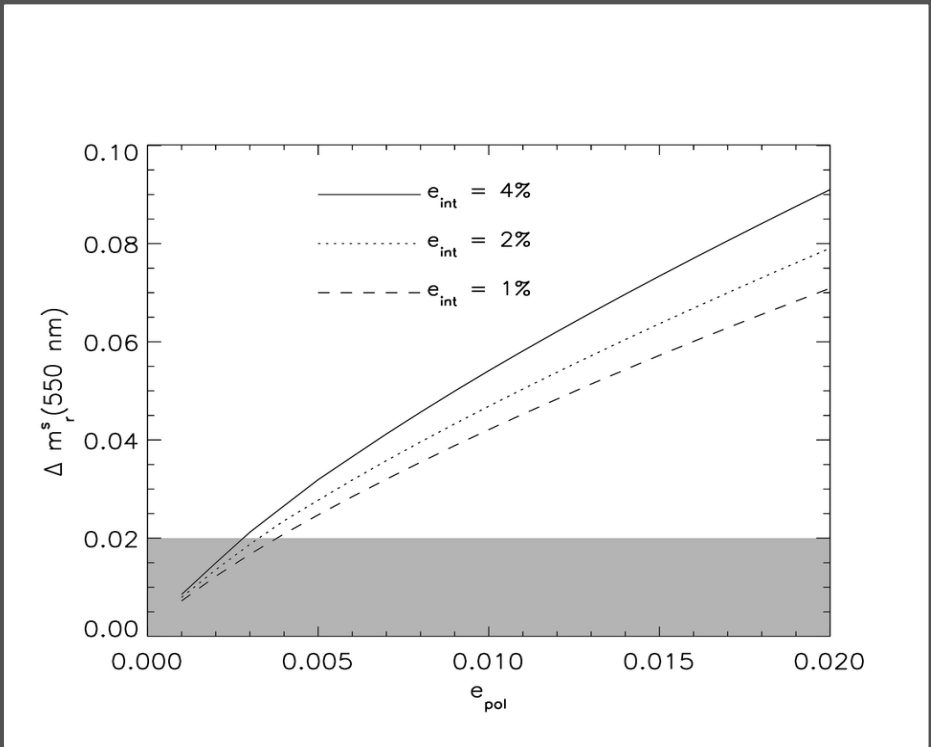
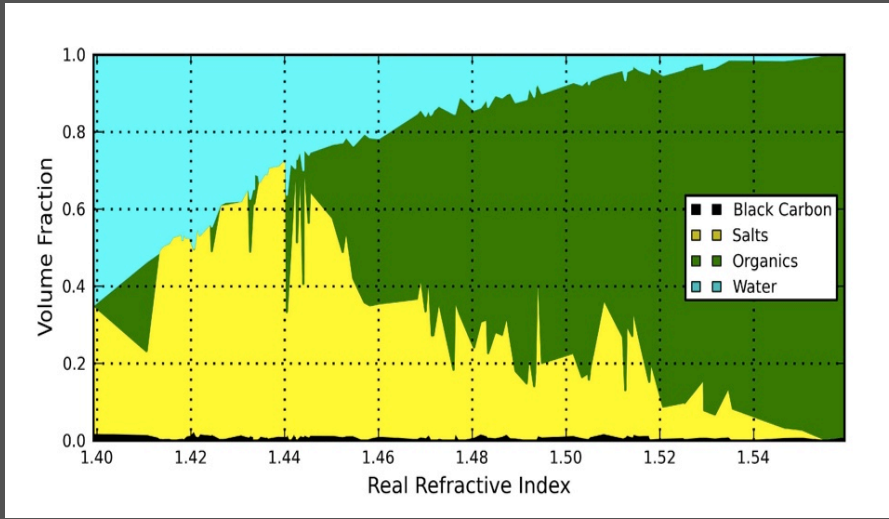
Polarimetric accuracy → Refractive index → water uptake





van Beelen et al, ACPD, 2013

See poster Arjan van Beelen

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SPEX: Polarimetry for aerosol characterization

Multi-angle spectropolarimeter

Innovative instrument concept:

Simultaneous measurement of polarization and radiance

Wavelength range 370- 850 nm

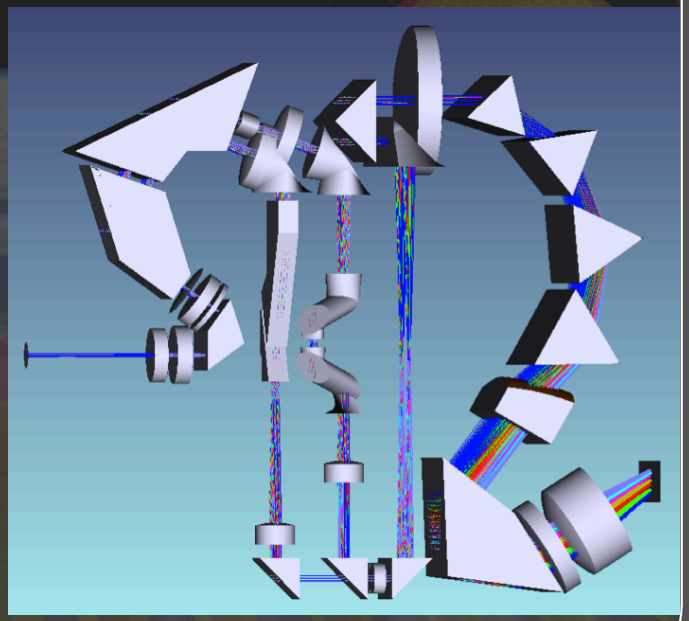
1200-1600 nm

30° swath, 0.29° x 0.35° IFOV

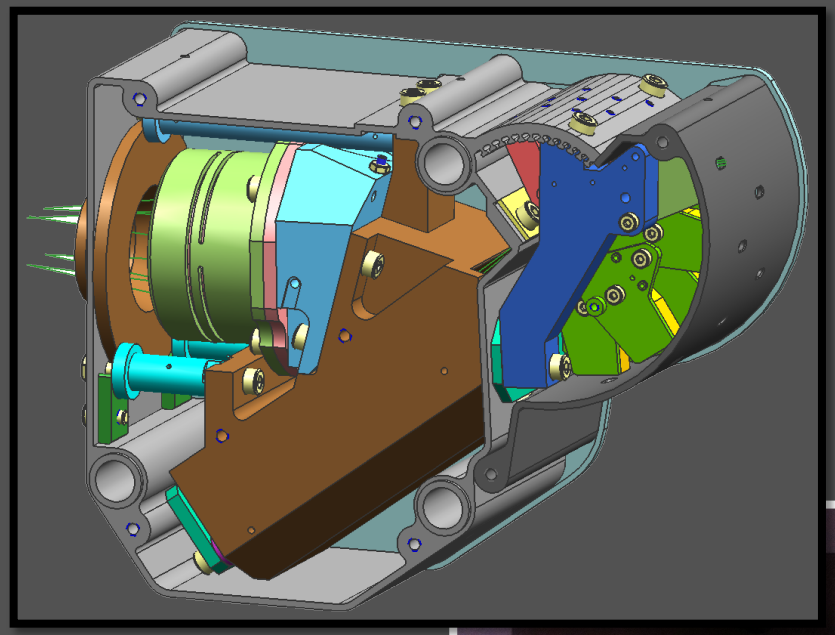
30 viewing directions

No moving parts in optics

Modular design

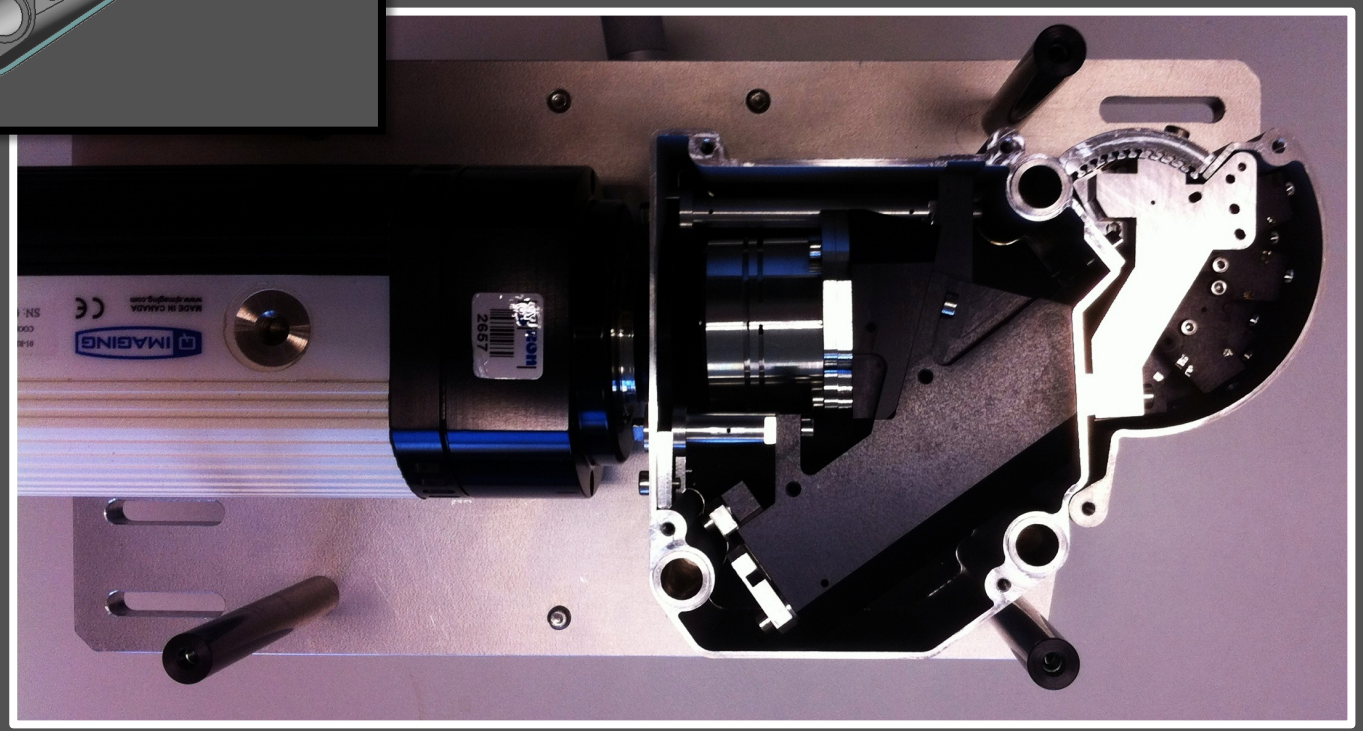


SPEX: Prototype for Mars Mission



- 9 viewing directions
- Single spectrograph

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



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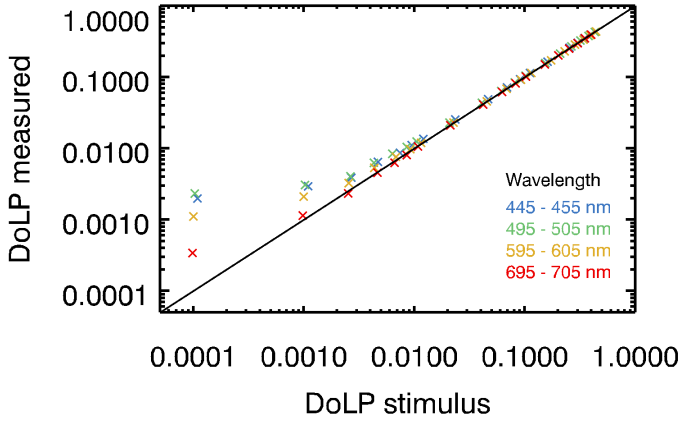
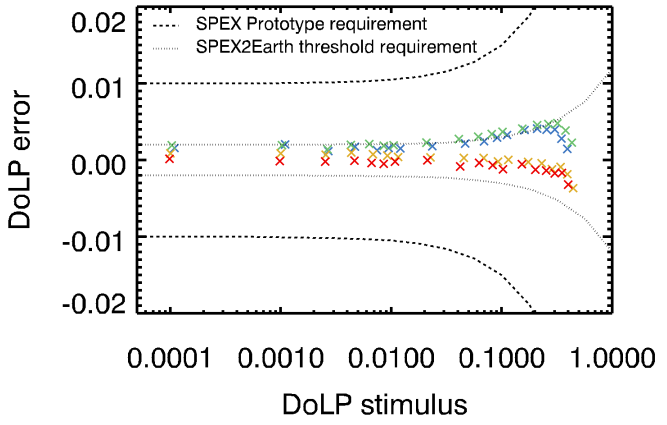
Summary of latest SPEX results (Nov 2013)

- SPEX absolute DoLP Calibration with Leiden Polarization Stimulus (ESA-MREP program)
- Further optimization of stimulus: ΔDoLP(SPEX-testpol) can improve!

Prototype: demonstrates the capabilities of the SPEX modulation technology!





Summary

- Novel algorithm fully exploits available information.
- No restriction to standard aerosol models
- Retrieve ocean / land properties simultaneously with aerosols
- Retrieval of new aerosol products (SSA, refractive index) possible.

- AOT, Angstrom Exponent and SSA compare well with AERONET.
- Refractive index hard to compare, but seems to be in agreement
- Banizoumbou performance is worse than for other sites.
- SSA retrieval more accurate over land than over ocean

Beyond POLDER

- POLDER's successor 3MI will provide operational monitoring of aerosols with (near) daily global coverage > 2020
- In addition there is need for a high accuracy polarimeter for SSA and refractive index (process studies, climatology → daily global coverage not esential).

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