Error Analysis for Simultaneous Retrieval of Marine and Aerosol Properties from SeaWiFS measurements

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Introduction

Usually in ocean color retrieval, sky radiances are removed through atmospheric correction; a semi-empirical bio-optical model relates ocean color to marine retrieval parameters [1]. Atmospheric radiative transfer (RT) is decoupled from surface/ocean. Water-leaving radiance is a small part of total radiance at satellite: small errors in atmospheric correction can generate large uncertainties in marine constituent estimates. Very difficult to get systematic and reliable error budgets with two-step methods. Improvement: regard retrieval as a classic inverse problem for simultaneous estimation of aerosol distribution and marine constituents. Minimization of a cost function obtained by comparison of measured radiances with simulated values. Retrieval proceeds iteratively: at each stage, the forward model is linearized about the current atmosphere/ocean state to update the state vector estimate. Ocean color retrieval is an ill-posed problem: constrain it by statistical regularization (e.g., a priori information).

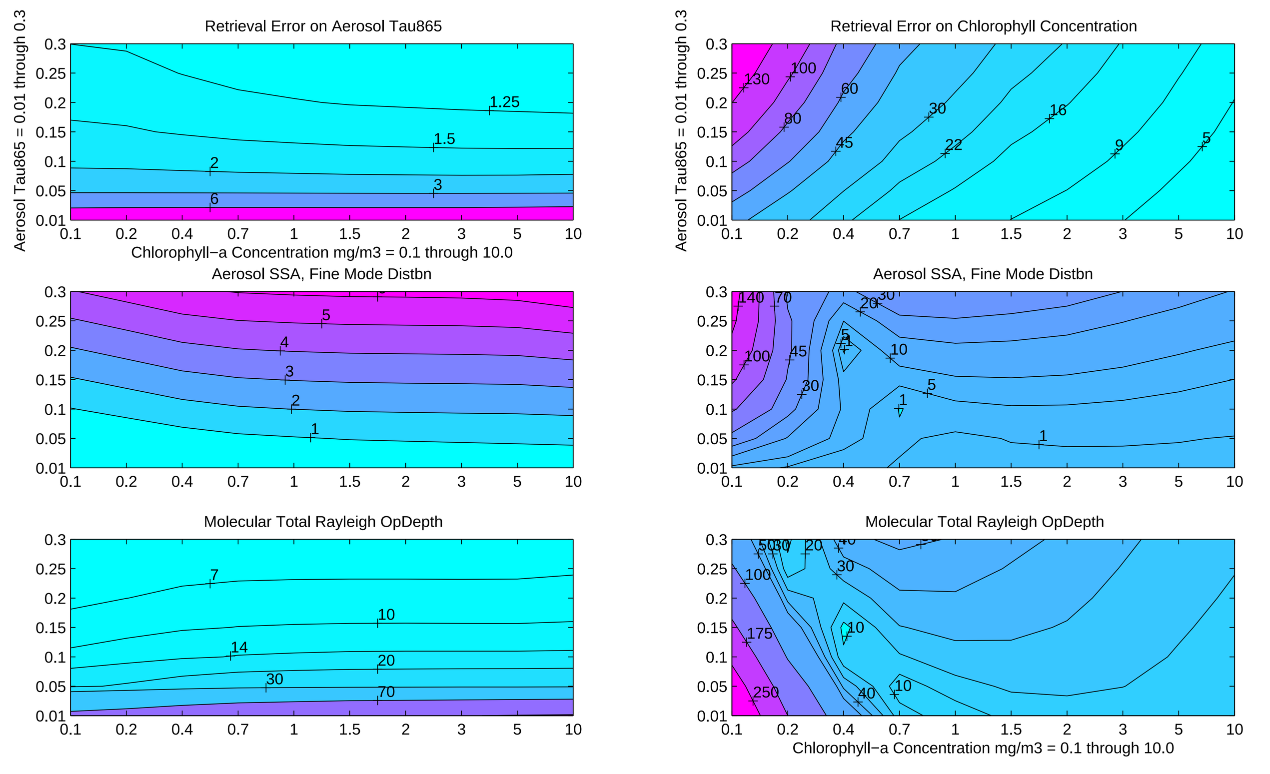
Inverse model, error analysis methods

Iterative inversion with a priori optimal estimation regularization [2]. Linearize about state vector **x** of retrieval parameters and vector **b** of model parameters. Estimate:

$$\hat{\mathbf{x}} - \mathbf{x} = (\mathbf{A} - \mathbf{E})\ (\mathbf{x} - \mathbf{x}_a) + \mathbf{G}_y\ \mathbf{K}_b\ (\mathbf{b} - \hat{\mathbf{b}}) + \mathbf{G}_y\ \Delta\ \mathbf{f}(\mathbf{x,b,c}) + \mathbf{G}_y \varepsilon; \qquad (1)$$

Forward $model$ F(**x,b,c**) is an approximation of precise forward $function$**f(x,b,c)**. $\mathbf{K}_b$ = matrix of radiance derivatives w.r.t. model parameter elements of **b** ($sensitivity Jacobians$); **E** = identity matrix, $\mathbf{x}_a$ is $apriori$ state vector. $\mathbf{G}_y$ = contribution matrix, **A** = averaging kernel;

In (1), first term $(\mathbf{A} - \mathbf{E})\ (\mathbf{x} - \mathbf{x}_a)$ is *smoothing* error; second term $\mathbf{G}_y\ \mathbf{K}_b\ \Delta\mathbf{b}$ is *model parameter* error due to uncertainty $\Delta\mathbf{b}$ in parameter **b**; third term is *forward model* error $\mathbf{G}_y\ \Delta\ \mathbf{f}(\mathbf{x,b,c})$ due to assumptions in forward model; fourth term is *measurement* error (random part is retrieval noise).



(Left panels) Errors on aerosol τ_{865}. (Right panels) Errors on chlorophyll concentration C. Top row: From the retrieval (measurement and apriori). Middle row: From 5% uncertainty in the fine-mode aerosol single scattering albedo (SSA). Bottom row: From 2% uncertainty in the total atmospheric Rayleigh optical depth. Solar angle 45°, sensor angle 20°, relative azimuth 60°.

Linearized RT model CAO-LDISORT

CAO-LDISORT [3] will deliver radiances and any number of analytic Jacobians (radiance derivatives) w.r.t. retrieval and model sensitivity parameters. Model features:

- Atmosphere and water are coupled plane-parallel media, Fresnel's equations at interface.
- Optically uniform strata to resolve variation of inherent optical properties (IOPs) with depth.
- RTE is solved separately for each layer using the discrete-ordinate method
- Boundary conditions: (1) at top of atmosphere and bottom of ocean, (2) Continuity at air-water interface and intermediate boundaries. Output radiation field at any sensor geometry.
- Direct and reflected solar beams in atmosphere, transmitted solar beam in ocean. Pseudo-spherical treatment of solar beams in atmosphere (attenuation in spherical-shell geometry)
- Full **linearization**: Radiation field is analytically differentiable w.r.t retrieval or sensitivity parameters
- **CAO-LDISORT inputs for radiance field** $-->$ IOPs $\Delta_n, \omega_n, \beta_{nl}$ for each layer n. Δ_n = layer optical thickness, ω_n = single-scattering albedo, and β_{nl} = phase function Legendre expansion coefficients.
- **CAO-LDISORT linearized inputs for weighting functions** $-->$ derivatives of IOPs $\Delta_n, \omega_n, \beta_{nl}$ w.r.t. retrieval or sensitivity parameter ξ in layer n.

Optical models

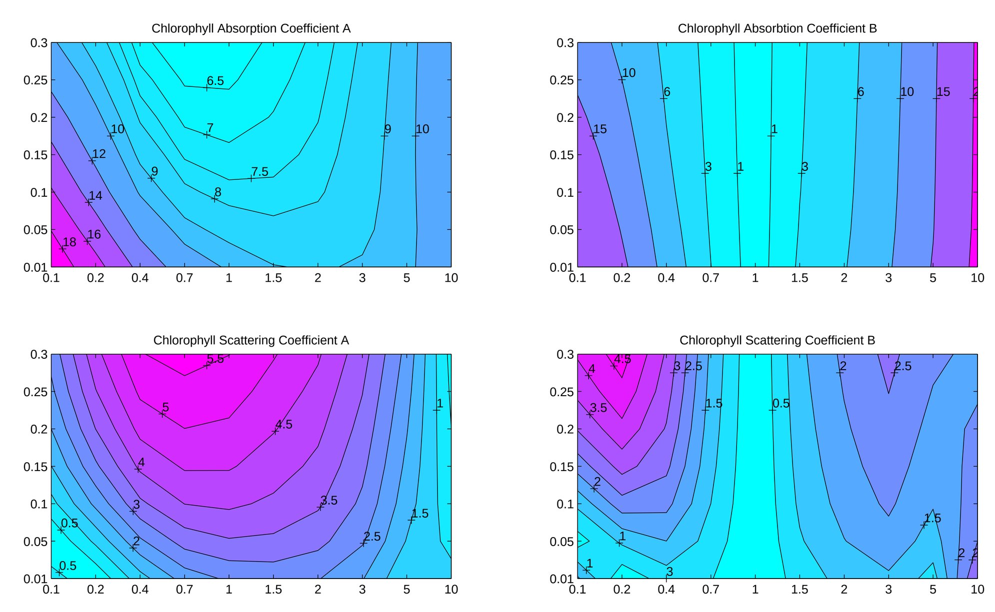
Aerosol and atmospheric model. Bimodal combination of fine-mode + coarse-mode sea-salt aerosols, lognormal distributions, external mixing when computing IOPs. 2-parameter aerosol optical model: optical thickness τ_{865} at 865 nm and fractional weighting f between two modes:

$$\Delta_{aer} = \tau_{865}\ e_A = \tau_{865}\ [f\ e_1 + (1-f)\ e_2];\ \omega = \frac{S_A}{e_A} = \frac{f\ z_1\ e_1 + (1-f)\ z_2\ e_2}{e_A};\ \beta_{l,A} = \frac{f\ z_1\ e_1\ \beta_l^{(1)} + (1-f)\ z_2\ e_2\ \beta_l^{(2)}}{S_{aer}}$$

$[e_k, z_k, \beta_l^{(k)}]$ are extinction coefficients (normalized to 865-nm values), single-scattering albedos and phase expansion coefficients.

Bio-optical ocean model [4]. 2-parameter empirical model, chlorophyll-a concentration C in $[mg.m^{-3}]$ and CDOM absorption coefficient Y in $[m^{-1}]$ at 443 nm. IOPs Δ, ω, β_l are:

$$\Delta = d\ (\alpha_{water} + \sigma_{water} + \alpha_{chlro} + \sigma_{chlro} + \alpha_{cdom});\ \omega = \frac{d\ (\sigma_{water} + \sigma_{chlro})}{\Delta};\ \beta_l = \frac{\beta_{water,l}\ \sigma_{water} + \beta_{chlor,l}\ \sigma_{chlor}}{\sigma_{water} + \sigma_{chlor}}$$



Errors on chlorophyll concentration C, from 10% uncertainties on the four empirical parameters for chlorophyll absorption and scattering. Solar angle 45°, sensor angle 20°, relative azimuth 60°.

Error analysis: settings

- 1) 3-parameter retrieval: **x** = $[\tau_{865}, f, C]$ with Y regarded as a model parameter error.
- 2) 4-parameter retrieval: **x** = $[\tau_{865}, f, C, Y]$ with Y included in retrieval.
- 8 SeaWiFs channels (412,443,490,510,555,670,765,865 nm). Measurement error = 0.002
- A priori state vector same as **x**. Covariance: diagonal entries, loosely constrained.
- Atmosphere: 13 layers, aerosol 0-2 km, bimodal fraction 0.99. 2 retrievals. 6 model parameters:
  1. Mie aerosol extinction + single-scattering albedos $[e_1, z_1]$ and $[e_2, z_2]$ for 2 modes
  2. Rayleigh scattering + trace gas absorption: total-atmosphere optical depths .
- Ocean model: 2 layers. CDOM assumption set to 0.01. 1 or 2 retrieval, 7 or 8 model parameters.
- Ocean: chlorophyll empirical constants a_1, a_2, b_1 and b_2 model parameter errors
- Forward model error Δf = difference between pseudo-spherical and plane-parallel radiances.

Results for aerosol τ_{865} 0.01 to 0.3, chlorophyll concentrations C 0.1 to 10.0.

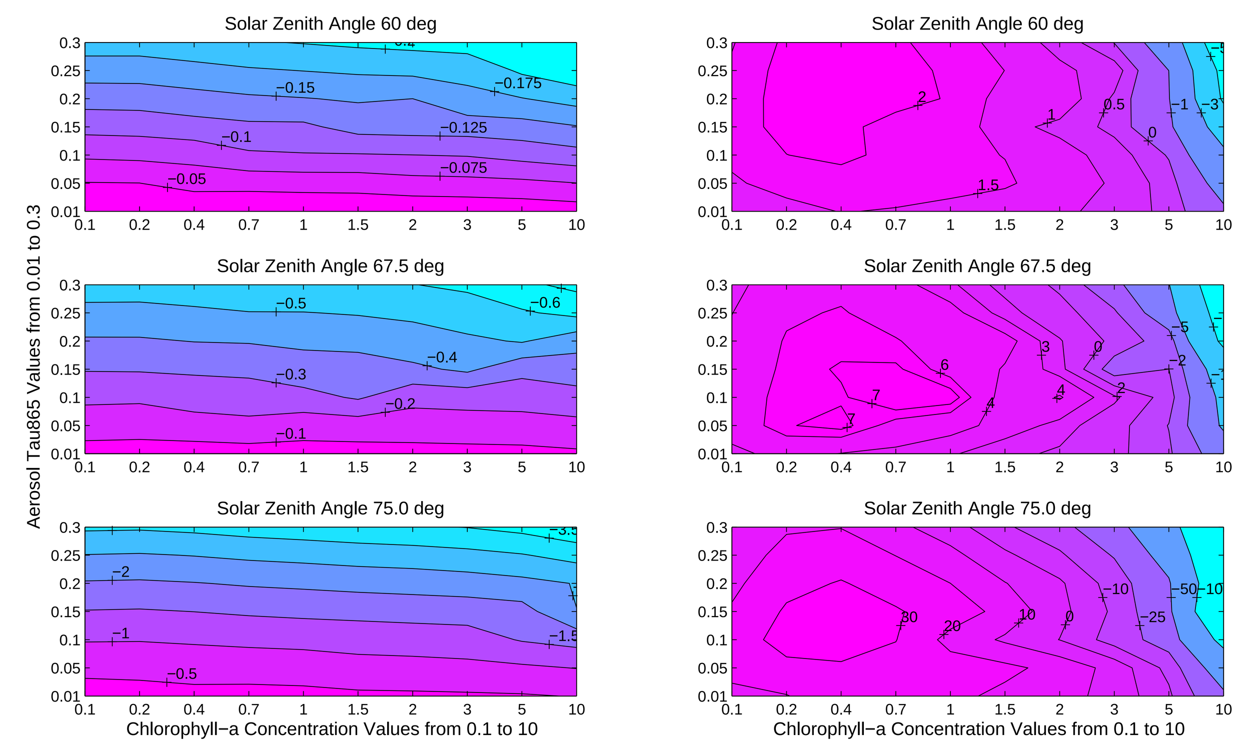
Summary and future work

Some conclusions. Shown facility to derive wide range of new error information for ocean color retrieval. Samples for a few scenarios, many more results available.

- Figures 1 & 2 show model parameter errors for largest contributors. Other parameters (pure water and CDOM quantities, other aerosol, trace gas) generate lesser errors (by 1/2 orders of magnitude).
- Figure 3 shows plane-parallel assumption is highly signficant source of error.
- For small C and large τ_{865} values, the 4-parameter retrieval of C is less accurate than 3-parameter retrieval of C with CDOM treated as a source of model parameter error.
- CDOM retrieval in our bio-optical model is very hard. Large retrieval and model parameter errors.

Future work. Extend analysis to MODIS observations (including infrared channels).

- Improved bio-optical models: Effect of ocean phase function assumptions (model parameter error).
- Effects of Raman scattering + fluorescence, polarization. Important forward model error sources



Forward model errors due to plane-parallel approximation, for solar angles 60°, 67.5° and 70°. (Left panels) on τ_{865}. (Right panels) on Chlorophyll concentration C. Sensor angle 20°, relative azimuth 60°.

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