Retrieval of Marine Parameters in Coastal Waters from Satellite Data (Extended Abstract)

著者	Knut Stamnes, Wei Li, Hans Eide, Rune Storvold
雑誌名	The science reports of the Tohoku University. Fifth series, Tohoku geophysical journal
巻	36
号	4
ページ	416-421
発行年	2003-05
URL	http://hdl.handle.net/10097/45415

Tôhoku Geophys. Journ. (Sci. Rep. Tôhoku Univ., Ser. 5), Vol. 36, No. 4, pp. 416-421, 2003

Retrieval of Marine Parameters in Coastal Waters from Satellite Data (Extended Abstract)

KNUT STAMNES[1], WEI LI[1], HANS EIDE[1] and RUNE STORVOLD[2]

[1]Light and Life Laboratory, Department of Physics and Engineering Physics
Stevens Institute of Technology, Hoboken, NJ 07030, USA.
[2]Geophysical Institute, University of Alaska Fairbanks Fairbanks, AK 99775, USA.

(Received January 3, 2003)

Abstract : A new method has been developed for simultaneous retrieval of aerosol optical properties and chlorophyll concentrations in Case 1 waters (Stamnes *et al.*, 2003a). This method is based on an improved, complete model for the inherent optical properties (Li and Stamnes, 2002) and accurate simulations of the radiative transfer process in the coupled atmosphere-ocean system. It has been implemented in NASA's SeaWiFS Data Analysis System (SeaDAS) and tested on SeaWiFS imagery obtained off the East Coast of the US. We summarize the salient features of this approach, and describe the steps required to adapt it for application to more complex (Case 2) coastal waters.

1. Introduction

The feasibility of measuring marine chlorophyll concentrations from space was demonstrated by the CZCS (Coastal Zone Color Scanner) mission (Gordon *et al.*, 1980 ; Hovis *et al.*, 1980) showing that (1) there is a relationship between ocean color and chlorophyll concentration for most of the open ocean, (2) it is possible to remove the interfering effects of the atmosphere from satellite imagery. Recently sensors with more channels and higher radiometric sensitivity, such as SeaWiFS (the Sea-viewing Wide Field-view Sensor) (Hooker *et al.*, 1992), MODIS (the Moderate-Resolution Imaging Spectroradiometer) (Salomonson *et al.*, 1989), OCTS (Ocean Color and Temperature Scanner) (Saitoh *et al.*, 1995), MERIS (Medium Resolution Imaging Spectrometer) (Rast *et al.*, 1995), GLI (Global Imager onboard the Advanced Earth Observing Satellite ADEOS-II) and others, have been designed and deployed for remote sensing of ocean color.

It is customary to retrieve the chlorophyll concentration in two independent steps : (i) an atmospheric correction algorithm is applied to separate the atmospheric radiance from the radiance that comes from the ocean (the water-leaving radiance) ; (ii) an empirical bio-optical model is used to relate this water-leaving radiance to the chlorophyll concentration. Most bio-optical models are based on empirical or semi-empirical relations derived by statistical regression of remote sensing reflectance versus chlorophyll concentration (O'Reilly *et al.*, 1998 ; Gordon *et al.*, 1988 ; Reynolds *et al.*, 2001 ; Carder *et al.*, 1999 ; Garver and Siegel ; 1997), and many of them have been validated against the SeaBAM (SeaWiFS Bio-optical Algorithm Mini-Workshop) data base

(O'Reilly *et al.*, 1998).

Gordon and co-workers (Gordon and Wang, 1994 ; Wang and Gordon, 1994 ; Gordon, 1997) proposed an operational procedure for atmospheric correction, which has been used in the SeaWiFS algorithm. Similar procedures have been proposed for the MERIS (Antoine and Morel, 1999) and OCTS instruments (Fukushima *et al.*, 1997). These algorithms are based on the assumption that the ocean is black in the near infrared, and this black-pixel assumption is applied to the NIR channels (at 765 nm and 865 nm). Although an attempt was recently made to remedy this black-pixel assumption (Siegel *et al.*, 2000), three major sources of uncertainty still remain : (i) the decoupling of the atmospheric and oceanic radiative transfer problems makes it difficult to quantify the retrieval error, (ii) current algorithms are based on the questionable assumption that the water-leaving radiance is isotropic (Morel and Gentili, 1996 ; Yang and Gordon, 1997 ; Li and Stamnes, 2001 ; Yan *et al.*, 2002b), and (iii) a simple reflectance model has been used (Siegel *et al.*, 2000), in which the absorption and backscattering coefficients are empirically related to the chlorophyll concentration (Gordon *et al.*, 1975 ; Gordon *et al.*, 1988).

Recently we developed an atmospheric correction algorithm that does not rely on several assumptions employed in previous algorithms (Stamnes *et al.*, 2003a). This algorithm employs a radiative transfer model for the *coupled* atmosphere-ocean system based on the discrete-ordinate method (CAO-DISORT) to circumvent these unnecessary assumptions. It has been implemented in the SeaWiFS Data Analysis System (SeaDAS) and tested on ocean color data. Here we summarize the salient features of this algorithm and describe the work required to adapt it for application to coastal (Case 2) waters.

Summary of Our Case 1 Ocean Color Algorithm

To remove the uncertainties inherent in current algorithms our development is based on a rigorous discrete-ordinates solution of the radiative transfer equation pertinent to the coupled atmosphere-ocean system (CAO-DISORT (Stamnes *et al.*, 1988 ; Jin and Stamnes, 1994 ; Thomas and Stamnes, 1999 ; Yan and Stamnes, 2003), which provides accurate results in a computationally efficient manner (Gjerstad *el al.*, 2002). The CAO-DISORT code has already been used to create algorithms for retrieval of marine constituents in Case 2 waters (Frette *et al.*, 1998 ; Frette *el al.*, 2001), but these algorithms rely on a simplified description of atmospheric parameters, and have not been tested on real data. As aquatic input to the CAO-DISORT code we use an improved, complete model for the inherent optical properties (IOPs) of Case I waters that was specifically designed for this purpose, and that has been tested against remote sensing reflectances compiled in the SeaBAM data base (Li and Stamnes, 2002). We use the CAO-DISORT code to compute TOA reflectances, and store the results in lookup tables (LUTs) to enable rapid access to these reflectances $\rho^{LUT}(\lambda)$. Based on these accurate simulations of the light field throughout the coupled atmosphere-ocean system we have developed a method for simultaneous and self-consistent retrieval of atmospheric aerosol properties and chlorophyll concentrations in Case 1 waters (Stamnes *et al.*, 2003a).

In our new atmospheric correction algorithm we employ two parameters to select an aerosol model from a suite of candidate models, and a third parameter to retrieve the corresponding aerosol optical depth. We use the parameter $\varepsilon_{ms}(\lambda, 865)$ defined as:

$$\varepsilon_{ms}(\lambda, 865) \equiv [\rho_{path}(\lambda) - \rho_{ray}(\lambda)] / [\rho_{path}(865) - \rho_{ray}(865)]$$

to obtain initial estimates of the aerosol model. Here $\rho_{path}(\lambda)$ is the atmospheric contribution (aerosols plus molecules) to the TOA reflectance, and $\rho_{ray}(\lambda)$ is the contribution from molecules in the absence of aerosols. To finalize the aerosol model selection we employ a second parameter defined as:

$$\rho_{diff}(\lambda_j) \equiv \frac{\rho_{tot}^{meas}(\lambda_j) - \rho_{tot}^{LUT}(\lambda_j)}{\rho_{tot}^{meas}(\lambda_j)} \times 100$$

where $\rho_{tot}^{LUT}(\lambda_j)$ is the TOA reflectance for wavelength λ_j, as inferred from the lookup tables (LUTs) based on the retrieved aerosol optical properties and chlorophyll concentration. The third parameter is defined as:

$$\gamma_{diff}(\lambda, 865) \equiv \gamma(\lambda) - \gamma(865)$$

where $\gamma(\lambda) = \rho_{path}(\lambda) / \rho_{ray}(\lambda)$.

The aquatic contribution to the TOA reflectance $t\rho_w(\lambda)$ is obtained simply by subtracting the inferred atmospheric contribution to the TOA reflectance $\rho_{tot}^{LUT}(\lambda)$ from the inferred total TOA reflectance $\rho_{tot}^{LUT}(\lambda)$: $t\rho_w(\lambda) = \rho_{tot}^{LUT}(\lambda) - \rho_{path}^{LUT}(\lambda)$. We use the ratio $R_w = t\rho_w(\lambda_1) / t\rho_w(\lambda_2)$ to retrieve the chlorophyll concentration, where ($\lambda_1 = 490$ nm and $\lambda_2 = 555$ nm (Stamnes *et al.*, 2003a).

In our iterative method for simultaneous retrieval of the chlorophyll concentration C and the aerosol optical properties (Stamnes *et al.*, 2003a), we use the parameters ε_{ms} (765,865) and γ_{diff}(765,865) to select the aerosol model, the aerosol optical depth $\tau(865)$, and the chlorophyll concentration the *first two times* through the algorithm iteration loop. Subsequently we use $\rho_{diff}(\lambda_j)$ to select that combination of aerosol model, aerosol optical depth, and chlorophyll concentration that gives the best match between inferred and measured reflectances for *all* available channels (Stamnes *et al.*, 2003a). Typically, 3-4 iterations are sufficient for convergence. Performance tests based on synthetic data show that our algorithm provides self-consistent and accurate retrievals, and applications to SeaWiFS data shows that it produces realistic results with quantifiable errors (Stamnes *et al.*, 2003a).

Extension of Algorithm to Coastal (Case 2) Waters

In order to adapt our algorithm for Case 1 waters to the more complex situation encountered in Case 2 coastal waters there are a number of issues that require attention. Some of these are: (i) How do we identify and deal with transition from Case 1 waters, where our current algorithm (hereafter called ALGO-C1 for short) applies, to Case 2 waters? (ii) How do we identify and deal with absorbing aerosols? (iii) How do we deal with sunglint and whitecaps? (iv) How do we deal with the bidirectional reflectance distribution function (BRDF) caused by ocean waves? (v) How do we establish an error budget for retrievals in Case 2 waters?

To deal with absorbing aerosols we must establish an algorithm (called ALGO-C1A) for simultaneous retrieval of aerosol properties and chlorophyll concentration, when absorbing aerosols are present. In order to address the questions raised above we envision that the algorithm development will proceed in a number of steps approximately as follows:

- Step 0: For each image we start by establishing a Abs-no/Abs-yes mask that will allow us to distinguish between non-absorbing (Abs-no) and absorbing aerosols (Abs-yes), so that we can apply the proper algorithm AGLO-C1 or ALGO-C1A.
- Step 1: For a given scene, we use the ALGO-C1 algorithm (or ALGO-C1A as appropriate) to retrieve aerosol properties and chlorophyll concentration, C_{C_1}. If C_{C_1} $1.0\ \mathrm{mg} \cdot \mathrm{m}^{-3}$, we classify this pixel as Case 1 water.
- Step 2: If $C_{C_1} > 1.0\ \mathrm{mg} \cdot \mathrm{m}^{-3}$, we use the ALGO-C2 algorithm to retrieve the properties of Case 2 water using the results from ALGO-C1 obtained in Step 1 as initial values of aerosol properties and $C_0 = C_{C_1}$. If the sediment concentration S_{C_2} ε_1, and $|C_{C_1} - C_{C_2}| \leq \varepsilon_2$, we set $C = C_{C_1}$, and classify this pixel as Case 1 water. Otherwise, we classify this pixel as Case 2 water, and S_{C_2}, C_{C_2}, and τ_{C_2} are the retrieval results.
- Step 3: By repeating steps 1 and 2, we cover the entire scene.

Finally, we use the information obtained in steps 1 through 3 above as a *priori* information available to constrain the final retrieval, based on standard optimization techniques such as optimal estimation theory (Rodgers, 2000) or simulated annealing (Frette *et al.*, 1998; Frette *et al.*, 2001), of a complete set of aerosol properties and marine constituents in Case 2 waters that minimizes the difference between inferred and measured radiances. The output of this algorithm will be: (i) Marine Constituents in Case 2 waters (Chlorophyll, CDOM, Sediments), (ii) Aerosol Optical Properties (single scattering albedo and optical depth), and (iii) Estimates of Errors Associated with the Retrievals.

Summary

The main advantages of our new algorithm compared to current approaches appear to be fourfold: (i) many unnecessary assumptions invoked in current algorithms are avoided; (ii) our new algorithm is expected to perform more satisfactorily than current ones in situations with high relative humidity (Yan *et al.* 2002a; Stamnes *et al.*, 2003b); (iii) it is expected to be useful for addressing problems associated with absorbing aerosols as well as simultaneous retrieval of aerosol optical properties and marine constituents in Case 2 waters (Frette *et al.*, 1998; Frette *et al.*, 2001); (iv) it lends itself readily to the inclusion of more comprehensive IOP models, such as that presented by Stramski *et al.* (2001). Finally, a summary has been provided of the steps required to extend this algorithm to coastal waters.

Acknowledgements: We gratefully acknowledge partial support from the National Aeronautics and Space Administration (NASA), and the National Oceanographic and Atmospheric Administration (NOAA) Ocean Remote Sensing Program.

References

Antoine, D. and A. Morel, 1999: A multiple scattering algorithm for atmospheric correction of remotely sensed ocean color (MERIS instrument): principle and implementation for atmospheres carrying various aerosols including absorbing ones, *Int. J. Remote Sens.*, **20**, 1875-1916.

Carder, K.L., F.R. Chen, Z.P. Lee, S.K. Hawes and D. Kamykowski, 1999: Semianalytic moderate-resolution imaging spectrometer algorithms for chlorophyll a and absorption with bio-optical domains based on nitrate-depletion temperatures, *J. Geophys. Res.*, **104**, 5403-5421.

Frette, O., J.J. Stamnes and K. Stamnes, 1998: Optical remote sensing of marine constituents in coastal waters: A feasibility study, *Appl. Opt.*, **37**, 8218-8326.

Frette, O., S.R. Erga, J.J. Stamnes and K. Stamnes, 2001: Optical remote sensing of waters with vertical structure, *Appl. Opt.*, **40**, 1478-1487.

Fukushima, H. and M. Toratani, 1997: Asian dust aerosol: optical effect on satellite ocean color signal and a scheme of its correction, *J. Geophys. Res.*, **102**, 17119-17130.

Garver, S.A., and D.A. Siegel, 1997: Inherent optical property inversion of ocean color spectra and its biogeochemical interpretation, 1, Time series from the Sargasso Sea, *J. Geophys. Res.*, **102**, 18607-18625.

Gjerstad, K.I., J.J. Stamnes, J.K. Lotsberg, B. Hamre, B. Yan, and K. Stamnes, Monte Carlo and discrete-ordinate simulations of irradiances in the coupled atmosphere-ocean system, *Appl. Opt.* (submitted for publication).

Gordon, H.R., 1997: Atmospheric correction of ocean color imagery in the Earth Observing System era, *J. Geophys. Res.*, **102**, 17081--17106.

Gordon, H.R., O.B. Brown and M.M. Jacobs, 1975: Computed relationships between the inherent and apparent optical properties of a flat homogeneous ocean, *Appl. Opt.*, **14**, 714-427.

Gordon, H.R., D.K. Clark, J.L. Mueller and W.A. Hovis, 1980: Phytoplankton pigments derived from the Nimbus-7 CACS: initial comparisons with surface measurements, *Science*, **204**, 63-66.

Gordon, H.R., O.B. Brown, R.H. Evans, J.W. Brown, R.C. Smith, K.S. Baker and D.K. Clark, 1988: A semianalytic radiance model of ocean color, *J. Geophys. Res.*, **93**, 10909-10924.

Gordon, H.R. and M. Wang, 1994: Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm, *Appl. Opt.*, **33**, 443-452.

Hooker, S.B., W.E. Esias, G.C. Feldman, W.W. Gregg and C.R. McClain, SeaWiFS Technical Report Series, vol. 1, 1992: An overview of SeaWiFS and ocean color, NASA Tech. Memo. 104566, NASA, Greenbelt Space Flight Center, Greenbelt, MD, USA.

Hovis, W.A., D.K. Clark, F. Anderson, R.W. Austin, W.H. Wilson, E.T. Baker, D. Ball, H.R. Gordon, J.L. Mueller, S.Y.E. Sayed, B. Strum, R.C. Wrigley and C.S. Yentsch, 1980: Nimbus 7 coastal zone color scanner: system description and initial comparisons with surface measurements, Science 210K, 60-63.

Jin, Z. and K. Stamnes, 1994: Radiative transfer in nonuniformly refracting media: atmosphere-ocean system, *Appl. Opt.*, **33**, 431-442.

Li, W. and K. Stamnes, 2002: Inherent optical properties of case I waters: A complete model suitable for use in radiative transfer computations, *J. Geophys. Res.*, submitted.

Morel, A. and B. Gentili, 1996: Diffuse reflectance of oceanic waters. III. Implication of bidirectionality for the remote-sensing problem, *Appl. Opt.*, **35**, 4850-4862.

Rast, M. and J.L. Bezy: The ESA medium resolution imaging spectrometer (MERIS): requirements to its mission and performance of its system, *RSS95, Remote Sensing in Action, Proceedings of the 21st Annual Conference of the Remote Sensing Society, University of Southampton, UK, 11-14 September, 1995*, P.J. Curran and Y.C. Robertson, eds. (London: Taylor and Francis, 1995), 125-132.

O'Reilly, J.E., S. Maritorena, B.G. Mitchell, D.A. Siegel, K.L. Carder, S.A. Garver, M. Kahru and C.

McClain, 1998: Ocean color chlorophyll algorithm for SeaWiFS, *J. Geophys. Res.* **103**, 24937-24953.

Reynolds, R.A., D. Stramski and B.G. Mitchell, 2001: A chlorophyll-dependent semianalytical reflectance model derived from field measurements of absorption and backscattering coefficients within the Southern Ocean, *J. Geophys. Res.*, **106**, 7125-7138.

Rodgers, C., *Inverse methods for atmospheric sounding : Theory and practice* (World Scientific, Singapore, 2000).

Saitoh, S., 1995: OCTS on ADEOS, in *Oceanographic Application of Remote Sensing*, M. Ikeda and F.W. Dobson, eds. Boca Rota, FL: CRC, 473-480.

Salomonson, V.V., W.L. Barnes, P.W. Maymon, H.E. Montgomery and X. Ostrow, 1989: MODIS: advanced facility instrument for studies of the earth as a system, *IEEE Transactions in Geosciences and Remote Sensing*, **27**, 5954-5964.

Siegel, D.A., M. Wang, S. Maritorena and W. Robinson, 2000: Atmospheric correction of satellite ocean color imagery: the black pixel assumption, *Appl. Opt.*, **39**, 3582-3591.

Stamnes, K., S.-C. Tsay, W.J. Wiscombe and K. Jayaweera, 1988: Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media, *Appl. Opt.*, **27**, 2502-2509.

Stamnes, K., W. Li, B. Yan, A. Barnard, W.S. Pegau and J.J. Stamnes, 2003a: A New Ocean Color algorithm: Simultaneous Retrieval of Aerosol Optical Properties and Chlorophyll Concentrations, *Appl. Opt.*, in press.

Stamnes, K., B. Yan, W. Li, J.J. Stamnes and S.C. Tsay, 2003b: Reply to Comment on *Pitfalls in atmospheric correction of ocean color imagery : how should aerosol optical properties be computed ?*, *Appl. Opt.*, in press.

Stramski, D., A. Bricaud and A. Morel, 2001: Modeling the inherent optical properties of the ocean based on the detailed composition of the planktonic community, *Appl. Opt.*, **40**, 2929-2945.

Thomas, G.E. and K. Stamnes, 1999: *Radiative Transfer in the Atmosphere and Ocean* (Cambridge University Press, New York).

Wang, M., and H.R. Gordon, 1994: A simple, moderately accurate, atmospheric correction algorithm for SeaWiFS, *Remote Sensing of the Environment*, **50**, 231-239.

Yan, B. and K. Stamnes, 2003: Fast yet accurate computation of the complete radiance distribution in the atmosphere-ocean system, *J. Quant. Spectrosc. Radiat. Transfer*, 207-223.

Yan, B., K. Stamnes, W. Li, B. Chen, J.J. Stamnes and S.C. Tsay, 2002a: Pitfalls in atmospheric correction of ocean color imagery: How should aerosol optical properties be computed ?, *Appl. Opt.*, **41**, 412-423.

Yan, B., K. Stamnes, M. Toratani, W. Li and J.J. Stamnes, 2002b: Evaluation of a reflectance model used in the SeaWiFS ocean color algorithm: Implications for chlorophyll concentration retrievals, *Appl. Opt.*, in press.

Yang, H. and H.R. Gordon, 1997: Remote sensing of ocean color: assessment of water-leaving radiance bidirectional effects on atmospheric diffuse transmittance, *Appl. Opt.*, **36**, 7887-7897.