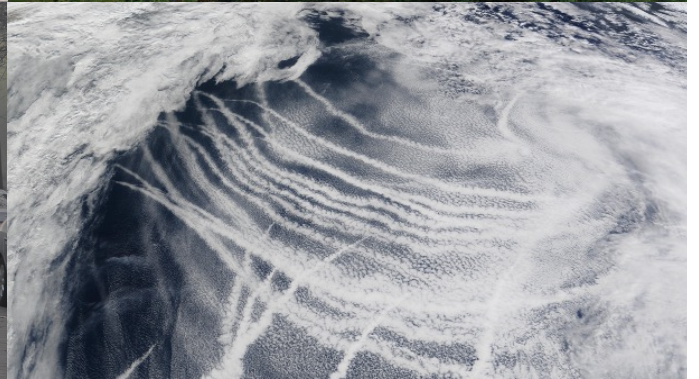


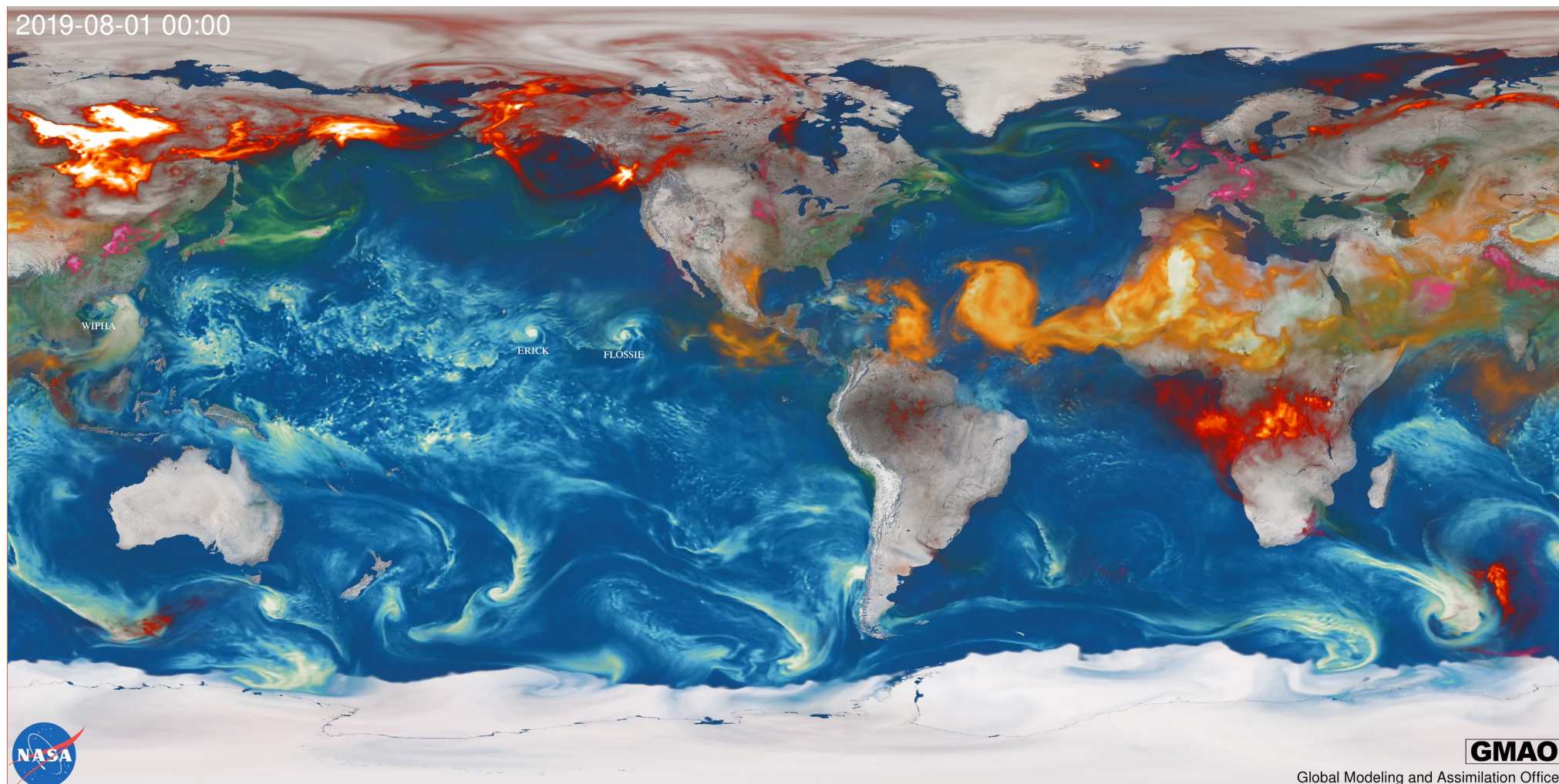
Aerosol Remote Sensing from Polarimetric Measurements

Otto Hasekamp

SRON
SPACE
RESEARCH
ORGANISATION
NETHERLANDS



2019-08-01 00:00



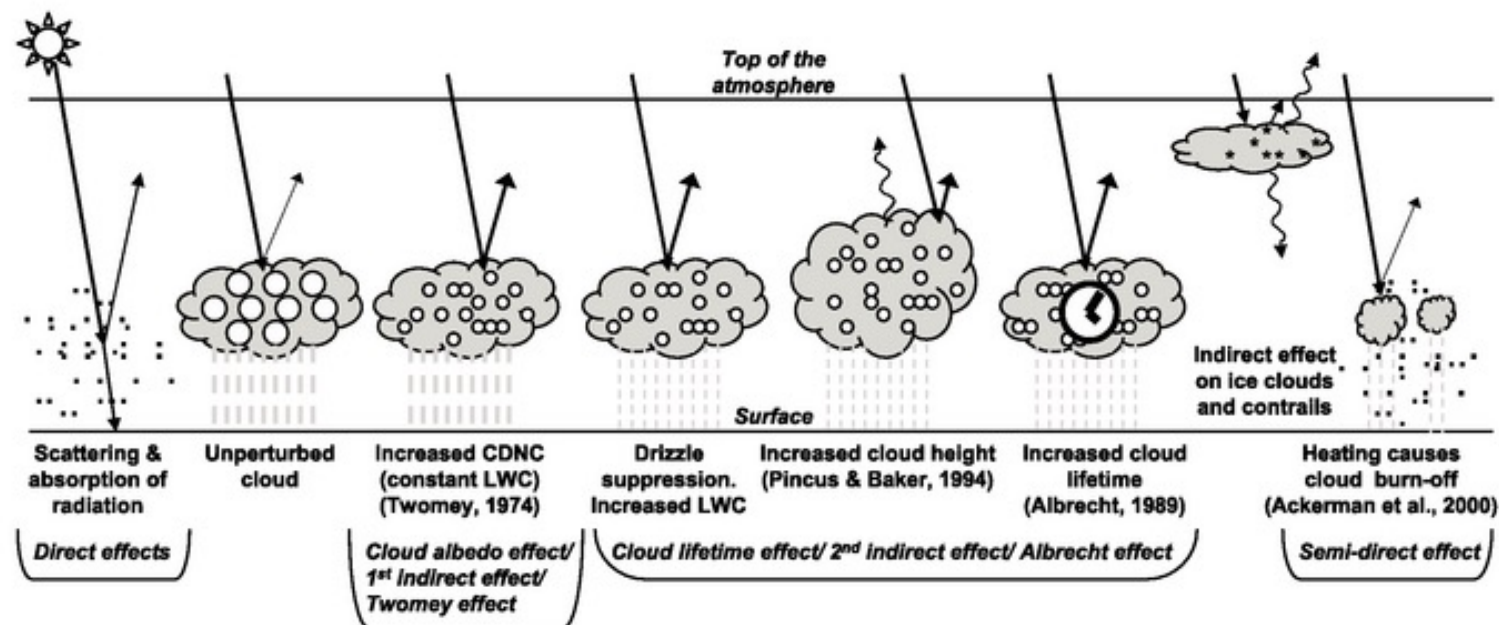
GMAO

Global Modeling and Assimilation Office

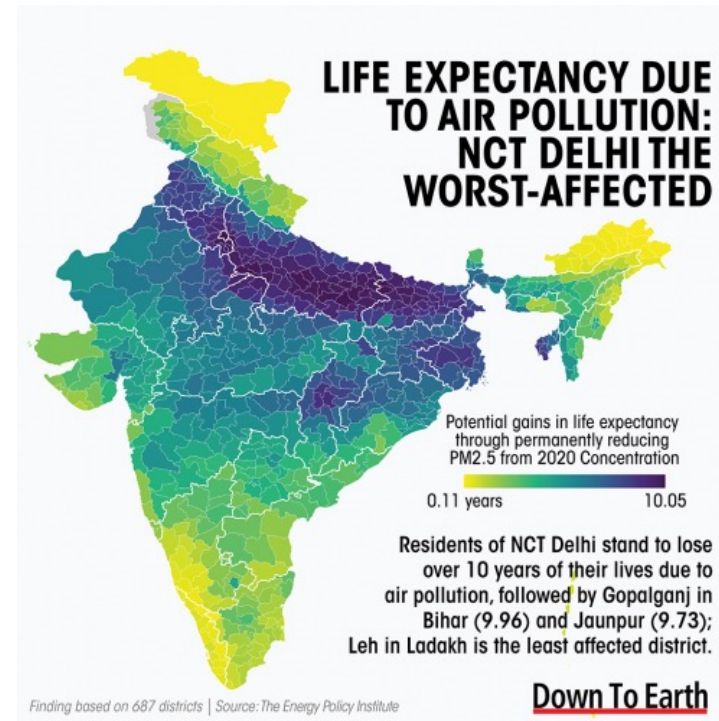
Aerosol Optical Depth at 550 nm



Aerosol Effects on Climate



Aerosols and Air Quality



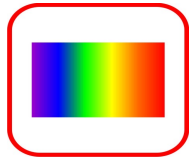
What Aerosol properties do we need to measure?

- Optical properties such as Aerosol Optical Depth (AOD) and Single Scattering Albedo (SSA): Needed to quantify aerosol-radiation interactions (climate) but also serve as proxy for aerosol amount and composition (climate & air quality).
- Aerosol size distribution: Needed for air quality research (fine particles are most harmful and also for aerosol cloud interactions).
- Composition: Needed to quantify emission sources and aerosol water uptake (climate and air quality). Refractive index can be used to distinguish between the most important aerosol components: Dust, Sea Salt, Sulfates/Nitrates, Black Carbon, Brown Carbon, aerosol water.

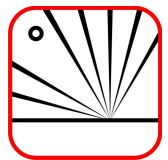


Measurement Principle

Aerosol properties can be derived from measurements of scattered light



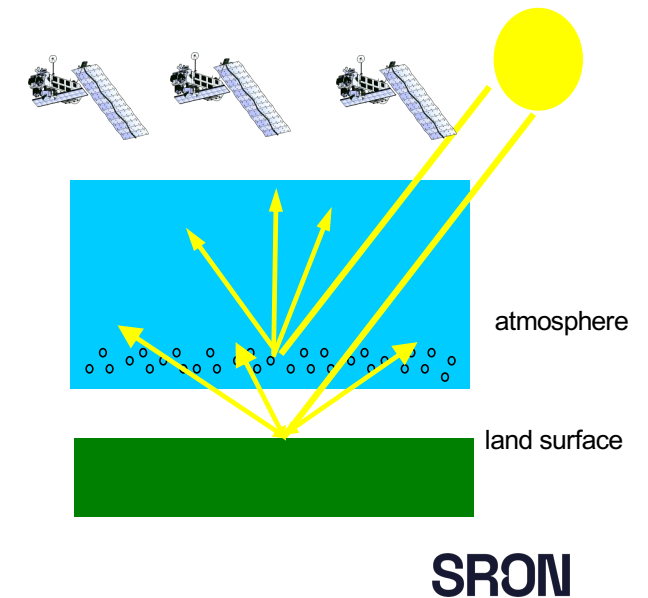
radiance spectrum



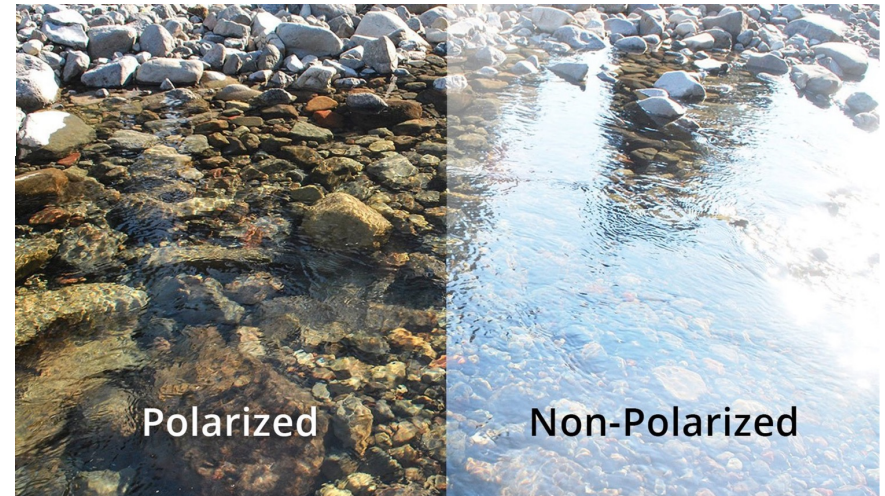
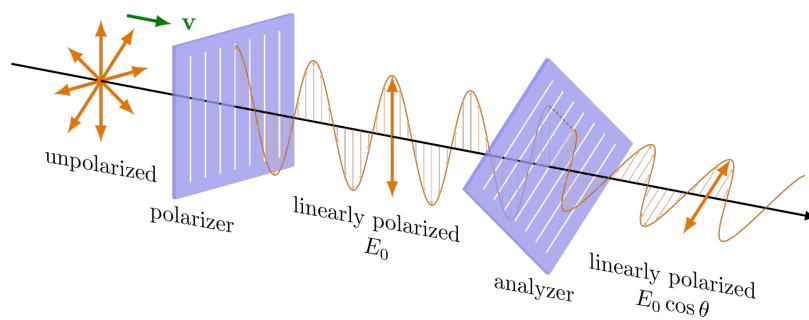
Multiple viewing angles



polarization



$$\begin{aligned}
 I &= I(0^\circ) + I(90^\circ) && \text{(total intensity)} \\
 Q &= I(0^\circ) - I(90^\circ) && \text{(horizontal vs vertical polarization)} \\
 U &= I(45^\circ) - I(135^\circ) && \text{(+45^\circ vs -45^\circ linear polarization)} \\
 V &= I_{\text{RCP}} - I_{\text{LCP}} && \text{(right vs left circular polarization)}
 \end{aligned}$$



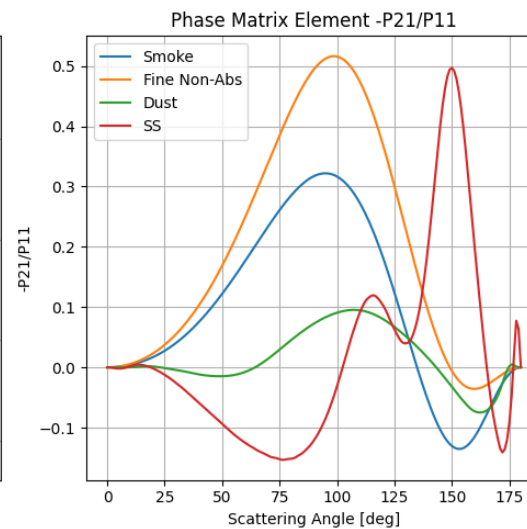
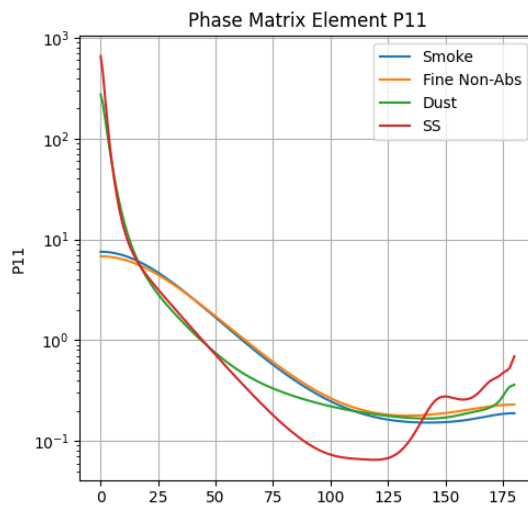
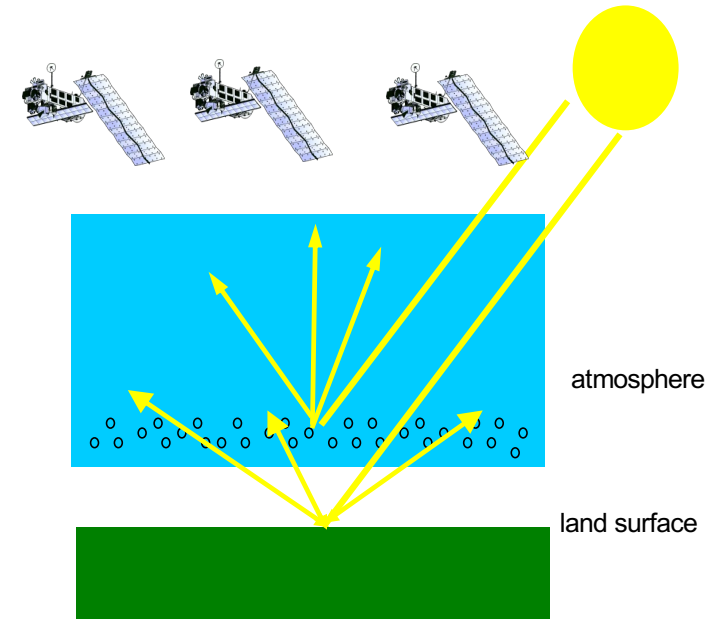
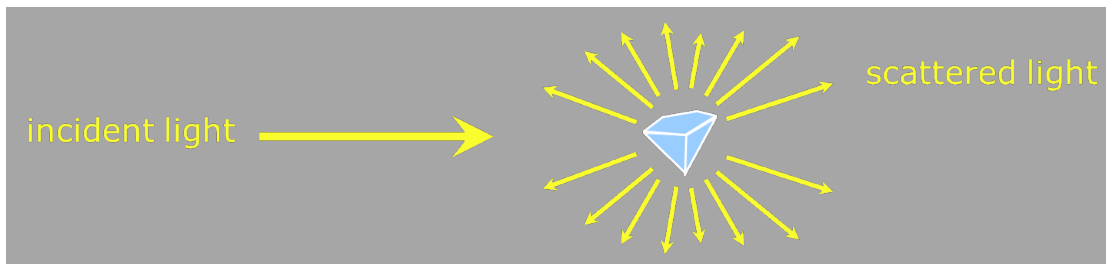
Degree of Linear Polarization (DoLP):

$$\text{DoLP} = \frac{I}{\sqrt{Q^2 + U^2}}$$



How to Best Measure Aerosol Properties with a satellite?

The angular and spectral dependence of intensity and degree of polarization depend on the particle on which it is scattered.



$$\begin{bmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{21} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & P_{43} & P_{44} \end{bmatrix} \begin{bmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{bmatrix}$$

Typical Polarization Features from Aerosol Scattering

- Fine mode aerosols (typical effective radius between 0.10-0.2 micron):
 - Strong polarization peak near 90-100° scattering angle → Rayleigh like scattering mixed with larger particles.
 - Peak shifts to larger scattering angles when particle size increases.
 - Absorption slightly reduces the peak
- Mineral Dust (Coarse non spherical particles, typically modeled as ellipsoids).
 - Weak polarization with broad maximum for scattering angle 100-120°.
- Sea salt (Hydrated spherical particles with refractive index close to water)
 - Rainbow-like features with strong polarization near 150°.
 - When sea salt becomes dryer (smaller particles, larger refractive index) weaker polarization with peak shifted toward larger scattering angles, and broader (negative) maximum between scattering angles 120-130°.

Polarimeters in Space

2005

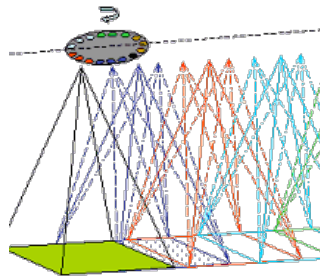
2013

2024

2025

2026

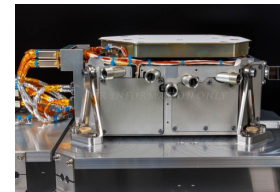
PARASOL



>10 year GAP!

PACE

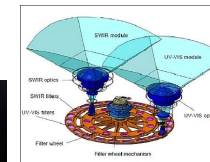
SPEXone – PACE



HARP2 – PACE

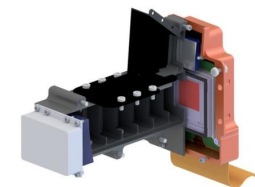


3MI



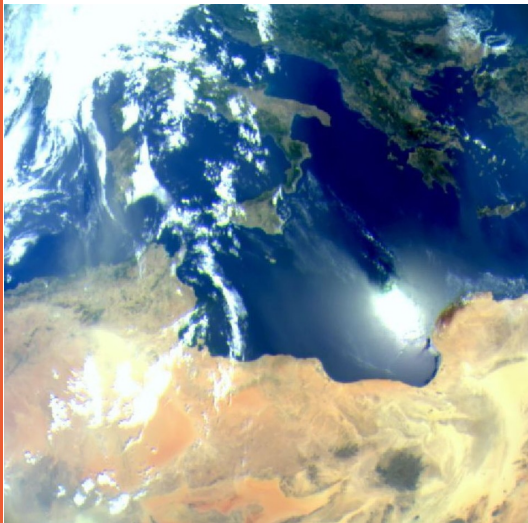
CO2M

MAP

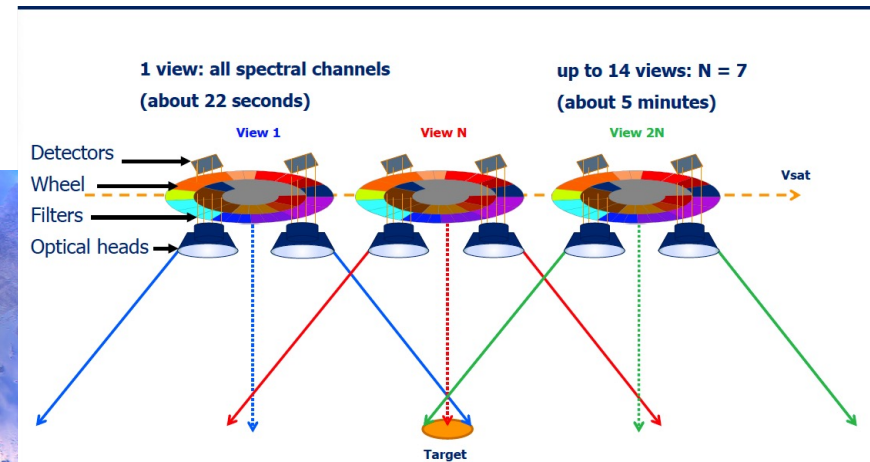
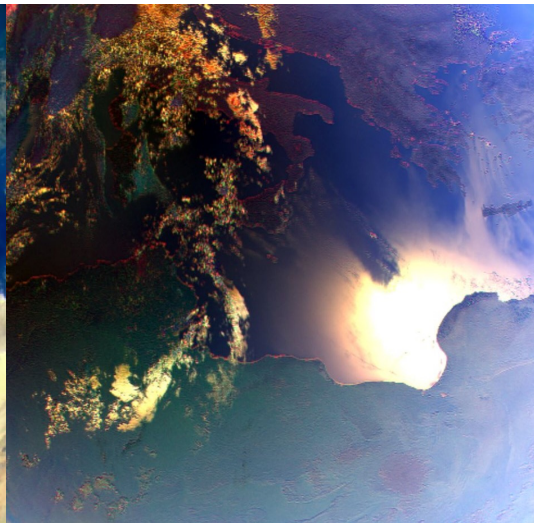


3MI: Launch August 2025

natural light



polarized light

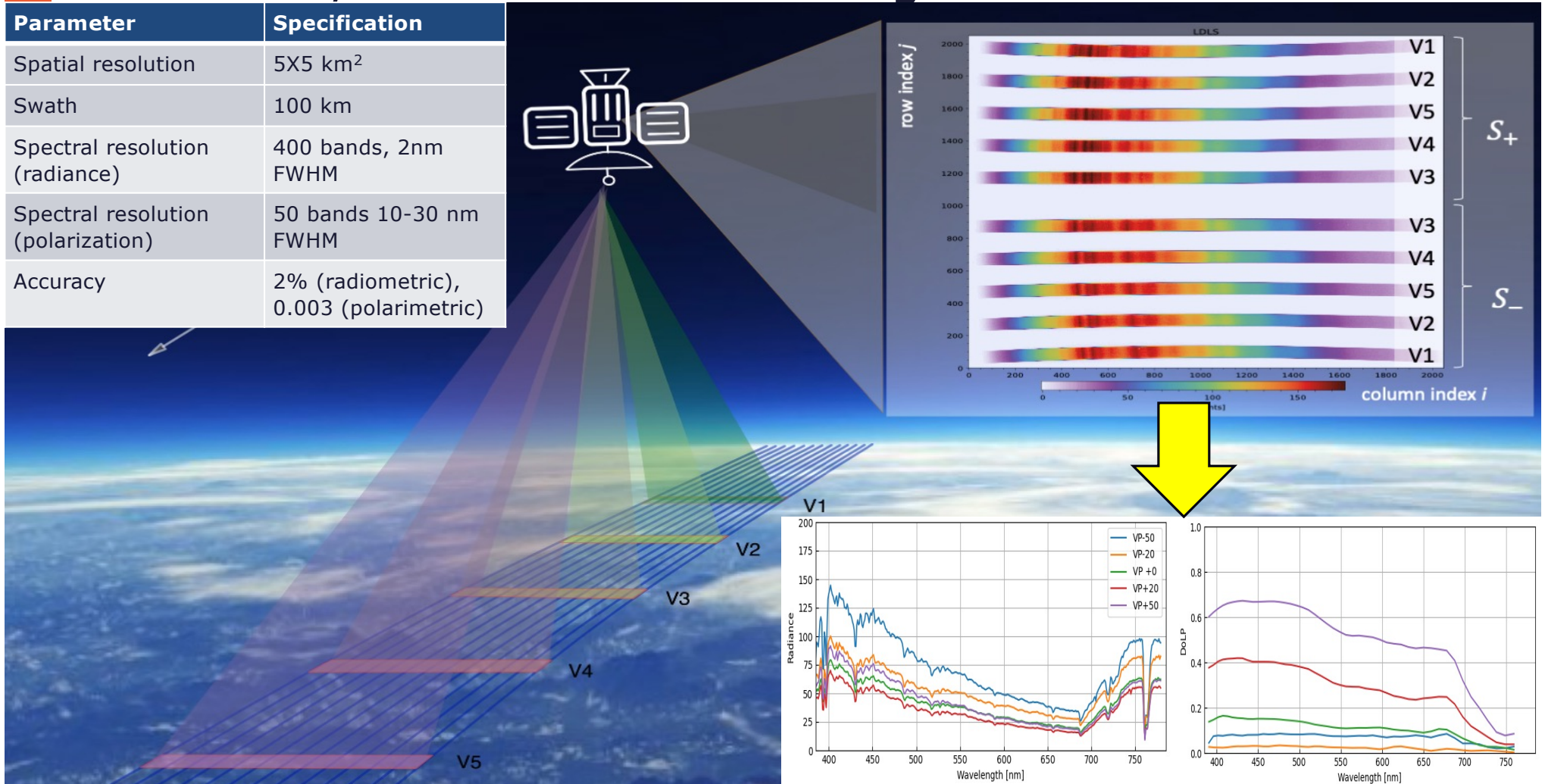


3MI	
Channel	Bandwidth (nm)
3MI-2b	400-420
3MI-3	433-453
3MI-4	480-500
3MI-5	545-565
3MI-6	660-680
3MI -7	758-768
3MI -8	745-785
3MI -9	845-885
3MI-9a	900-920
3MI -10	1350-1390
3MI -11	1630-1670
3MI -12	2110-2150



SPEXone/PACE: Launch February 2024

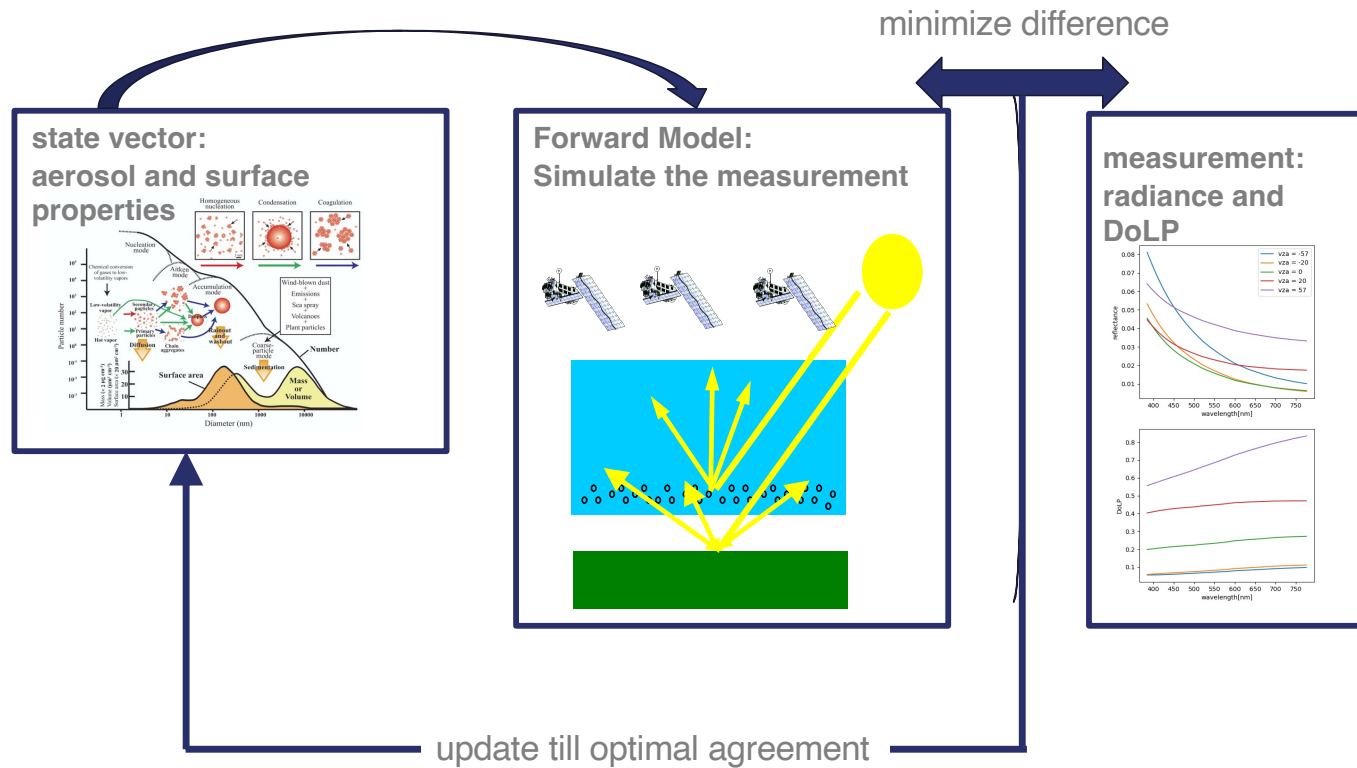
Parameter	Specification
Spatial resolution	5X5 km ²
Swath	100 km
Spectral resolution (radiance)	400 bands, 2nm FWHM
Spectral resolution (polarization)	50 bands 10-30 nm FWHM
Accuracy	2% (radiometric), 0.003 (polarimetric)





Deriving Aerosol Properties from Polarimetric Measurements

Overview of Retrieval Procedure



RemoTAP and GRASP

- ✓ **RemoTAP**  algorithm
(Hasekamp et al., 2011; 2019; Fu et al., AMT, 2018;2020;2025; Lu et al., Frontiers, 2022)
Remote Sensing of Trace Gas and Aerosol Products

- ✓  **GRASP** algorithm
(Dubovik et al., 2011, 2014, 2021; Chen et al., ESD, 2020)
Generalized Retrieval of Atmosphere and Surface Properties

Other algorithms (Applied to airborne data): Waquet et al. (2009), Xu et al. (2017), Stamnes et al. (2018), Zhai et al. (2018), Gao et al. (2019)

Forward Model

Optical properties:

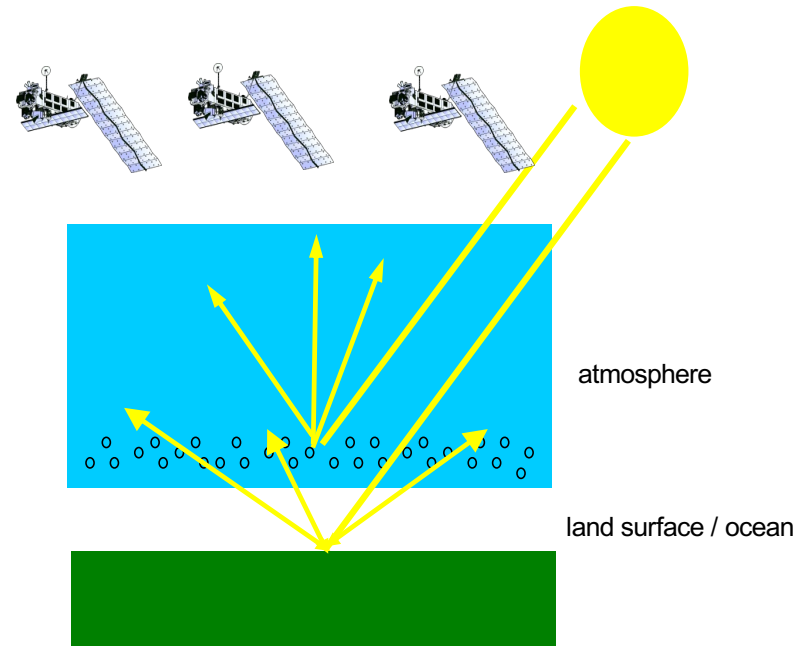
Mie/T-matrix /Geometrical Optics table from Dubovik et al. (2006) for mixture of spheroids and spheres.

Surface Reflection:

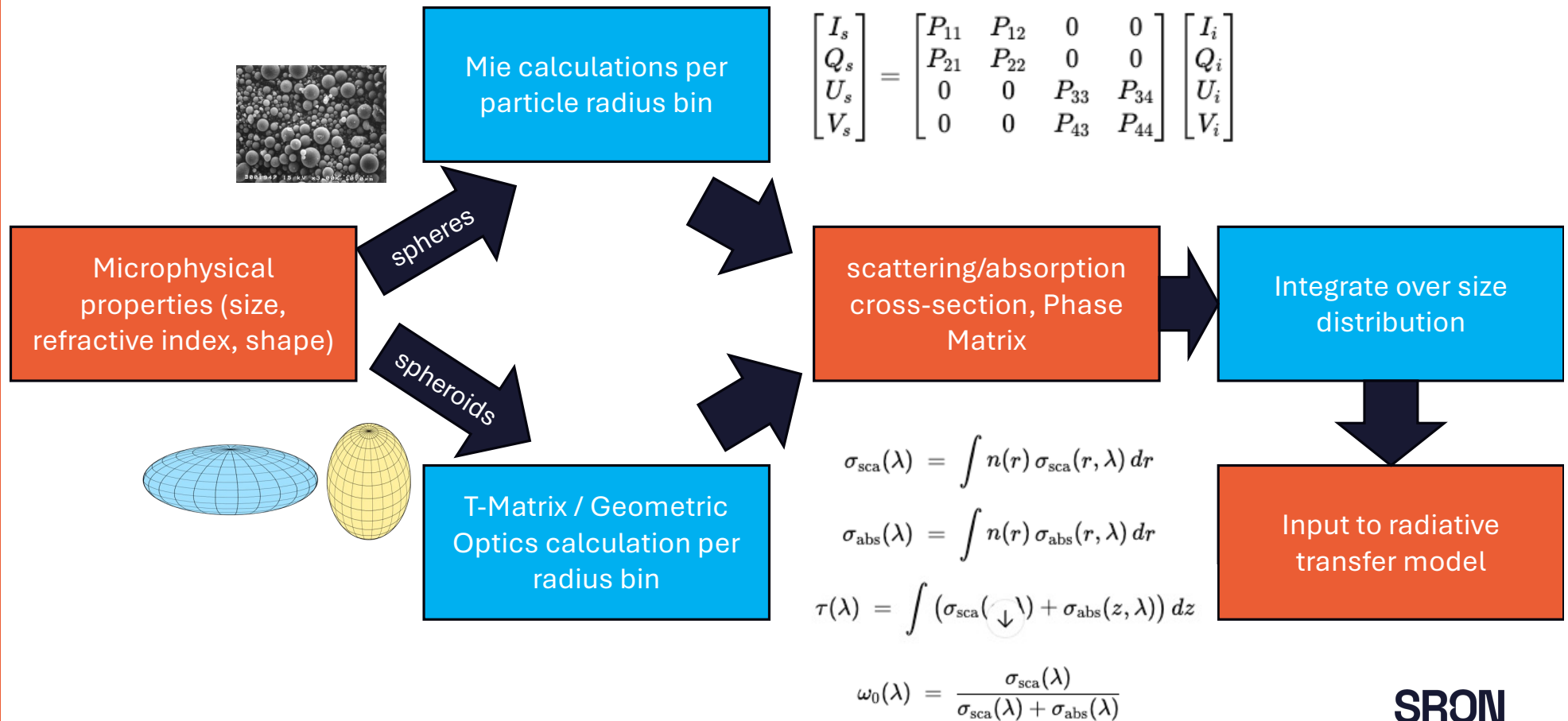
Take into account the multi-directional and polarization aspects of surface reflection. Over land, this is done using semi-empirical models. Over ocean, the model takes into account reflection by the rough ocean surface (depending on wind-speed) and transport of radiation in the ocean body.

Radiative Transfer:

Having the optical properties of atmosphere and surface, we can model the transport of radiation in the atmosphere to simulate the satellite measurement of radiance and polarization at the top-of-atmosphere.

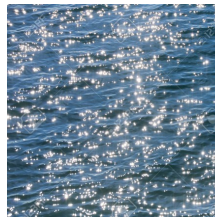


Forward Model: Aerosol Properties to Optical Properties



Forward Model: Ocean Reflection Matrix

$$\mathbf{R}_s(\lambda, \theta_{in}, \theta_{out}, \Delta\varphi) = \mathbf{R}_{frn}(\theta_{in}, \theta_{out}, \Delta\varphi) + \mathbf{R}_{ul}(\lambda, \theta_{in}, \theta_{out}, \Delta\varphi) + A(\lambda) \mathbf{D}$$



$\mathbf{R}_{frn}$: Fresnel reflection matrix on a rough ocean surface. Cox-Munk model, wind speed as free parameter (optional in 2 directions).

$\mathbf{R}_{ul}$: Ocean body contribution. Bio-optical model of Chowdhary et al. for case 1 waters. Chl_a concentration as free parameter. RT insider ocean body replaced by NN (Fan et al., 2019).

$A(\lambda)$: Lambertian albedo term (separately fitted for each wavelength) to account for foam and to compensate for errors in $\mathbf{R}_{ul}$.

State vector elements:

- wind speed
- Chl_a concentration
- $A(\lambda)$ for each wavelength separately

Forward Model: Land Reflection Matrix

$$\mathbf{R}_s(\lambda, \theta_{\text{in}}, \theta_{\text{out}}, \Delta\varphi) = \boxed{r_{11}(\lambda, \theta_{\text{in}}, \theta_{\text{out}}, \Delta\varphi) \mathbf{D}} + \boxed{\mathbf{R}_{\text{pol}}}$$

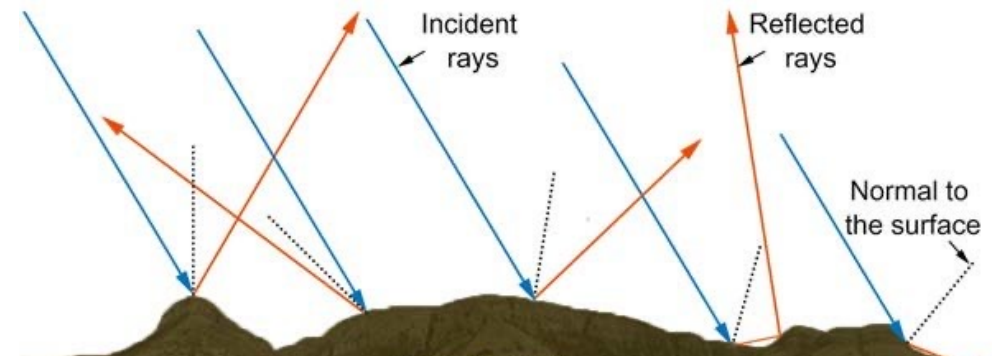
total reflectance
polarized reflectance

$$r_{11}(\lambda, \theta_{\text{in}}, \theta_{\text{out}}, \Delta\varphi) = A(\lambda) (1 + k_{\text{geo}} f_{\text{geo}}(\theta_{\text{in}}, \theta_{\text{out}}, \Delta\varphi) + k_{\text{vol}} f_{\text{vol}}(\theta_{\text{in}}, \theta_{\text{out}}, \Delta\varphi))$$

$$\mathbf{R}_{\text{pol}}(\theta_{\text{in}}, \theta_{\text{out}}, \phi_v - \phi_0) = B_{\text{pol}} \left(\frac{\exp(-\tan(\frac{\pi - \Theta}{2})) \exp(-v) F_p(m, \Theta)}{4(\mu_{\text{in}} + \mu_{\text{out}})} \right)$$

State vector elements:

- $A(\lambda)$ for each wavelength separately
- k_{geo}
- k_{vol}
- B_{pol}



Atmospheric Radiative Transfer

The last step of the forward model is to solve the Radiative Transfer Equation (RTE):

$$\mu \frac{d\mathbf{I}(\tau, \mu)}{d\tau} = -\mathbf{I}(\tau, \mu) + \omega_0(\tau) \int_{-1}^1 \mathbf{P}(\mu, \mu') \mathbf{I}(\tau, \mu') d\mu'$$

$$\mu_i \frac{d\mathbf{I}_i(\tau)}{d\tau} = -\mathbf{I}_i(\tau) + \omega_0(\tau) \sum_{j=1}^N w_j \mathbf{P}(\mu_i, \mu_j) \mathbf{I}_j(\tau), \quad i = 1, \dots, N$$

For this purpose, RemoTAP uses the LINTRAN RT model (Schepers et al., 2014, Hasekamp et al., 2005, Landgraf et al., 2001; Hasekamp and Butz, 2008), based on the Gauss-Seidel method. GRASP uses Successive Order of Scattering (SOS) RT method (J. Lenoble, M. Herman et al., 2007)

Inversion Procedure

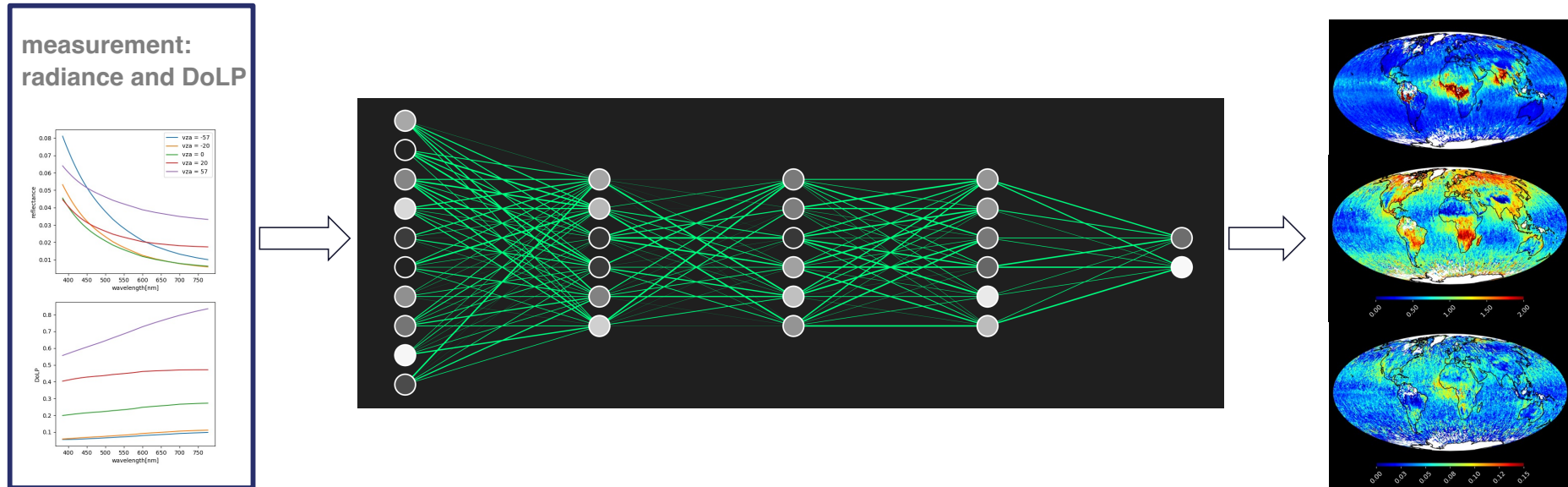
$$\mathbf{y} = \mathbf{F}(\mathbf{x}, \mathbf{b}) + \mathbf{e}_y$$

$$\mathbf{F}(\mathbf{x}) \approx \mathbf{F}(\mathbf{x}_n) + \mathbf{K} [\mathbf{x} - \mathbf{x}_n] \quad K_{ij} = \frac{\partial F_i}{\partial x_j}(\mathbf{x}_n)$$

$$\mathbf{x}_{n+1} = \min_{\mathbf{x}} \left([\mathbf{K} \mathbf{x} - \mathbf{y}]^T \mathbf{S}_y^{-1} [\mathbf{K} \mathbf{x} - \mathbf{y}] \right) + \left([\mathbf{x} - \mathbf{x}_a]^T \gamma^2 \mathbf{H}^{-1} [\mathbf{x} - \mathbf{x}_a] \right)$$

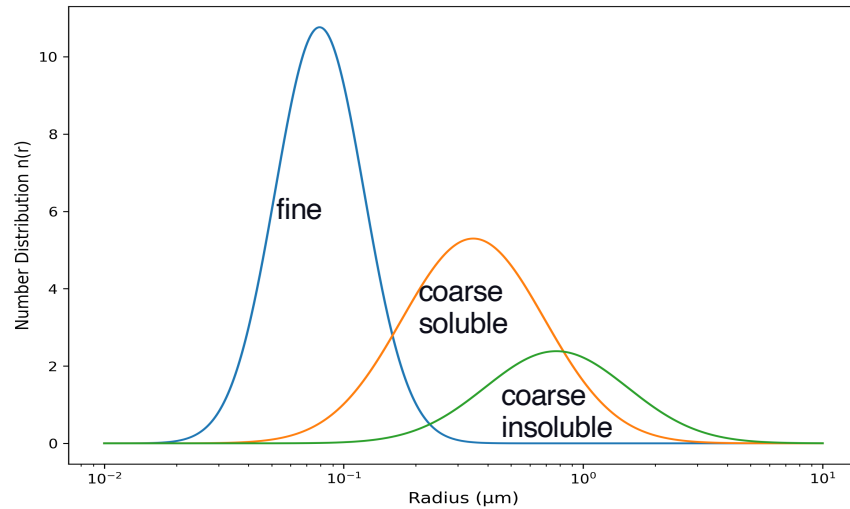
- $\mathbf{F}$: Forward model, $\mathbf{K}$ is Jacobian.
- $\mathbf{y}$: measurement vector with covariance matrix $\mathbf{S}_y$.
- $\mathbf{x}$: State vector with prior $\mathbf{x}_a$.
- $\mathbf{H}$: Regularization matrix (puts all elements of $\mathbf{x}$ in the same range and gives more freedom to some elements compared to others (similar to prior covariance in Optimal Estimation)).
- γ : regularization parameter

Alternative Approach: Make use on Neural Networks (NNs)

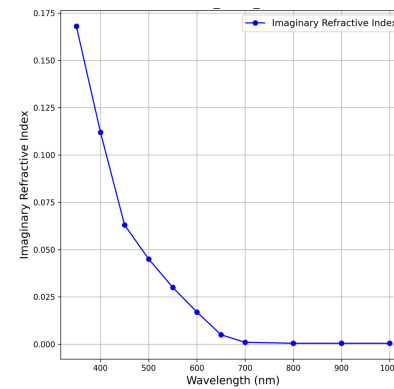


- Create millions of training samples: Simulated measurements of radiance and polarization for varying aerosol and surface properties, for actual satellite geometries.
- Train an NN: Input simulated measurements and corresponding geometry; Output aerosol and surface properties.
- Apply the NN by giving real measurements and geometry as input.
- Advantage: much faster and more flexible (potentially more accurate)
- Disadvantage: strongly dependent on the training set and more difficult to diagnose (once trained, it is used as black box)

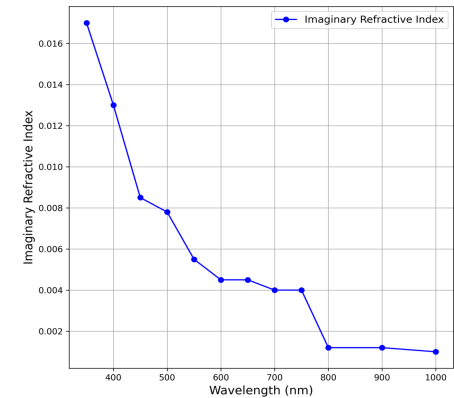
Retrieved Aerosol Parameters



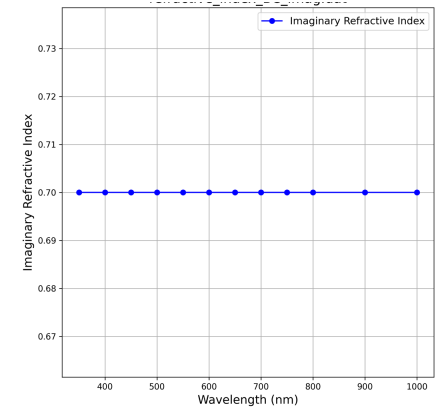
Brown Carbon



Dust



Black Carbon



	r_{eff}	v_{eff}	rri	iri	N	f_{sph}	ALH
fine mode	✓	✓	✓	✓	✓	✓	✓
coarse insoluble mode (dust)	✓	X	X	✓	✓	✓	✓
Coarse soluble mode	✓	X	✓	X	✓	X	✓
Surface	Land: BRDF Ross-Li, snow parameters, Maignan BPDF. ocean: Chlorophyll-a, wind-speed, + Lambertian correction term						
Optical Properties	AOT, SSA, phase function, Angstrom Exponent						

IRI is constructed from aerosol components Brown Carbon (BrC), Black Carbon (BC), and Dust.

Deriving Chemical Composition

- Coarse non-spherical mode → Mineral Dust
- Coarse spherical mode → Hydrated Sea Salt
- Fine mode consists of sulfates and nitrates (non-absorbing), black carbon, brown carbon, dust, and water:
 - $m(\lambda) = f_{dust}m_{dust}(\lambda) + f_{nonabs}m_{nonabs}(\lambda) + f_{bc}m_{bc}(\lambda) + f_{brc}m_{brc}(\lambda) + f_{h2o}m_{h2o}(\lambda)$
 - Volume fractions of BC, BrC, and Dust can be derived from spectral dependence of imaginary refractive index: $m_i(\lambda) = f_{dust}m_{dust}(\lambda) + f_{bc}m_{bc}(\lambda) + f_{oc}m_{oc}(\lambda)$
 - Then fraction of non-absorbing aerosol (sulfates, nitrates) and water can be derived from real part.
- The total volume of each mode can be computed from the retrieved size distribution. With the fractions above, we can retrieve total volume for each component (and the volume fraction)

Aerosol Polarimetry: Expectations and Challenges

Expectations from multi-angle polarimetry:

- ✓ Improved accuracy on existing products (AOD)
- ✓ More information → new products such as size, absorption, composition/type, shape.
- ✓ Simultaneous retrieval of aerosol – surface – ocean – cloud properties

But very challenging to exploit this large information content at a global scale.

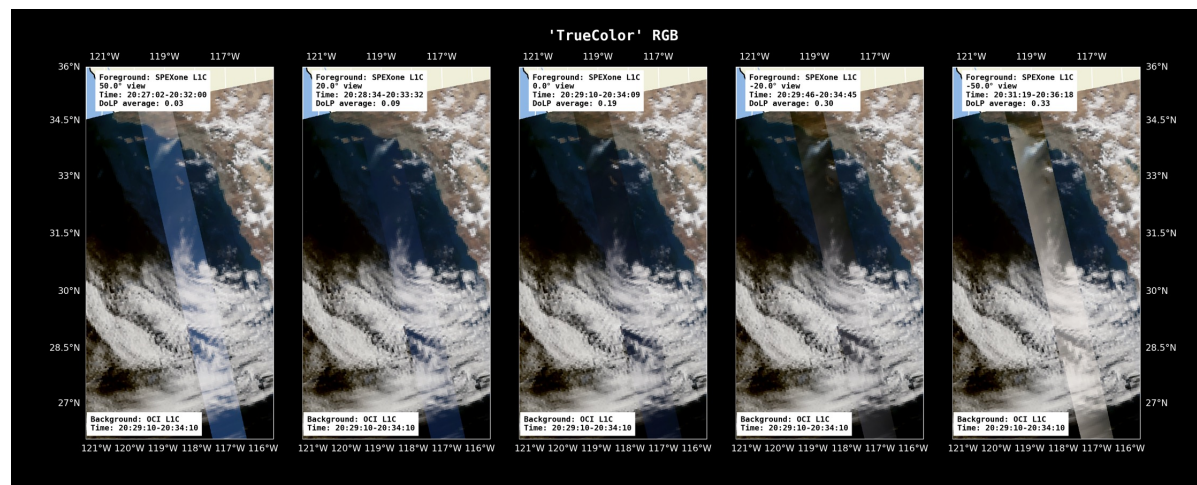
- ✓ Complex algorithms needed with many fit parameters (aerosol+surface/ocean).
- ✓ Accurate/detailed forward model with online RT calculations.
- ✓ Challenging instrumentation (multi-angle registrations, radiometric/polarimetric uncertainties)



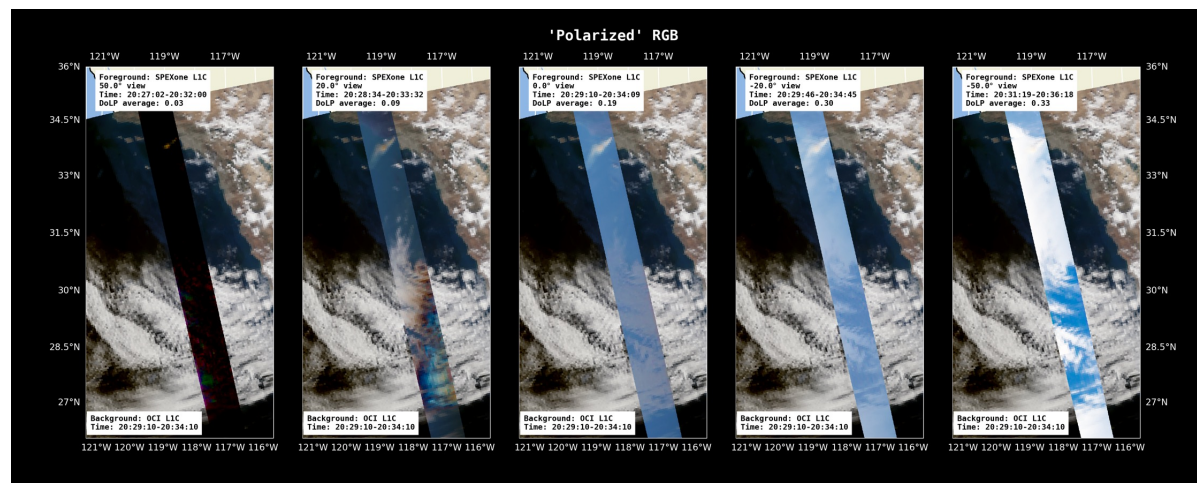
Examples from SPEXone/PACE

LA Fires: January 7th 2025

Radiance

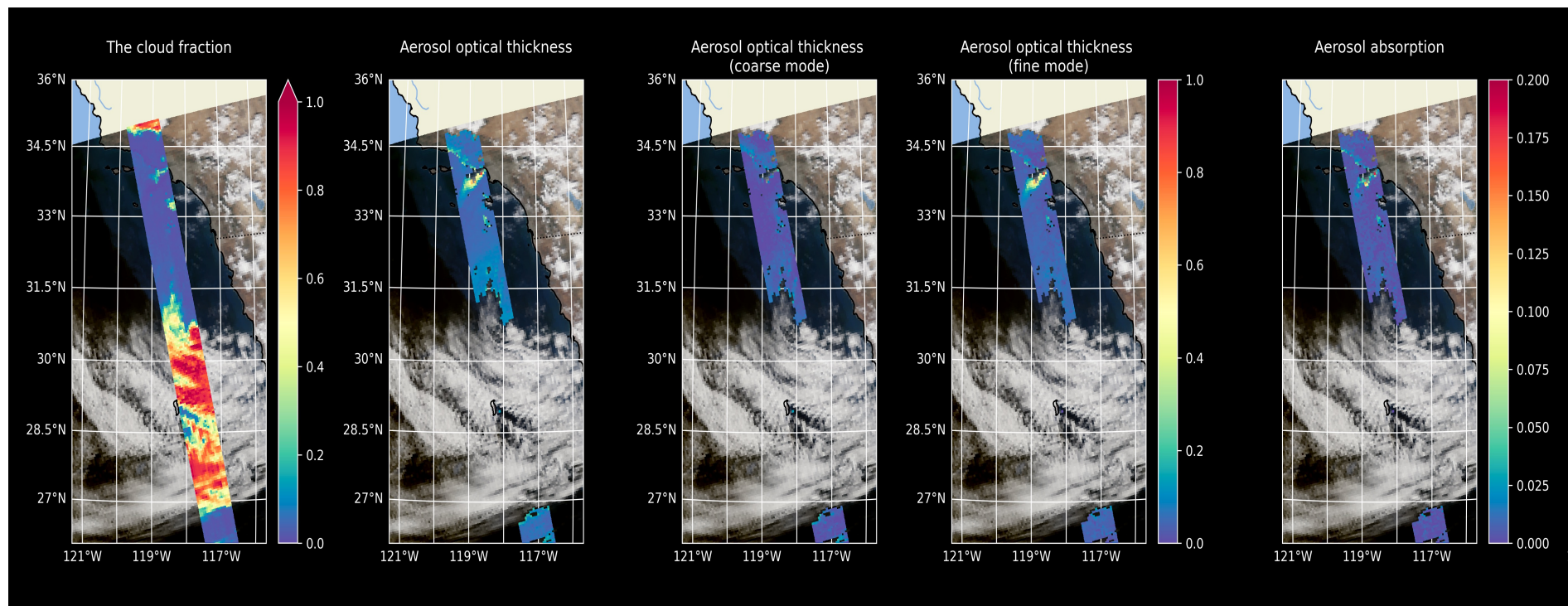


Polarized Radiance



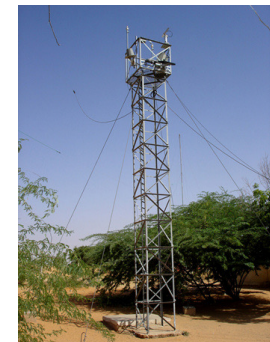
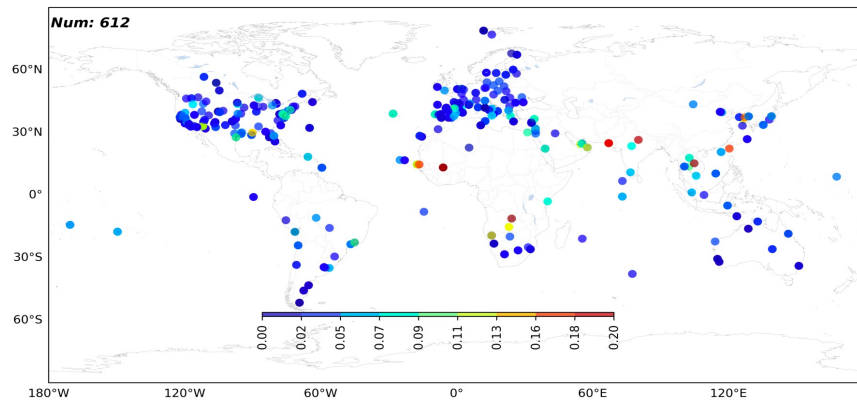
SRON

LA Fires: January 7th 2025



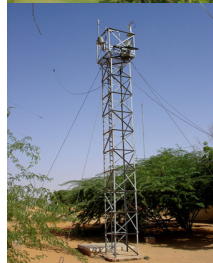
Validation of Aerosol Properties

AERONET Network



What can we validate with AERONET:

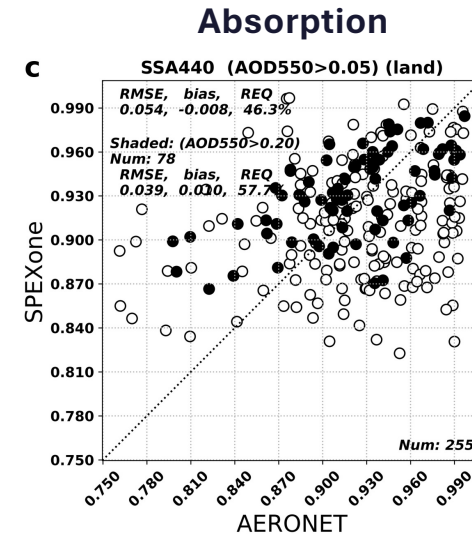
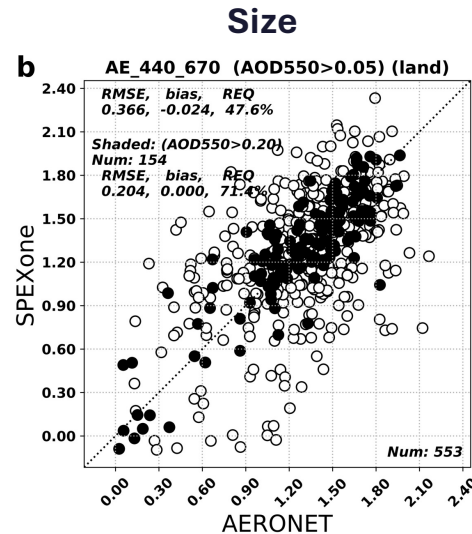
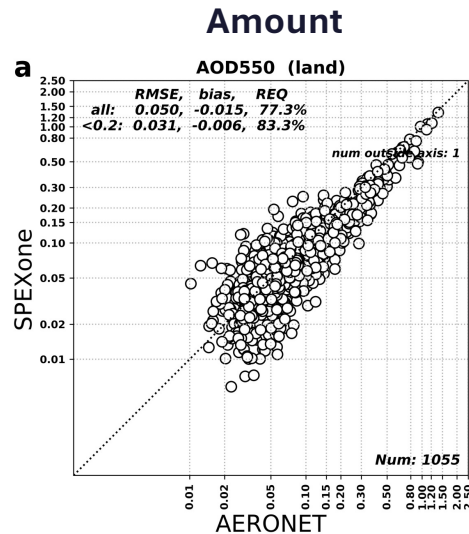
- Aerosol Optical Depth (AOD)
- Angstrom Exponent: $AE = \frac{\log(\frac{AOD_{\lambda 1}}{AOD_{\lambda 2}})}{\log(\frac{\lambda 1}{\lambda 2})}$. Wavelength
- dependence of AOD: High AE $\rightarrow$ small particles; low AE $\rightarrow$ large particles
- Single Scattering Albedo (SSA): Measure for absorption (high SSA $\rightarrow$ low absorption)
- Effective radius
- For AOD and AE, AERONET provides a very accurate reference. For SSA and effective radius, AERONET relies on many assumptions and is not necessarily more accurate than polarimetric satellite products.



SRON

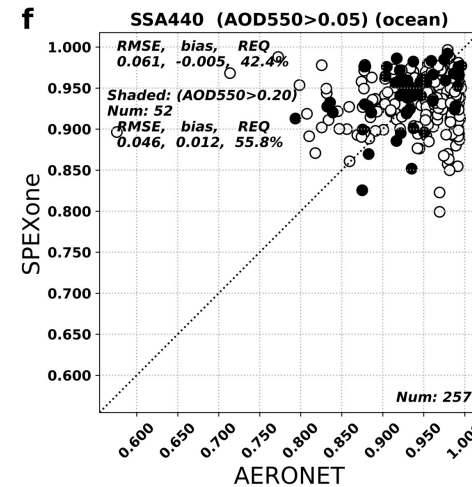
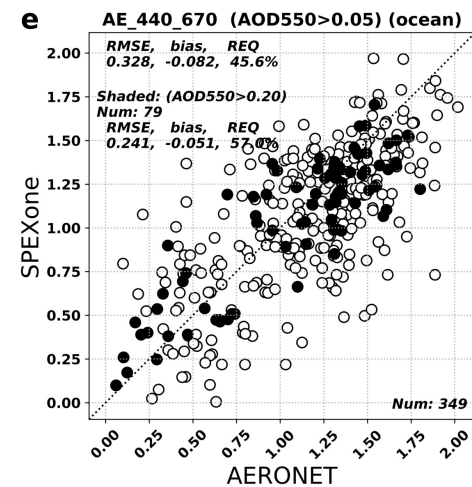
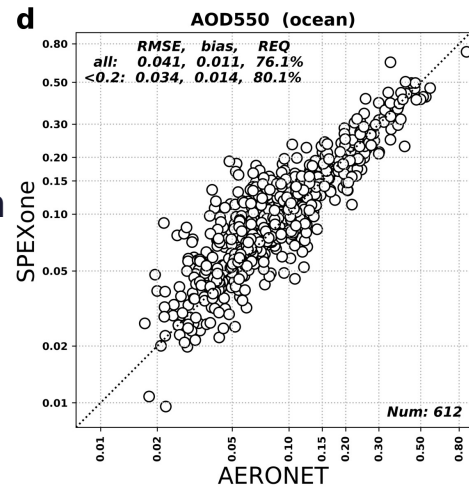
Validation of SPEXone with AERONET (One Year)

Land



- Unprecedented agreement with AERONET reference.
- Very similar performance over both land and ocean

Ocean



SRON

Performance towards low AOD

Land

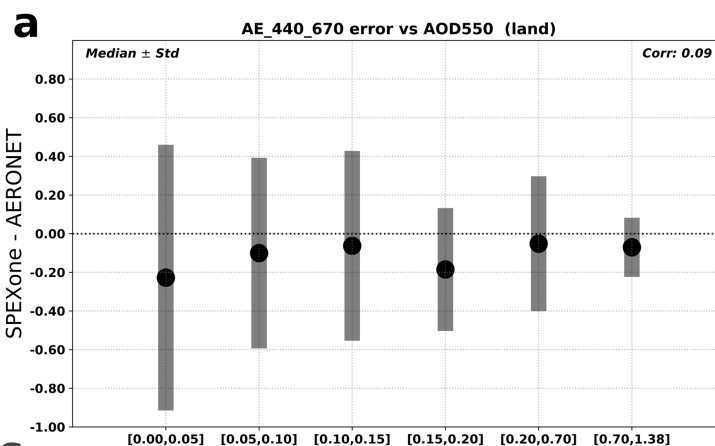


Mostly increase in spread but not in bias (low correlation of error with AOD)

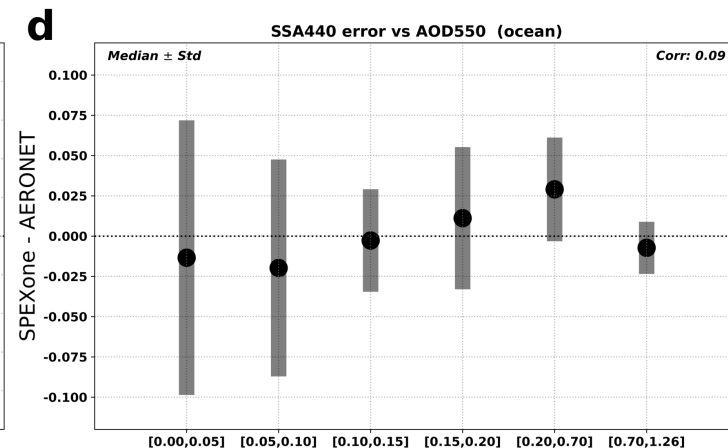
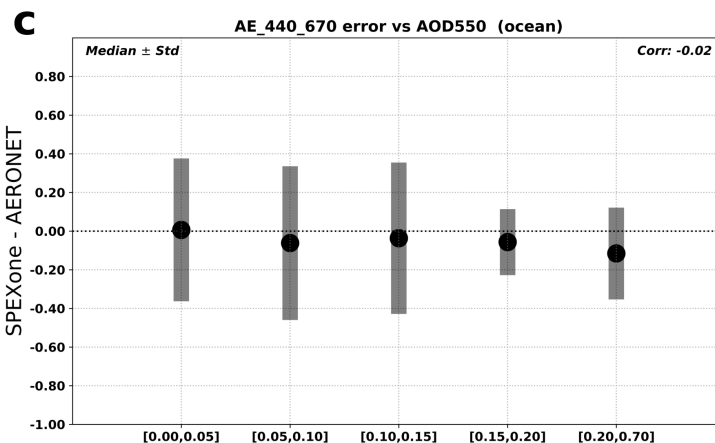
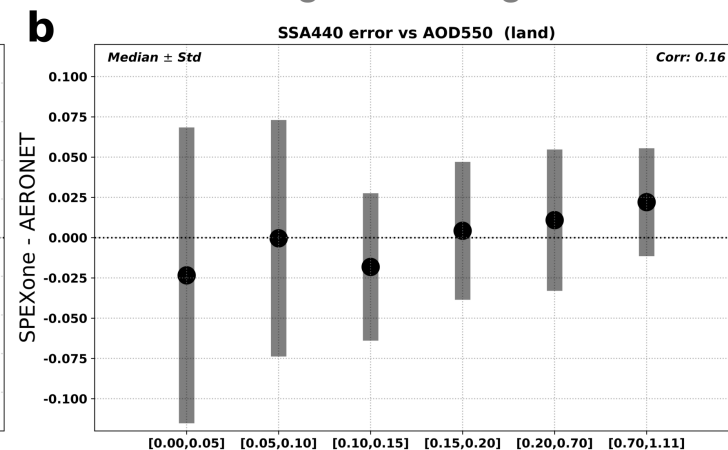
Ocean



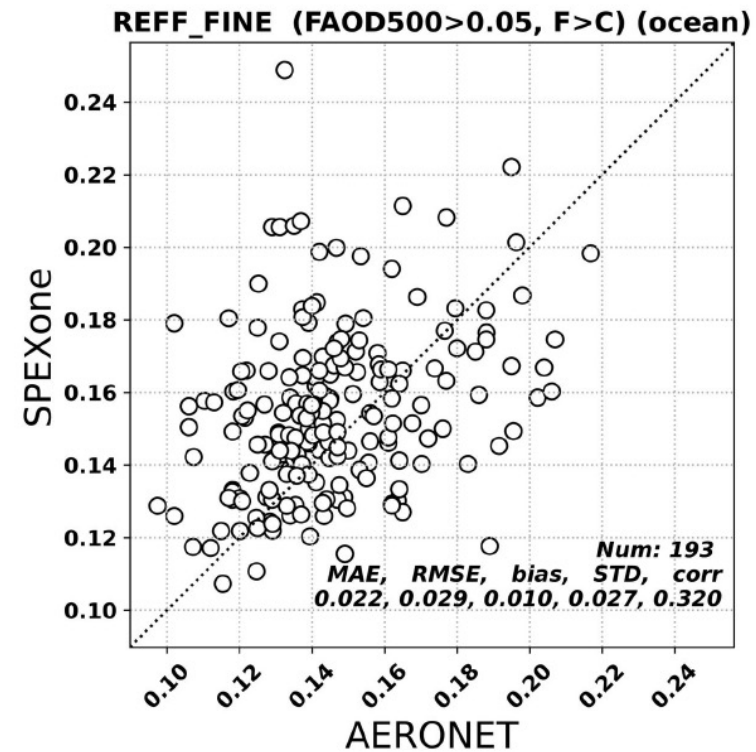
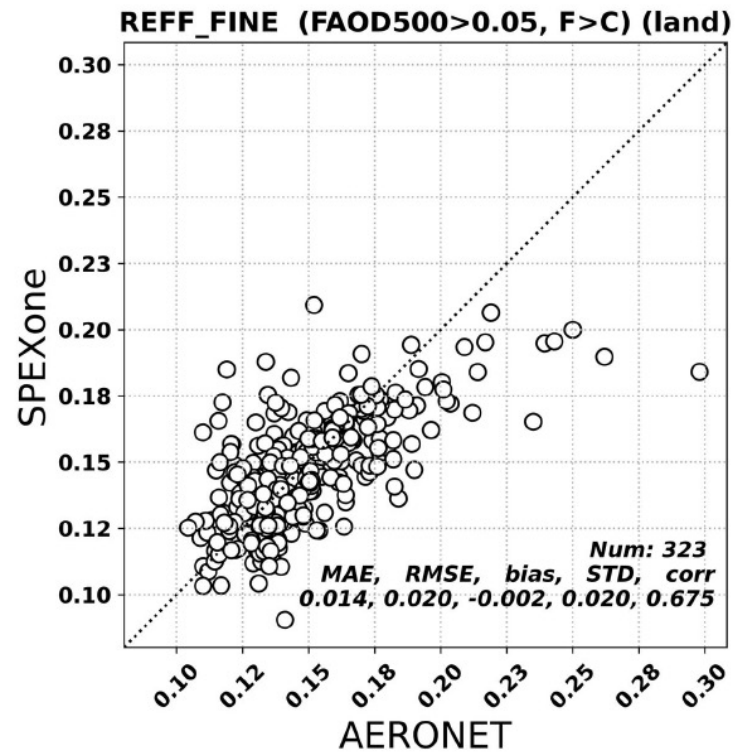
Angstrom Exponent



Single Scattering Albedo

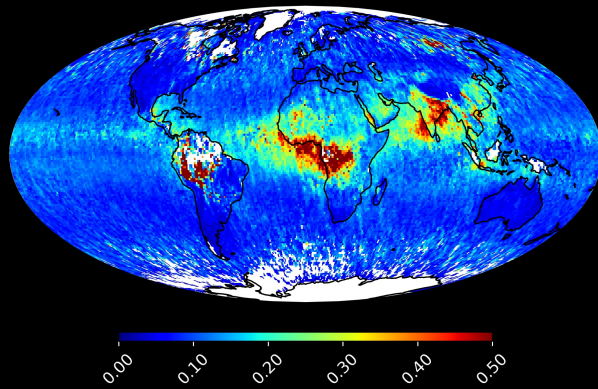


Validation of fine mode effective radius

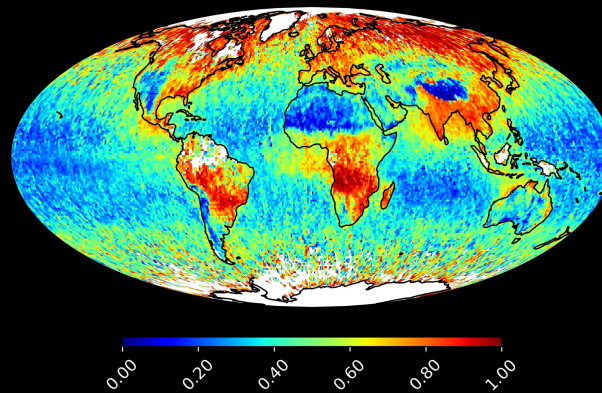


First Year of SPeXone Data: AOD, size & absorption

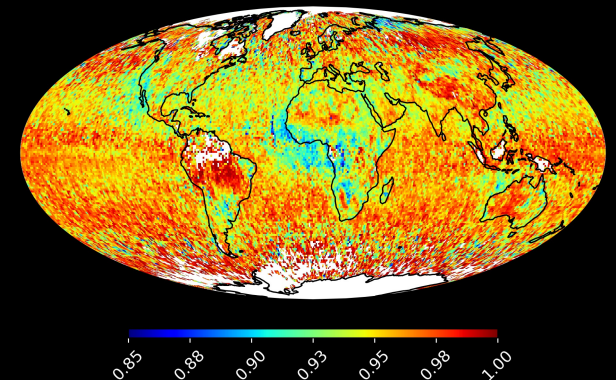
Amount



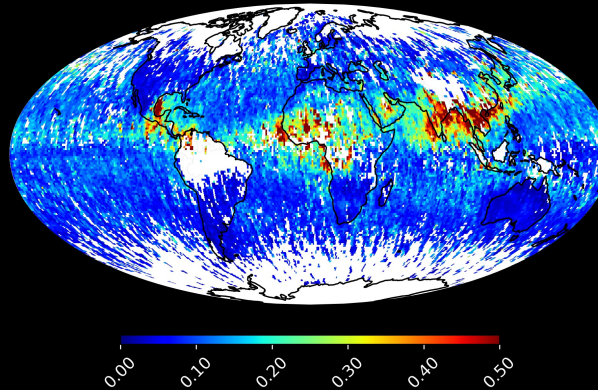
Size



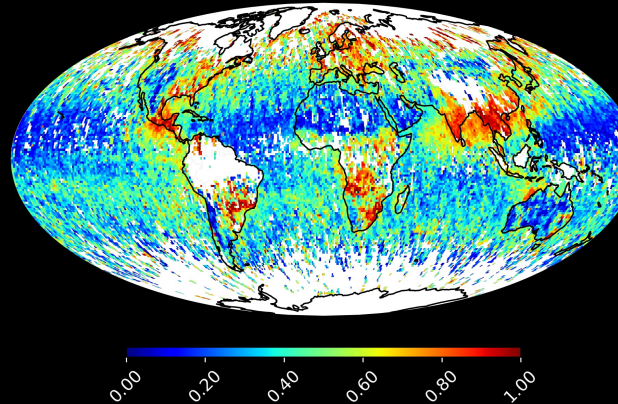
Absorption



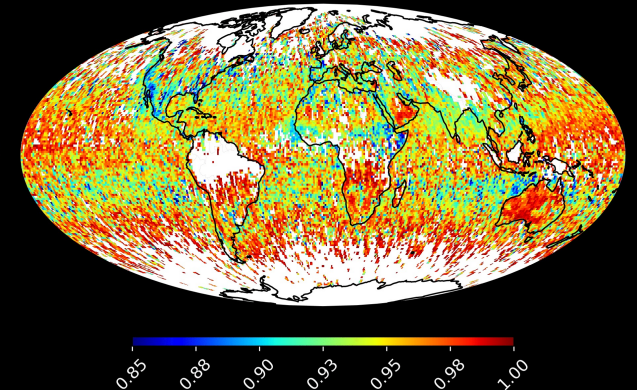
aot_spring



fmf_spring



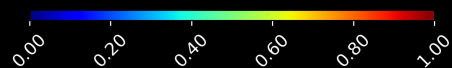
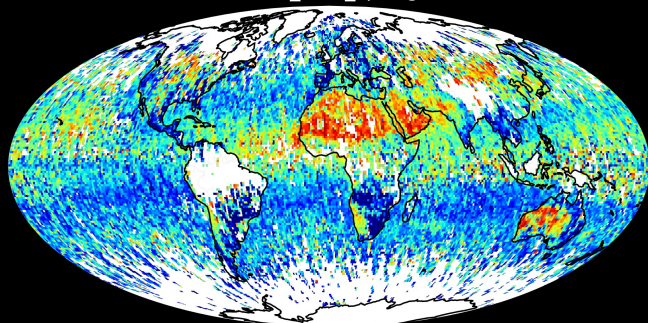
ssa_spring



Chemical Composition

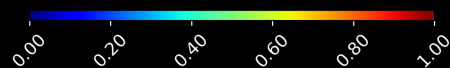
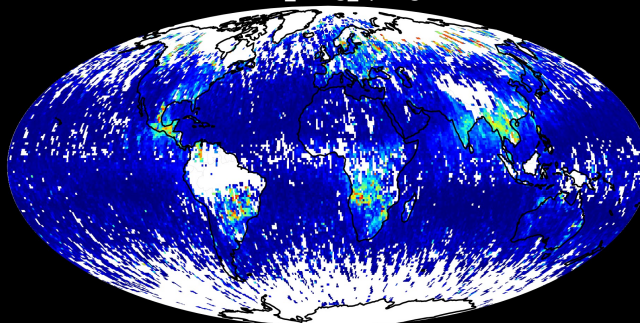
Dust

vfrac_dust_spring



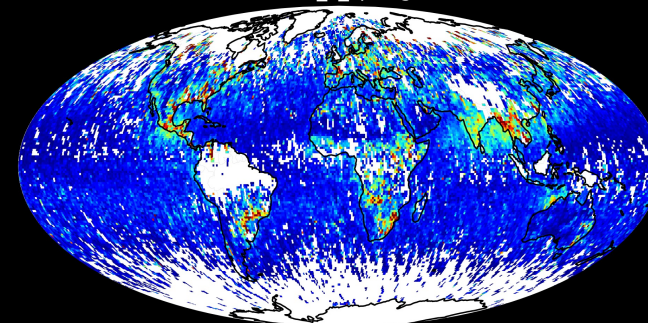
Fine mode non-absorbing

vfrac_inorg_spring



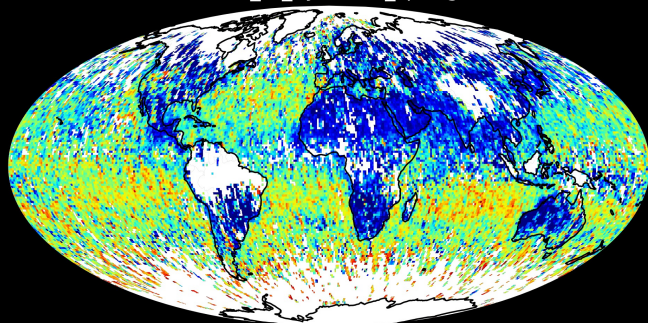
BC+BrC

vfrac_c_spring



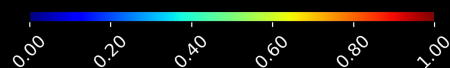
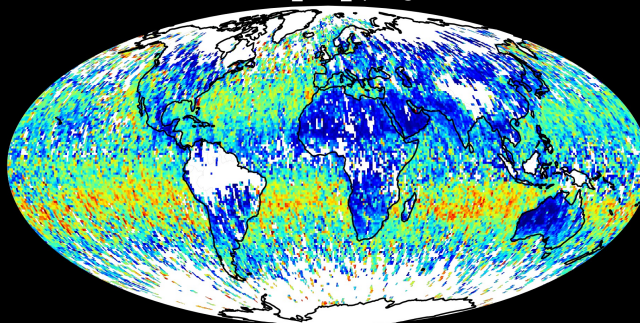
Sea Salt (hydrated)

vfrac_ss_hydrated_spring



Aerosol Water

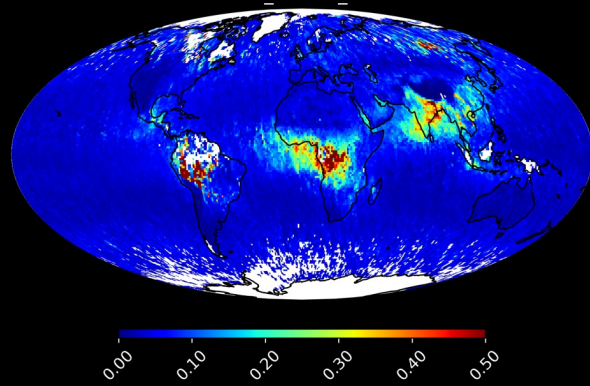
vfrac_h2o_spring



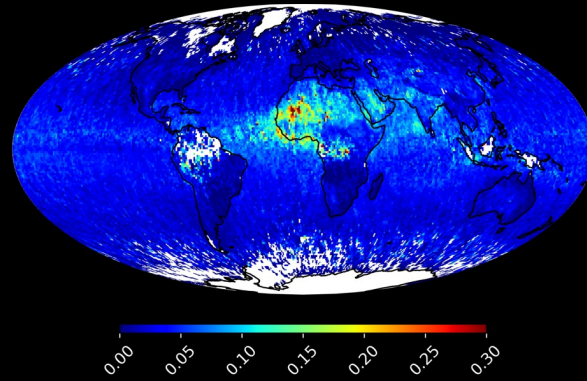
- Dust dominated close to desert (Sahara, Namibia, Australia) and outflow
- Fine mode 'nob-absorbing' (IA+OA) over industrial regions and BB
- Sea salt over the ocean
- Most of the sea salt contains a lot of water. Small water fraction over most of land
- BC+BrC over dominates Africa

AOD Per Mode

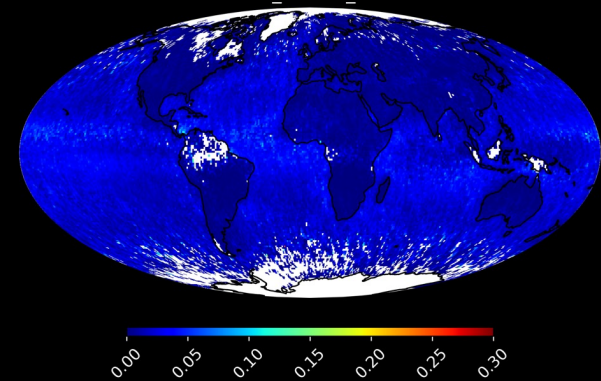
Fine Mode



Dust Mode

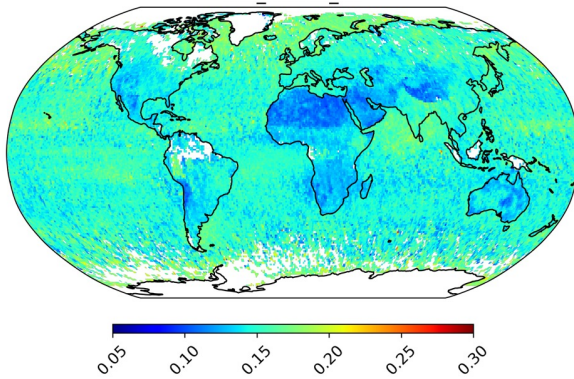


Sea Salt Mode

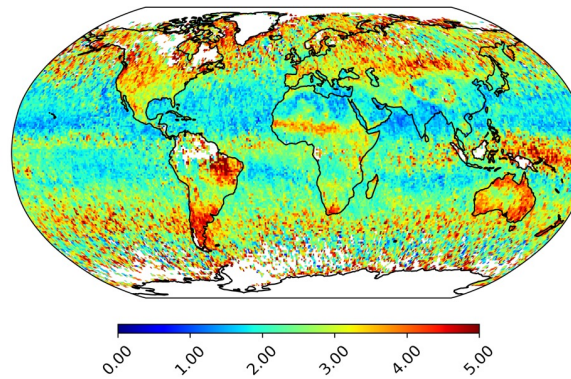


Effective Radius, Refractive Index, and Aerosol Layer Height

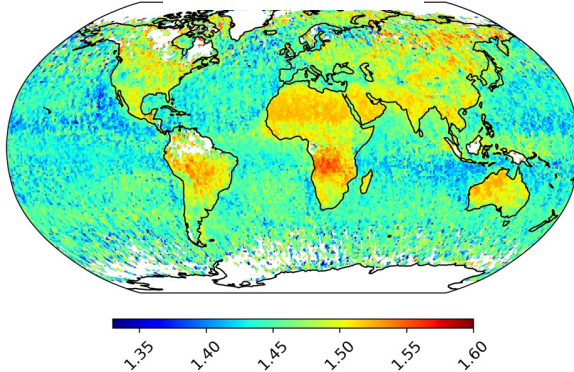
Fine Mode Effective Radius (micron)



Aerosol Layer Height (km)

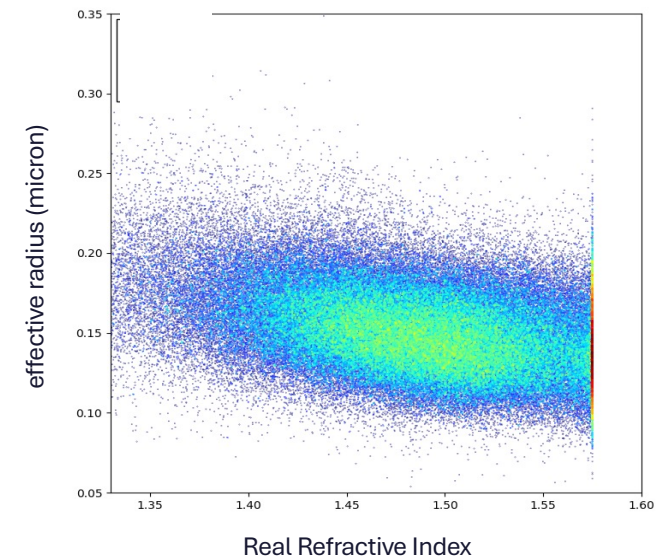


Real Refractive Index



- The relation between Reff and RRI can be explained by water uptake: for humidified aerosol, particles are large and the RRI close to that of water (~ 1.33)
- Aerosol Layer Height (ALH) is an effective value for the 3 modes together. Note that at small AOD retrieval of ALH becomes very challenging.

Reff vs RRI (global)

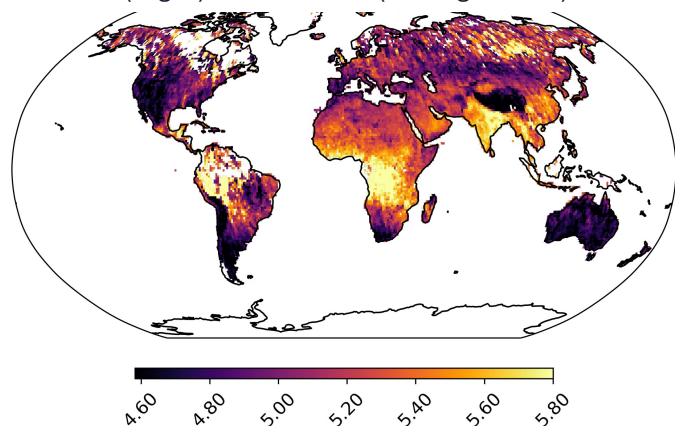


Can we derive PM2.5 from polarimetric aerosol data?

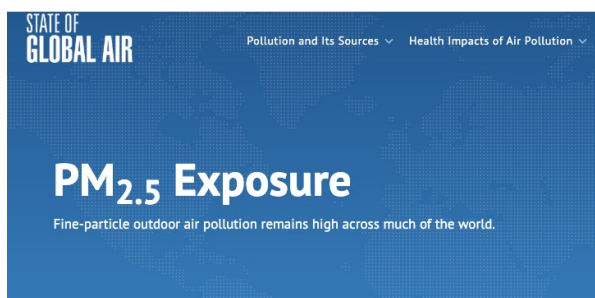
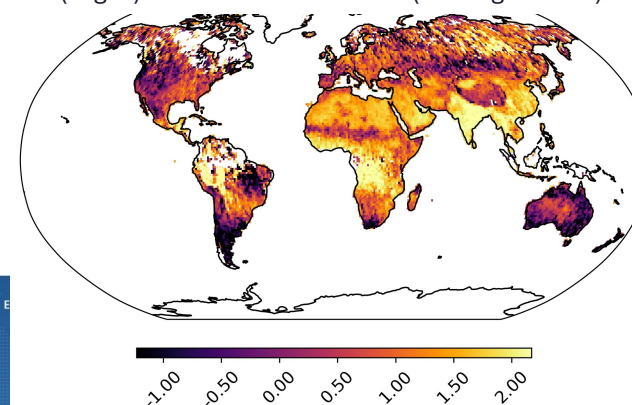
- PM2.5 (Particulate Matter < 2.5) are aerosols with a dry diameter < 2.5 micron. For AQ purpose, PM2.5 mass concentration close to the surface is relevant.
- Polarimeters can provide aerosol size distribution (wet), volume of water, and volume of dry components.
- This information can be used to derive the dry size distribution and (dry) volume of particles with diameter < 2.5 micron. Using the specific density of different aerosol components, we can translate volume into mass.
- This gives the PM2.5 total column. Based on the aerosol layer height, we can translate this into surface concentration.
- Caveats: Uncertainty in ALH will have large impact; Optical measurements are insensitive to very fine particles (< ~0.05 micron); retrieval of chemical composition makes many assumptions, which translate into uncertainty in PM2.5.

Preliminary maps of PM_{2.5} from space (SPeXone)

(Log of) PM_{2.5} Column (micro-gram /m²)



(Log of) PM_{2.5} BL concentration (micro-gram /m³)



Typical ranges PM_{2.5} surface concentration:

•Clean background / remote regions:

~1–5 $\mu\text{g}/\text{m}^3$

•Rural / suburban areas:

~5–15 $\mu\text{g}/\text{m}^3$

•Urban background in developed countries:

~10–30 $\mu\text{g}/\text{m}^3$

•Highly polluted urban/industrial regions:

50–200+ $\mu\text{g}/\text{m}^3$

•Extreme episodes (wildfires, dust storms):

can exceed 500 $\mu\text{g}/\text{m}^3$ locally.

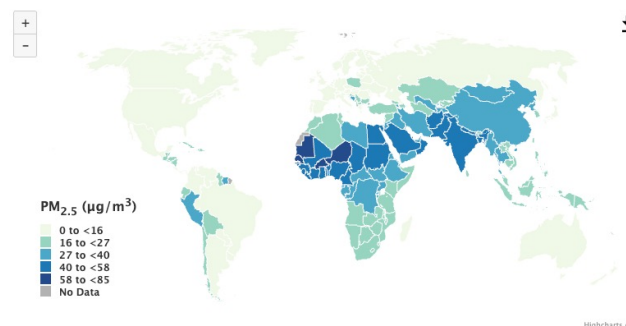


Figure B. Population-weighted annual average PM_{2.5} concentrations in 2019. Hover or tap to explore the data.

SRON

Key Take-aways

- The angular and spectral, and polarization characteristics of scattered light depends on aerosol size, shape, composition (refractive index).
- That is why Multi-Angle Polarimeters can provide detailed information on aerosol properties.
- To extract this information, a retrieval algorithm is needed that matches a forward model (modeling optical properties, surface reflection, and transport of radiation through the atmosphere) to the satellite observations.
- SPEXone on PACE (launched Feb 2024) provides aerosol information with unprecedented accuracy. 3MI (launch Aug 2025) is now in commissioning phase and data will become available in 2026.
- Using retrieved size, composition, and aerosol layer height, boundary layer PM_{2.5} can be approximated. This is still a very preliminary product and extensive validation and (probably) algorithmic improvements are needed.