os-2015-31 Authors' replies to the comments from Referee #2 on "Estimation of upward radiances and reflectances at the surface of the sea from above-surface measurements"
by Ø. Kleiv et al.

We have numbered the comments to avoid repetition and simplify the discussion.

The comments from our reviewer are in bold italics, and our replies are in normal font..

Overall
The manuscript is of major relevance to the ocean color remote sensing community. With the technology getting affordable, smaller and better in terms of spectral resolution there is need to improve accuracy in observations and obtain optical closure. However, in this work several aspects need to be addressed to make this manuscript a useful contribution to the community in my opinion.

(1) ***The authors need to be consistent with NASA protocols in terms of abbreviations e.g. spectral irradiance is commonly defined as E_d or E_s, radiance is L_w or L_u as given in a previous publication by one of the co-authors (Aas, 2010)***
We have mainly followed the standard nomenclature from Jerlov (Marine Optics, Elsevier, 1976), with the addition of some extra indices wherever necessary. We cannot see that our symbols are different from those used by *e.g*. Mueller et al. in the NASA protocols. However, the index a in E_{da} and L_{da} is not necessary, since we only discuss the downward irradiance and radiance in air, and not the corresponding ones in water. Similarly the index L in K_L for the vertical attenuation of radiance can be omitted, which is also in accordance with the notation of Jerlov. Accordingly we have changed E_{da} to E_{d} throughout the text, and on page 1059, line 20, we have changed L_{da} to L_{d}. K_L have been simplified to K.

(2) ***and also feel there are too many equations which are basic in the ocean color.***
Here we disagree. We have included only those equations that are need in order to define the different quantities and to explain the different procedures.

(3) ***Due to variable environmental conditions it is best to carry out such a study at optimal conditions and maybe non optimal conditions to fully address possible uncertainties as it is well known that at sea conditions can change and are dynamic.***
A method that is valid only at optimal conditions would be interesting for a comparison with our method based on conditions with 1-6 oktas of cloudiness, but its practical use in our areas would be limited. The same applies to a method valid only in completely overcast conditions. See (22) and (23) below.

(4) ***In the methods section, I feel the authors can make it brief and provide only relevant information to what they did in this study and maybe provide a sketch of the setup.***
Here we agree with the principle, but not with the actual case. The way we see it, all information in this section is needed in order to understand the described methods. A sketch of the instrumental set-up can be instructive, but in our case, with only two

vertically oriented sensors, we do not find that it will provide any more information than is already presented in the text.

(5) ***In my opinion you can replace Maybe replace "in air" with above-water since in protocols it is widely known that you measure radiometric quantities from in-water, above-water, airborne and satellite platforms.***
It is correct that in NASA terminology the standard terms are "in-water" and "above-water", while we have used "in water", "in air", "sub-surface" and "above-surface" to obtain some variation. We cannot see that our terms may reduce the clarity or create any confusion. We have, however, substituted "sub-surface" by "in-water" at two places.

(6) ***In my opinion to determine if the approach is robust the manuscript should showcase that the method used here provides comparable observations with other platforms or have a reference measurement for the uncertainty check see for example (Garaba and Zielinski, 2013a; Hooker et al., 2002; Lee et al., 2013; Zibordi et al., 2011).***
We agree, but unfortunately we have not found many other investigation that studies upward radiance from nadir in water and air. We had planned to make a comparison of the ratio L_{ua}/L_{da} (L_{da} being the downward radiance from zenith in air) with similar estimates by other researchers (e.g. Fig. 4 in Mobley, 1999), but while the recordings in 2009 provided reasonable results, most of the recordings in 2010 and 2011 were corrupted, due to a failure in the instrumental set-up. We have to redo these recordings.

Our uncertainty check is the root-mean-square (rms) deviations between the traditional in-water measurements and the new above-water method.

(7) ***The authors should also state in the methods how they determine uncertainty see e.g.(Hooker et al., 2002).***
This is described in Sect. 2.4 of the method section entitled "Uncertainties of L_{ua}, L_r and L_w".

Hooker et al. (2002) introduces a new error estimate (Unbiased Percent Differences) based on absolute differences, but we prefer to use the rms method, based on squared differences, which is a well established statistical quantity.

(8) ***I also suggest the authors provide only the most relevant equations,***
As we see it, we have only included those equations that are needed in order to define the discussed quantities and explain the applied procedures.

(9) ***also because of the notations you use different from standard ocean color notations it is difficult to follow your many equations and steps see for example (Aas et al., 2009; Mueller et al., 2003; Zibordi et al., 2011).***
See (1). We could add that we present 22 equations and 16 symbols. The non-standard symbols are: A, B, C (statistical best-fit constants), C_L (transmittance factor for nadir radiance), F (calibration factor), f (self-shading factor), N (number of applied depths), r (radius in Eq. (4) and correlation coefficient in Eq. (20)), s (standard deviation), ε (relative error). The standard symbols are: E (irradiance), L (radiance), R (reflectance), K (vertical attenuation coefficient), n (refractive index), z (vertical coordinate). We cannot

see that the latter 6 symbols are different from those commonly used in papers related to ocean colour.

Specific comments

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(10) Line 1 – ***I am not sure I understand what you mean by series is it time series or number of repetitive observations***

Here series is meant to be the data set consisting of all the applied data (L_{ua}, L_{uw}, E_d) leading to one spectral distribution of the water-leaving radiance. We agree that "series" can be confused with "time series", and we have changed "series" to "data sets".

(11) Line 2 – ***maybe add the country or region for clarity***

We have added "Norway".

(12) Line 5 – ***would be nice to define MERIS and add the wavebands just a suggestion***

Since this is an Abstract, we think that information that is not strictly necessary should be avoided. However, we have now listed all the wavebands and omitted MERIS. The definition of MERIS has been moved from Sect. 2.1 to Sect. 1, page 1052, line 26.

(13) Line 7 to 8 - ***maybe rephrase this because it is not clear what the message is here, it is well known that you can determine radiance in-water or above-water.***

The message is that while the traditional method to obtain water-leaving radiance and upward reflected radiance at the surface requires both in-water and above -water observations, our suggested new method only need above-water observations of upward radiance and downward irradiance. We have made a small change of the text.

(14) Line 12 – ***'..by the two methods..' which methods can you state them here?***

The methods were described by line 7-11 in the previous paragraph. We have changed "the two methods" to "the two mentioned methods".

(15) Line 15 – ***in ocean color see works on MOBY the uncertainty is less than 5 %***

Yes, but this value of 5 % refers to the uncertainty of the water-leaving radiance, calculated from in-water MOBY data, while the 24 % referred to in line 15 is the deviation between two different methods to determine the radiance: the in-water and the in-air methods. We should point out that the estimated error of the water-leaving radiance based on our in-water recordings, is less than 5 % in the spectral range 443-681 nm (Table 2).

(16) Line 20 - ***maybe you can provide the full definition of ESA since in the text you provide definitions for other abbreviations?***

We have now provided definitions for EU, ESA and NASA. The reason these acronyms were not defined, is that the we assume that most readers of our paper will be familiar with them. As mentioned above, we have now moved the definition of MERIS on page 1954, line 17, forward to line 26 on page 1052.

(17) Line 24 ***which directive can you provide a citation? Is it the (WFD, 2000)***

Yes, the proper reference within the EU is the Water Framework Directive (2000/60/EC). We have not included this in the reference list, but we have added the parenthesis to line 24.

(18) Line ***25 – which recordings ocean color or water quality?***
Water quality. The motivation behind the projects described in Section 1 is mainly to develop methods to monitor water quality by radiometric and other sensors mounted on ships of opportunity, and to compare the recorded water quality parameters with similar satellite products. We have added this explanation to the text.

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(19) Line 4 to 5 – ***I suggest this can be moved to be part of the methods section***
We agree, and the lines have been moved.

(20) Line 6 to 8 – ***suggest you add a reference here see for example see these works (Bissett et al., 2004; Hestir et al., 2015; Zibordi et al., 2015)***
We have found that especially the description by Bissett et al. was relevant for our project, and we have added this reference.

(21) Line 6-23 ***the aspects you explain have been reviewed or explained in e.g. (Garaba and Zielinski, 2013b; Hooker and Morel, 2003; Mueller et al., 2003)***
Line 6-15 is a general description that can be found in most of the papers related to monitoring of water quality by remote sensing and ship-mounted sensors. However, we have added the references.

(22) ***-maybe I did not understand it here, but your message is observations need to be made at optimal sensor geometry and environmental conditions***
Yes, but while we can (at best) control the sensor geometry, we cannot change the environmental conditions. Unfortunately these conditions are seldom optimal at our latitudes. Based on observations by the Norwegian Meteorological Institute from the last 10 years, the average number of days with a cloudiness of 0-1 okta at 12:00 UTC in Oslo during the 61 days of May and June is 4.5 (7.4 % probability). If a cloudiness of 0 is required, the average number of days is reduced to 0.3 (0.5 % probability). This means that on an average we would need 3-4 years of observations in May and June to obtain 1 day with a completely clear sky at noon. The average cloudiness at 12:00 UTC in these months, based on the 10-years series, is 5.4 oktas. We have now added some of this information to Section 2.1.

(23) ***-doing a number of observations at non-optimal conditions or sensor geometry will not produce good results so I suggest you make it clear here, the number of measurements will not matter if the precision and accuracy is bad***
We agree that one good measurement may be better than a high number of less good ones, but it also depends on what we are searching for. Results obtained during perfect conditions are fine if we want a method that will only be used under such conditions. But they are of less value to us than results obtained during average conditions, if we want a method that can be applied in the average environment. In (22) above we described how the cloudiness in Oslo is far from the less than 10 % cloud cover required by NASA.

(24) ***-ship based measurements also require you do quality control especially for irradiance which is assumed to be valid for a plus minus 5 degree accuracy from zenith***
We are not sure what is meant by this comment. Is it that the direction of the normal to the

irradiance collector should not deviate more than 5 degrees from the zenith? If yes, the irradiance sensors were mounted on a pole that visually was vertical. This means that errors up to 5 ° might occur. Occasional greater angles could be caused by passing ships, Such tilts, however, only happened for rather short periods of time. We have added a comment about the angle on page 1054.

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(25) Line 5-18 ***the instrument description can be brief. I suggest authors rewrite this paragraph.***

See (4).

(26) ***-I suggest the abbreviations be consistent with prior publications in ocean color***

We have mainly followed the standard nomenclature from Jerlov ("Marine Optics", Elsevier, 1976), with the addition of some extra indices wherever necessary. We cannot see that our symbols are different from those used by *e.g*. Mueller et al. in the NASA protocols. However, the index a in E_{da} and L_{da} is not necessary, since we only use the in-air downward irradiance and in-air downward radiance in this paper. Similarly the index L in K_L for the vertical attenuation of radiance can be omitted, which is also in accordance with the notation of Jerlov. Accordingly we have changed E_{da} to E_{d} throughout the text, and on page 1059, line 20, we have changed L_{da} to L_{d}. K_L have been changed to K in relation to Eq. (1).

(27) - ***TriOS is a common instrument and providing the diameter and length is not necessary in my opinion***

See (4).

(28) ***-the notations used should be consistent with Ocean Color notations see (Mobley, 1994, 1999; Mueller et al., 2003)***

See (26).

(29) - ***did you centre the TriOS wavebands to match the MERIS wavebands and maybe add the MERIS wavebands***

The TriOS channels closest to the MERIS wavebands were chosen. We have now added this information to line 18.

(30) Line 11 to 12 – ***you checked the sensors at the start of the cruise? Why was it to clean them? Or make sure they were working or ..?***

The calibration of the sensors were tested against the calibration device FieldCAL from the TriOS company. This information has been added to line 11-12. (The same sensors were compared with similar sensors from other institutions in the EU project HighROC, in 2014 and 2015, with satisfactory results.)

(31) Line 19-23 ***suggest rephrase***

-Why did you put the sensor above the bridge? Why not near the other sensor

-you also mention 'usually the recordings…' did you have them at any other depth?

The irradiance sensor was mounted above the bridge because it was a good place to avoid shading effects from the ship. The rig of the sensor for upward radiance was submerged part of the time, and was consequently not a suitable place for in-air recordings of irradiance. The sensor might have been mounted on the bar extended from the shipside that carried the wire and the meter-wheel of the radiance rig, but that would not have provided a continuous time series of the irradiance, because when the ship had to move, the bar had to be taken in for safety reasons. Part of the project mission was to make a comparison with recordings made by passing ships of opportunity, and then it was useful to have a continuous recording of E_d. We have added a few words explaining that the sensor was mounted above the bridge to avoid shading effects.

A few times the depth range was extended to greater depths to check the linearity indicated by Eq. (2), while on a few other occasions one or two of the mentioned depths had to be omitted because the ship had to move to another position. Whenever possible the depth range 0.5-3 meters was used for the analysis, because this was the homogeneous part of the water column. We have added the last information to the text.

(32) Line 24-26 ***what do you mean by 22 series? Did you make 22 measurements or you made 22 measurements but each measurements over time? Can you be specific here***
See (10).

(33) Line 26 – ***why did you calculate this ratio at 560 nm? Why use the mean instead of the median? Since it was an non-optimal weather is it possible some of the min or max was going to be outlier data?***
The water-leaving radiance obtains its peak value at the MERIS waveband 560 nm in our waters, which makes it useful as a reference wavelength. This is explained on page 1064, line 27. The mean value was used here instead of the median, because the mean value is a more representative statistical value than the median. However, the mean value for each day was calculated from the different data sets obtained for that day, and in these data sets the median value had been chosen at each wavelength to avoid spikes, wave effects and other disturbances. Thus the outlier data had already been removed, and the variation displayed by Table 1 is not the result of real glints, but of major changes in the irradiance conditions. Some of this information has now been added to the text.

Page 1055
(34) Line 6-12 ***it was a median of how many measurements?***
The time series for a spectrum lasted for 60 seconds, and during that time around 14-38 spectra could be recorded. In 2009 the average number of spectra was 22. Thus we could say that the median is based on 26±12 values. We have added this information.

(35) ***-how big is the difference between the mean and median? It would be interesting to know what you mean by insignificant***
For the 9 data sets in 2009 the rms deviation between the median and mean values of L_{ua} at 560 nm was 0.12 mW m^{-2} nm^{-1} sr^{-1}. The mean values of the 9 median and mean values were 3.04 and 3.08 mW m^{-2} nm^{-1} sr^{-1}, respectively, while the medians of the 9 median and mean values were 3.23 and 3.21 mW m^{-2} nm^{-1} sr^{-1}. However, since the signals at 560 nm varied by a factor of up to 6 in the 9 data sets, it is the relative differences between median and mean that is of importance.

Compared with the great variation of the signals, we have judged a relative difference between median and mean value less than 5 % to be insignificant. 77 % of the L_{ua} data in 2009 had differences less than 5 %, as shown by line 9-13. We have added the information that the numbers represent L_{ua}, which to a great extent is determined by E_d and follows the variation of E_d.

(36) Line 13-18 *can you quantify the CDOM? What is yellow-substance rich?*
The content of CDOM or yellow substance can be quantified by its absorption coefficient at e.g. 442 nm. The mean value±the standard deviation of the coefficient at this wavelength, based on data mainly from the Skagerrak and the Oslofjord, is 0.62±0.60 m^{-1}, according to Sørensen et al., 2007. The observed range was 0.18-1.59 m^{-1}, implying that the size distribution was not Gaussian.

There is no established lower value for what can be considered as yellow substance-rich waters. But based on the numbers above it can be assumed that this term applies to waters where the absorption coefficient at 442 nm of a filtered water sample is >0.1 m^{-1}. The reference to Sørensen et al. is introduced in line 15-16.

(37) *-what bio-optical properties can you be specific?*
The bio-optical properties were the chlorophyll content and the absorption coefficient of pigments. The MERIS L2 products to be validated in the mentioned projects were: water-leaving reflectance, algae pigments index 2, total suspended matter, and the sum of yellow substance absorption and bleached particles absorption. All of these products are related to the bio-optical properties. These details are described in the reference Sørensen et al. (2007). We have added the information about the MERIS L2 products to the text.

(38) Line 19-25 *I suggest using 'zenith' and 'nadir' instead of 'tilted'*
We agree and have changed "tilted angle" to "nadir angle".

(39) *-was the azimuthal angle exactly 135 degrees or about 135 degree because at sea getting exact sensor geometry is a challenge*
-if it was exactly at these angles can you explain how because it will be a new approach important for the ocean color community
Doxaran et al. just state that the azimuth angle was 135°, "as recommended by Mobley (1999)", with no further information.

(40) *-Did you get above water data? Is it comparable to your in-water data?*
We made some in-air and above-water recordings of upward radiance at angles tilted from the nadir. Some of the recordings were reasonable, but others could not be used due to an error in the instrumental set-up for the in-air recordings (see also (6)). We have now omitted line 24-25 and moved line 19-23 to Section 1.

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(41) Equation 1 – *is your K_L not commonly known as K_D? if different please provide a reference see e.g. (Lee et al., 2014; Morel, 1988)*
It is our experience that K_d usually denotes the vertical attenuation coefficient of downward irradiance, E_d. As a reference we have Jerlov (1976). He uses K for the corresponding coefficient of radiance L. In the referred papers by Lee et al. and Morel

above, K_d is used for downward irradiance. We have now omitted the index L and added the reference to Jerlov (Marine Optics, Elsevier, 1976).

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(42) Line 22 – *what is Br is it B*r or another term? What is the value of r if the diameter is 4.83 cm since you state no unit for B.*

Br is the product of *B* and *r* defined in line 14-16. Unfortunately this product was not printed in italics in line 22. The product has a unit of meter (line 22), and since *r* also has the unit meter, *B* has to be dimensionless. This can also be deduced from Eq. (4). We have now added the information that *Br* is the product of *B* and *r*, and that *B* is a dimensionless number.

We have written "Combined with the dimensions of the TriOS radiance sensor described in Sect. 2.1, the corresponding value of *Br* becomes....", because the effective value of *r* is not the same as half of the diameter. Due to the spray protection cap of the sensor, combined with the geometry of the refracted sun rays, the value becomes somewhat greater, as demonstrated by the equation in line 22.

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(43) Equation 6 – *is this a true value or a best approximation?*

$L_{\mathrm{uw,true}}(0)$ is the best approximation provided by Eq. (5), as described in line 7-8.

(44) Equation 6 – *Is C_L not radiance transmittance (Tr)?*

Yes, it is radiance transmittance through the surface, from water to air. The notation C_{L} from Aas et al. (2009) was used in case some readers would consult that reference. We have now added a comment about C_L representing transmittance.

(45) Equation 8- *did you measure the temperature and salinity which you suggest are useful in getting a precise transmittance value? So what value did you use for transmittance here? 0.556 or 0.546 or 0.5458?*

Yes, temperature and salinity was continuously recorded by sensors on the ship, and we have used Eq. (8). In our case, the relative difference between the average number 0.546 and Eq. (8) will be less than 1.5 % for the spectrum 350-750 nm. We have added the information that we used Eq. (8). The number 0.556 represents $1/n_{\mathrm{w}}^2$, not C_L, and has been omitted. A reference to Austin (1974) has been added.

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(46) *assuming the L_R which is the surface reflected glint to be negligible means you collected you data at optimal conditions clear skies and little or no wind. From your methods this is not the case right? It therefore means even if you made an uncertainty budget you still do not account for the error in L_R*

We cannot see that we have written anywhere that the radiance reflected upward at the surface, L_{r} , should be negligible for a clear sky and no wind. The error of L_{r} is described and estimated on page 1062, line 23. The text says that the uncertainty of L_{r}, depending on L_{ua} as well as L_{w}, is around 5 %.

We should like to add a comment on the use of the term "glint". During the last two decades it has become common practice to refer to the radiance reflected at the surface of the sea as a "glint", often separated into a "sky glint" and a "sun glint". If there are no glints, then L_r=0 in this terminology. However, this is not consistent with our definition of the term "glint". By a glint we mean:

- a small flash of light (Merriam-Webster dictionary)
- a tiny, quick flash of light (dictionary.com)

As explained in (34), our values of the total upward radiance in air L_{ua} and the water-leaving radiance L_w represent the medians of around 26 spectra. The reflected radiance L_r is found as the difference between L_{ua} and L_w, as shown by Eq. (10). Both of the two latter radiances are the results not only of real glints, but also the results of a continuous, more slowly varying stream of light, as confirmed by our direct recordings of the upward radiance in air, L_{ua}.

(47) ***-Fresnel reflectance is applicable for a flat sea and this is also not the case based on Table 1 data so maybe avoid using 0.021 or maybe leave this information out of the manuscript***

Here we disagree. This information is part of the background to explain why we had to search for a new method to estimate the reflected radiance.

(48) ***-In the work by (Ruddick et al., 2006) they present an approach to estimate the correction factor for glint which is a product of cloud cover and wind speed***

Yes, in this paper (which is in our reference list) Ruddick et al. present two formulas for the reflection coefficient of sky radiance from the zenith angle 40°: one for a clear sky and one for overcast conditions. Hopefully we may be able to test their formulas during future field work, provided we can obtain reliable upward radiances from the 40° nadir angle.

(49) Figure 1 – ***the high reflectance in the NIR is indicative of surface reflected glint or highly turbid waters, can you say something about this? The absorption feature at 760 nm is related to oxygen and glint so maybe your measured data had so much glint***

We cannot see that the reflectance in NIR of Fig. 1 is high. On the contrary, it is lower than in other parts of the spectrum.

We appreciate the time spent by our reviewer on commenting general parts and details of our paper. This gives us the chance to improve the text, correct errors and clear up misunderstandings.