Full Physics-based Radiative Transfer Model for Ocean Observation: Application to HyspIRI-type Imaging Spectrometer

Peng-Wang Zhai[1], Yongxiang Hu[2], Bryan Franz[3], Jeremy Werdell[3]

[1]JCET/Physics Department, UMBC

[2]NASA Langley Research Center

[3]NASA GSFC

Why do we care about RT?

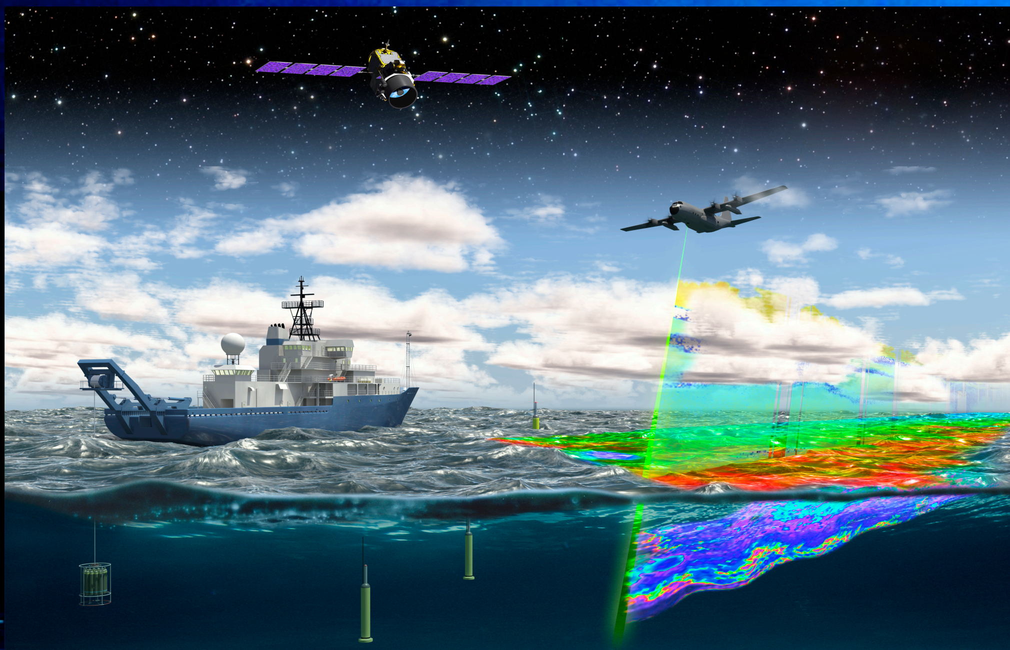


Image Credit: NASA/ Tim Marvel
https://naames.larc.nasa.gov

B.-C. Gao et al. / Remote Sensing of Environment 113 (2009) S17–S24

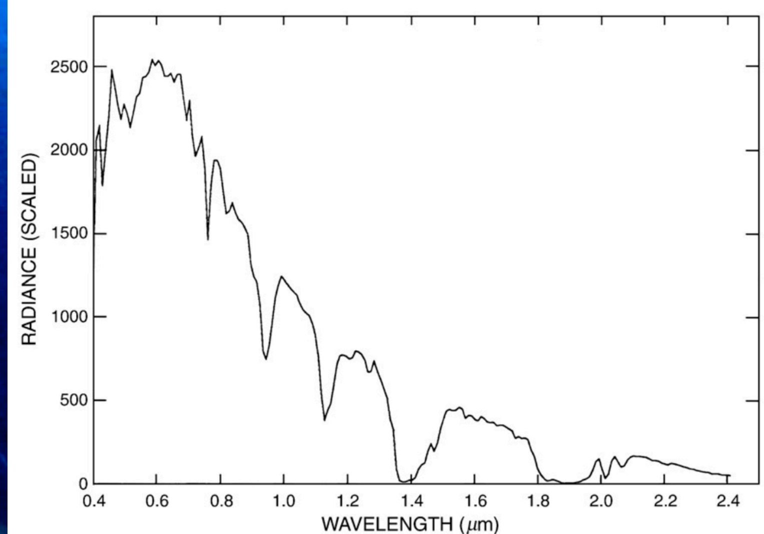


Fig. 1. A sample AVIRIS spectrum. Several absorption bands of atmospheric gases are easily seen.

Source: Bo-Cai Gao et al.
RSE, 2009

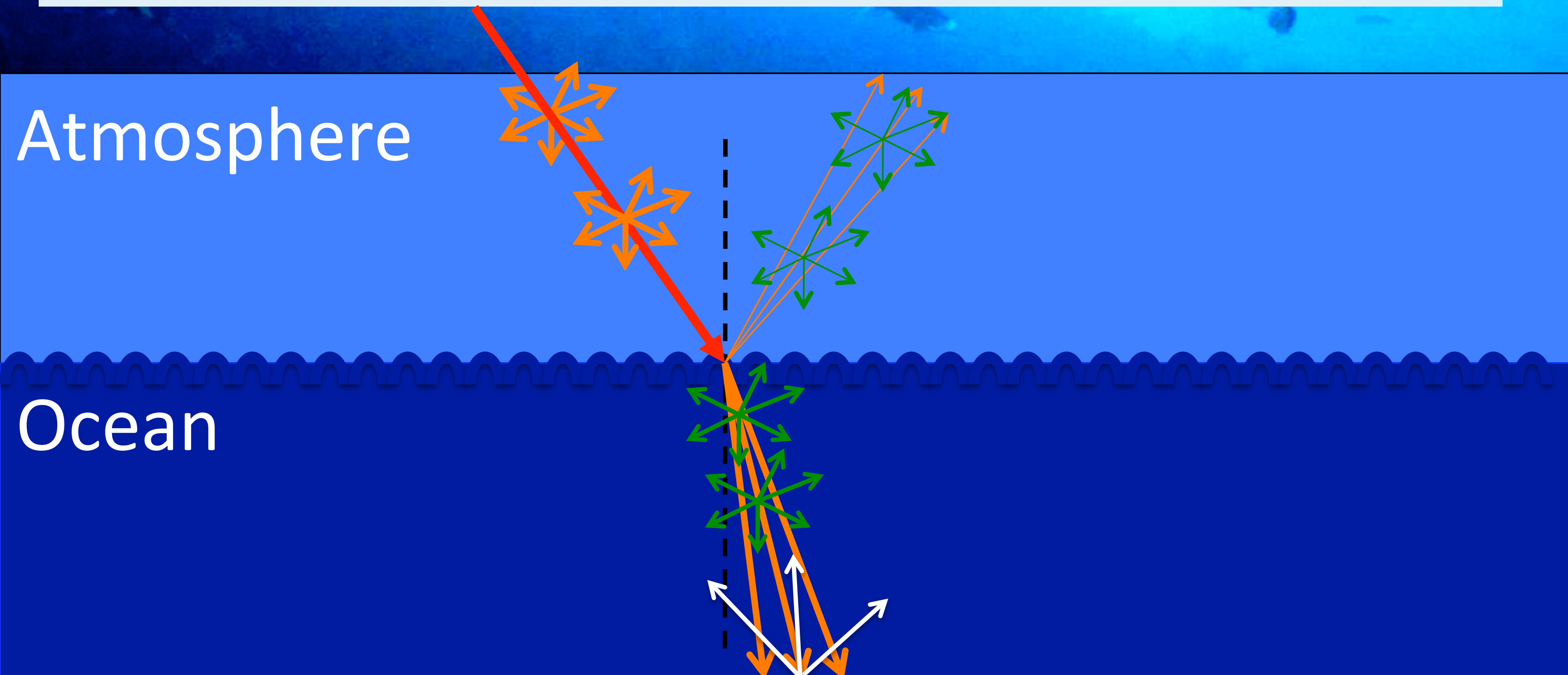
$$\mu \frac{d\mathbf{L}(z, \mu, \phi, \lambda)}{dz} = -c(z, \lambda)\mathbf{L}(z, \mu, \phi, \lambda) + \mathbf{S}(z, \mu_0, \mu, \phi, \lambda) + \mathbf{S}_i(z, \mu_0, \mu, \phi, \lambda),$$

How can RT help for HyspIRI?

Many uses, for example:

- New atmospheric correction schemes;
- New retrieval algorithms;
- Sensitivity study for environmental parameters;
- Validating remote sensing algorithms;
- Understand optical scattering and absorption processes…

So, How do you solve the RT equation?



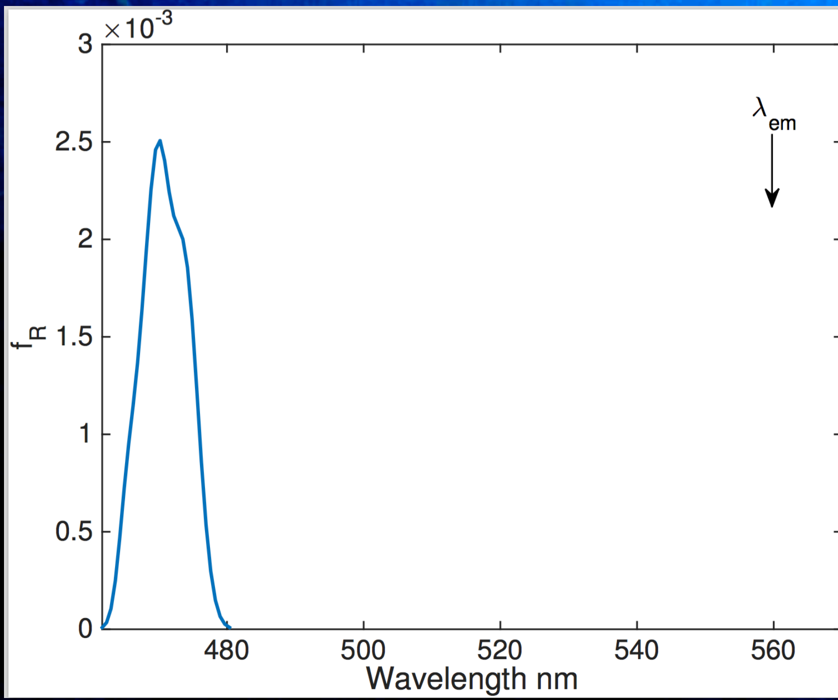
Zhai, P, et al., “A vector radiative transfer model for coupled atmosphere and ocean systems with a rough interface,” J Quant Spectrosc Radiat Transf, **111**, 1025-1040 (2010).

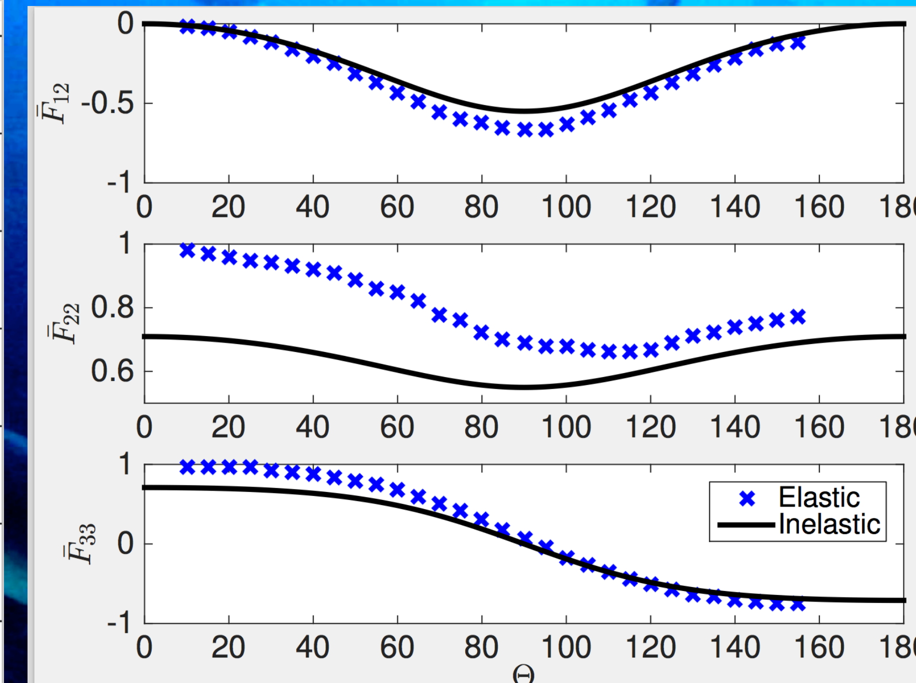
Zhai, P, et al., "A vector radiative transfer model for coupled atmosphere and ocean systems based on successive order of scattering method," Opt. Express **17**, 2057-2079 (2009).

What is special about your model?

- Full Stokes vector solution, i.e., polarization is preserved.
- Atmosphere-ocean coupling,
- Flexible detector location;
- Major gas absorption is included in the visible and near infrared, and SWIR.
- Inelastic scattering in ocean water;
  - ✓ Raman scattering
  - ✓ Chlorophyll Fluorescence;
  - ✓ Fluorescent Dissolved Organic Matter;

Raman scattering characteristics

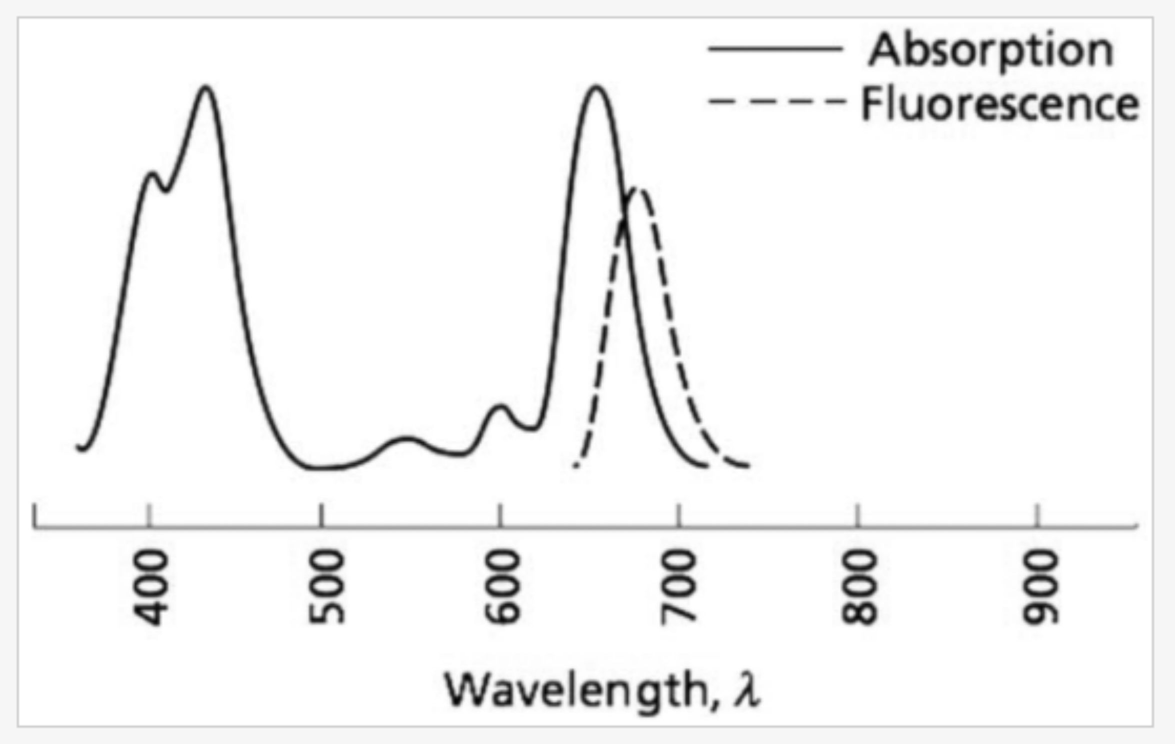




- ❖ The mean frequency shift is around 3000 cm^{-1} between excitation and emission wavelengths.
- ❖ Inelastic scattering depolarizes the scattered light more than elastic scattering.

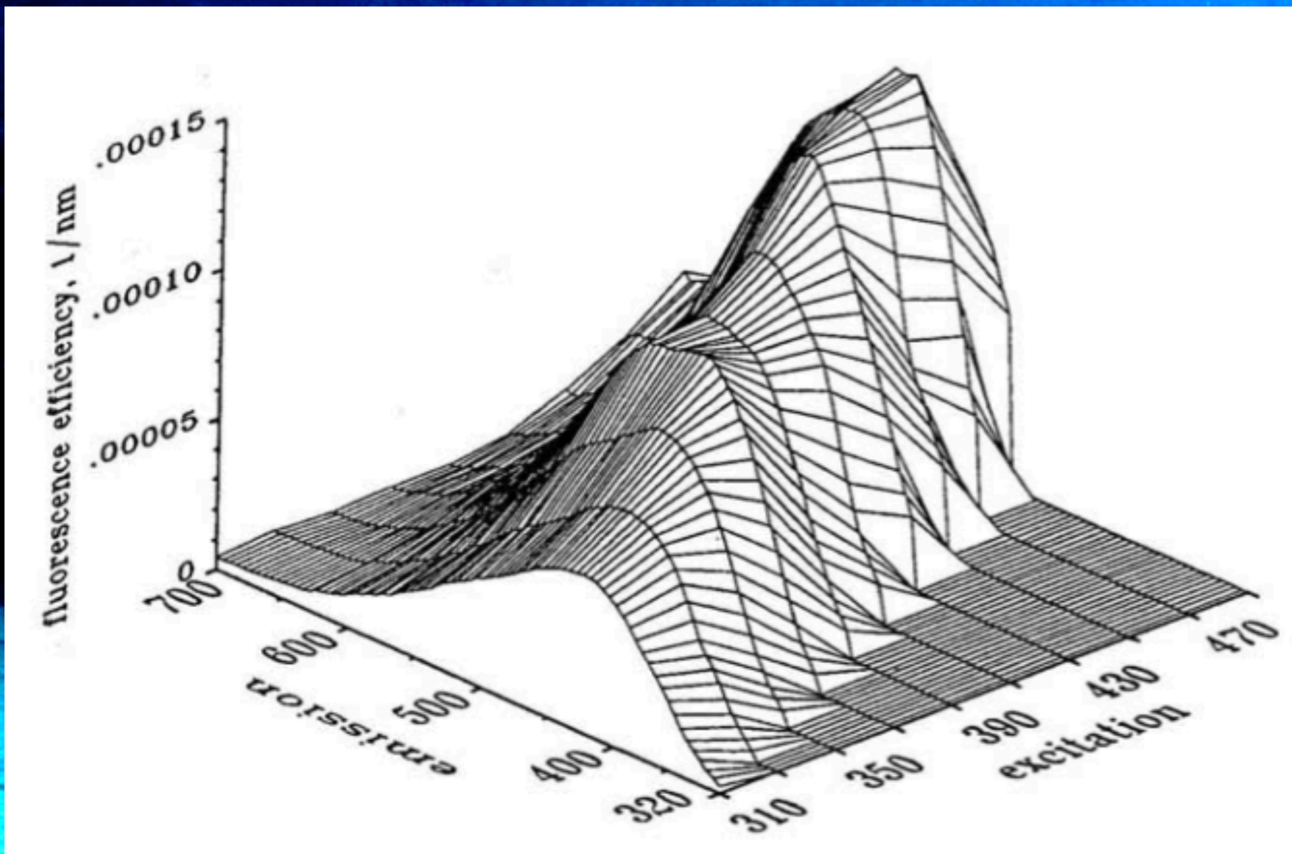
Reference: Mobley, 1994; Kattawar, 1992

Chlorophyll fluorescence



- Taiz, L.; Zeiger, E. Plant Physiology, 5th ed.; Sinauer Association; Sunderland, MA, USA, 2002; pp. 111-192.
- Fernandez-Jaramillo, A.A.; et al. Instrumentation in Developing Chlorophyll Fluorescence Biosensing: A Review. *Sensors* **2012**, *12*, 11853-11869.

FDOM Response Function



Example of the spectral fluorescence quantum efficiency function for yellow matter (Hawes, 1992)

Inelastic Scattering in VRT

$$\mu \frac{d\mathbf{L}(z, \mu, \phi, \lambda)}{dz} = -c(z, \lambda)\mathbf{L}(z, \mu, \phi, \lambda) + \mathbf{S}(z, \mu_0, \mu, \phi, \lambda) + \mathbf{S}_i(z, \mu_0, \mu, \phi, \lambda),$$

$$\mathbf{S}_i = \mathbf{S}_R + \mathbf{S}_Y + \mathbf{S}_C$$

$$\int_0^{\lambda} \int_0^{2\pi} \int_{-1}^{1} b_R(z, \lambda, \lambda_e)\mathbf{P}_R(z, \mu, \phi, \mu', \phi', \lambda, \lambda_e) \cdot \mathbf{L}(z, \mu', \phi', \lambda_e) d\mu' d\phi' d\lambda_e$$

$$\mathbf{S}_F(z, \mu, \phi, \lambda) = \int_0^{\infty} \int_0^{2\pi} \int_{-1}^{1} b_F(z, \lambda, \lambda_e)\mathbf{P}_F(z, \mu, \phi, \mu', \phi', \lambda, \lambda_e) \cdot \mathbf{L}(z, \mu', \phi', \lambda_e) d\mu' d\phi' d\lambda_e,$$

F can be either CDOM or Chlorophyll A.

Solving an Inelastic RT

$$\mathbf{S}_F(z,\mu,\phi,\lambda) = \int_0^\infty \int_0^{2\pi} \int_{-1}^{1} b_F(z,\lambda,\lambda_e)\mathbf{P}_F(z,\mu,\phi,\mu',\phi',\lambda,\lambda_e)\cdot\mathbf{L}(z,\mu',\phi',\lambda_e)d\mu' d\phi' d\lambda_e,$$

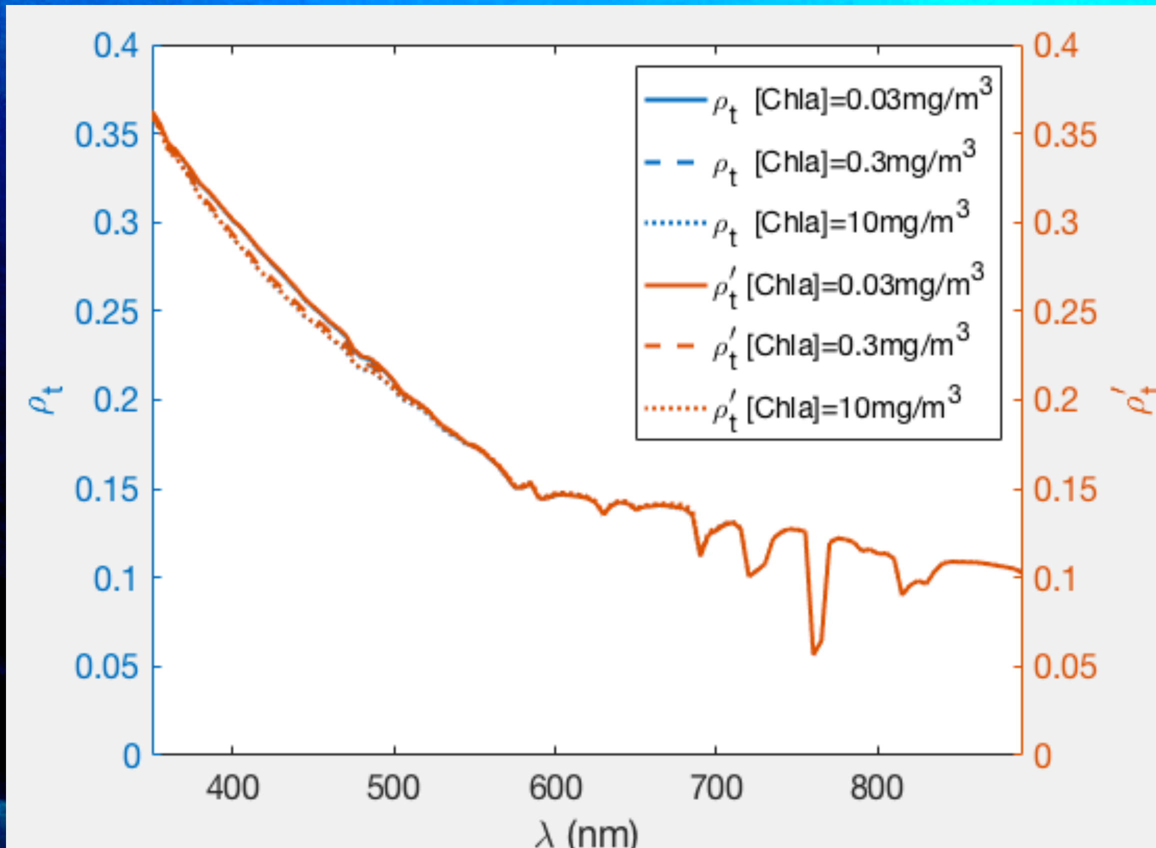
- ✓ Initialize atmosphere and ocean properties with spectral dependence well defined.
- ✓ For each emission wavelength, find excitation wavelengths that have non-negligible contributions to the emission wavelength.
- ✓ Run elastic vector radiative transfer model over all excitation wavelengths.
- ✓ Evaluate the inelastic source terms with the excitation radiation field found in the last step.
- ✓ Run the elastic vector radiative transfer field at the emission wavelength, with inelastic source term included.

How about gas absorption?

Yes, we have them built in:

- ✓ HITRAN 2012 for H_2O, O_2, CH_4, CO_2 Hyperspectral, 0.005 nm resolution in visible, near infrared, and SWIR. (400000 lines for H_2O, 303800 lines for CO_2, 243200 lines for CH_4, 162000 lines for O_2)
- ✓ NO2: K. Bogumil, J. Orphal, and J. P. Burrows, University of Bremen - Institute of Environmental Physics
- ✓ Ozone: Daumont et al., J.Atmos.Chem.15, 145(1992)

A TOA Reflectance Example

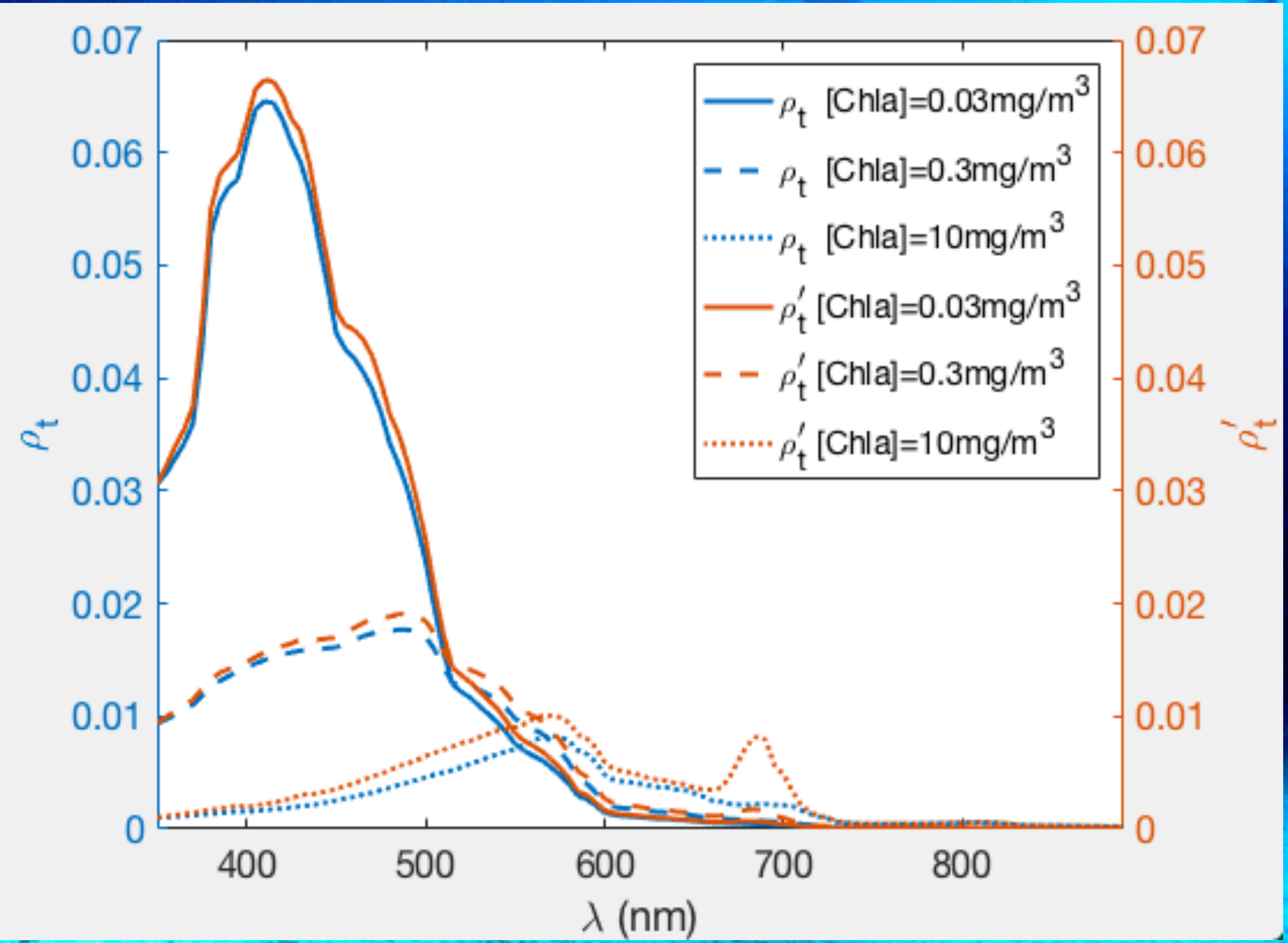


Atmosphere:
$\tau_{a,550\ nm}$=0.15
Aerosol model: Ahmad et al, 2010
Fine-mode volume fraction: 20%
Relative humidity: 80%
Gas absorption: (H_2O, CO_2, CH_4, O_2, O_3, NO_2)

Ocean water model:
pure sea water,
phytoplankton covariant particle,
CDOM

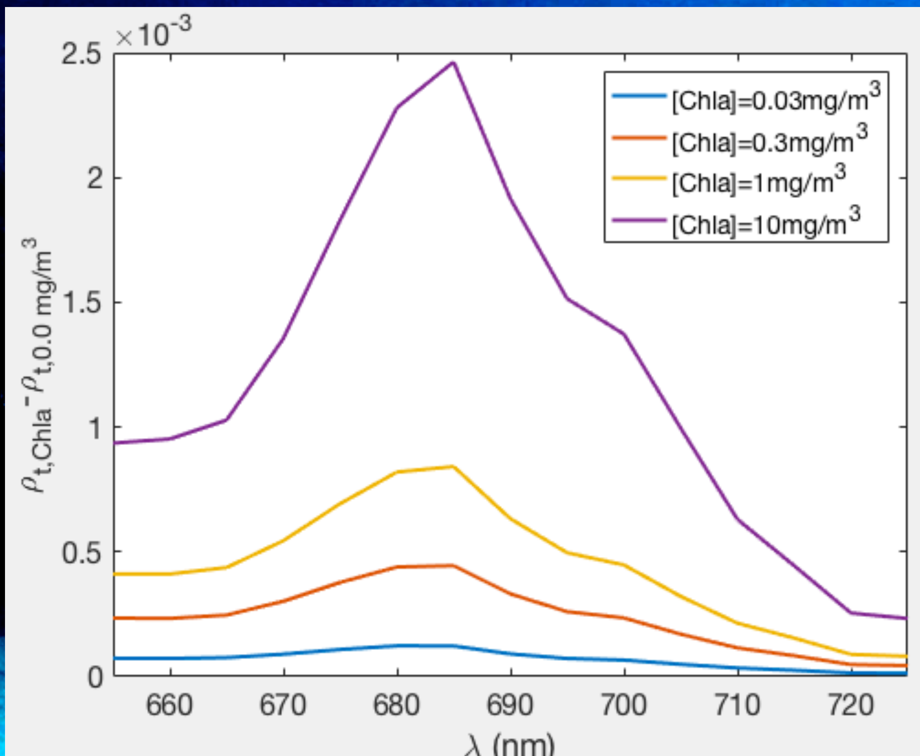
Solar zenith angle: 45 degree.

TOO reflectance

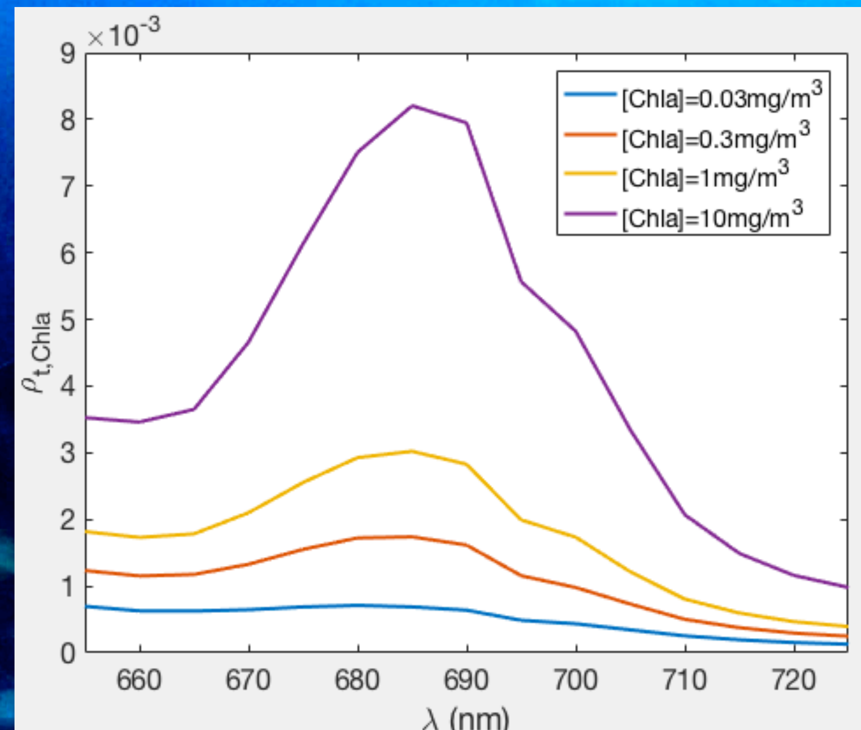


Atmosphere and ocean: the same as previous slides

Fluorescence



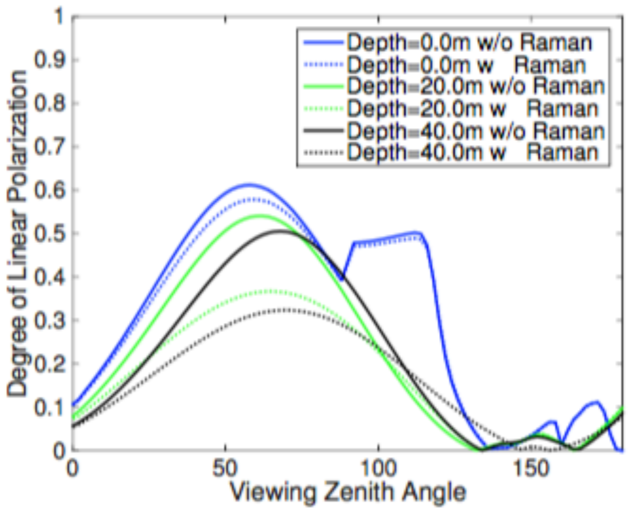
TOA



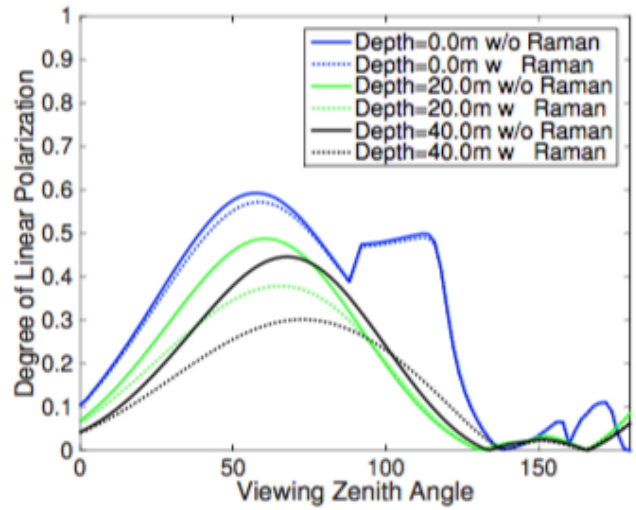
TOO

Quantum yield: 0.02

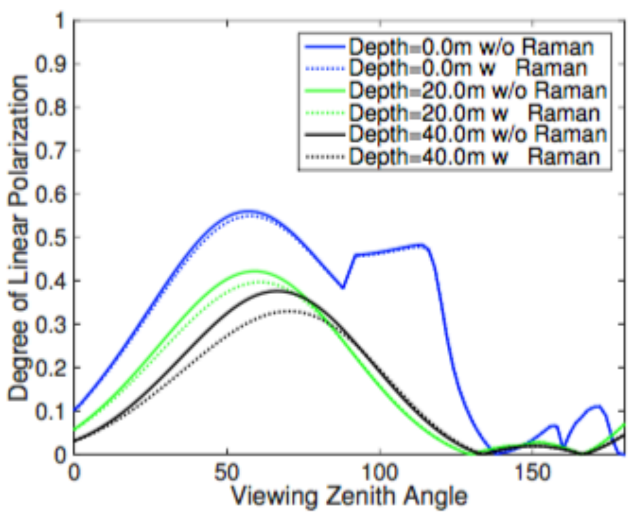
Degree of Linear Polarization



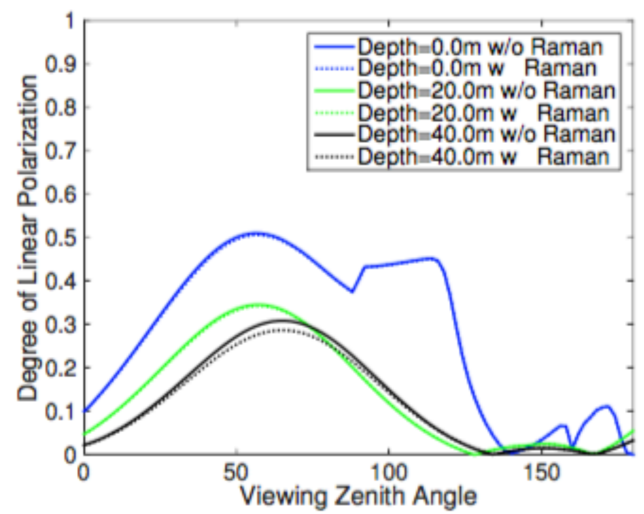
(a) [Chla]=0.03 mg m^{-3}



(b) [Chla]=0.1 mg m^{-3}



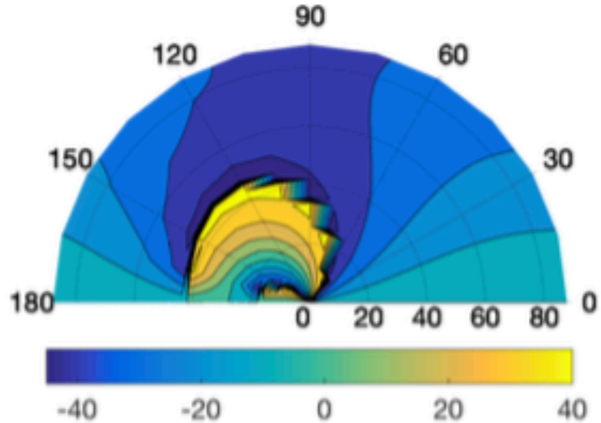
(c) [Chla]=0.3 mg m^{-3}



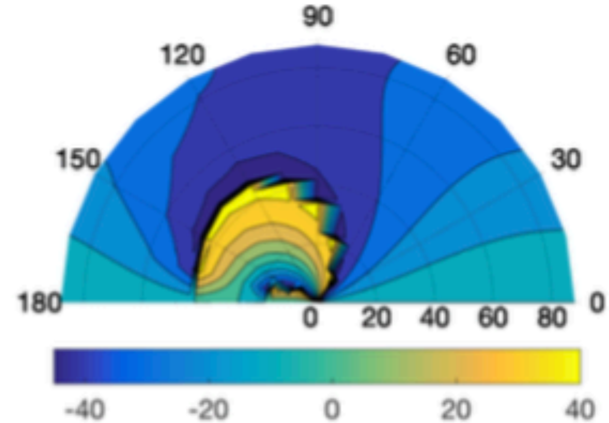
(d) [Chla]=1.0 mg m^{-3}

$\lambda = 560nm$; Solar zenith angle: 45∘; Wind speed: 5 m/s.

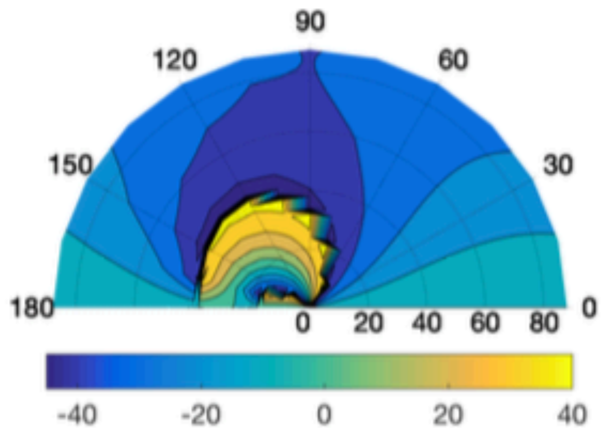
Orientation of Polarization Ellipse



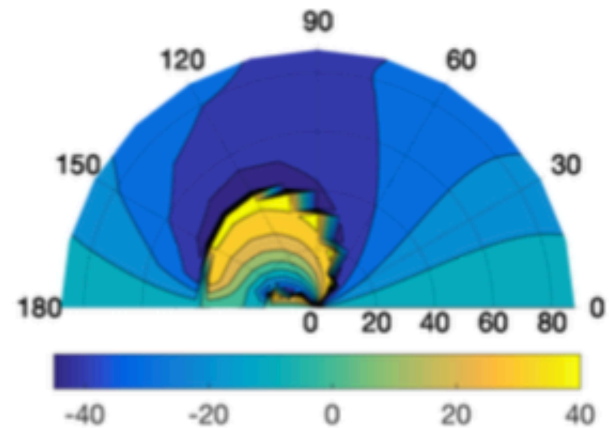
(a) Elastic scattering for a detector just below ocean surface



(b) Total scattering for a detector just below ocean surface



(c) Elastic scattering for a detector 30 meters below the ocean surface



(d) Total scattering for a detector 30 meters below the ocean surface

Take Home Messages

- The vector radiative transfer (VRT) equation is solved by the SOS method which rigorously accounts for all physical interactions between light and medium:
  - atmosphere-ocean coupling,
  - full Stokes parameter solution,
  - all major inelastic scattering mechanism.
  - Major gas absorption in the visible and near infrared, and SWIR.
- The VRT model can be applied many studies: sensitivity study
  - simulation of synthetic data to test retrieval algorithms,
  - sensitivity study of the impacts of different components,
  - development of new algorithms for ocean color remote sensing.

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