UNIVERSITY OF MIAMI

Polarization in Sky and water

At least an hours worth of it

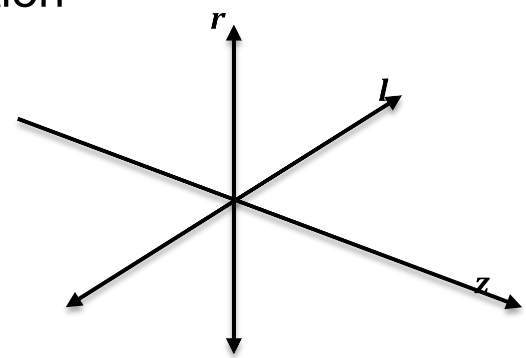
Ken Voss, Ocean Optics Summer class, 2017

Polarization important as another parameter of the light field you can measure for additional information….or it may be a problem in your measurement. Simplest light field….plane wave

Can describe plane wave propagating in z direction as:

$$E_l(z,t) = a_l \cos(\omega t - kz + \delta_l)$$

$$E_r(z,t) = a_r \cos(\omega t - kz + \delta_r)$$



Let: $\delta = \delta_r - \delta_l$

can describe the electromagnetic radiation (l and z) using a simple cosine

Some simple cases can be seen:
$\delta=0$,(or a_l or $a_r=0$) light is linearly polarized
$\delta=\pi/2$, $a_l = a_r$ light is circularly polarized
Everything else is called elliptically polarized

Introduction

Now in general, ω, for visible light is on the order of 6 x 10^{14}Hz, we can't really measure these oscillations directly, in general. Also the natural light field is not a single plane wave, but a superposition of many waves. So we need a more conv. description….the Stokes vector.

tells you how much light is polarized along the l or the r axis

These are stokes vectors

$$I = \langle a_l^2 \rangle + \langle a_r^2 \rangle = \langle E_l E_l^* \rangle + \langle E_r E_r^* \rangle = I_l + I_r$$

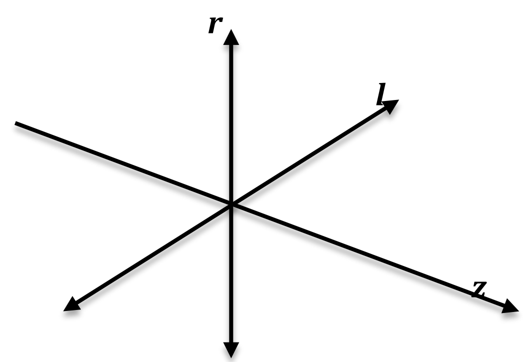
part of linear polarization:

$$Q = \langle a_l^2 \rangle - \langle a_r^2 \rangle = \langle E_l E_l^* \rangle - \langle E_r E_r^* \rangle = I_l - I_r$$

the rest of hte linear polarization

$$U = \langle 2 a_l a_r \cos\delta \rangle = \langle E_l E_r^* \rangle + \langle E_r E_l^* \rangle = I_{45} - I_{-45}$$

$$V = \langle 2 a_l a_r \sin\delta \rangle = i\left(\langle E_l E_r^* \rangle - \langle E_r E_l^* \rangle \right) = I_{RCP} - I_{LCP}$$



Some Simple Stokes Vectors:

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

has intensity but no direction

Unpolarized light

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I \\ I \\ 0 \\ 0 \end{bmatrix}$$

some intensity in Q as I

Polarized along *l*

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I \\ -I \\ 0 \\ 0 \end{bmatrix}$$

Polarized along *r*

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I \\ 0 \\ 0 \\ I \end{bmatrix}$$

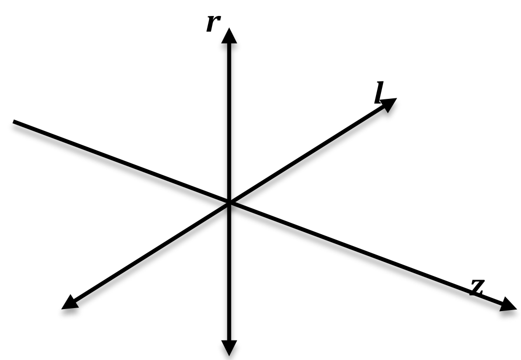
Right Circularly polarized light

$$I = I_l + I_r$$

$$Q = I_l - I_r$$

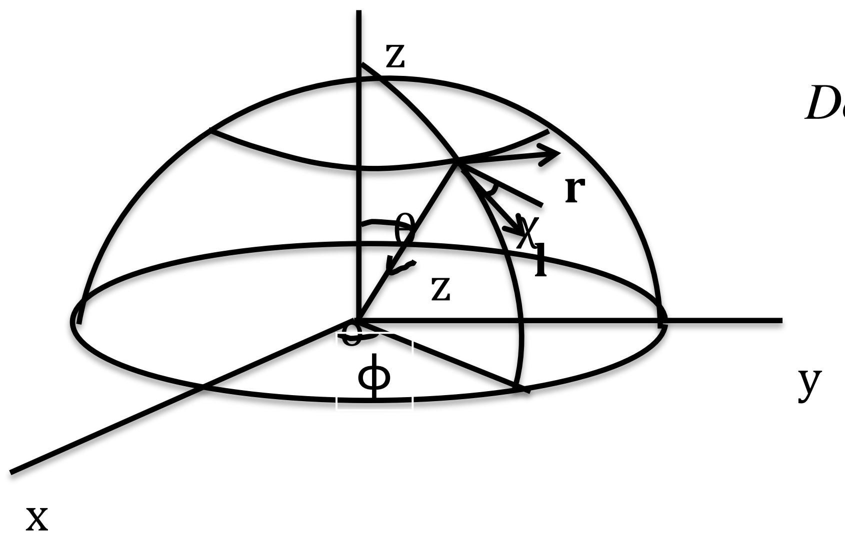
$$U = I_{45} - I_{-45}$$

$$V = I_{RCP} - I_{LCP}$$



no linear but polarized along v axis

Can't figure out where to put this slide…so here it is….



Degree of polarization

$$DoP = \frac{(Q^2+U^2+V^2)^{1/2}}{I}, \quad 0 \le DoP \le 1$$

Plane of polarization

$$\tan 2\chi = \frac{U}{Q}, \quad -90^0 \le \chi \le 90^0$$

For completeness, ellipticity $\sin 2\beta = \frac{2a_l a_r \sin\delta}{a_l^2 + a_r^2} = \frac{V}{(Q^2+U^2+V^2)^{1/2}}$

Can transform these Stokes vectors in a linear process, using Mueller Matrices:

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = \begin{bmatrix} M11 & M12 & M13 & M14 \\ M21 & M22 & M23 & M24 \\ M31 & M32 & M33 & M34 \\ M41 & M42 & M43 & M44 \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

If i ahve a four element column vextor and I Want to change this one into another one, what do I need to do?

If I did a four element row I would just get four of those things
I need a 4X4 element

Modify incoming Stokes Vector to outgoing Stokes Vector.

Can transform any incoming Stokes vector using a mueller matrix

M11 - is the volume scattering function

Examples, linear polarizer, q, is angle between reference plane and polarizer axis of acceptance.

Q is theta

$$1/2\begin{bmatrix} 1 & \cos 2\theta & \sin 2\theta & 0 \\ \cos 2\theta & \cos^2 2\theta & \sin 2\theta \cos 2\theta & 0 \\ \sin 2\theta & \sin 2\theta \cos 2\theta & \sin^2 2\theta & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

this is fully polarized light

$$\frac{I+Q}{2}\begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} = 1/2\begin{bmatrix} I+Q \\ I+Q \\ 0 \\ 0 \end{bmatrix} = 1/2\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

This becomes NO LIGHT

Two crossed polarizers

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = 1/2 \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} 1/2 \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

horizontal polarizer and vertical polarizer

$$0 = 1/4 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = 1/4 \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I \\ I \\ 0 \\ 0 \end{bmatrix}$$

Two crossed polarizers, with another one inbetween

$$1/2\begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} 1/2\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} 1/2\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$1/8\begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} I \\ I \\ 0 \\ 0 \end{bmatrix}$$

with one 45 degrees in between

Two crossed polarizers, with another one in between continued

$$= 1/8 \begin{bmatrix} I \\ -I \\ 0 \\ 0 \end{bmatrix} = 1/8 \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I \\ 0 \\ I \\ 0 \end{bmatrix}$$

A quarter wave plate has

How about a circular polarizer?

- Need a quarter wave plate after a polarizer

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = 1/2 \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} 1/2 \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = 1/4 \begin{bmatrix} I \\ 0 \\ 0 \\ I \end{bmatrix} = 1/4 \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I \\ 0 \\ I \\ 0 \end{bmatrix}$$

Take a light

To determine the Stokes vectors, need at least 4 carefully determined measurements. To determine Mueller matrix, need 16 measurements:

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = \begin{bmatrix} M11 & M12 & M13 & M14 \\ M21 & M22 & M23 & M24 \\ M31 & M32 & M33 & M34 \\ M41 & M42 & M43 & M44 \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

Typically, normalize by M11 (which is normal light scattering volume scattering function). This emphasizes the polarization properties of the matrix.

Instruments to measure the Stokes Vector are variations on radiance instruments.

Two types, either single direction at a time (such as 4 co-bore sighted Gershun tubes or 3, since the circular polarization is very small or zero for the most part) or some sort of imaging device, such as fisheye camera with polarizers.

Example Sky instrument

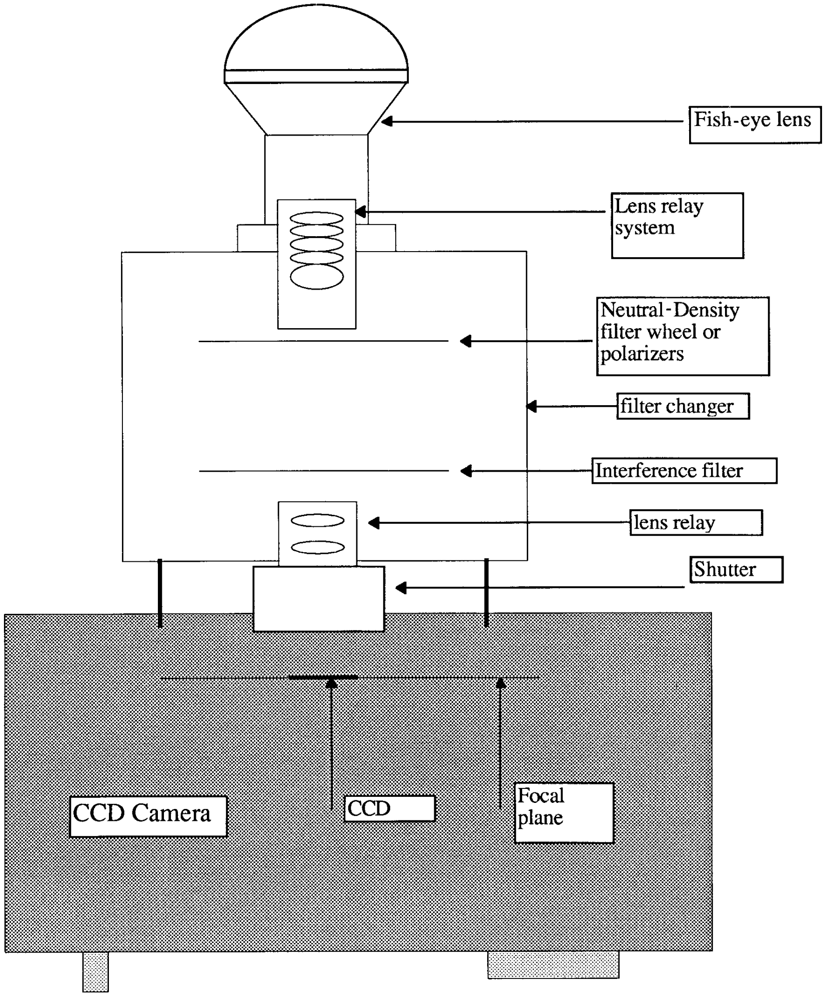
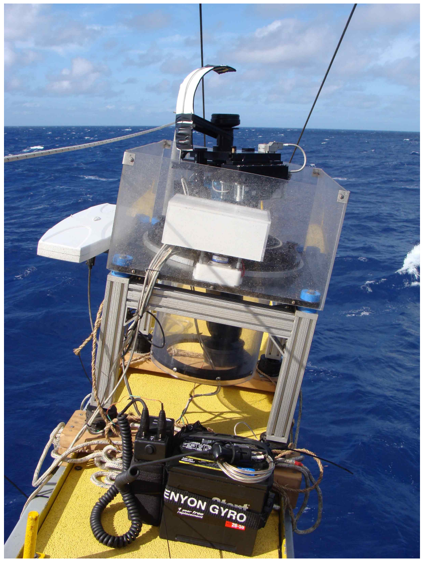
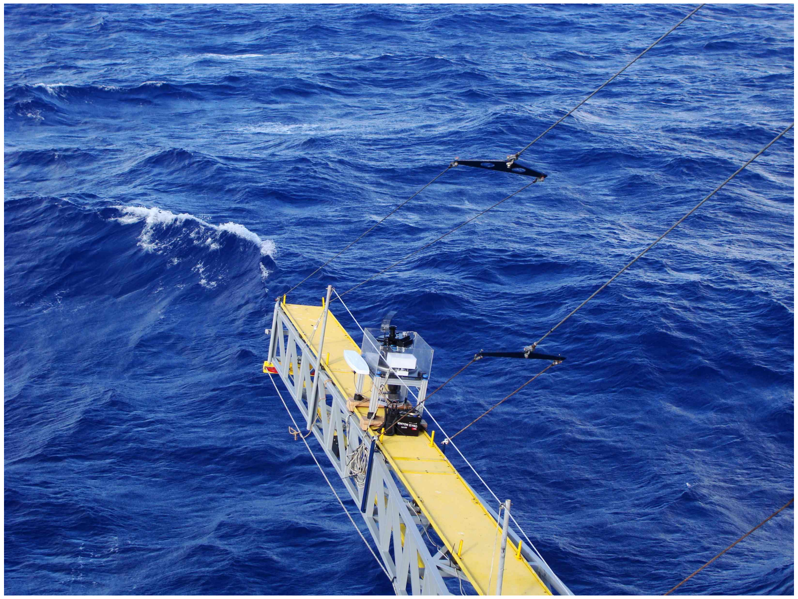


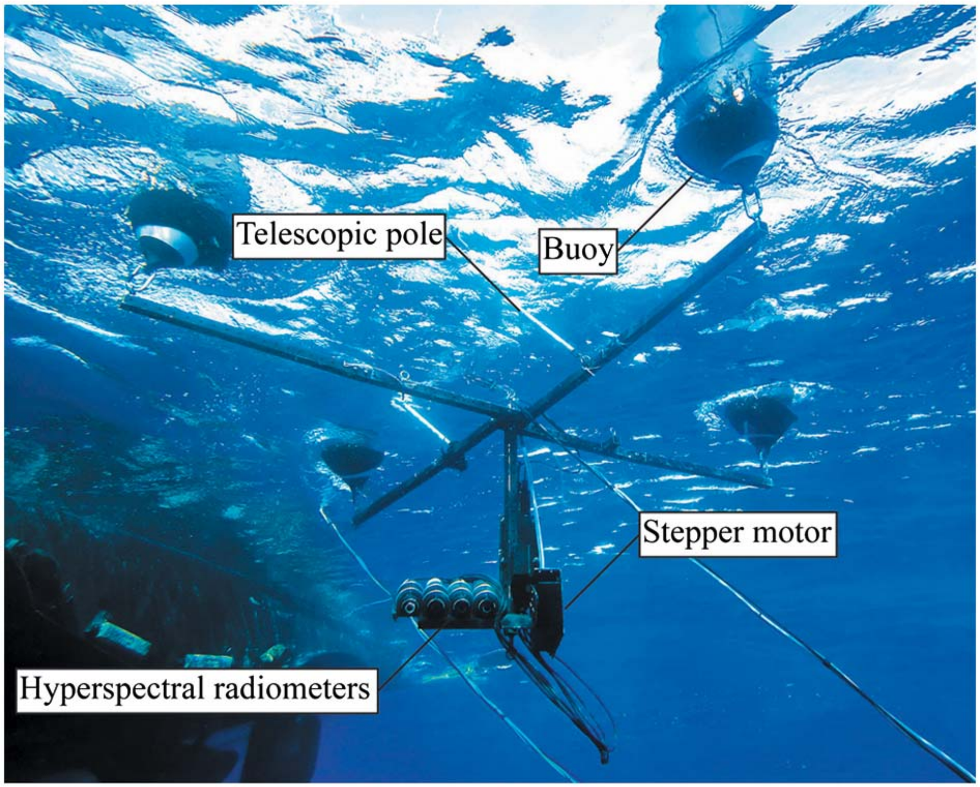
Fig. 1. Block diagram of the RADS-IIP instrument.

- Sky scene relatively stable, hence time sequence can be used
    - Example K. J. Voss and Y. Liu, “Polarized radiance distribution measurements of skylight: I. system description and characterization”, 1997, Applied Optics, **36** :6083-6094.
- Must have stabilization to use on ships/moving platforms: Adapt system used by filming crews



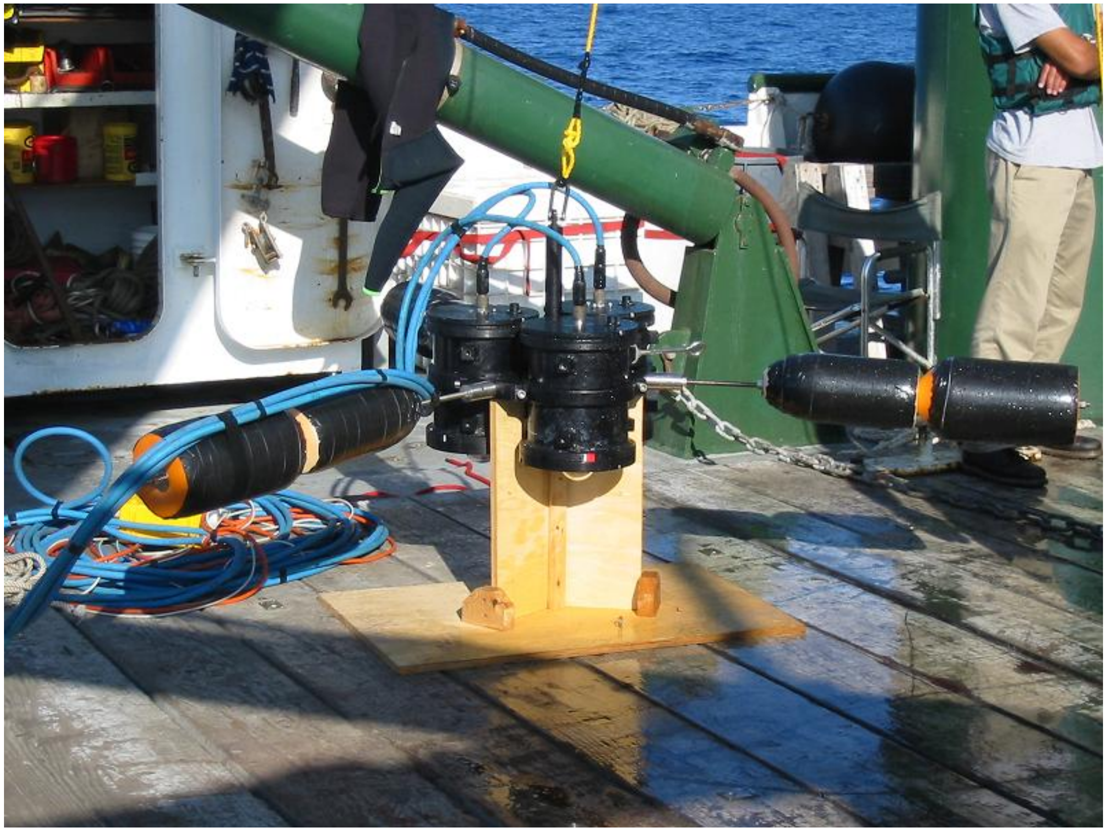


In-water…need simultaneous measurements…either with Gershun tube radiometers fitted with polarizers



Estimating particle composition and size distribution from polarized water-leaving radiance, Alberto Tonizzo,1,* Alex Gilerson,1 Tristan Harmel,1 Amir Ibrahim,Jacek Chowdhary, Barry Gross,Fred Moshary, and Sam Ahmed1, Applied Optics, Vol 50, 5047-5058

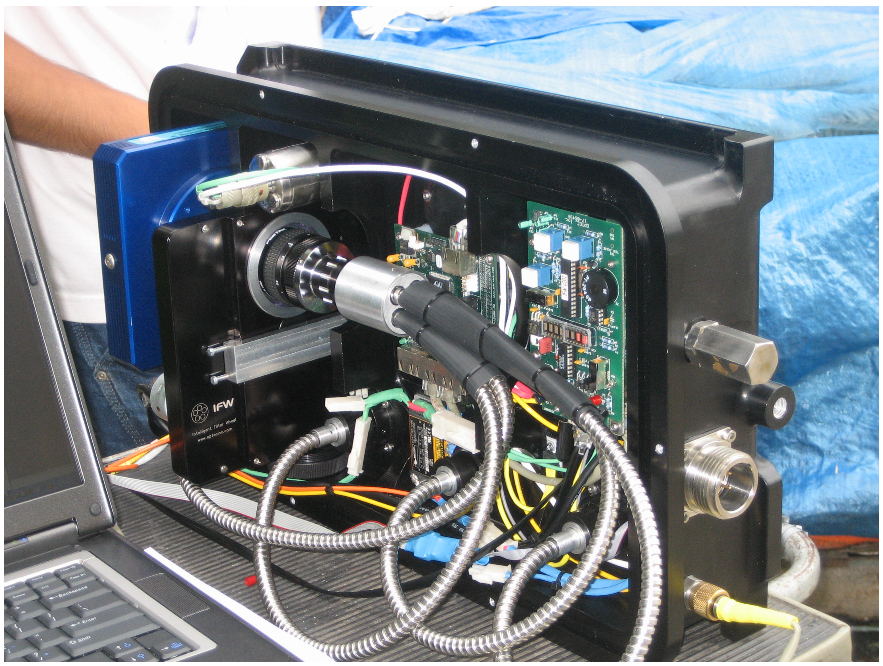
Or simultaneous fisheye systems, with polarizers:

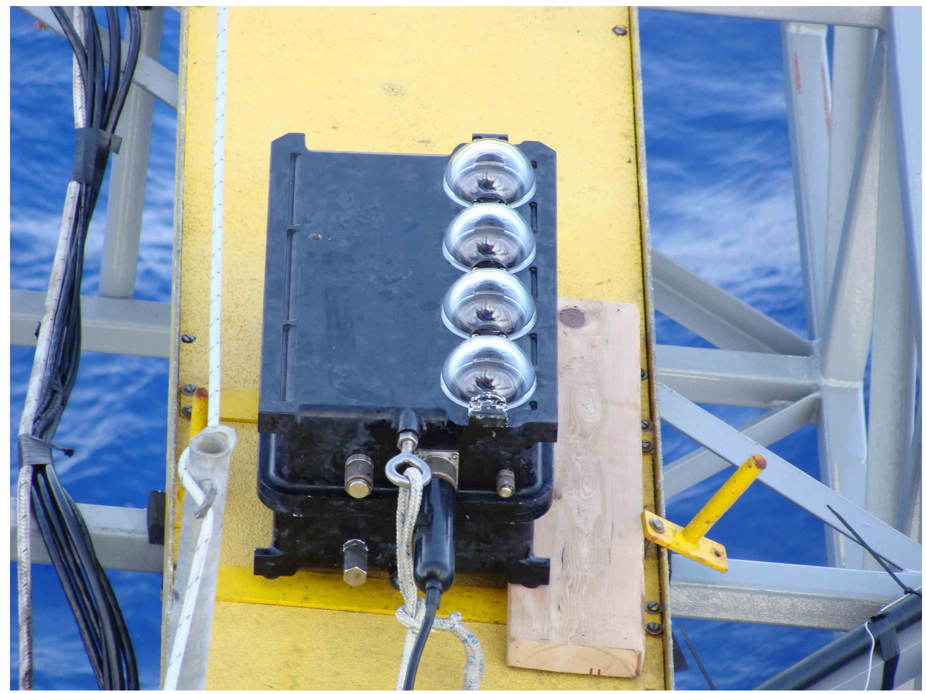


{Polrads

DPOL instrument:

- System has 4 lenses, polarizer's in each
- Fiber Optic bundle collects light from each image into one super image
- Super image focused onto camera through spectral filter changer





To measure the Mueller matrix need 16 measurements (set of 4 different input Stokes vectors permutated with 4 polarization analyzers). Either do this serially or another method was:

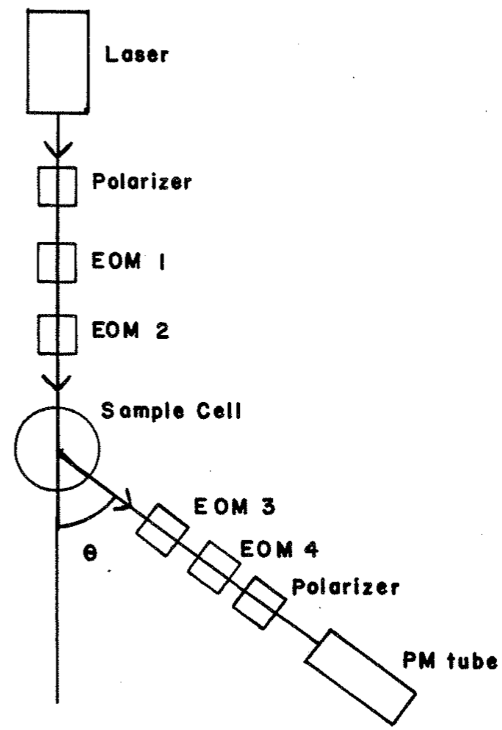
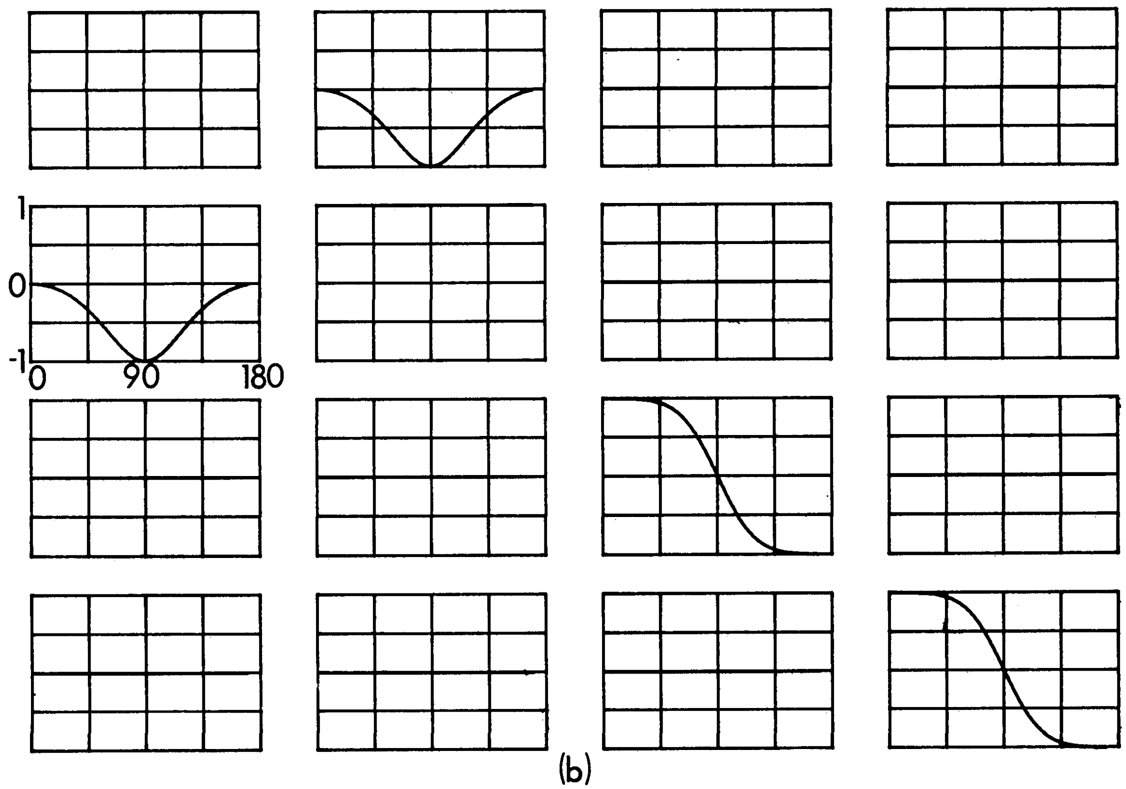


Figure 11. General Instrument Layout

each mueller matrix is a function of scattering

Mueller matrix for Rayleigh scattering.



Low index particles also scatter this way (Rayleigh-Gans approx.)

Mueller matrix for Rayleigh scattering. Lets look at some specific angles:

$$M(0°)=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

this is the identity matrix

$$M(90°)=\begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

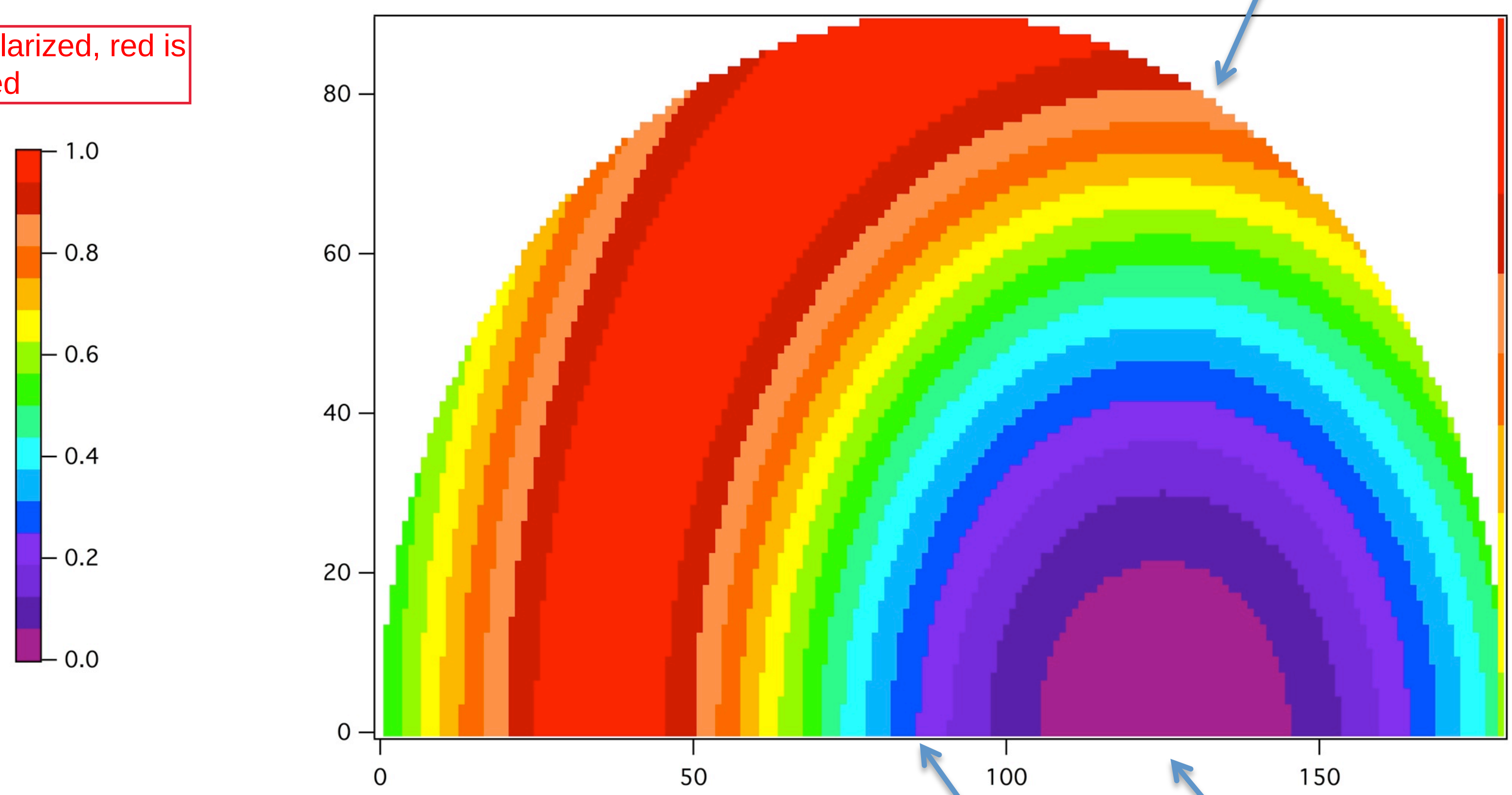
$$M(180°)=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

What do these do?

Case for Rayleigh single scattering in Sky, Degree of polarization.

purple is unpolarized, red is highly polarized

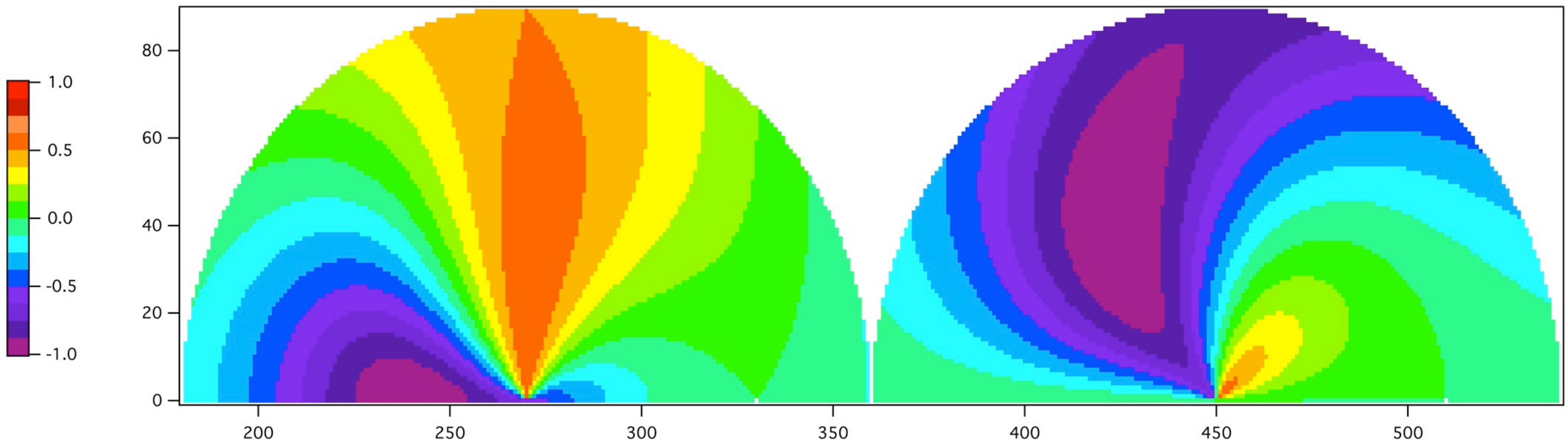
Outside edge is horizon



Solar position

Zenith

Case for Rayleigh single scattering in Sky.

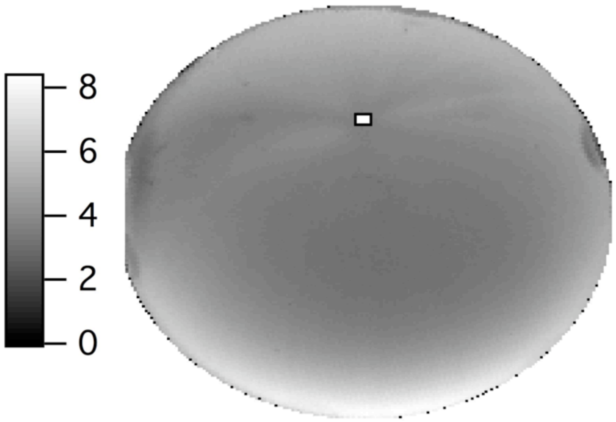


Q/I

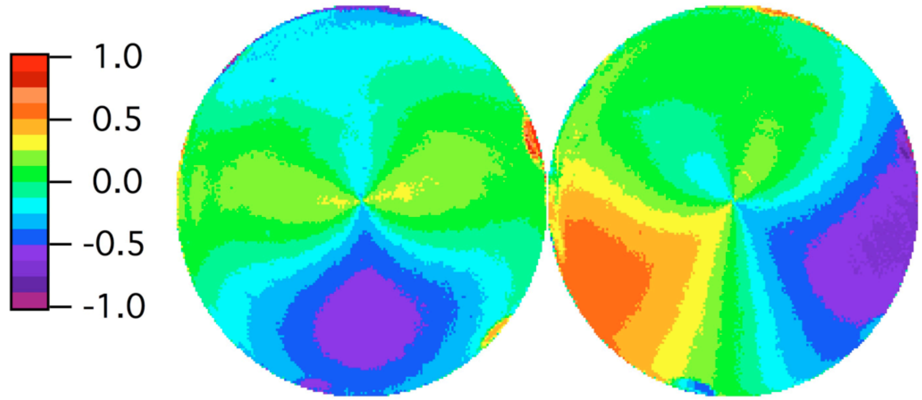
U/I

V/I = 0

60 degree zenith angle



Radiance



Q/I U/I

The radiance units are mW cm^{-2} nm^{-1} sr^{-1}, Q/I and U/I are dimensionless

Hawaii (December 2, 2005, 20.83^{0} N, 157.18^{0} W, 10:25 local time).

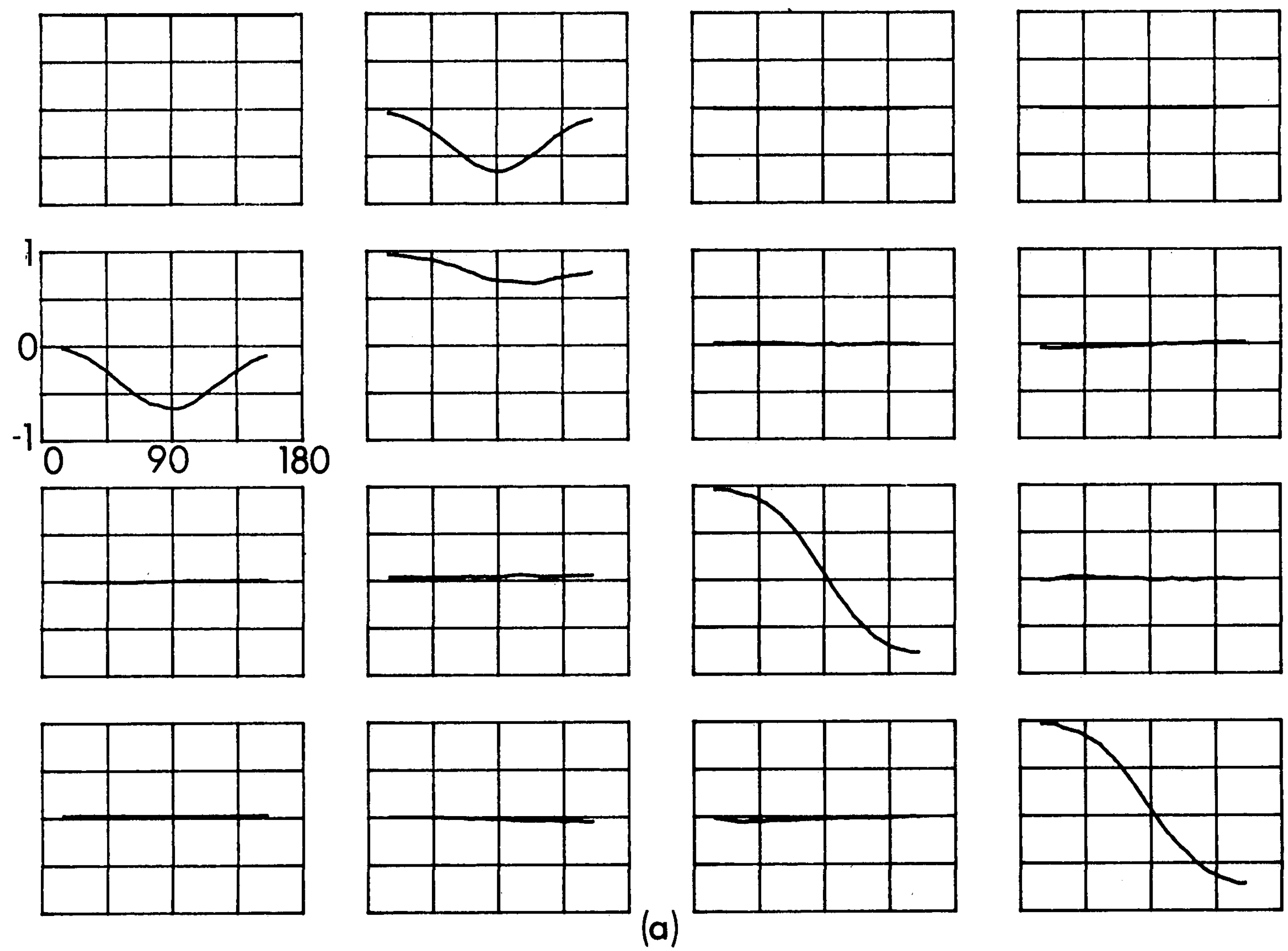
Wavelength is 436 nm

solar zenith angle is 51^{0}.

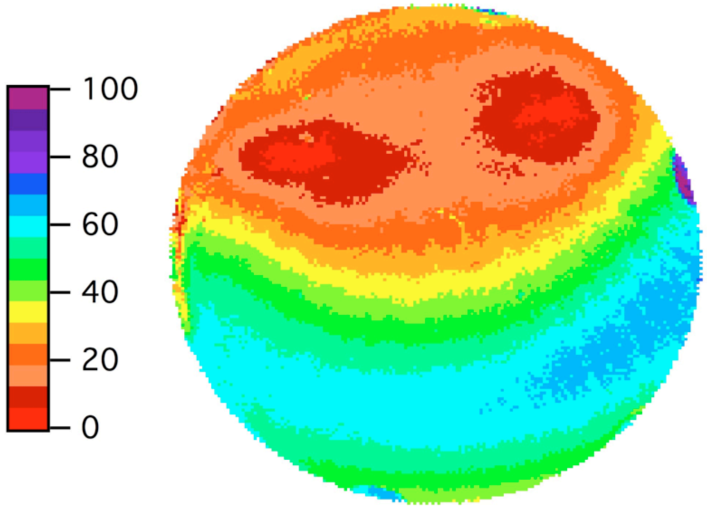
Measured with POLRads instrument (recent article in OE)

Mueller matrix for Ocean water (Voss and Fry, 1984).

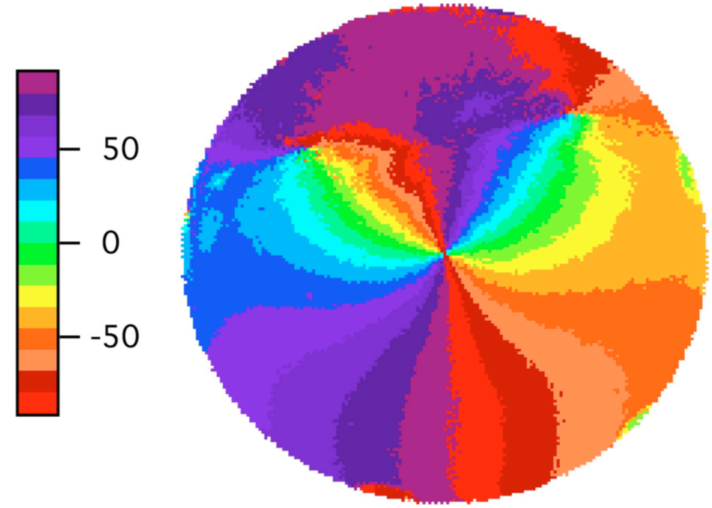
What are the differences?



Example continued

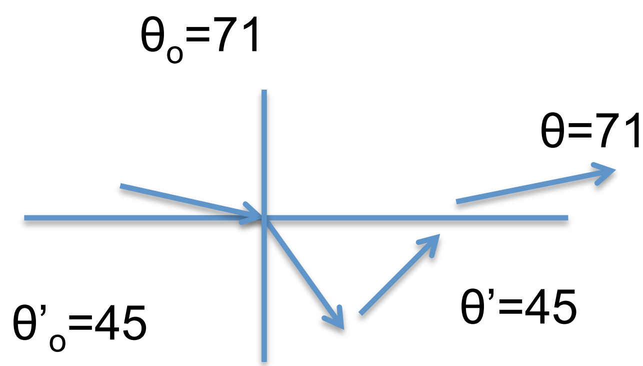


Degree of Polarization



Plane of Polarization

Note high degree of polarization, 90 degrees to refracted solar position, probably lost in glitter pattern, however still significant polarization in other areas.



Why do you care?

Other recent applications of polarization:

Use of polarized light for enhanced imaging: scattered light is more polarized than light from target (many people, early work by Gilbert, AO, 1967)..keeps getting rediscovered.

Polarized detection by animals..and polarized light camouflage (Molly Cummings, UT, Roger Hanlon, MBL).

Depolarization due to minerals?

2 possible remote sensing applications, change in M12/M11

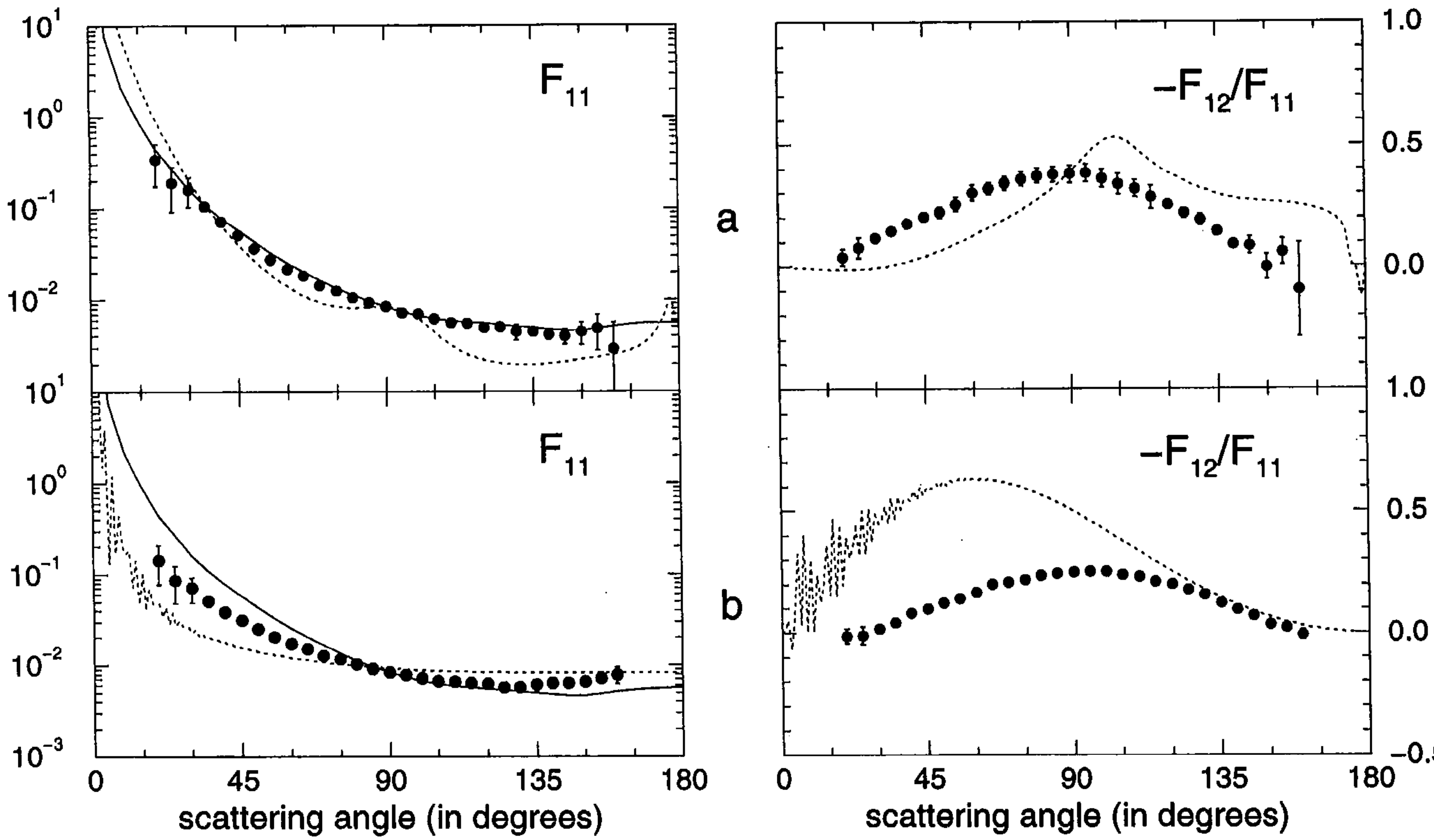


Fig. 9. Same as Fig. 6 for (a) Westerschelde silt with diameters ranging between 3 and 5 μm, and (b) Westerschelde silt with diameters ranging between 5 and 12 μm.

Volten et al., L&O, 1998, Vol 43, 1180-1197

Other ideas about polarization

- Ibrahim et al. 2012, Optics Express

Retrieve c/a

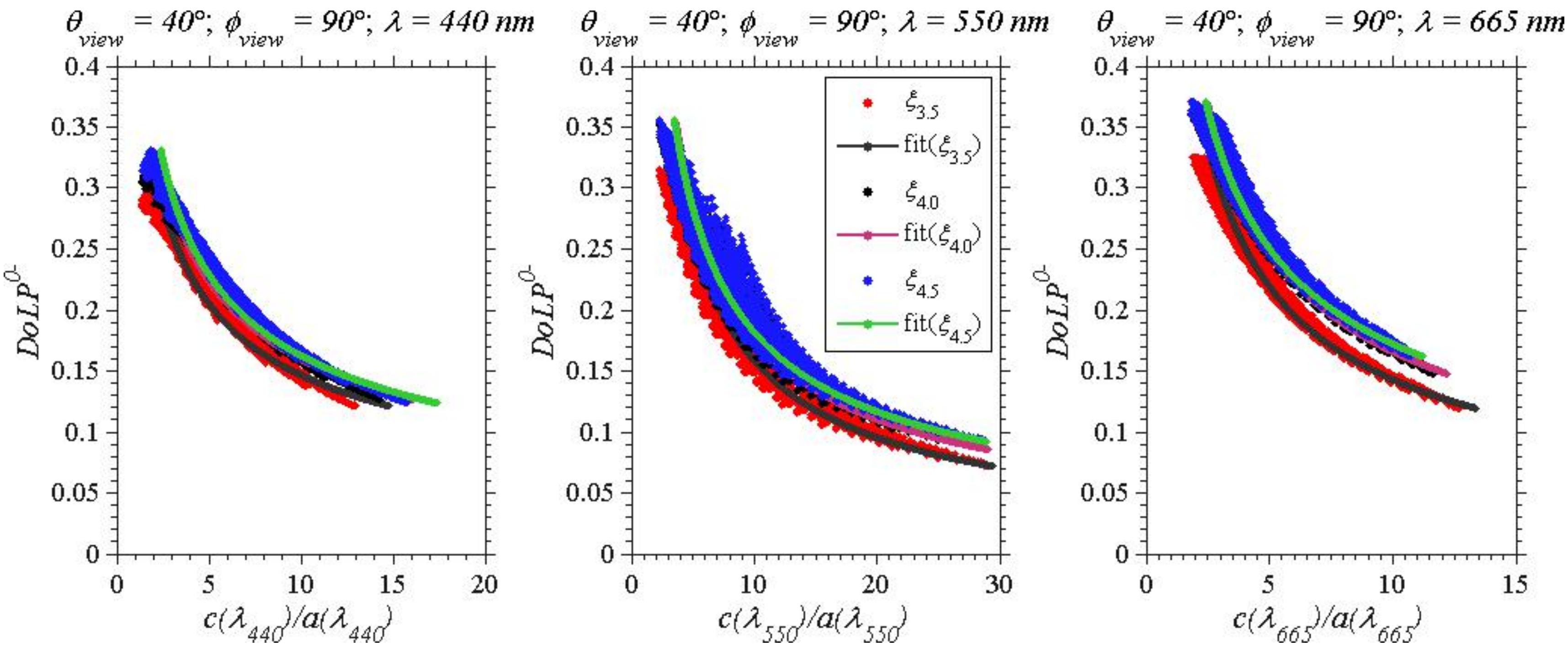


Fig. 8. Fitted relationship between DoLP at θ_{view} = 40° and φ_{view} = 90° and c/a ratio at three wavelengths for three different NAP slopes of the particle size distribution (PSD).

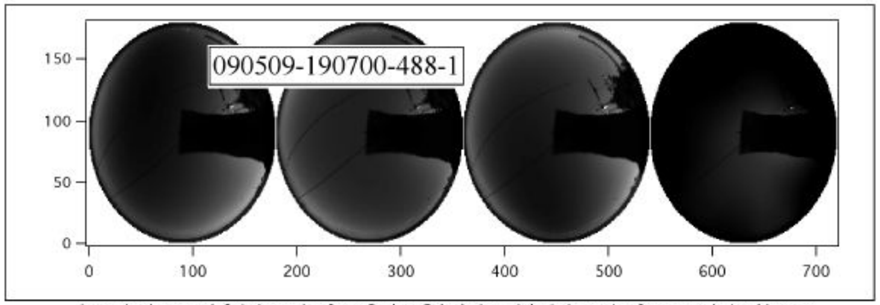
Your instrument may have a polarization sensitivity (old RSR instruments, spectrometers without scrambling)

The satellite instrument is polarized, to greater or lesser extent.

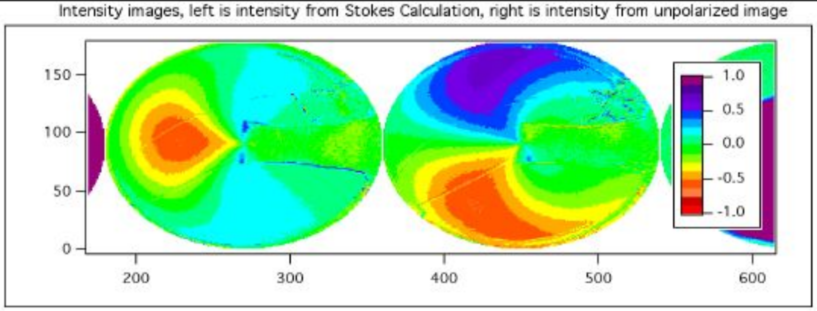
Might be more information in the polarization signal, new sensors will be developed (one sank…APS on Glory, trying for one with PACE) especially important for atmospheric aerosols.

Extra slides

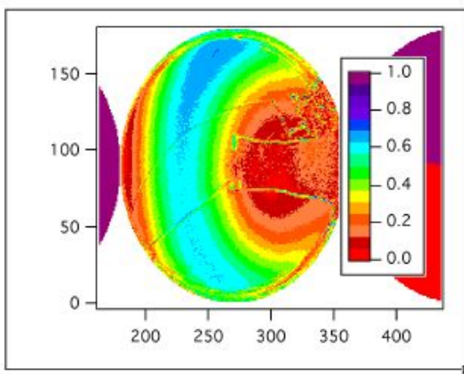
Sky light radiance distribution.



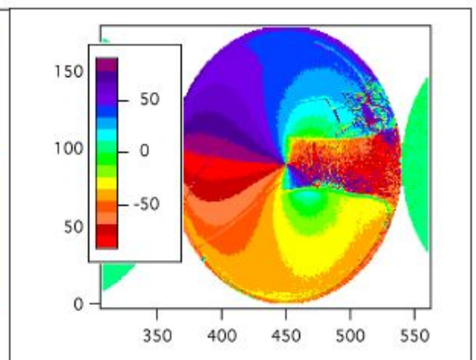
Intensity images, left is intensity from Stokes Calculation, right is intensity from unpolarized image



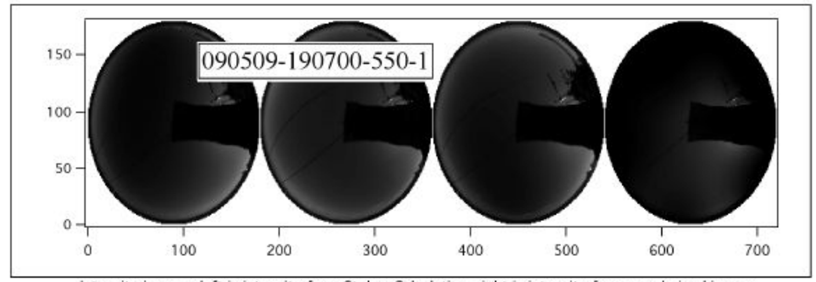
Normalized Stokes vectors Q (on left) and U (on right).



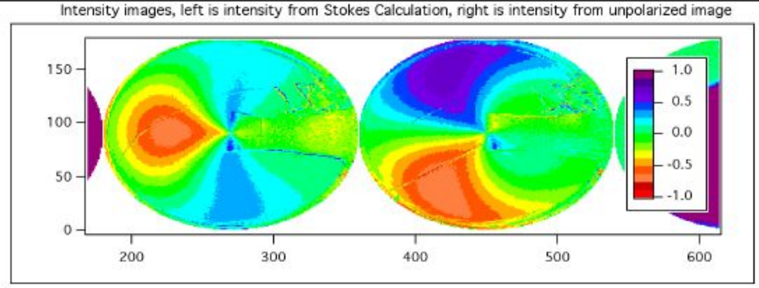
Degree of linear polarization



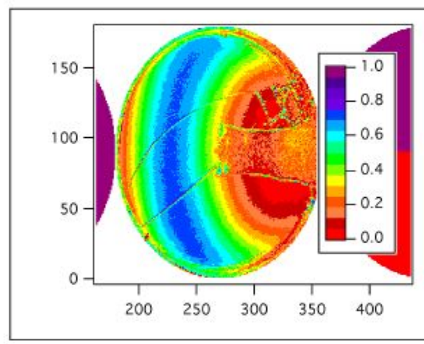
Plane of polarization, in degrees. Reference frame defined relative to plane with zenith and view direction. 0 deg is in the reference plane, positive angles rotate clockwise (looking along direction of propogation) towards the perpendicular to this plane.



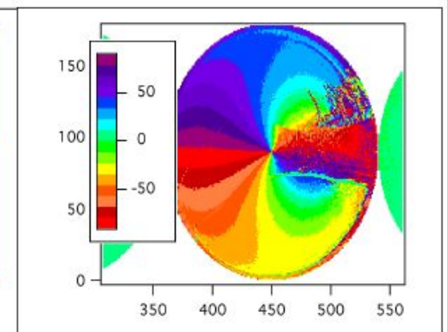
Intensity images, left is intensity from Stokes Calculation, right is intensity from unpolarized image



Normalized Stokes vectors Q (on left) and U (on right).

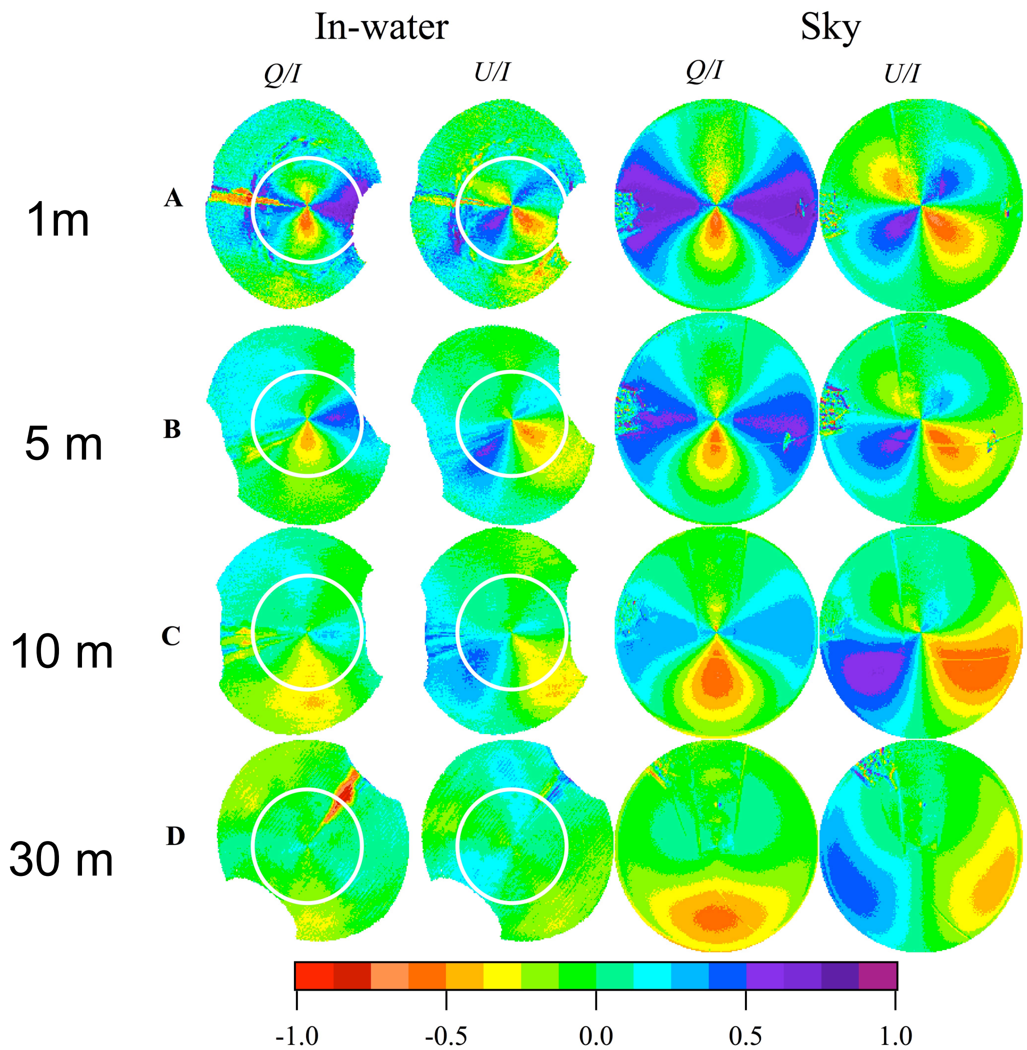


Degree of linear polarization



Plane of polarization, in degrees. Reference frame defined relative to plane with zenith and view direction. 0 deg is in the reference plane, positive angles rotate clockwise (looking along direction of propogation) towards the perpendicular to this plane.

Downwelling radiance distribution.



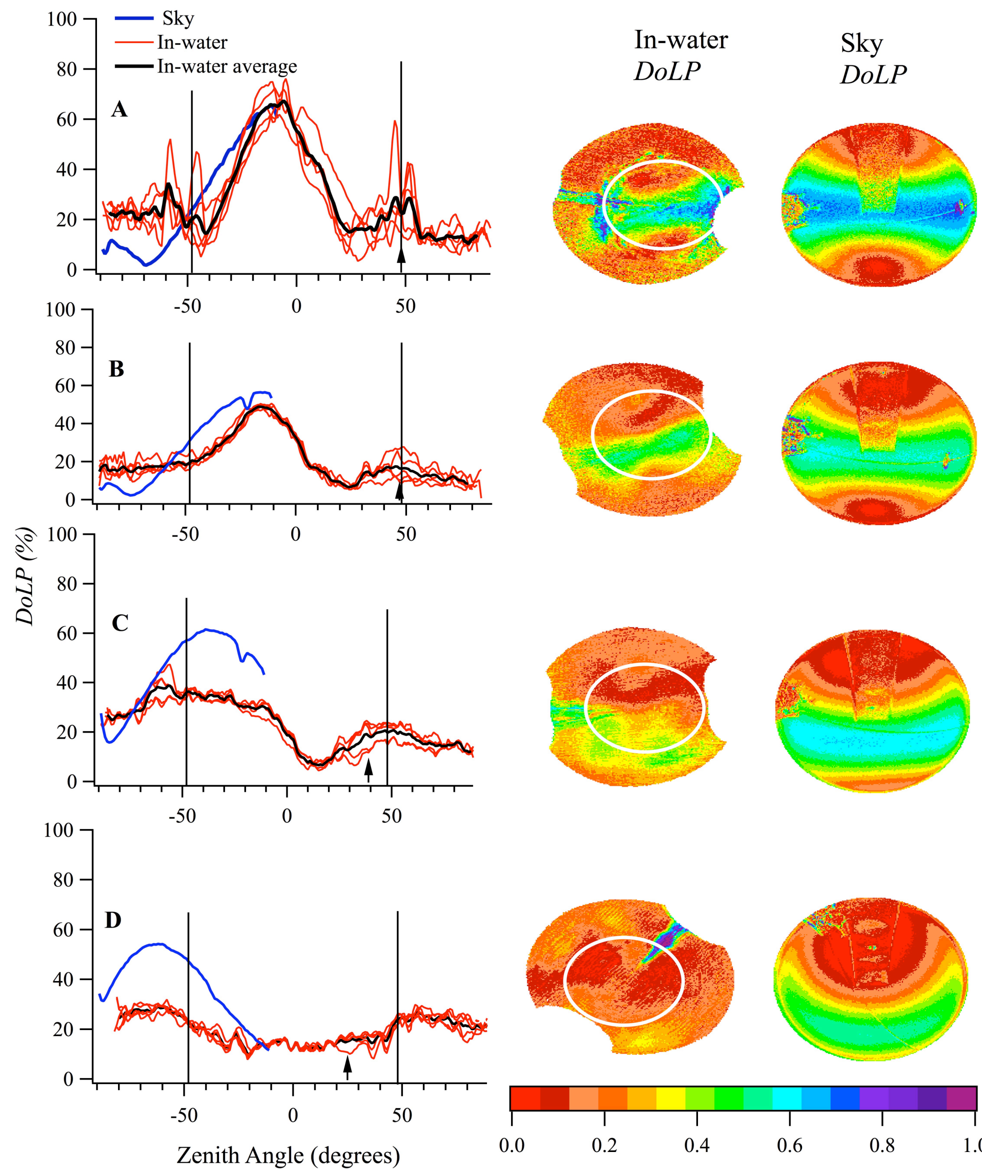
Downwelling radiance distribution.

1m

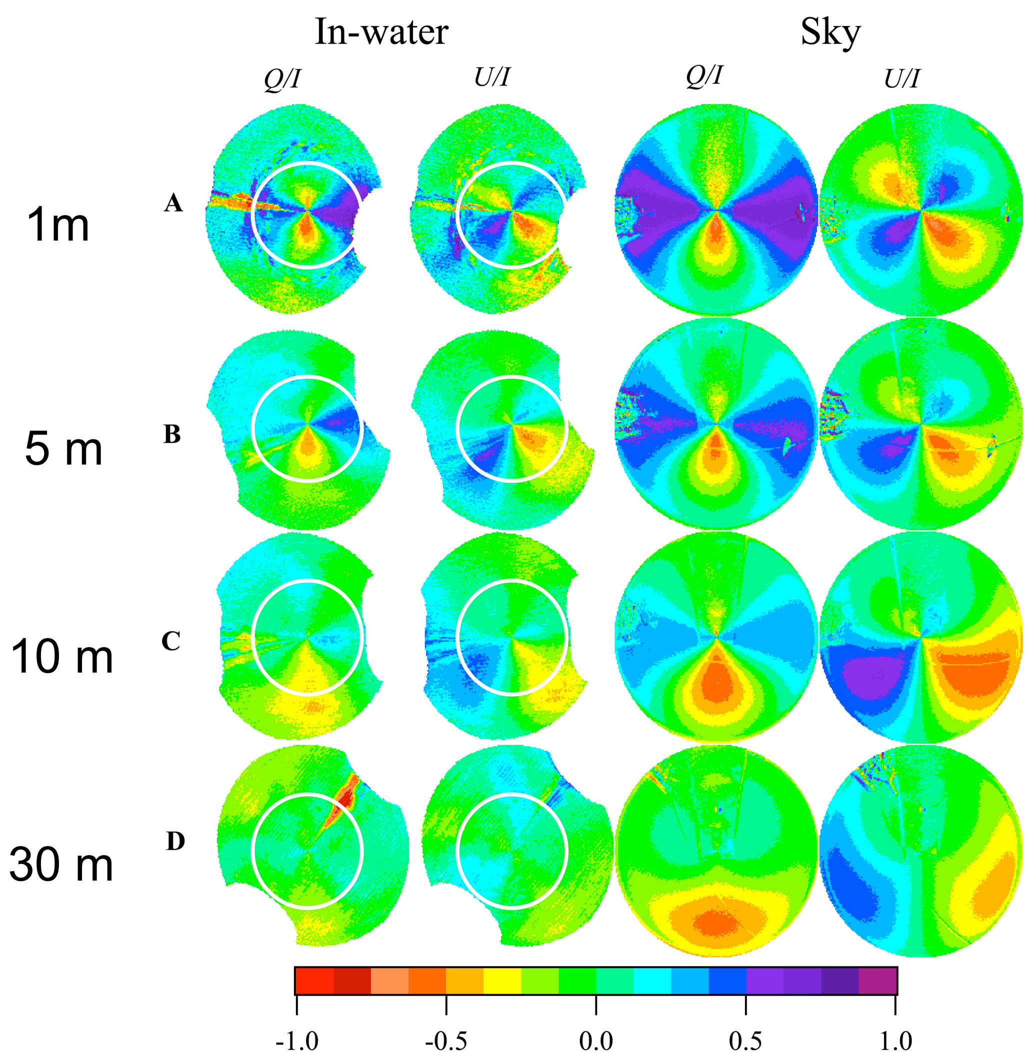
5 m

10 m

30 m

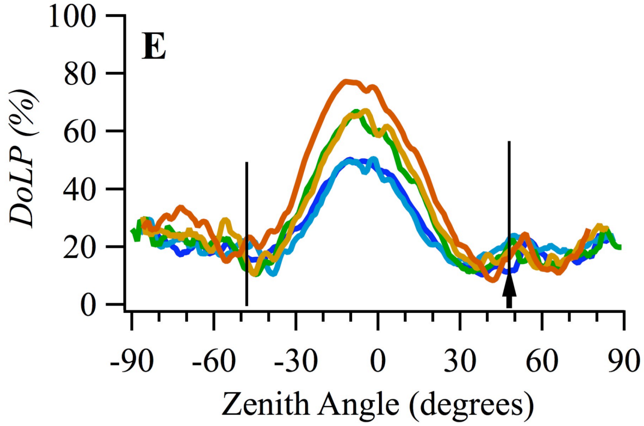


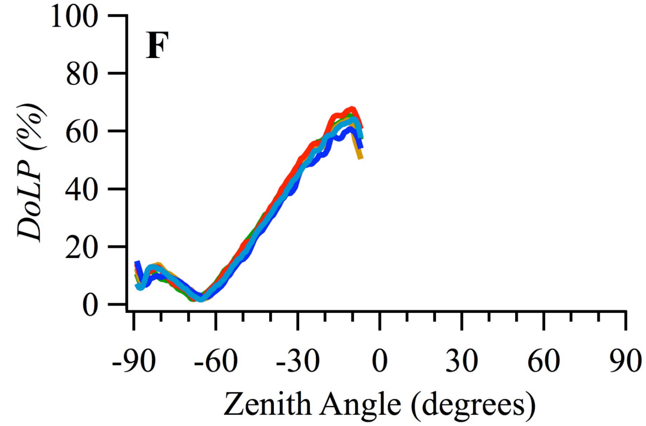
Downwelling radiance distribution.



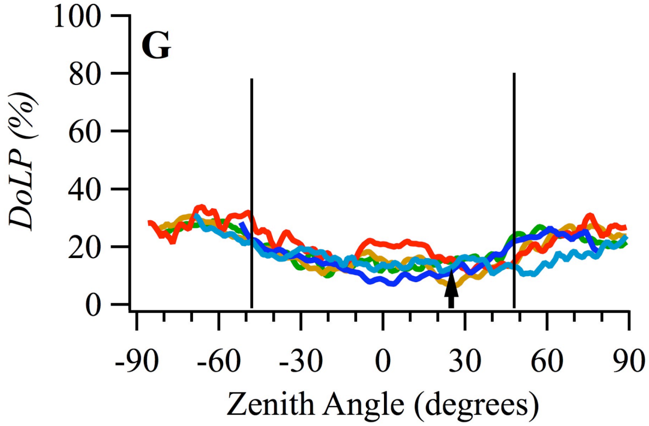
Downwelling spectral variation, coastal

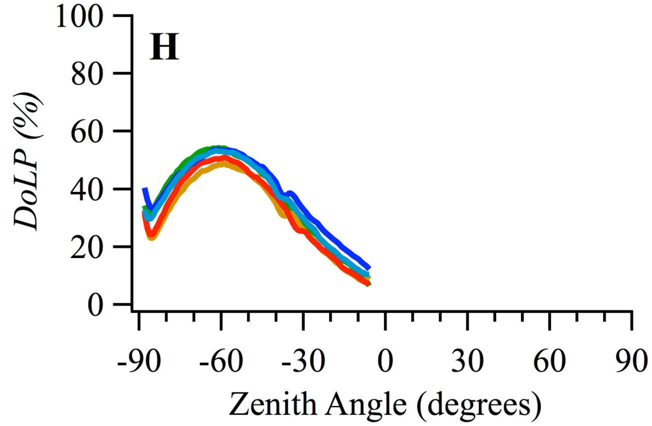
1 m



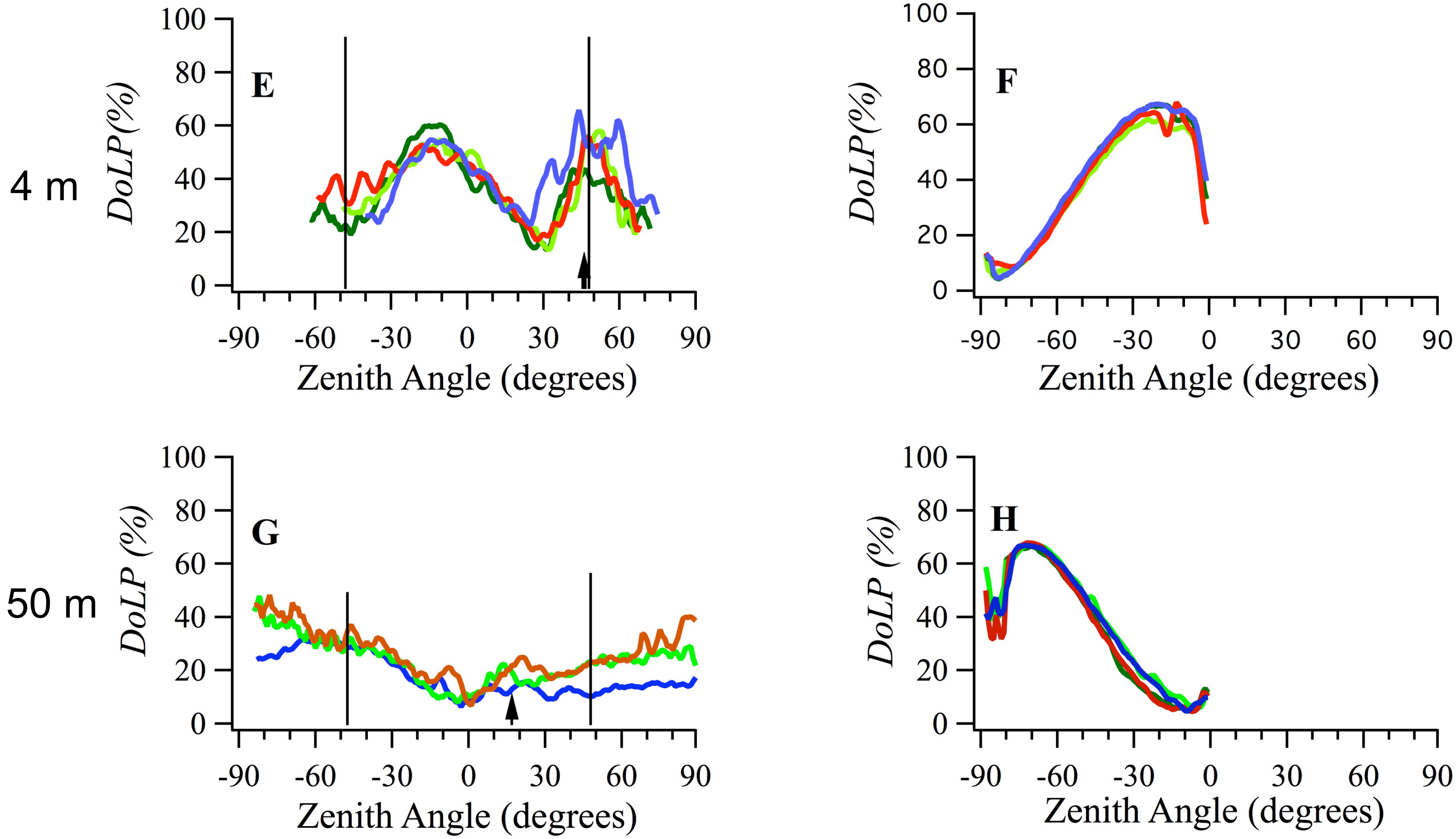


30 m



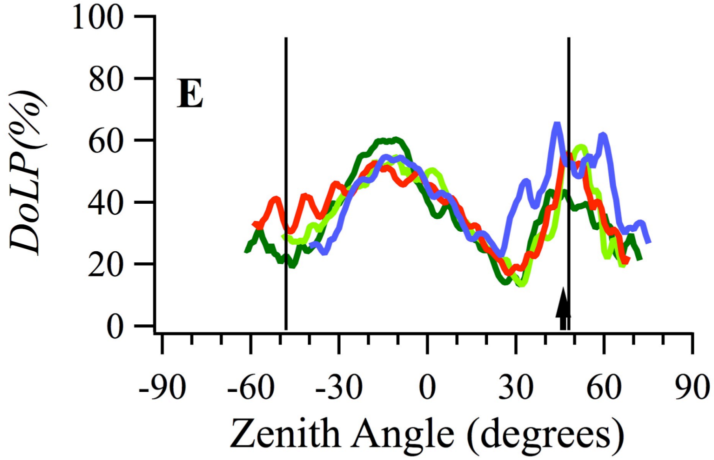


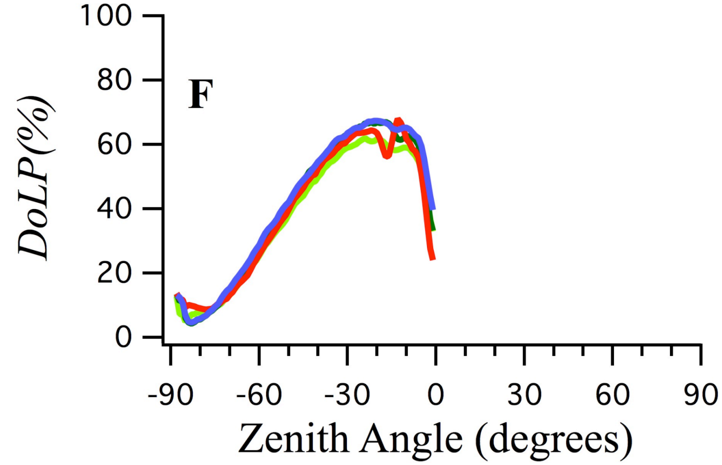
Downwelling spectral variation, clear water



Downwelling spectral variation, clear water

4 m





50 m