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Answers to interactive comment on "Retrieving the availability of light in the ocean utilising spectral signatures of Vibrational Raman Scattering in hyper-spectral satellite measurements" by T. Dinter et al.
Anonymous Referee #2
Received and published: 3 March 2015

Reviewer:
Hyperspectral image acquisition of ocean colour holds great potential as the present article describes. Obviously, it is possible to extract the spectral signature of inelastic radiative processes associated with Raman scattering by water molecules from satellite data and from this draw conclusions on the photosynthetically available radiation in the ocean. A comparison of the diffuse attenuation coefficient from the GlobColour dataset and from the vibrational Raman scattering signal retrieved values show consistent results. In my opinion, the article is a valuable contribution for the exploitation of hyperspectral satellite data and should be accepted after minor revisions.

Answer: We thank Reviewer 2 for his valuable comments which helped to improve the manuscript. In the following we answer to each comment and clarify where we changed the manuscript accordingly.

Reviewer:
1) The processing and obvious usability of the proposed scheme refers to case 1 waters. The comparison with the GlobColour data excludes the first 1x1 deg pixels nearest the coastline in order to avoid optically complex case 2 waters. Lee and Hu show that in fact wide sea areas are rather case 2 with strong seasonal variations (Z. Lee and C. Hu (2006): "Global distribution of Case-1 waters: An analysis from SeaWiFS measurements", Remote Sensing of Environment, 101.2, 270-276). Could this be another explanation for deviations and the "butterfly distribution"?

Answer:
We do not think that the general case 1 versus case 2 water criteria could be an explanation for the "butterfly distribution". Although Lee & Hu (2006) set up fixed criteria of reflectance ratios for the case 1 or case 2 water definition and applied these as thresholds to SeaWiFS data, the transitions of case 1 to case 2 waters are generally very smooth and should lead to a more randomly scattered plot at least for open ocean scenarios. Nevertheless, extreme variations from case 2 waters (e.g. illuviations of rivers) could contribute to the "butterfly distribution". However, these pixels should mostly excluded from our comparison by removing all coastal adjacent pixels. We still think the main causes are (as pointed out in the manuscript in section 5, first paragraph):
a) that the SCIAMACHY data set is much more patchy than the GlobColour data due to the fact that SCIAMACHY achieves in its nadir-mode global coverage at the equator in 6 days whereas GlobColour in 1 day
b) the impact of partial clouds is significantly larger in the case of SCIAMACHY data due to much worse spatial resolution.

Reviewer:
What IOP ranges and ranges of water constituent concentration are necessary for the described method of VRS utilization?

Answer:
To model the VRS weighting function used in the VRS retrieval and also further on to assess the retrievals sensitivity we used simulations with our RTM SCIATRAN where the variation of IOPs was basically varied in relation to changes of the chl-a conc. (which was varied from 0 to 30 mg/m^3 in 23 steps- see chapter 3.1, 1st sentence). In our RTM simulations the IOPs were used as outlined in the manuscript on chapter3, under the 2nd paragraph.
Therefore, all variations of the VRS signal in our simulations are related to variation in the chl-a conc. which has a parameterized relationship to the IOPs of all water constituents. Figure 7 shows clearly a asymptotic relationship of increasing VRS fit factors to increasing chl-a conc. (on log scale). which nearly reaches saturation for chl-a concentrations above 10 mg/m^3. One reason for that is that the one parameter Haltrin (1999) approximation is limited to chl-a concentrations lower than 10 mg/m^3. This approximation is used (which describes the relationship of the small/large particle distribution in the ocean depending on the chl-a concentration) in our RTM simulations as input for the Kopelevich scattering model. The variation of IOPs reflected in the VRS signal is. The best sensitivity of the VRS signal is obtained for chl-a concentrations up to 1 mg/m^3. For 1 to 10 mg/m^3 the change of the VRS signal is about 10% of the total variability (fit factors range from 0.22 to 0.3 as opposed to -0.4 to +0.3 for 0.001 to 1 mg/m^3).

Reviewer:
Can it be applied to optically complex waters?

Answer:
We think, that this method can be applied also to optically complex waters. First investigations to test the sensitivity of the VRS retrieval to different water body compositions were included in the manuscript by testing the influence of different specific phytoplankton absorption spectra (reflecting three different phytoplankton types: diatoms, coccolithphores (Emiliania huxleyi) and cyanobacteria) and different water body types (stratified versus mixed water profile according according to Uitz et al. 2006), see Section 3.4, 4rth paragraph ff.. The results (see Figures 8 and 9.) show a very stable relationship between the filling in due to VRS (expressed by its fit factor) and the availability of light (E_0) despite the variations in IOPs and IOP distribution within the water column. These results indicate that this method may also be applicable to optically complex waters. Nevertheless, this task will need the incorporation of a much more complex radiative transfer model and extensive RTM calculations will be required to test and derive a much more enhanced LUT to represent the extended complexity of deriving the appropriate VRS WF.

Reviewer:
2) How sensitive is the method on uncertainties due to the spectral shape of absorption and scattering of different phytoplankton types and associated fluorescence?

Answer:
The uncertainties due to different spectral shapes of the phytoplankton absorbing constituents were investigated in Section 3.4 of the manuscript: The specific absorption spectra of the three different phytoplankton types varied alot in spectral shape and absolute values; e.g. as mentioned in the manuscript (Section 3.4, third paragraph) the absolute value of the absorption at 440nm varied between 1 (for the normalized phytoplankton spectrum of Prieur and Sathyendranath, 1981) and 0.015 (for the diatom specific absorption spectrum) which is a difference of about 1/60 (see page 51, 2nd paragraph). The different phytoplankton type specific absorption spectra were taken from measurements on in-situ and culture samples (see Bracher et al., 2009, and Sadeghi et al. 2012). Therefore these spectra represent “realistic” differences in shape.
The concentration of particles and the particle size distribution where changed according to the one parameter model (chl-a concentration) of Haltrin (1999)

which provides appropriate parameters for the Kopelevich scattering model. By considering different **specific** phytoplankton absorption spectra also the relationship between scattering and absorption changed extremely. (We added these two sentences into chapter 3.4, last paragraph). However, the results of this sensitivity tests (see Figure 9) show that despite these large variations still a robust relationship between the in-filling due to VRS (expressed by its fit factor) and the availability of light (E_0) is obtained with deviations below 10%.

We have not tested the influence of variations in phytoplankton fluorescence since phytoplankton fluorescence emissions can be neglected below 550 nm (e.g. Cowles et al. 1993:“In situ characterization of phytoplankton from vertical profiles of fluorescence emission spectra”).

Reviewer:
3) It is not clear to me how the sun zenith angle correction is applied. Is the correction related to 3-D effects of the Earth’s curvature that are important at low sun altitudes?

Answer:
No, all radiative transfer calculations including the VRS effect in the ocean were performed in the plane-parallel mode of the SCIATRAN model. The solar zenith angle correction described in Section 3.4.1 consists of a 3-D Look-Up-Table approach, where the solar zenith angle defines the third dimension. The relationship between fit factor of the VRS weighting function and the light availability E_0 is shown in Figure 9 for a solar zenith angle (SZA) of 40°. To extend this for other SZAs the calculations of Figure 9 have been repeated for SZAs from 20° to 80° in 10° steps, which is shown in Figure 10. The values of SZAs in between the 10° steps were calculated then by linear interpolation.

Reviewer:
4) There is a recent paper by Li et al. describing Raman effects on the light field within the ocean (L. Li, D. Stramski, and R. A. Reynolds (2014): "Characterization of the solar light field within the ocean mesopelagic zone based on radiative transfer simulations", Deep Sea Research Part I: Oceanographic Research Papers 87, 5369). They used the radiative transfer software Hydrolight (an often used reference). Could you discuss possible deviations to their findings? From the perspective of your coupled atmosphere-ocean RT model what Raman-related assumptions are possibly oversimplified?

Answer:
We are currently working on a manuscript (Rozanov, V.V., Dinter, T., Bracher, A., Burrows, J.P.: “Modeling of radiative transfer in the coupled ocean-atmosphere system including inelastic processes” in prep.) , which describes exactly how all inelastic scattering effects in water (VRS, CDOM and chl fluorescence) are implemented in SCIATRAN. We compared SCIATRAN to other radiative transfer models' simulations. We hope to submit this manuscript soon. The basis of our implementation of the water Raman scattering in SCIATRAN arises from the publication of Haltrin & Kattawar (1993). We expect that comparisons with the results of Li et al. (2014) will yield to small differences, because they assumed a simplified isotropic Raman scattering phase function instead of a commonly accepted function according to Mobley (1994) which was applied in SCIATRAN. Li et al. (2014) determined the uncertainties of their simulations within < 10%. Due to the lack of an own Hydrolight version (which is only commercially available), we have compared our results to the following models:

MOMO using the matrix operator method:
Bismarck & Fischer, 2013: ”An examination of errors in computed water-leaving radiances due to a simplified treatment of water Raman scattering effects”. AIP Conf. Proc. 1531, 939 (2013), doi: 10.1063/1.4804926)

Four different Monte Carlo models in:
Mobley et al., 1993: “Comparison of numerical models for computing

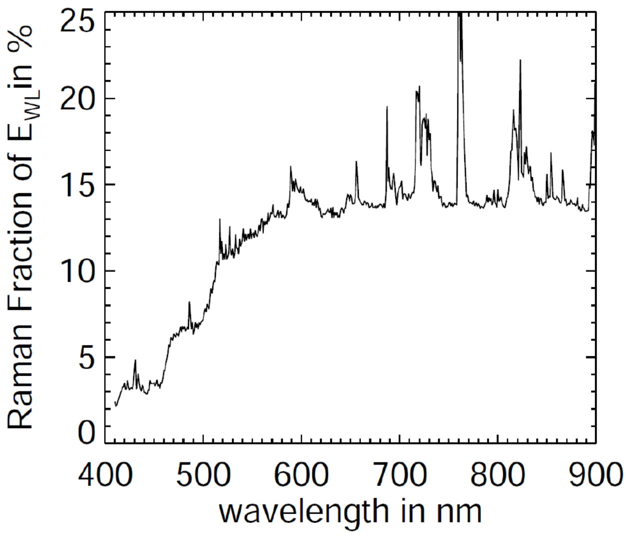
underwater light fields”. Applied Optics, 32(36):7484–504, 1993.

Also a Monte Carlo model in:
Kattawar & Xu, 1992: “Filling in of Fraunhofer lines in the ocean by raman scattering”. Appl. Opt., 31(30):64916500, 1992.

The comparisons of the underwater light field calculations by SCIATRAN with all other models show its very good conformance with deviations lower than 0.5% (with some exceptions). Also comparisons with in-situ ship-based oceanic radiation measurements show a quite good agreement within a few percent.

Reviewer:
5) With respect to Figures 12 and 13, how important is the consideration of VRS in terms of remote sensing? Maybe it is interesting to look at spatial differences on global maps without Raman?

Answer:
This depends clearly on the spectral resolution of the utilized instrument and the target wavelength region. Investigations of Bismarck & Fischer (2013) show that absolute values of the contribution of the VRS signal within the water-leaving irradiance reach values of approximately 5% (mean values around 3%) in the blue, 10% in the green and 12-25% in the red and SWIR spectral region.



From Bismarck & Fischer (2013): Fraction of Raman scattered light in the water leaving irradiance.

Reviewer specific comments:
- Equation 25 is unclear. Please explain all variables and unitise all labels in the figures including units.
Answer: We changed the variable name sigma_C to a compliant name f_K and added an explanatory sentence “This function shows a non-linear exponential relationship between the diffuse attenuation K_d(lambda_ex) and the chlorophyll a concentration C.”

- Figure 9 refers to different phytoplankton types, that are not further defined or discussed.
Answer: The spectra of these different phytoplankton types are from the publications by Bracher et al. (2009) and Sadeghi et al. (2012) – see citation in Section 3.4 third paragraph – were they are defined and discussed in detail (both publications are published in open access journals). To clarify we extended now Figure caption 8 to:
“E_0 vs. chl *a* for different phytoplankton types (using phytoplankton absorption

spectra specific for diatoms (dia), cyanobacteria (cya) and coccolithophores (Emi) taken from Bracher et al. 2009 and Sadeghi et al. 2012, respectively) and profiles (profile-1 for a stratified and profile-2 for a mixed water profile according to Uitz et al. 2006). **(b)** VRS fit factor delta *qv* vs. chl-a for the same scenarios as in **(a)**." and changed Figure caption 9 to:
"Resulting relationship between the VRS fit factor delta *qv* and E_0, derived according to Eq. (33) for different phytoplankton types and profiles as in Fig. 8. The solid magenta line is a fitted third order polynomial to the reference scenario (magenta points) with a SZA of 40 and is used as LUT for the satellite data retrieval"

- Figure 12 and 13: Some regions are marked without reference to the text, does it mean something?
Answer: These dashed lines are the country borders (same style also on land) of island groups.