Polarimetric Remote Sensing of Aerosols, Clouds, and Ocean Color

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PACE Workshop, Sponsor: OSB

Stokes Parameters

The electric field can be resolved into two components as follows:

$$\mathbf{E} = E_{\|}\hat{\mathbf{e}}_{\|} + E_{\perp}\hat{\mathbf{e}}_{\perp}$$

Where $E_{\|}$ and $E_{\perp}$ are components parallel and perpendicular to **a reference plane**, respectively.

The four component Stokes vector can now be defined as:

$$I = E_{\|}E_{\|}^{*} + E_{\perp}E_{\perp}^{*} = I_{\|} + I_{\perp}$$

What human eyes can see.

$$Q = E_{\|}E_{\|}^{*} - E_{\perp}E_{\perp}^{*} = I_{\|} - I_{\perp}$$

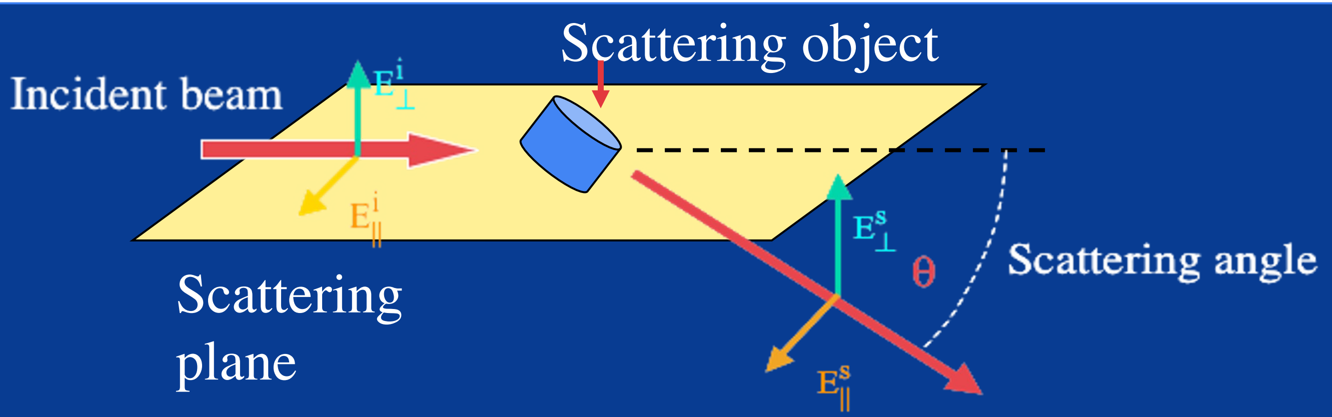
$$U = E_{\|}E_{\perp}^{*} + E_{\perp}E_{\|}^{*}$$

Linear polarization.

$$V = i\,(E_{\|}E_{\perp}^{*} - E_{\perp}E_{\|}^{*})$$

Circular polarization.

Light Scattering Geometry



Amplitude scattering matrix

$$\begin{pmatrix} E^s_\parallel \\ E^s_\perp \end{pmatrix} = \frac{e^{ikr}}{-ikr} \begin{pmatrix} S_2 & S_3 \\ S_4 & S_1 \end{pmatrix} \begin{pmatrix} E^i_\parallel \\ E^i_\perp \end{pmatrix}$$

Light Scattering: Mueller Matrix

$$\begin{pmatrix} I^s \\ Q^s \\ U^s \\ V^s \end{pmatrix} = \frac{1}{k^2 r^2} \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{pmatrix} I^i \\ Q^i \\ U^i \\ V^i \end{pmatrix}$$

$$M_{11} = \frac{1}{2}\left(|S_1|^2 + |S_2|^2 + |S_3|^2 + |S_4|^2\right)$$

$$M_{12} = \frac{1}{2}\left(|S_2|^2 - |S_1|^2 + |S_4|^2 - |S_3|^2\right)$$

$$M_{13} = \mathrm{Re}\{S_2 S_3^* + S_1 S_4^*\}$$

$$M_{14} = \mathrm{Im}\{S_2 S_3^* - S_1 S_4^*\}$$

$$p(\theta) = \frac{4\pi}{C_{scat}} M_{11}(\theta)$$

$$C_{ext} = C_{scat} + C_{abs}$$

$$\omega = \frac{C_{scat}}{C_{ext}}$$

Light scattering by a collection of particles: size distribution

- the modified gamma distribution

$$n(r) = \text{constant} \times r^{\alpha} \exp\left(-\frac{\alpha r^{\gamma}}{\gamma r_c^{\gamma}}\right);$$

- the log normal distribution

$$n(r) = \text{constant} \times r^{-1} \exp\left[-\frac{(\ln r - \ln r_g)^2}{2 \ln^2 \sigma_g}\right];$$

- the power law distribution

$$n(r) = \begin{cases} \text{constant} \times r^{-3}, & r_1 \le r \le r_2, \\ 0, & \text{otherwise}; \end{cases}$$

- the gamma distribution

$$n(r) = \text{constant} \times r^{(1-3b)/b} \exp\left(-\frac{r}{ab}\right), \quad b \in (0, 0.5);$$

$$r_{\text{eff}} = \frac{1}{\langle G \rangle} \int_{r_{\min}}^{r_{\max}} \mathrm{d}r\, n(r) r \pi r^2,$$

$$v_{\text{eff}} = \frac{1}{\langle G \rangle r_{\text{eff}}^2} \int_{r_{\min}}^{r_{\max}} \mathrm{d}r\, n(r) (r - r_{\text{eff}})^2 \pi r^2,$$

$$\langle C_{\text{ext}} \rangle = \int_{r_{\min}}^{r_{\max}} \mathrm{d}r\, n(r) C_{\text{ext}}(r)$$

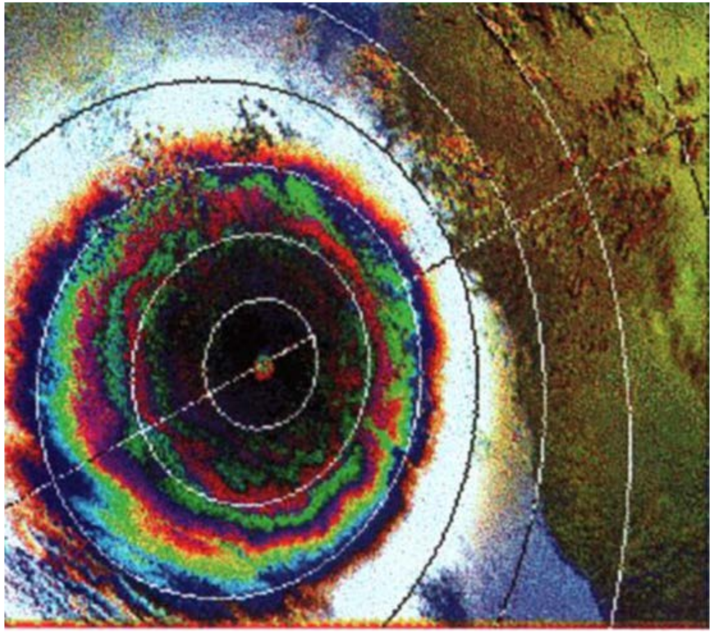
$$\langle C_{\text{sca}} \rangle = \int_{r_{\min}}^{r_{\max}} \mathrm{d}r\, n(r) C_{\text{sca}}(r)$$

$$\langle \mathbf{P}(\Theta) \rangle = \frac{1}{\langle C_{sca} \rangle} \int_{r_{min}}^{r_{max}} dr \mathbf{P}(r, \Theta) n(r) C_{sca}(r)$$

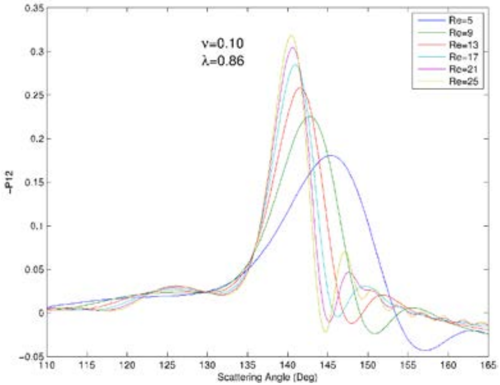
Source: Mishchenko et al., 2002

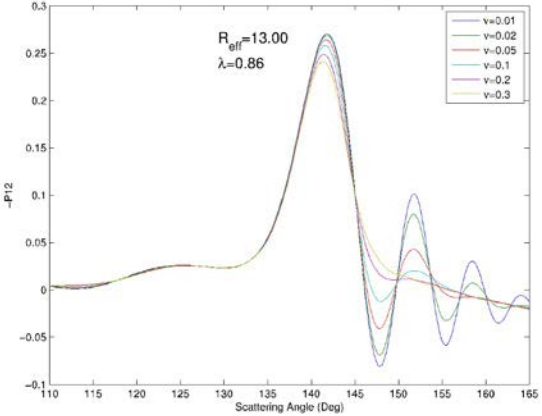
Water Clouds Remote Sensing Using Rainbow

Image credit: national geographic



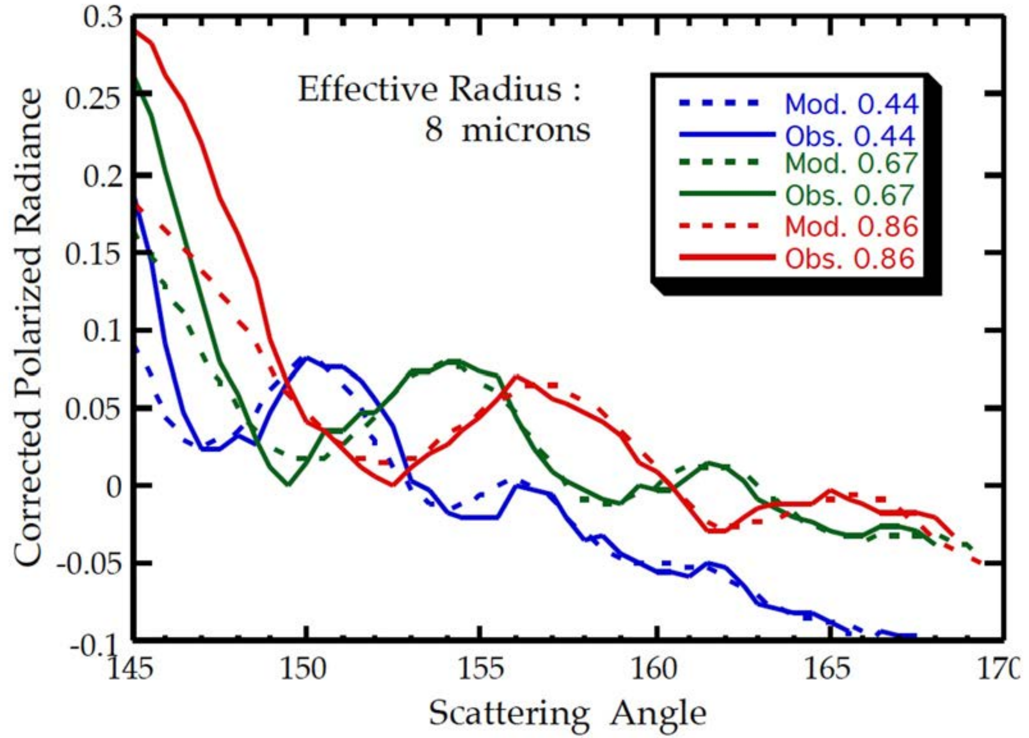
Three color composite (Blue: 0.43 gm, Green: 0.67 grn, Red: 0.86 grn) of the polarized POLDER measurements over the Atlantic ocean and Southern Africa on Nov. 3rd, 1996. Source: Bréon and Goloub, 1996.





Fitting of Supernumerary Rainbows

- Corr
  R_p
- Para
  $F($

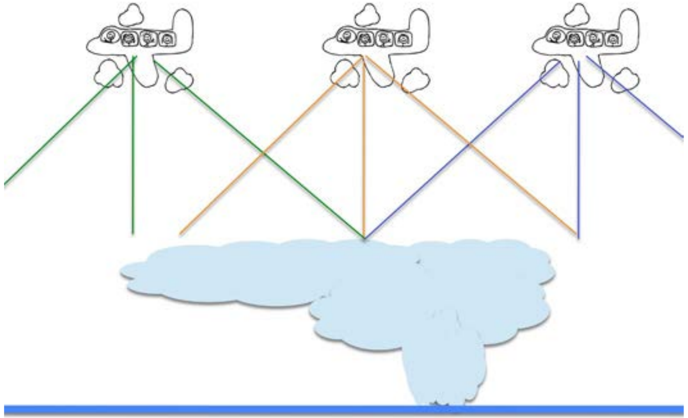


Source: Bréon and Goloub, 1996.

Research Scanning Polarimeter (RSP)

- Prototype for APS on Glory
- Two versions built in 1999 and 2001
- 152 viewing angles per scene + dark reference and unpolarized calibrator views on every scan
- 9 bands in visible and shortwave infrared:
  - 410, 470, 555, 670, 864, 960, 1593, 1880, 2263 nm for aerosols and clouds
  - 960 nm for column water vapor
  - 1880 nm for cirrus (lower atmosphere screened by water vapor absorption)
- 14 mrad Field of view
- Accuracy: polarimetric <0.5%, radiometric <5%

Image: Brian Cairns



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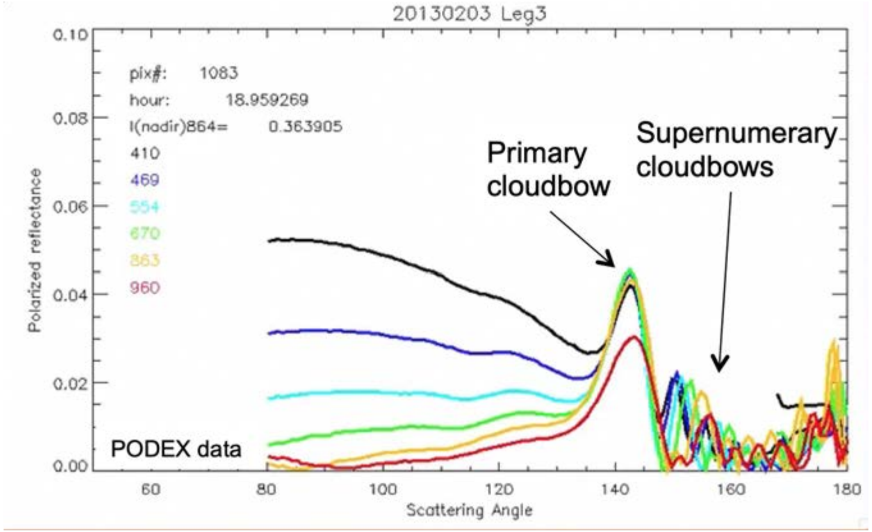
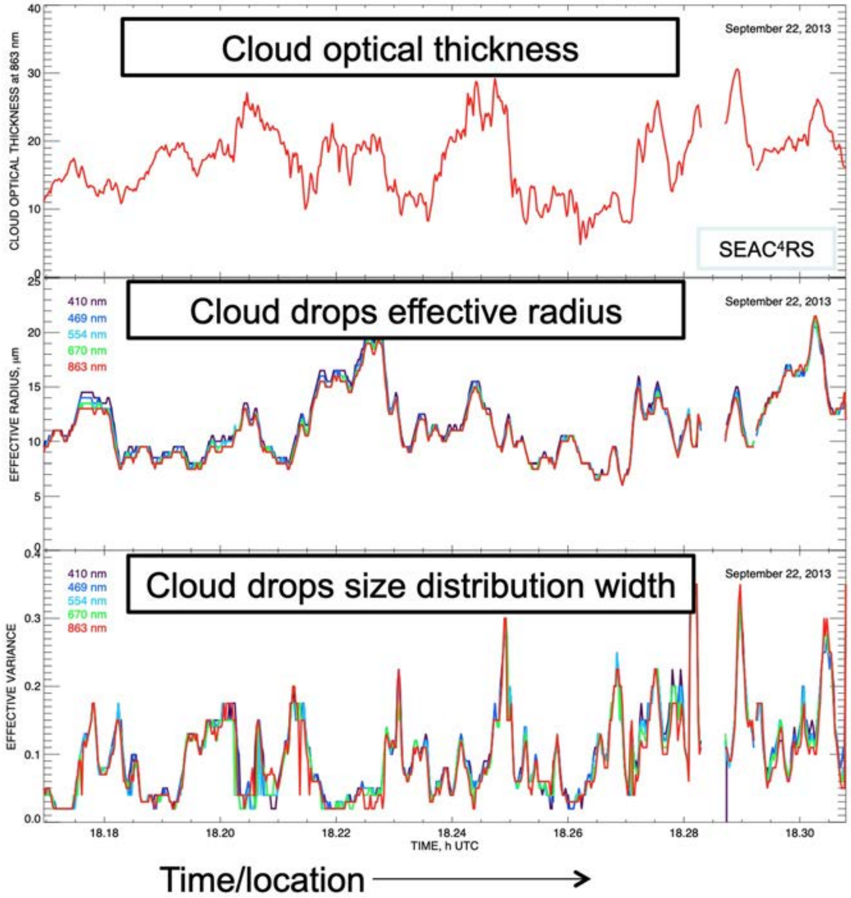
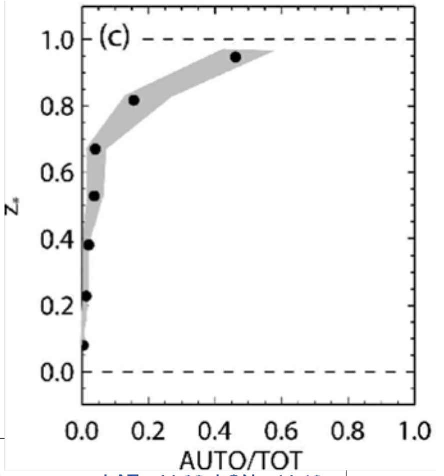
Remote Sensing of Water Clouds Using RSP

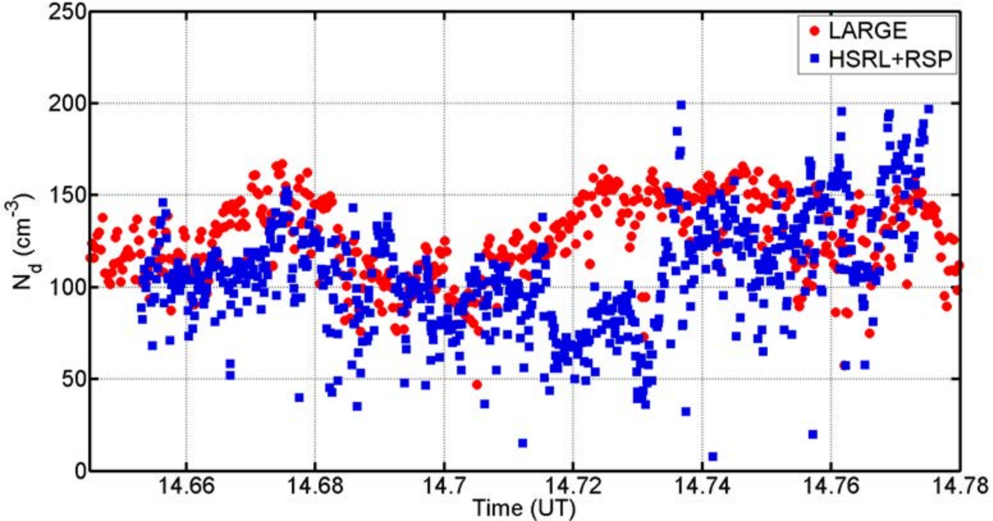


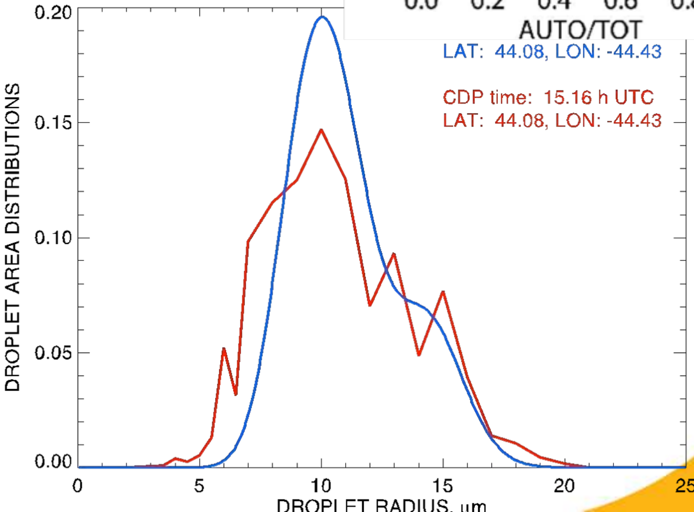


Alexandrov et al., 2014

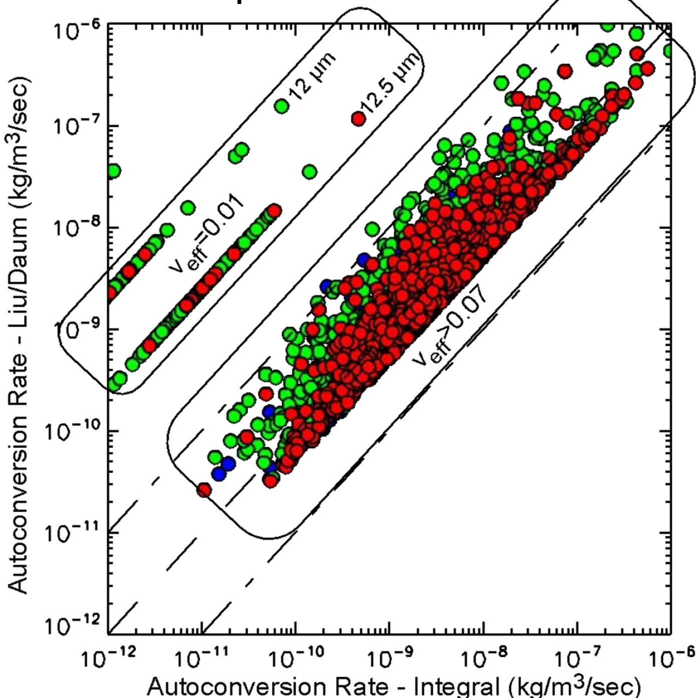
- Auto-conversion is important for the initial formation of drizzle near cloud top (e.g. Fig 9c from Wood 2005, JAS).
- Cloud top droplet number concentrations and size distributions from lidar and polarimeter allow auto-conversion rates to be directly estimate using the SCE kernel. Remote sensing provides large numbers of observations (e.g ~100,000 from the three NAAMES deployments) to evaluate against.

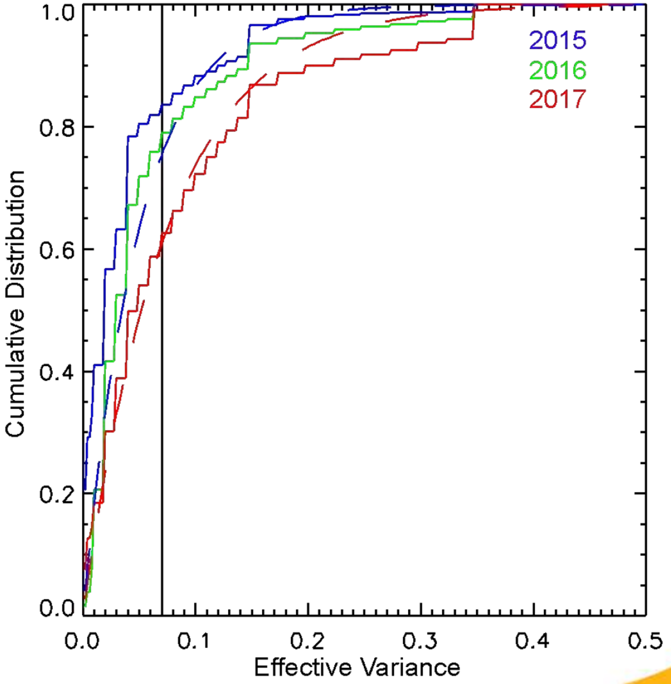




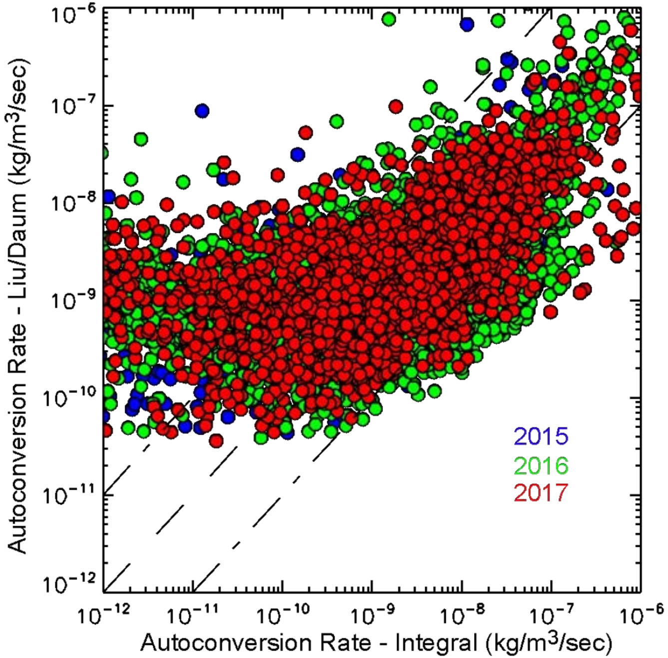


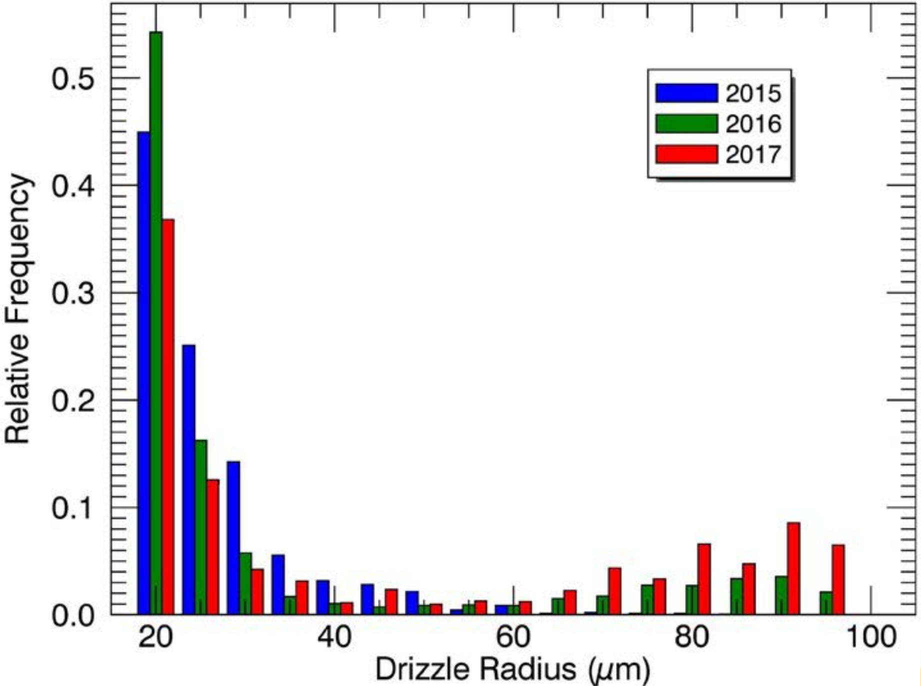
- The Liu-Daum (2004) Kessler type bulk auto-conversion parameterization works quite well for broader **monomodal** size distributions (v_{eff} > 0.07), but not for the narrow size distributions that are common at cloud top (60-80% of DSDs have v_{eff} < 0.07). Bulk parameterizations will hugely overestimate auto-conversion rates for narrow size distributions since they have similar dependencies on liquid water content and droplet number.



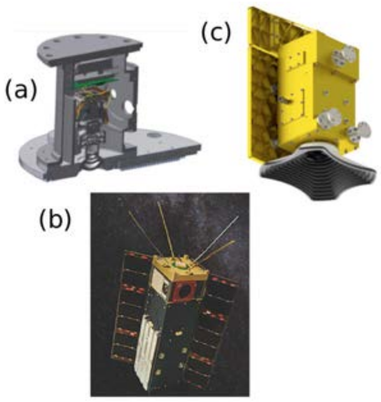


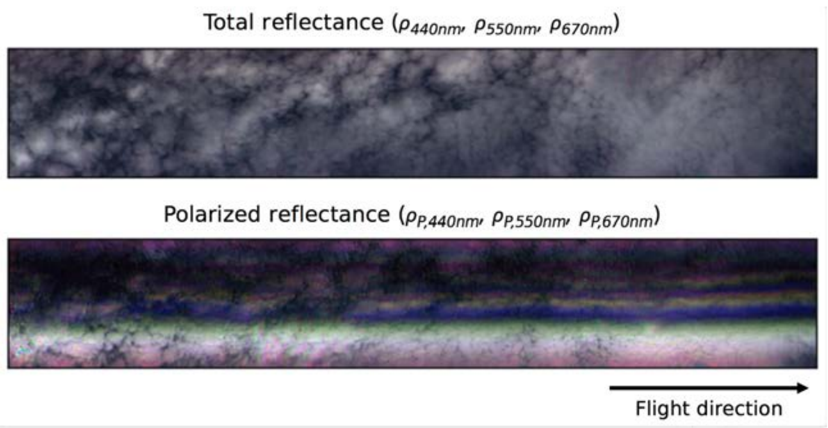
- Bimodal size distributions at cloud top are common (~10-20%) and show larger random differences between the Kessler type (LD2004) bulk parameterization and estimates of auto-conversion rate integrated over the SCE kernel than monomodal size distributions.
- Drizzle at cloud top is also quite frequent (~10%) and can also be detected from remote sensing observations.

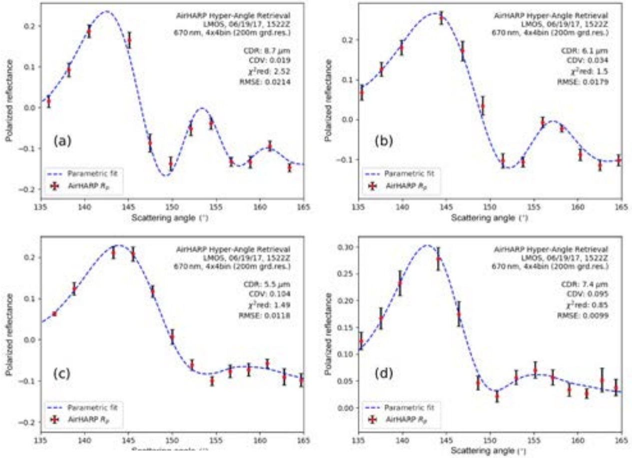


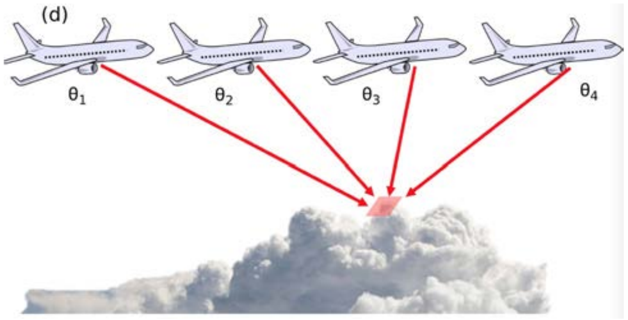


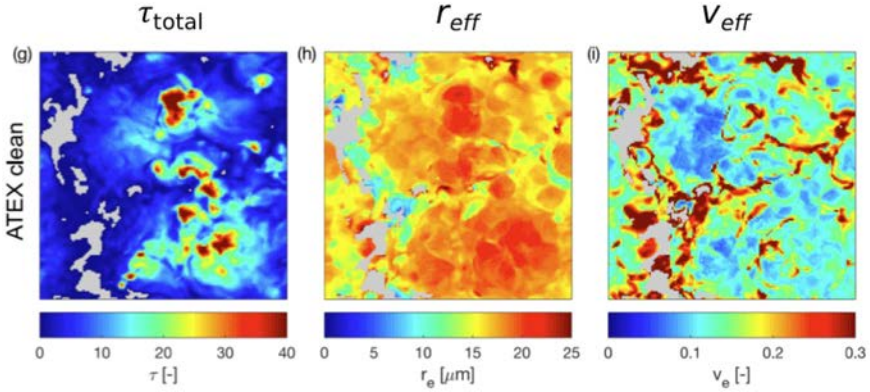
Cloud Size Distribution Retrieval Using air-HARP







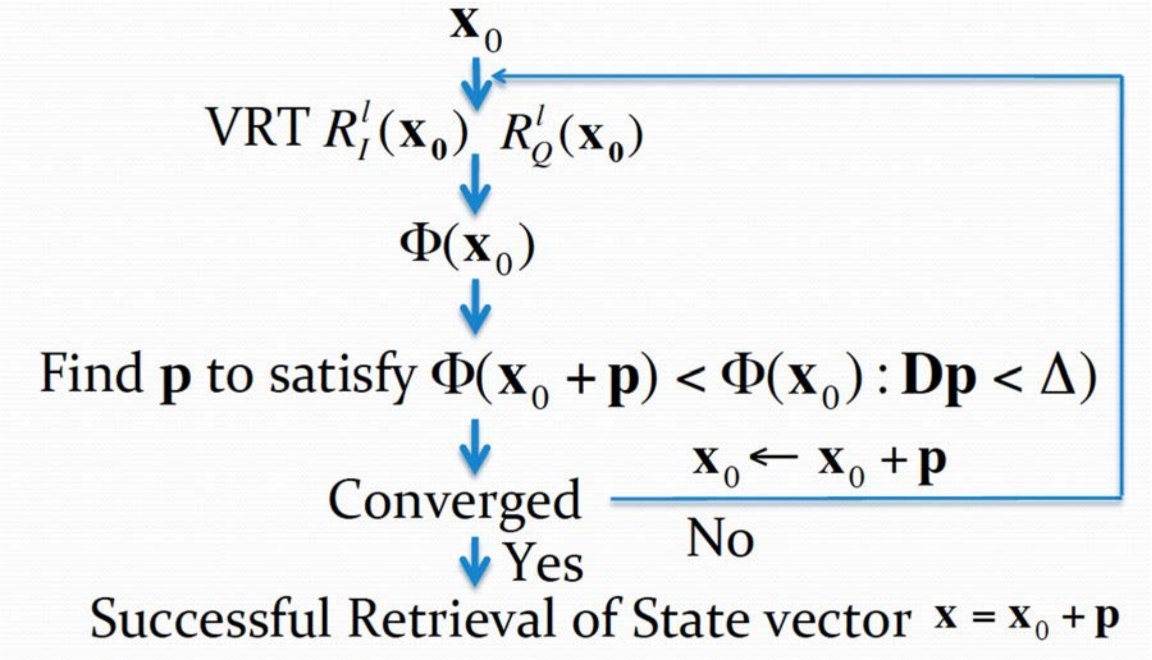




Source:
McBride et al.,
AMT, 2020

Joint Retrieval of Aerosols and Ocean Color: A Schematic View

- Different algorithms use different cost functions and retrieval parameter space.
- Different instrument/ measurement data have different information content, which leads to different designs of the cost function and retrieval parameters.



1. Moré, J. J., B. S. Garbow,, and K. E. Hillstrom, "User Guide for MINPACK-1, Argonne National, Laboratory Report ANL-80-74", Argonne, Ill., 1980. 7922

Joint Retrieval of Aerosols and Ocean Color: An Incomplete Survey

- Generalized Retrieval of Aerosol and Surface Properties (GRASP) (Dubovic et al., Front. Remote Sens., 2021)
    - Multi-pixel joint retrieval with smooth constraints.
    - Multiple instrument combined retrieval.
    - Aerosol oriented (ocean is not the focus).
- SRON Algorithm (Hasekamp et al., JQSRT, 2019)
- A Principal Component Based Algorithm (Xu et al., MDPI Remote Sensing, 2019).
- RSP algorithm (Chowdhary et al., RSE, 2012)
- MAPP algorithm (Stamnes et al., Applied Optics, 2018).
- MAPOL and FastMAPOL Algorithm (Gao et al., Optics Express, 2018; AMT, 2021)

MAPOL Joint Retrieval Algorithm

Retrieval Optimization

Forward Model (VRT for CAOS, Zhai. et al., (2009, 2011)**)**

Aerosol Model

- Six sub mode volume distribution (3 fine modes, 3 coarse modes)
- Refractive index based on PCA for real and imaginary spectra

Bio-optical Models

- Open waters – case 1 (Phytoplankton)
- Coastal waters – case 2 (Phytoplankton, CDOM, NAP)

Rough ocean interface

(Isotropic Cox-Munk Model)

Levenburg- Marquardt non-linear least squares optimization (More et al., 1980)

Cost function (χ^2)

$$\chi^2(x) = \frac{1}{N}\sum_i \left(\frac{\left[\rho_t^m(i) - \rho_t^f(x,i)\right]^2}{\sigma_t^2(i)} + \frac{\left[A^m(i) - A^f(x,i)\right]^2}{\sigma_A^2(i)}\right)$$

RSP: A – Polarized Reflectance

SPEX: A – DOLP

Parameters

Aerosol refractive index spectra – 8

Aerosol volume distribution – 6

Wind speed – 1

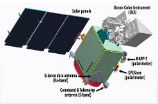
Hydrosol optical properties

[Chla] based model – 1

General model – 7

Gao M. et al., (2018,2019)

Coupled atmosphere and ocean system in retrieval



Gas absorption: ozone, oxygen, water vapor, nitrogen dioxide, methane, and carbon dioxide

Molecule (Rayleigh Scattering)

Molecule + Aerosol

Ocean

Sensitivities:

- Aerosol height
- Ocean water depth
- Surface pressure
- …

Fine mode aerosol

Coarse mode aerosol

Rough ocean
e

(w)

n (ph)

CDOM(g)

Non-algal Particle(d)

Retrieval Parameters

PCA /PCA+ adjustment

Refractive index spectra

Volume distribution (six

Glint/Cloud mask

Wind speed

+Depolarization

Ocean bio-optical model considering scattering and absorption of Water, Phytoplankton, CDOM, and NAP

Counts

8

6

1

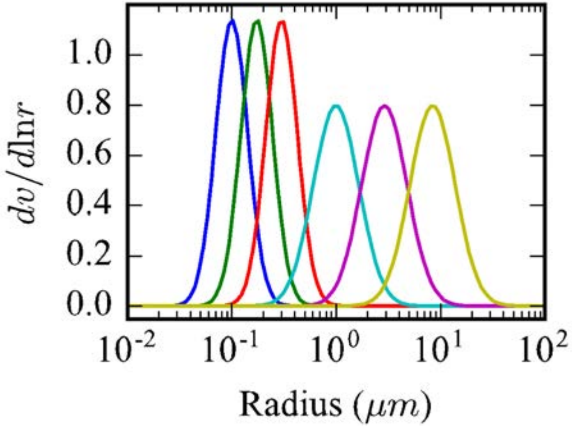
1/7/8

Aerosol models (8*+6 parameters)

- Refractive index spectra representation using PCA
  - Applicable for both discrete and hyperspectral bands
  - PCA can be updated with more datasets available

$$m(\lambda) = m_0 + \alpha_1 p_1(\lambda)$$

m_0: mean refractive index
$p_1(\lambda)$: First order of principle component(PC)
α_0: PC coefficients



- Volume distribution
  - Six sub mode summation
  - Look up table can be built with each fixed mode

Adopted from Xu et al, AMT 2016

Ocean Bio-optical model

- Sea water(w)
- Phytoplankton (ph)
- CDOM(g)
- Non-algal Particle(d)

$$a_{ph} = A_{ph}(\lambda)[Chla]^{E_{ph}(\lambda)}$$

$$a_{dg} = a_{dg}(440)\exp[-S_{dg}(\lambda - 440)]$$

$$b_{bp} = b_{bp}(660)(\lambda/660)^{-S_{bp}}$$

$$B_p = B_p(660)(\lambda/660)^{-S_{Bp}}$$

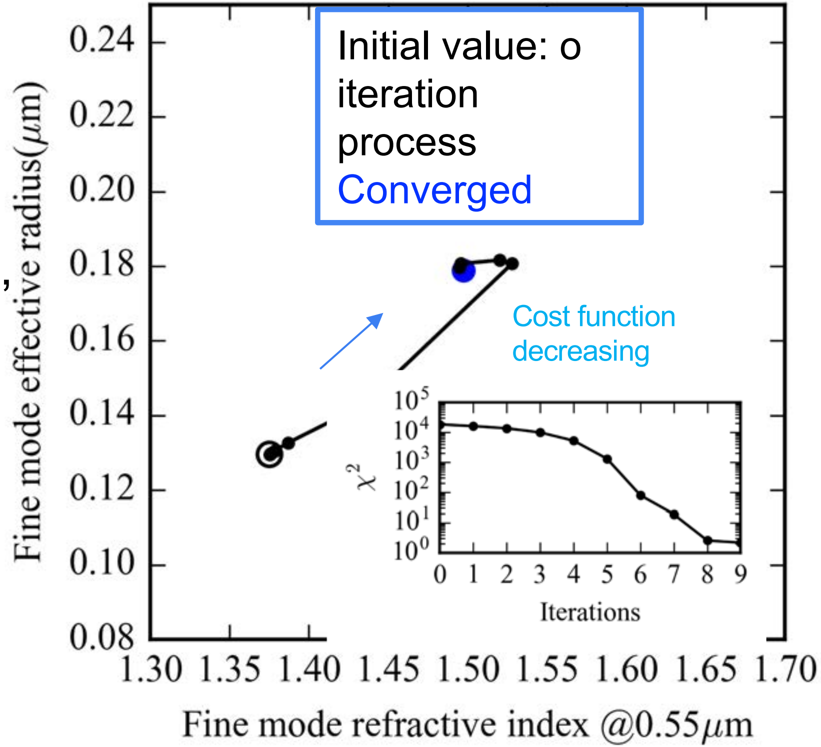
+Depolarization ratio

Potential retrieval parameters as highlighted

- Coastal waters: multiple parameters can be used for retrieval (Bio-2).
- For open waters, [Chla] is the single parameter used for retrieval (Bio-1).

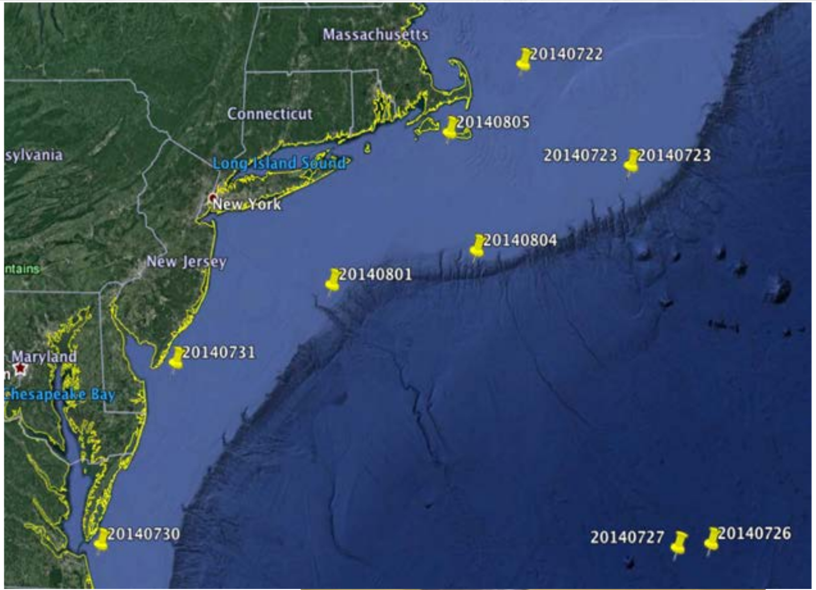
Inversion algorithm

- Inversion method
  - Levenberg–Marquardt algorithm
- Forward model
  - VRT SOS code for CAOS (Zhai et al, 2010)
- Cost function (χ^2)
  1. Radiance + Polarized Radiance
  2. Radiance
  3. Radiance + DOLP



SABOR 2014:
In-Situ measurement

Instrument	Satlantic HyperPro
Measurement	downwelling irradiance (0+) and upwelling radiance (0-), 5 min deployment
Wavelength	348.9-802.1 hyperspectral with resolution ~3.3nm
Depth	~0.2m
PI	Ivona Cetinic (at NASA Goddard) , Wayne Slade (Sequoia Scientific)



HyperPro

https://seabass.gsfc.nasa.gov/search/experiment/sabor
Calibration Report: SABOR (Ship-Aircraft Bio-Optical Research) HyperPro (surface mode) @SEABASS

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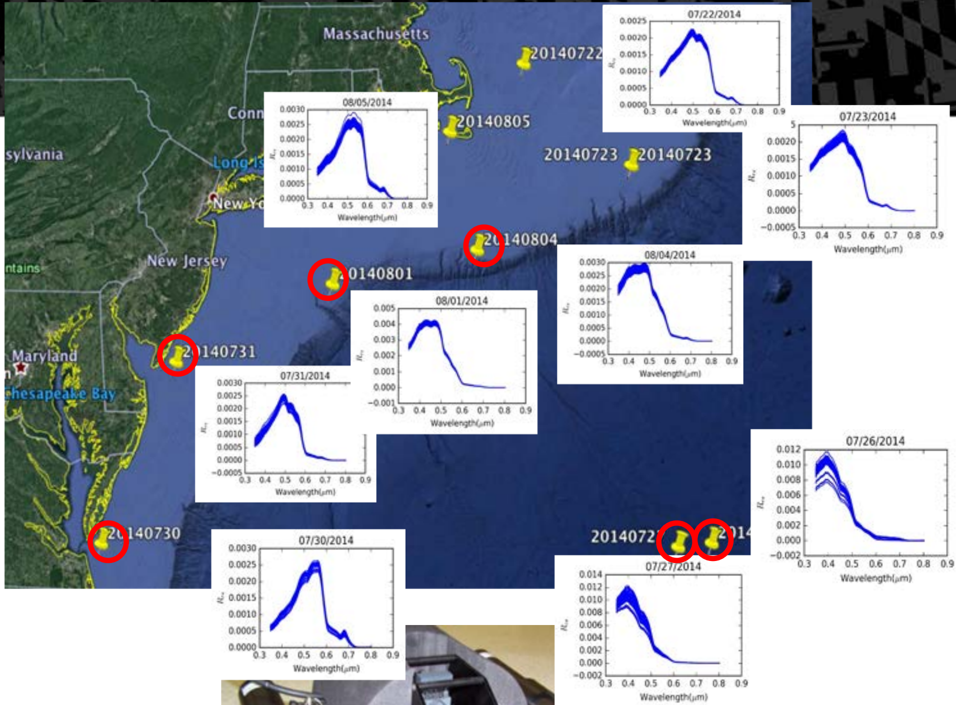


HyperPro

https://seabass.gsfc.nasa.gov/search/experiment/sabor

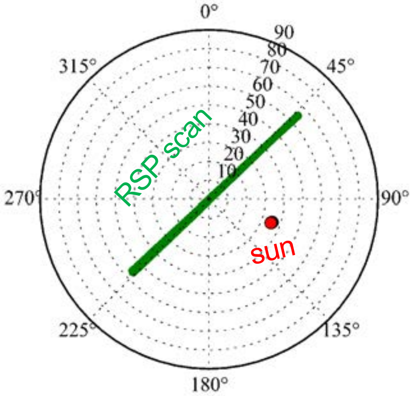
Calibration Report: SABOR (Ship-Aircraft Bio-Optical Research) HyperPro (surface mode) @SEABASS

Thank Alison Chase (University of Maine) for providing HyperPro the data.

SABOR 2014/07/27 : Open waters

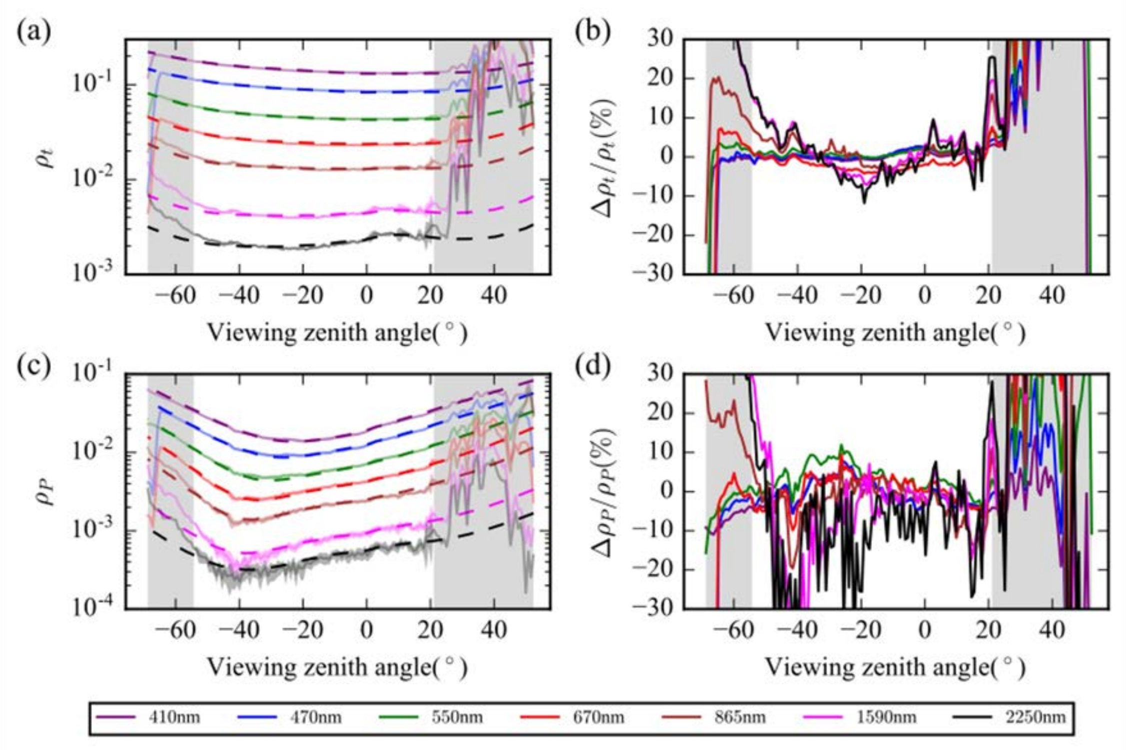
- RSP observation
  - 2014/07/27 UTC ~ 14.18-14.30 (Time zone: UTC-5)
  - Altitude 8.99km, track length: ~30km
  - Solar zenith angle: ~35 degree
  - Scattering angle: 103~148 degree

AOD@550nm~0.17

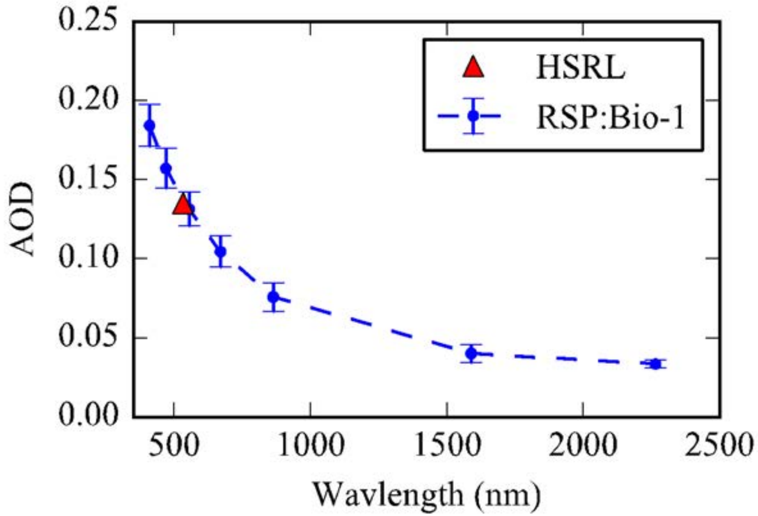


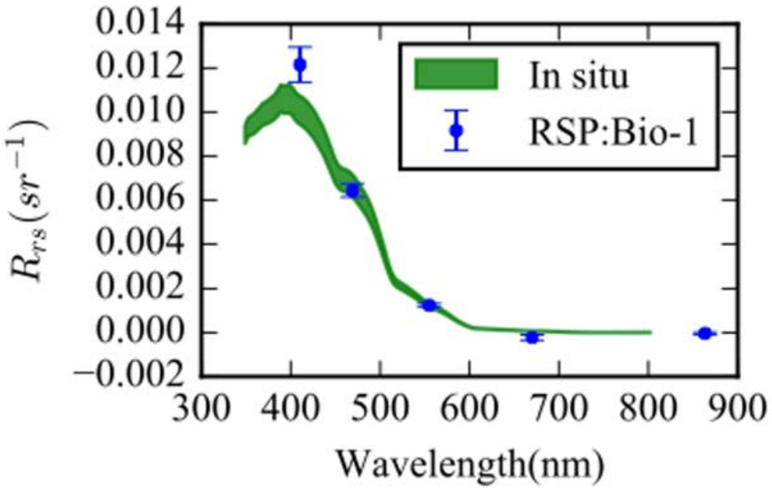
SABOR 2014/07/27 : Open waters

- Cost function: R+Rp
- Bio-optical model: Bio-1
- Remove major cloud influence.

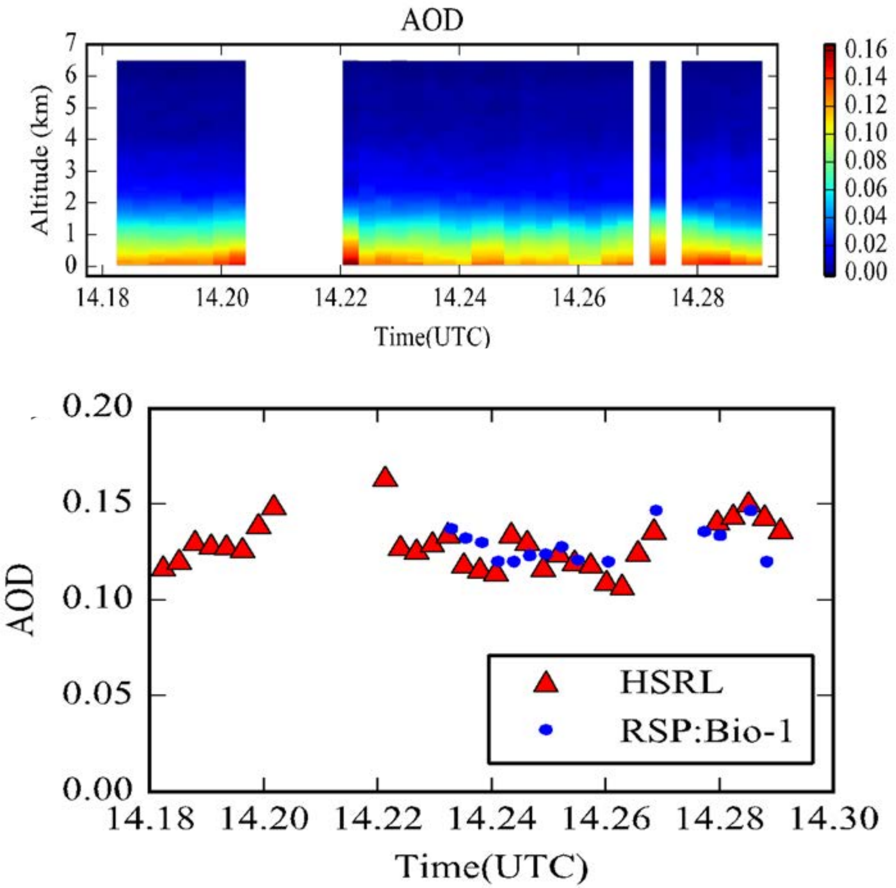


Retrieved AOD and Remote sensing reflectance





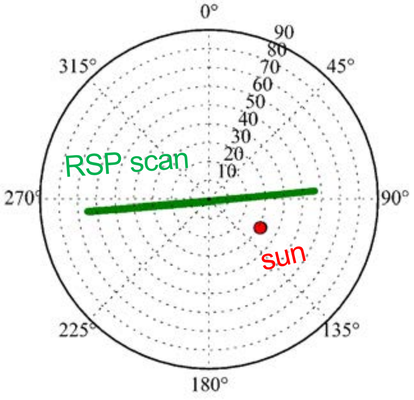
Retrieved AOD across RSP track



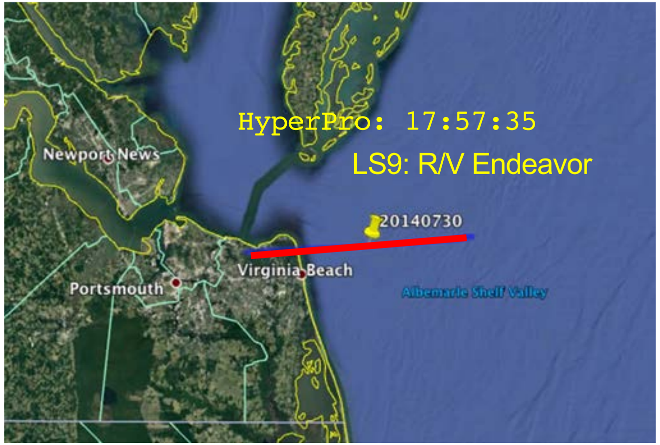
SABOR 2014/07/30 : Coastal waters

- RSP observation
  - 2014/07/30 UTC ~ 15.18-15.32 (Time zone: UTC-5)
  - Altitude 8.8km, track length: ~54km
  - Solar zenith angle: ~31 degree
  - Scattering angle: 88~164 degree

North

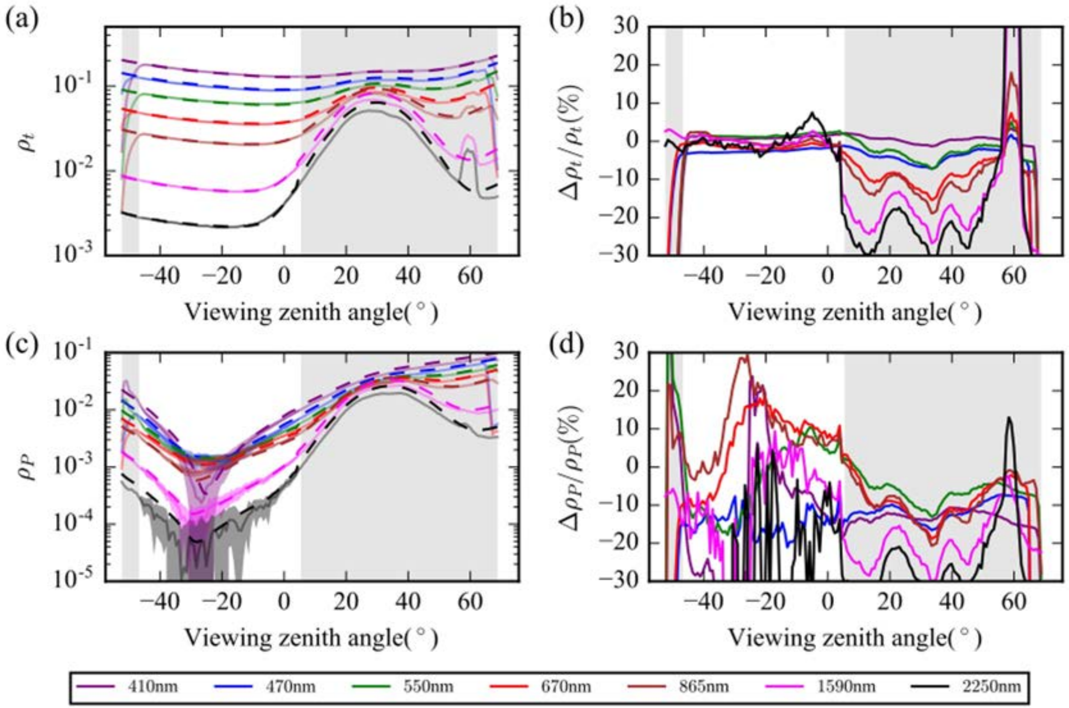


AOD@550nm~0.34

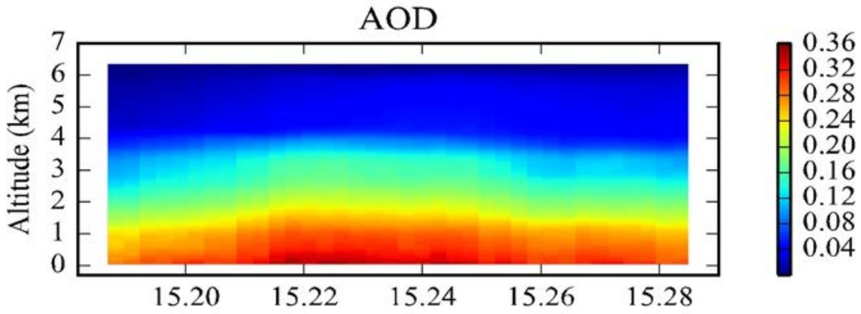


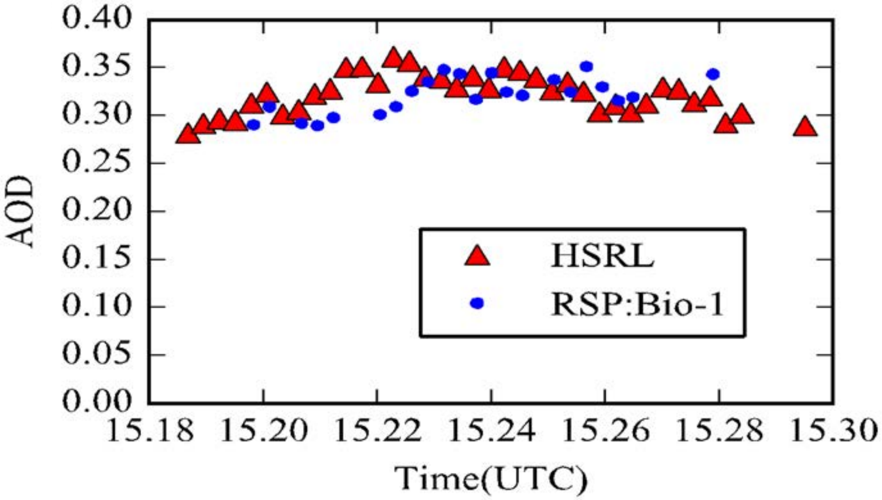
SABOR 2014/07/30 : Coastal waters

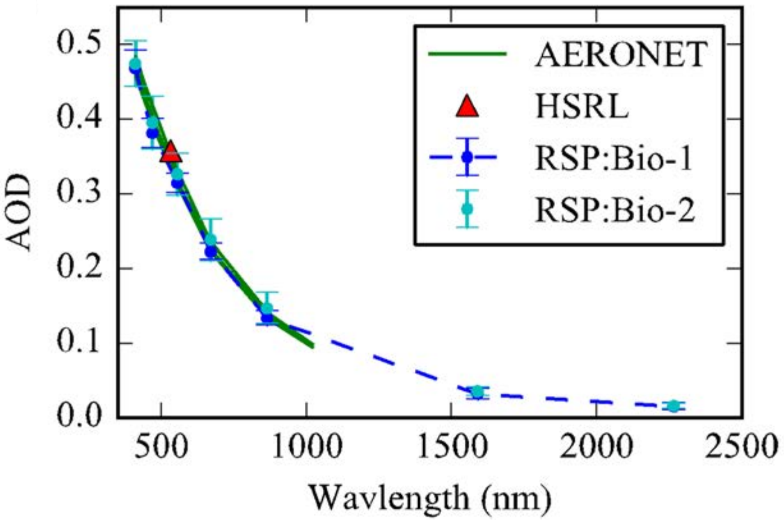
- Cost function: R+Rp ;
- Bio-optical model: Bio-2



Retrieved AOD across RSP track

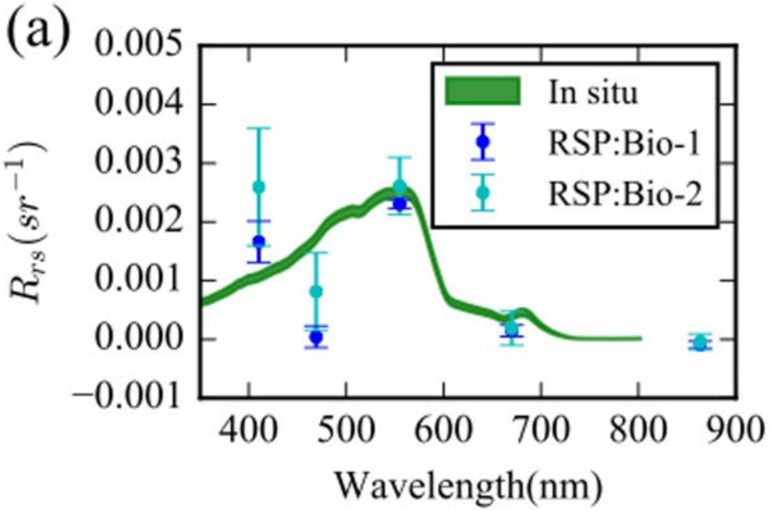




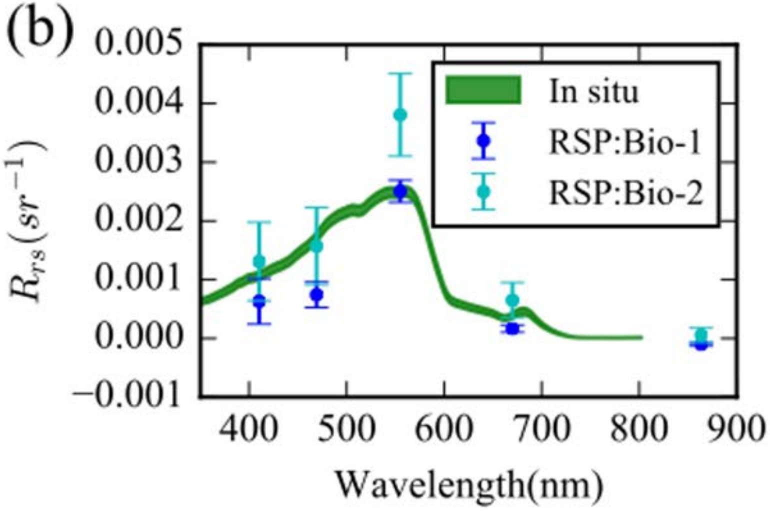


Remote sensing reflectance retrieval

Refractive index spectra: PCA

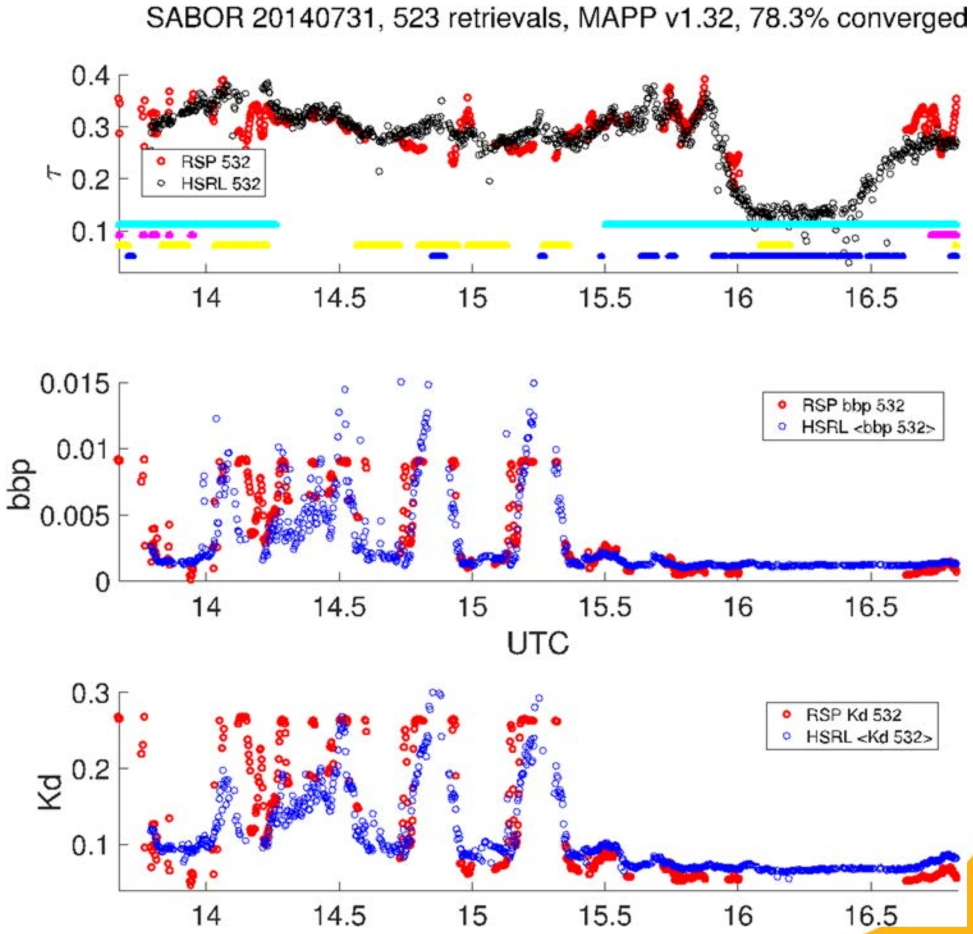


Refractive index spectra: PCA + adjustment at 410 and 470nm



Remote sensing reflectance retrieval

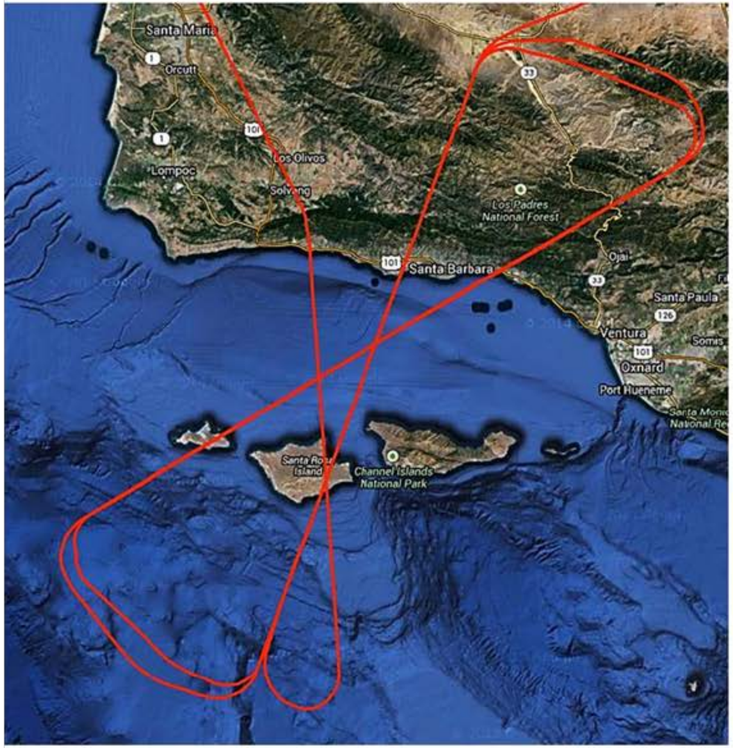
Multiple groups working on this approach, this example from collaboration between GISS and LaRC



Remote sensing reflectance retrieval

HySPIRI 2013/2014

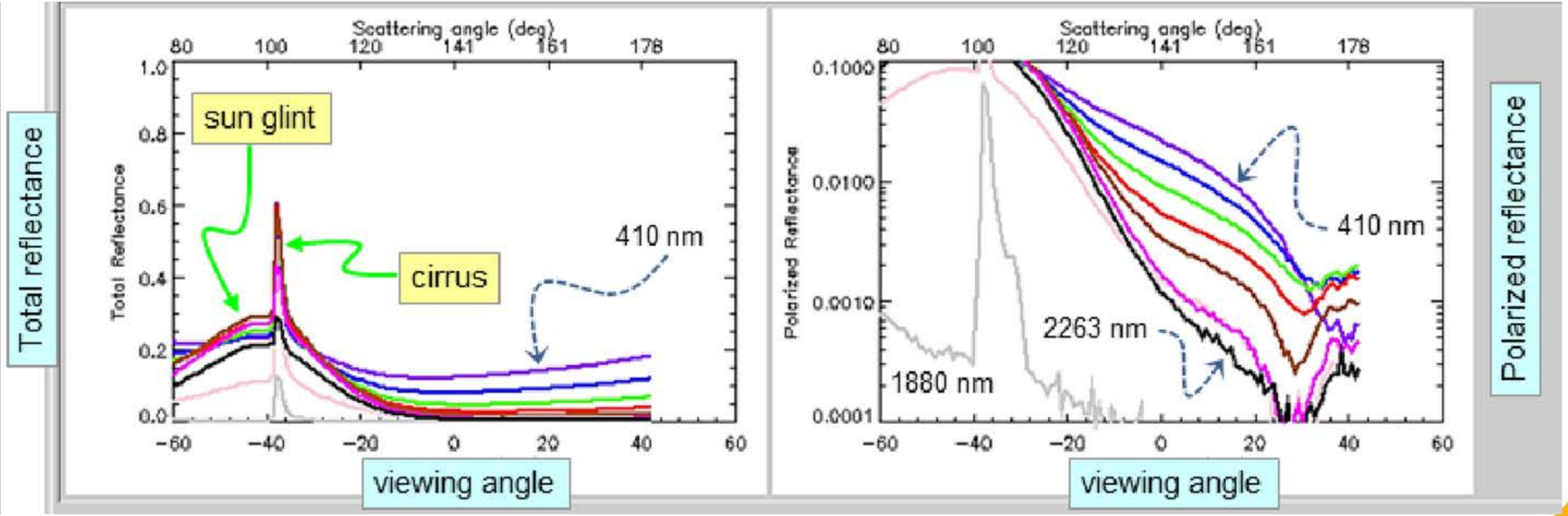
Santa Barbara, 10/21/2014.



Remote sensing reflectance retrieval

HySPIRI 2013/2014

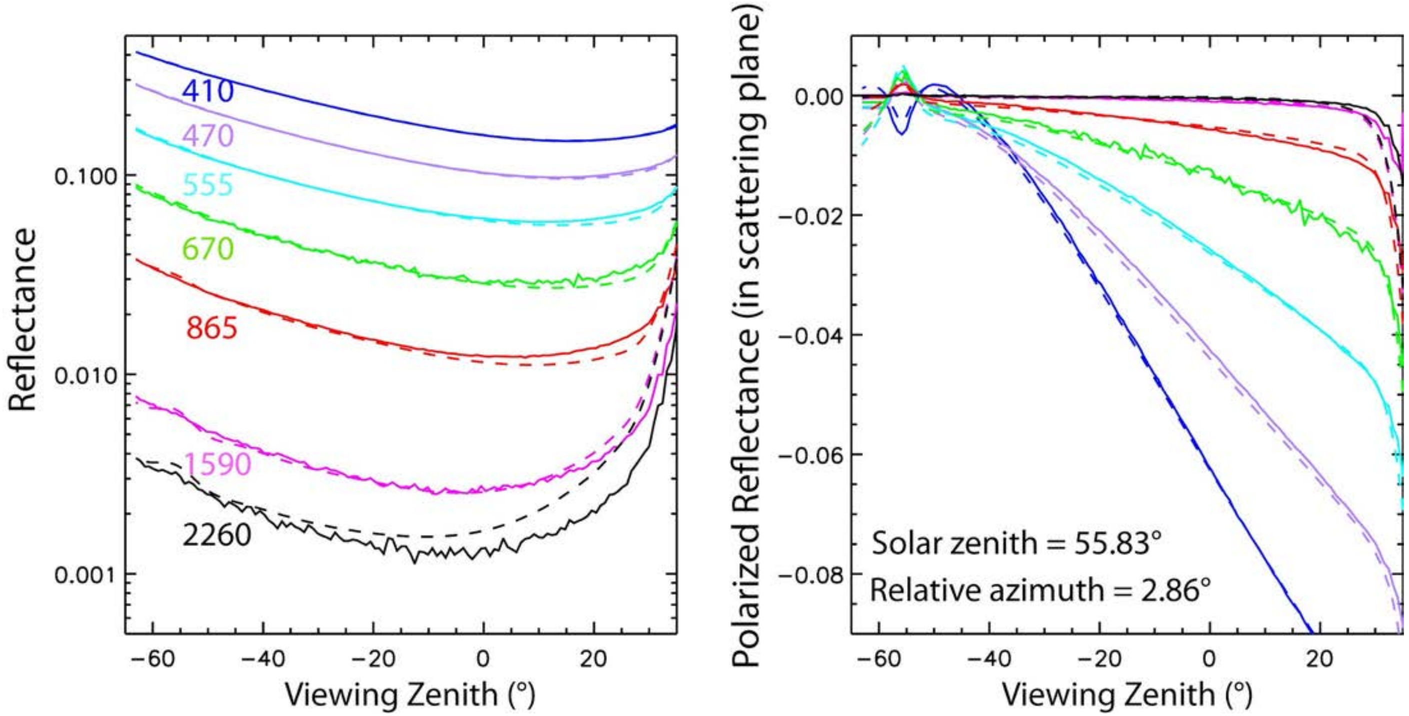
Santa Barbara, 10/21/2014.



Remote sensing reflectance retrieval

HySPIRI 2013/2014

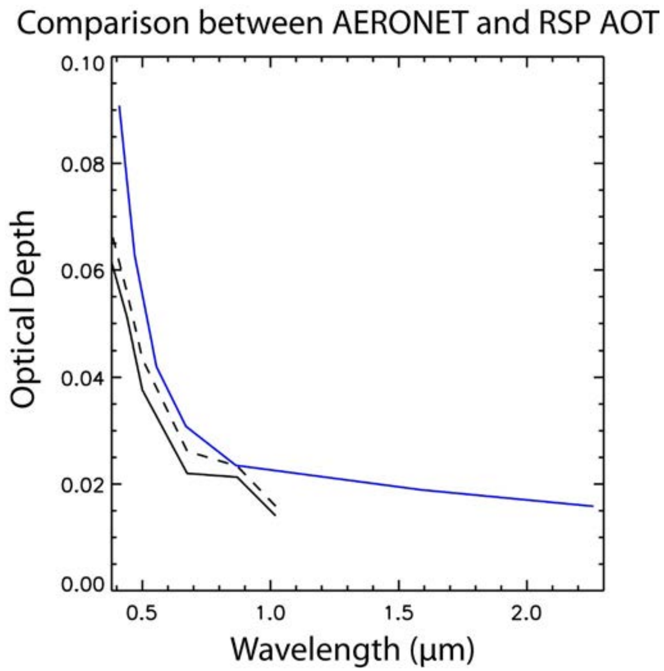
70% of coarse mode non-spherical, effective radii of 0.09 and 2.0 μm for fine and coarse mode (10/31/2013).

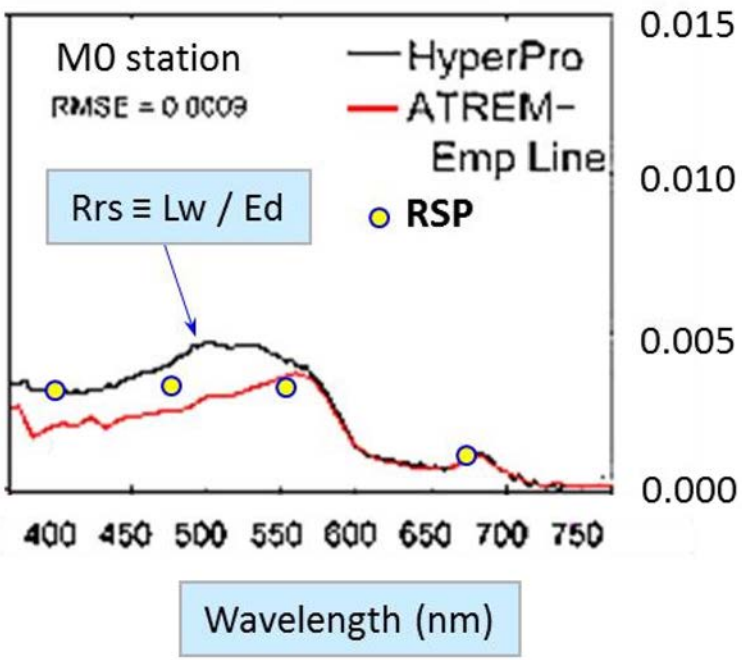


Remote sensing reflectance retrieval

HySPIRI 2013/2014

70% of coarse mode non-spherical, effective radii of 0.09 and 2.0 μm for fine and coarse mode.





Remote sensing reflectance retrieval

HySPIRI 2013/2014

Date	Campaign (*season*)	Target (*study case*)	RSP data	AVIRIS data	Boat data
Mar 31	*Check flight*	Ivanpah; Salton Sea (*dark target*)	Yes	Yes	No
Apr 7	HyspIRI (*Spring*)	Yosemite/Neon Box; Soda Straw	Yes	Yes	No
Apr 10	HyspIRI (*Spring*)	Tahoe Box	Yes	Yes	No
Apr 14	HyspIRI (*Spring*)	High Priority EcoHab; So Cal Box	Yes	Yes	No
Apr 16	HyspIRI (*Spring*)	Santa Barbara	Yes	Yes	No
Apr 18	HyspIRI (*Spring*)	Bay Area Box (*study case for dust*)	Yes	Yes	No
Apr 19	ACOCO; AirMSPI (*Spring*)	Santa Barbara (rosette); SeaPRISM (*study case for ACOCO*)	Yes	Yes	UCS cruise
Aug 18	HyspIRI (*Late Summer*)	So Cal Box (*study case for clouds*)	Yes	Yes	No
Aug 26	HyspIRI (*Late Summer*)	So Cal Box	Yes	Yes	No
Aug 28	HyspIRI (*Late Summer*)	So Cal Box (*night flight*)	Yes (dark)	Yes	No

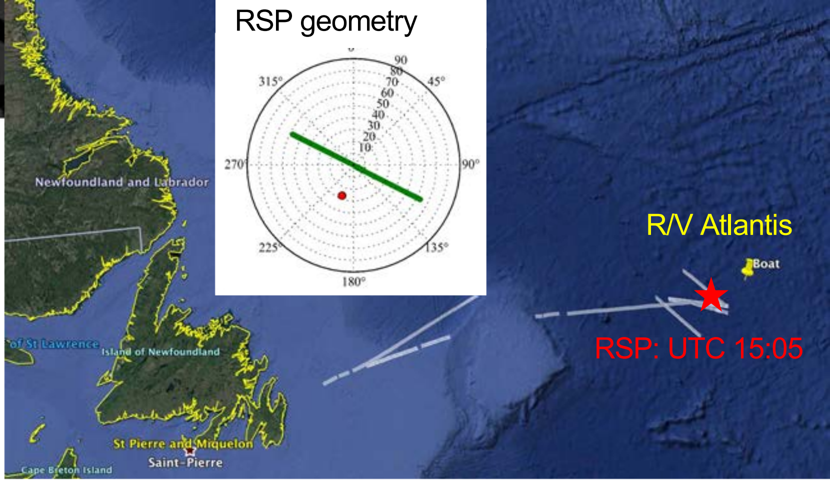
Sep 19	HyspIRI (*Fall*)	Tahoe Box; King & Irene fires (*study case for smoke*)	Yes	Yes	No
Oct 6	HyspIRI (*Fall*)	Yosemite Box; Soda Straw	Yes	Yes	No
Oct 21	ACOCO (*Fall*)	Santa Barbara rosette (*study case for ACOCO*) (*study case for clouds*)	Yes	Yes	PnB cruise
Oct 27	HyspIRI (*Fall*)	SF Bay Box	Yes	Yes	No
Nov 7	HyspIRI (*Fall*)	Ivanpah; Mtn. Pass (*AVIRIS calibration*)	Yes	Yes	No
Nov 17	HyspIRI (*Fall*)	Tahoe Box	Yes	Yes	No
Nov 24	HyspIRI (*Fall*)	SF Bay (*study case for clouds*)	Yes	Yes	No

NAAMES 2016/05/26: in-situ measurement

In-situ measurement

Instrument	Profiling reflectance radiometer
Measurement	downwelling irradiance and upwelling radiance
Wavelength	412, 443, 465, 490, 510, 532, 555, 560, 625, 665, 670, 683, 710, 780nm
Depth	~0.3-87m
UTC	14:20:00-14:22:58
PI	Norm Nelson (UCSB)

Thank Kirk and Joel for suggesting the data.

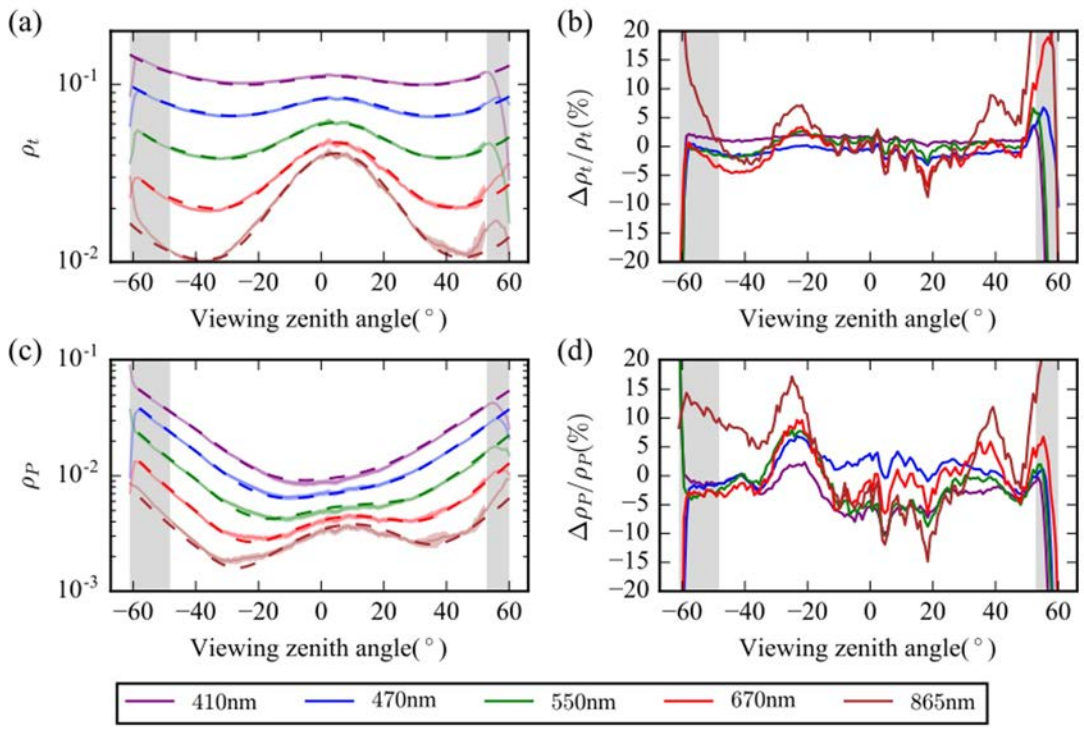


Profiling reflectance radiometer

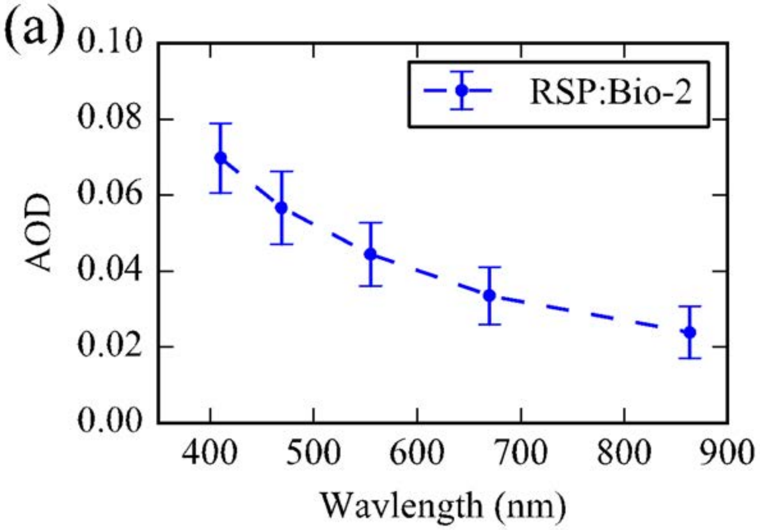
Retrieval and comparison

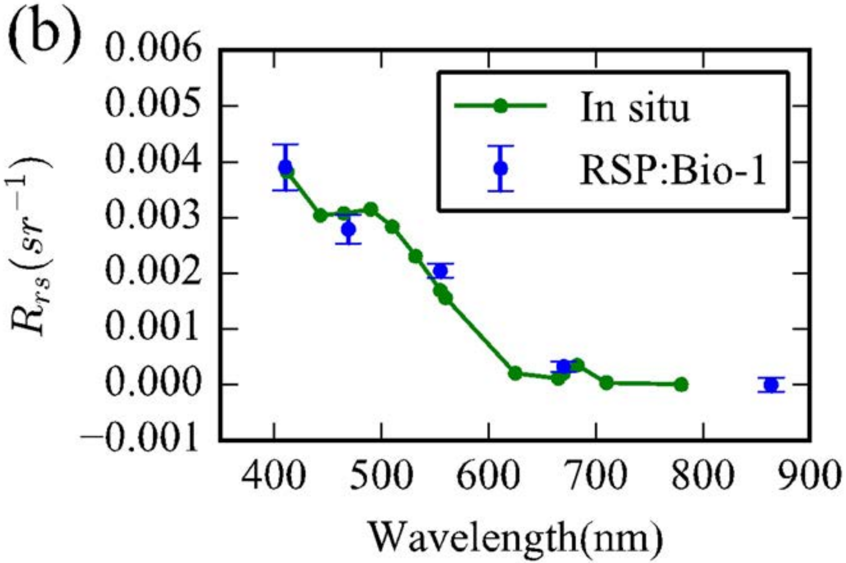
- Cost function: R+Rp ;
- Bio-optical model: Bio-1

Atmospheric correction over glint is challenging.



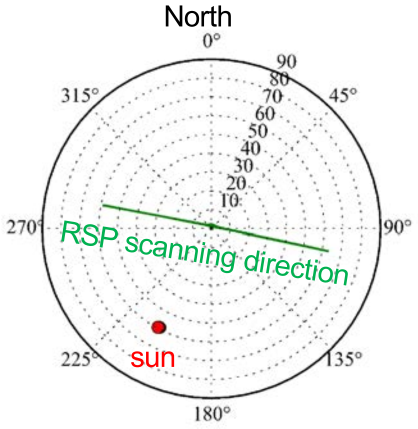
Retrieved AOD and Remote sensing reflectance





NAAMES 2015/11/04: Costal waters

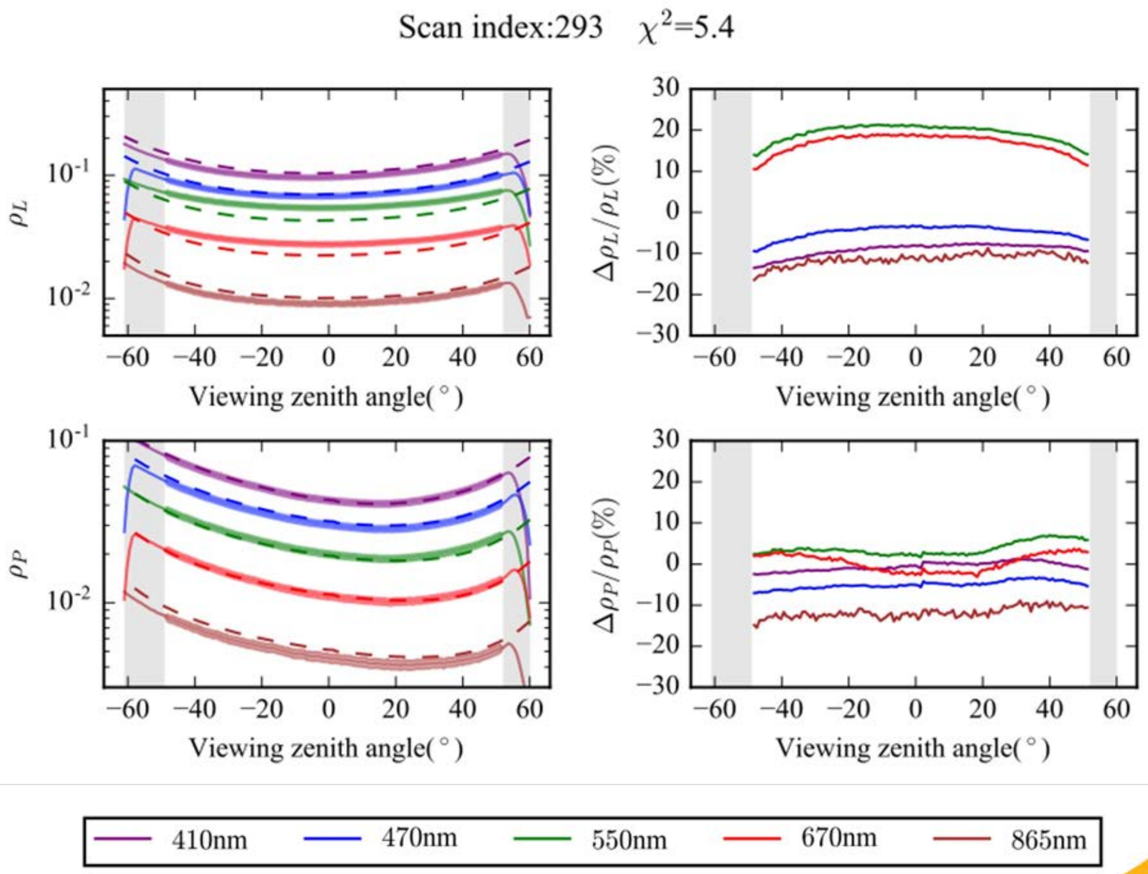
- RSP observation
  - 2015/11/04 UTC ~ 18:10-18:25
  - Altitude 6.3km, track length: ~150km
  - Solar zenith angle: ~60 degree
  - Scattering angle: 90~123 degree



AOD@0.55um~0.05

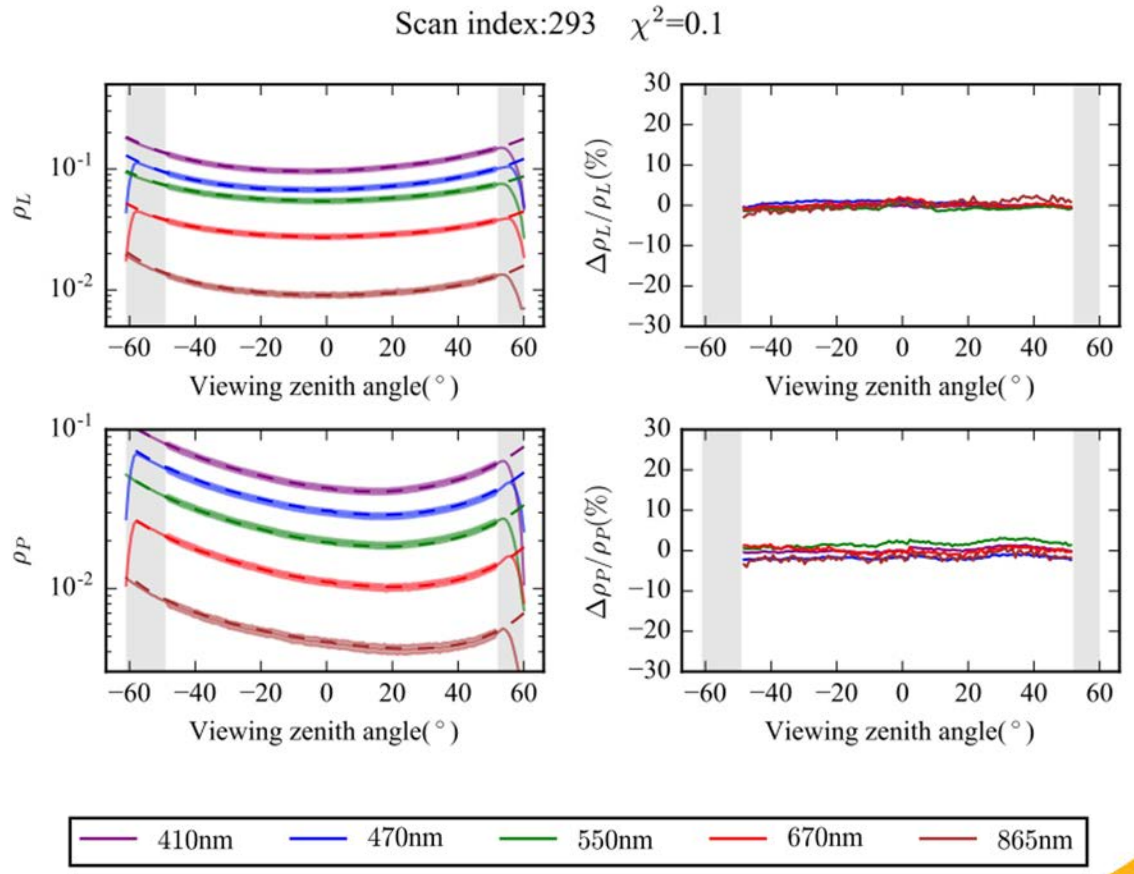
[Chla] based bio-optical model

- Cost function: R+Rp ;
- Bio-1

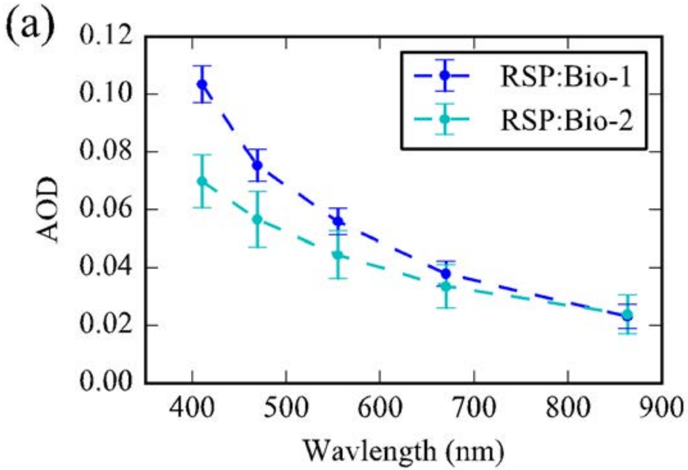


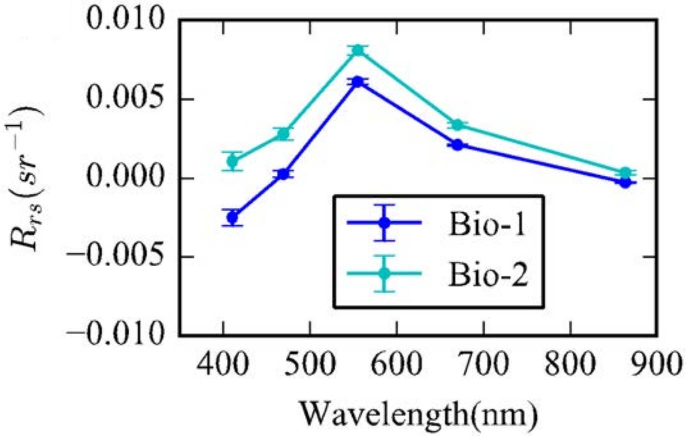
Seven parameter bio-optical model

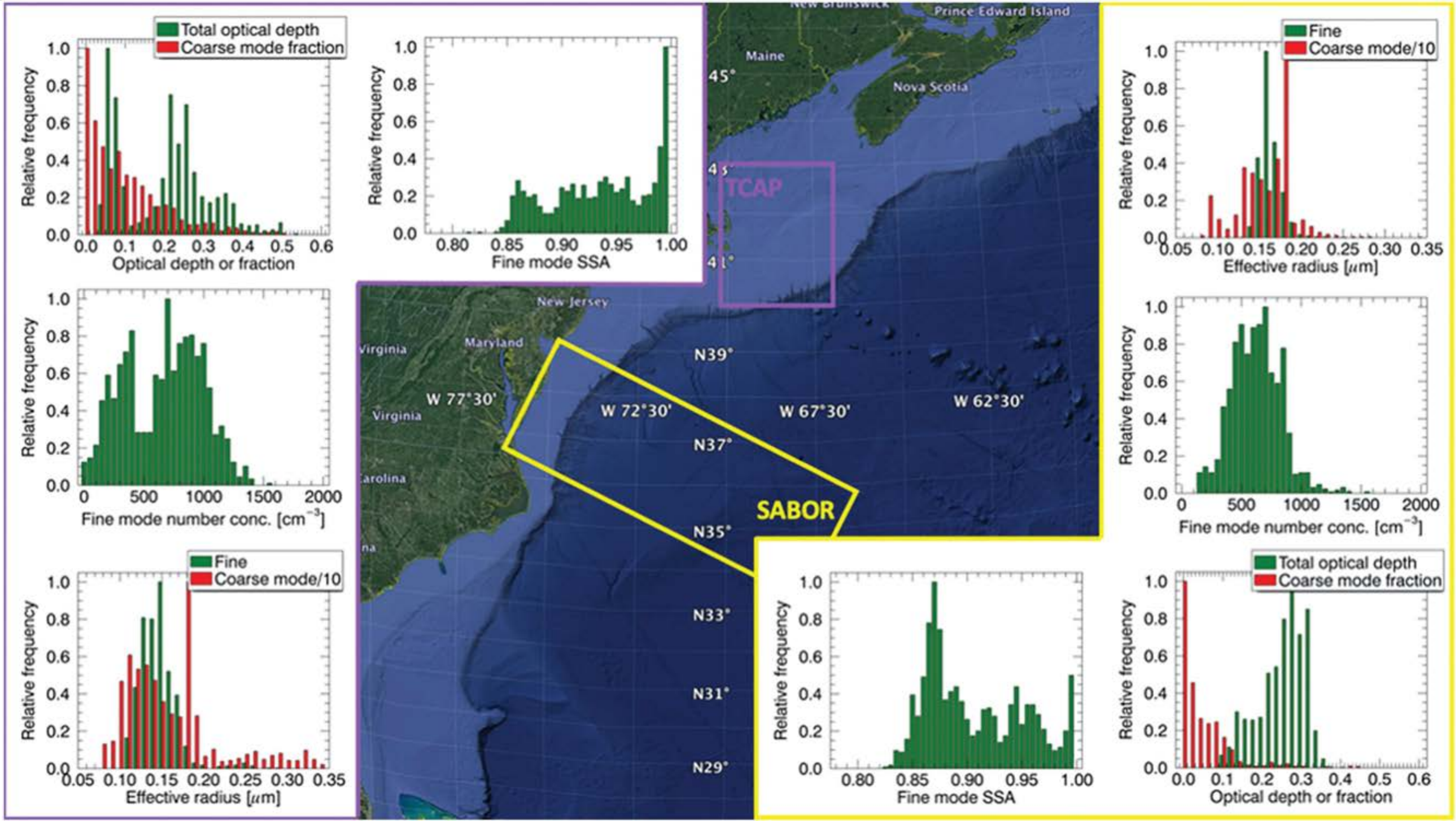
- Cost function: R+Rp ;
- Bio-2



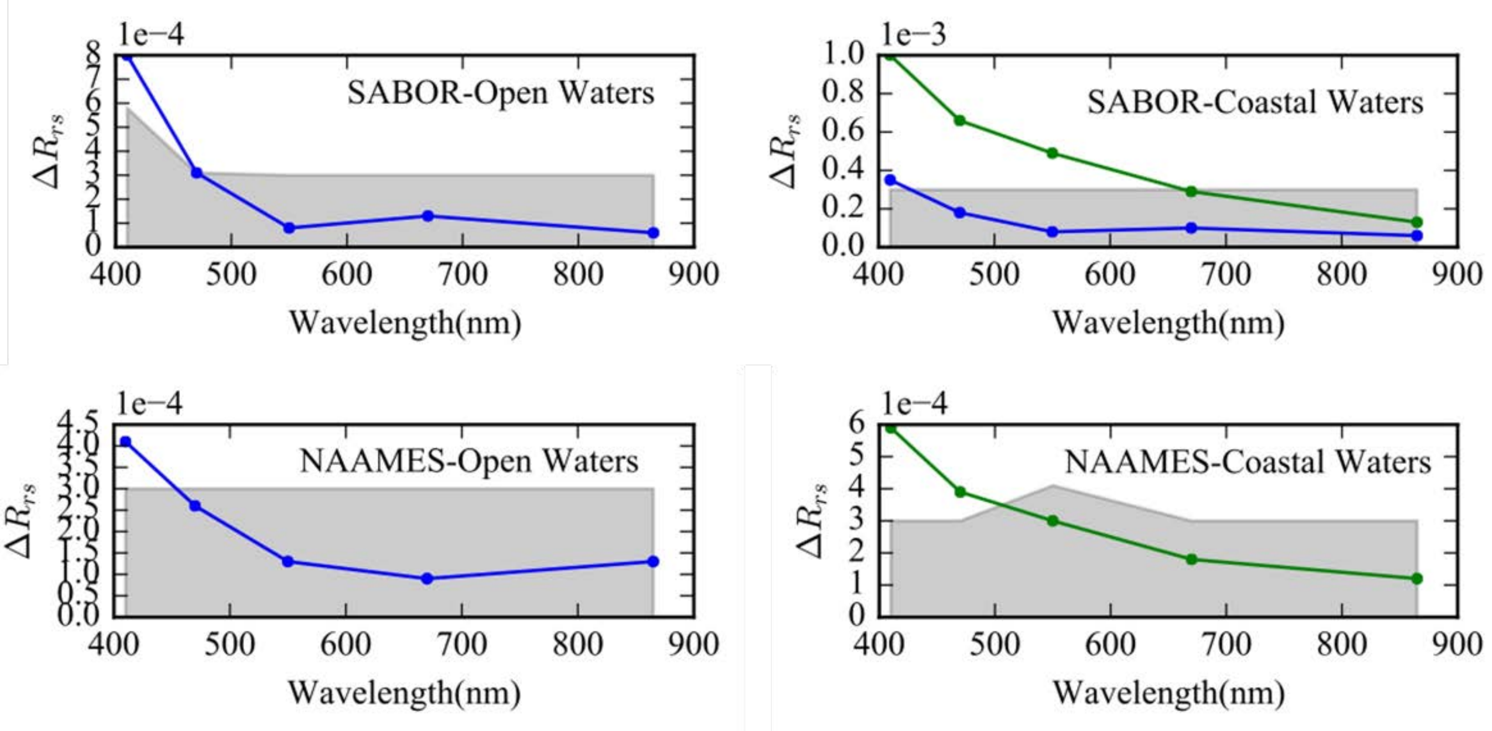
Retrieved AOD and Remote sensing reflectance






Total optical depth
Coarse mode fraction
Relative frequency
Optical depth or fraction
Fine mode SSA
Fine mode number conc. [cm⁻³]
Fine
Coarse mode/10
Effective radius [μm]
New Brunswick
Prince Edward Island
Maine
Nova Scotia
45°
43°
41°
TCAP
New Jersey
Maryland
Virginia
Carolina
N39°
N37°
N35°
N33°
N31°
N29°
W 77°30'
W 72°30'
W 67°30'
W 62°30'
SABOR

Retrieval uncertainties with PACE atmospheric correction requirement



Bio-1
Bio-2
PACE requireme
For Open waters

MAP retrieval speed is a major bottleneck

- MAP retrievals are often slow due to (~1000 forward calculation)
  - Large number of retrieval parameters (x ~15-20)
  - Multiple bands (x 4 for HARP)
  - Iterative iterations in optimization (x ~10)
  - High forward model accuracy
  - Coupled atmosphere and ocean system
- Lookup table could be too large to accommodate the large number of parameters (consider a table as large as 10^15 B ~ 10^6 GB)
- Forward model can be directly computed with accuracy often tuned down to improve speed.

Is it possible to improve both speed and accuracy simultaneously?

A deep feedforward NN fits RT well

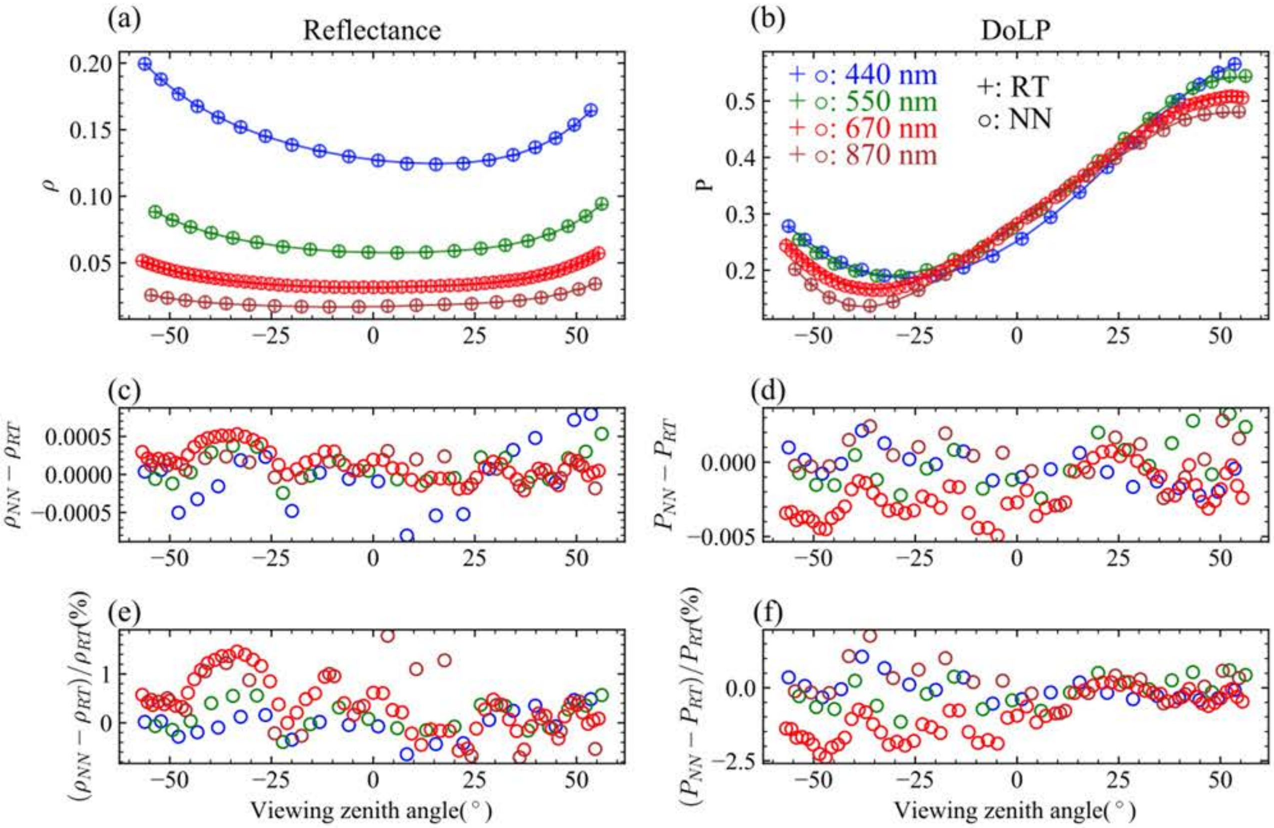
Layers	NN forward model
Input	$\mathbf{h}_0 = \mathbf{x}$
Layer 1	$\mathbf{h}_1 = \Phi(\mathbf{W}_1^T \mathbf{h}_0 + \mathbf{b}_1)$
Layer p+1	$\mathbf{h}_{p+1} = \Phi(\mathbf{W}_{p+1}^T \mathbf{h}_p + \mathbf{b}_{p+1})$
Output layer	$\mathbf{y} = \mathbf{W}_{k+1}^T \mathbf{h}_k + \mathbf{b}_{k+1}$

Uncertainty	Reflectance	DoLP
Measurement	3%	0.01
RT	0.4%	0.0007
NN	<1%	<0.003

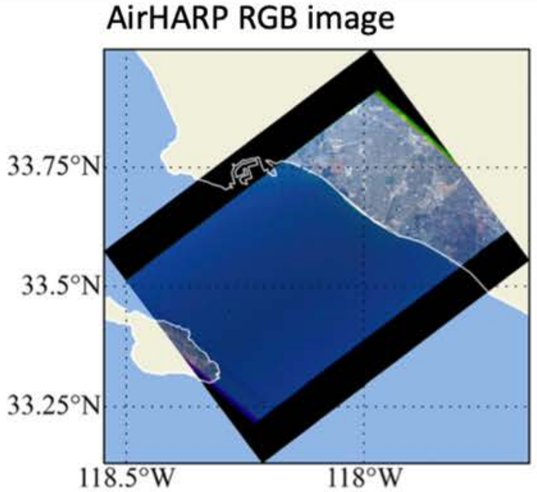
- **Two NNs** for reflectance and DoLP: 15 x 1024 x 256 x 128 x 4.
- **The NN and RT uncertainties** are included in the total uncertainty budget.
- **Additional 6 NNs** are developed for aerosol single scattering and ocean color retrieval

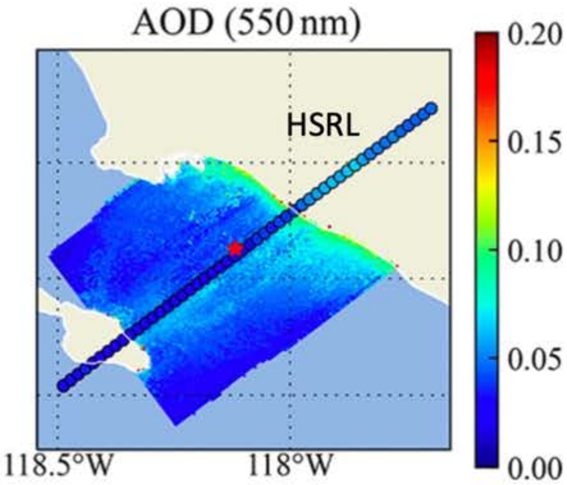
NN training and testing details: Gao et al, AMT 2021.

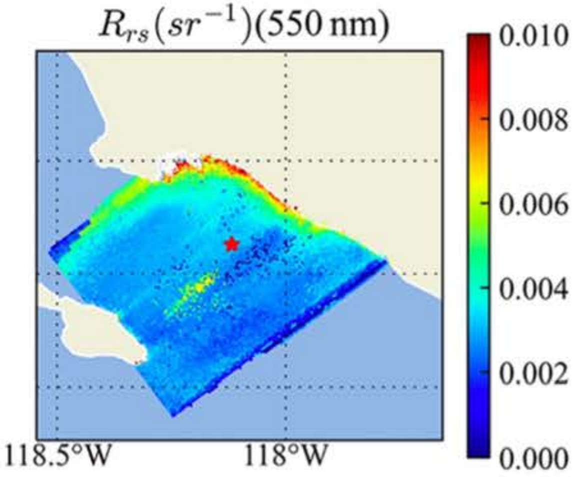
NN example on one synthetic AirHARP dataset

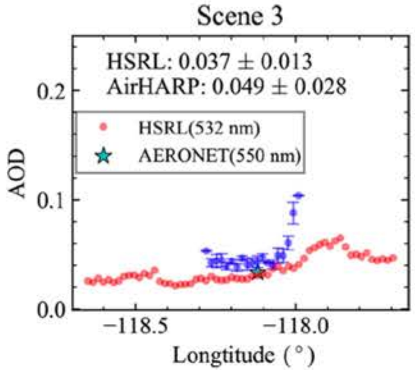


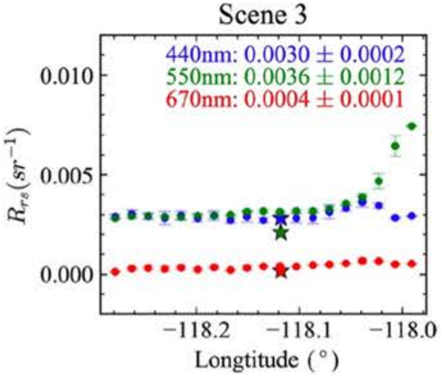
Retrievals on AirHARP/ACEPOL: Example 1











Thank HARP, HSRL, AERONET teams for providing data and support.

Gao et al, AMT 2021

Atmospheric correction over ocean for hyperspectral radiometers using multiangle polarimetric retrievals

MAP measurements → MAP retrieval with MAPOL (Aerosol and surface properties) → Estimate path radiance with forward RT model → Gas absorption correction applied on path radiance

↓

POLYAC parametrization → Hyperspectral atmospheric path radiance $\rho_{atm+sfc}(\lambda)$

↓

Hyperspectral gas absorption correction → Hyperspectral measurements → Water leaving radiance just above the water surface $L_w^+(\lambda)$

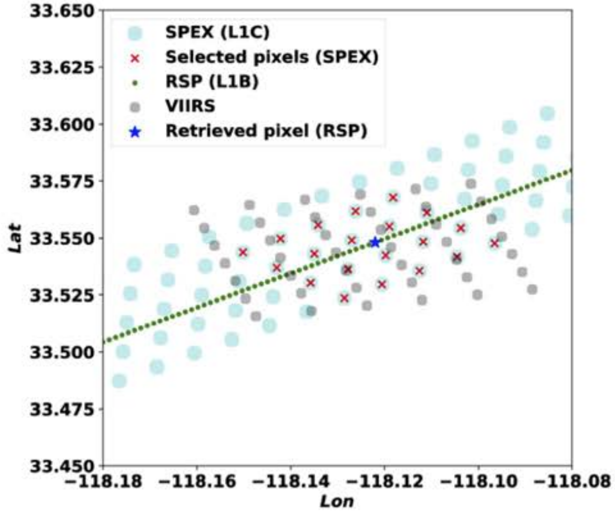
Atmospheric correction

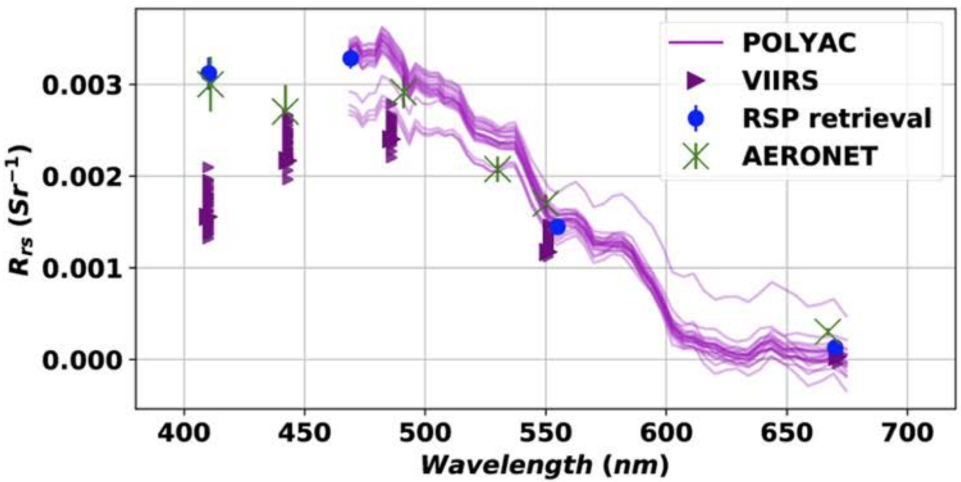
$$t_{u/d}(\lambda) = exp\left[c_3' \ \lambda^{-4.05} \times \frac{1}{\mu_{v/s}}\right]$$

$$R_{rs} = \frac{[L_w^+]_N^{ex}}{F_0}$$

Neranga et al., Optics Express, 2021

POLYAC Algorithm





Neranga et al., Optics Express, 2021

Take home messages

- Satellite or Airborne Multi-Angular-Polarimeters measure polarized radiance at multiple wavelengths and multiple viewing angles, which contains rich information on aerosol and hydrosol microphysical properties, including refractive indices, size distribution, as well as the total number concentration.
- Joint retrieval algorithms obtain the aerosol and hydrosol properties by minimizing a cost function, which represents the difference between the measurements and forward model simulations, which includes adjustable free parameters on aerosol and hydrosol properties.
- Once a minimization of the cost function is achieved, the free parameters represent the “best” representation of the scene through matching the measurement with forward models.
- Joint retrieval algorithms provide a viable approach to overcome some challenging scenes in ocean color involving absorbing aerosols and coastal waters.
- Aerosol information from polarimetric measurements can be used to help atmospheric correction of hyperspectral imagers.