Interactive comment on **"Acoustic and optical methods to infer water transparency at the Time Series Station Spiekeroog, Wadden Sea (southern North Sea)"** ***by*** **Anne-Christin Schulz et al.**

First of all we want to thank both reviewers for their time that they have taken to improve and comment this publication.

Blue – Author Response

Green – Manuscript text revised by authors

Anonymous Referee #1

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General comments

The paper presents an interesting approach by comparing both optical and acoustical methods for obtaining information about the suspended sediments in the water, which is a key parameter for deriving water transparency. The study design is reasonable and the instrumental setup is well described. The introduction gives a good overview about the relevant topics, although some more information about the link between water transparency and the investigated optical proxies could be added (see also specific comments). However, in my opinion, especially the Results and Discussion section needs some revision before final publication. The data shown and arguments given are plausible and interesting, but the argumentation needs more focus. By now, it is relatively difficult to get some of the findings right on the first view, especially the biofouling issue, which highlights the advantage of the reflectance and acoustic data. Hopefully, the following comments are helpful in this respect. Thank you for the positive feedback. Based on the two reviewers comments the manuscript was thoroughly revised and improved. We split up and rearranged the results and discussion section in two separate sections for a better structure and overview. Further, we focused more on the description of the results and especially pointing out the bio-fouling issue.

Specific comments

page 1, line 23: The optical properties of the water are also influenced by the dissolved and suspended matter present, so which additional factors play a role for determining water clarity/transparency? If it is only the dissolved and suspended matter, the reference to the optical properties is somewhat redundant and could be omitted.

The sentence intended to describe that the color and transparency is influenced by dissolved material, suspended material and the water itself (its scattering and absorption properties). We omitted the sentence since we rearranged the introduction.

page 2, line 1-11: Maybe it would be valuable to explain shortly how water color observations are linked to water transparency estimates. This would show the value of reflectance and Forel-Ule data more clearly.

A decrease of water clarity (resulting in lower Secchi depths) and therefore water transparency typically goes along with a shift to higher Forel-Ule-Colour indices. We rearranged the introduction to provide focus on the relevant parameters of this study.

page 3, line 28: How was the turbidity data quality-checked?

The quality control protocol is presented in the JEOS paper Garaba et al. (2014), it was an arbitrary threshold set based on mean turbidity changes just after cleaning. We explicitly added the link to the Garaba et al. (2014) paper to avoid doubling yet providing all necessary information to the reader.

page 4, line 15: The polynomial fitting method is basically a linear fit, isn't it?

Yes, it is a linear (first order polynomial) fit. We added that information to the manuscript.

page 4, line 15: "The top right graphic shows the extrapolation results." This is confusing, because also in the top left figure there are the three results of the fits shown. The difference between left and right figure is the exclusion of data because of the bottom layer. Please rephrase the sentence.

We changed the manuscript accordingly.

The top graphics show an exemplary 5 profile during low water and one during flood (violet and blue in Fig. 3) with different extrapolations to the surface layer. The top graphics distinguish with the range at which the extrapolation is applied: The extrapolation through the whole water column is shown in the left column. The right graphic shows the extrapolation applied on data where no influence through bottom friction is. Here, the data derived in the near bottom range up to 4 m are excluded since it is highly influenced by strong currents during ebb and flood.

page 4, line 23-24: Unfortunately, figure 5 confuses me a little bit. It is clear that you get an R^2 value for the correlation between the measured data and the fitted curves as a quality indicator of the respective fit. But I don't understand the histogram, where also R^2-values are shown. Have you repeated the respective fit several times and got different results? If this is the case, can you explain the reason? Otherwise, if the histogram has no special meaning and only the overall R^2-value is the important point, you should omit the histogram and give the R^2 values directly in the upper part of the figure (e.g. in the legend).

We applied the different extrapolation methods to the entire data set. For every acoustic backscatter profile, we got a corresponding R^2 value. To evaluate which of the methods would be best, we made histograms of all the resulting R^2 values.

page 4, line 24: This is the only point in the manuscript where figure 6 is mentioned. The data shown are not used in the Results and Discussion section to explain certain issues, so if it is not necessary, you should remove it.

We removed the figure and changed the manuscript accordingly.

page 4, line 27 to end of chapter: These paragraph should be moved to the Introduction, since it describes previous work, relationships between parameters and aims of the study.

We changed the manuscript accordingly.

page 5, line 3: Figure 8 shows the field of view of the sensors of the station. Maybe the figure should be mentioned and described the first time in the Materials and Methods section, since it is related to the measurement setup. Then it can be referred to in the Results and Discussion section.

We changed the manuscript accordingly.

Results and Discussion in general:

At the beginning, the authors speak of a moderate correlation between the data shown in figure 7 observed by visual inspection. I assume that these are the same data which were used in table 1 for the one-day-correlation?

Yes, that is right

If this is the case, please state this and refer also to these results at this point in the text to support your argumentation. Then there is no need to "confirm" correlations (line 19) afterwards, as they were already given and can be explained in the following.

We changed the manuscript accordingly.

Generally, I would give the results of the Spearman-tests at the beginning of the chapter and then start to explain them (sediment types and different response of instruments). By now, it is the other way around. Furthermore, since the Forel-Ule data were already given in figure 7 and table 1, I would mention this method earlier in the section.

We rearranged the results section and separated it from the discussion section improving the logical flow of manuscript however we stick to the line of argument that we found more appropriate in this case.

page 5 line 17: Do you mean the data shown in figure 7? If this is the case, why don't you give the tidal signal in the figure to support your statement?

Yes. We added the water level as a variable which represent the tidal signal and describe it in the text.

page 5, line 26 - page 6, line 6: The differences between the correlations for the various tidal phases are shown, but not completely discussed. What are the reasons for the observed differences? The different kinds of sediments (fine, coarse) transported in the different tidal phases?

One difference causes probably from the different kinds of sediments. At the moment we have only modelling data about the sediment distribution and dynamics. For a detailed and qualified statement we have to measure the particles size from sampling at that location over a tidal cycle and longer. Thank you for this comment, we will keep this in mind for a future field campaign.

page 5, line 29: Is figure 9 the visual representation of two of the correlations shown in table 1? Why are explicitly these data shown again? Maybe this figure is redundant to table 1?

Yes, it is redundant. We removed that figure.

page 5, line 31 - page 6, line 2: It is mentioned two times that figure 10 shows a comparison between backscatter and turbidity data. Please rephrase the sentence. Are the data shown also identical to the data used in table 2?

We changed the manuscript accordingly. Yes, the figure is redundant. We removed it.

page 6, line 8-9: Where in the data or the Results and Discussion section has been shown the influence of biofouling? I assume it is the difference in the correlations between the one day period and the longer period (table 1). However, this should be clearly mentioned in the Results and Discussion, otherwise it is confusing why this statement is given in the conclusions and also in the abstract.

It is shown in Fig. 2. We explained it in more detail in the text.

Turbidity time series (Fig. 2) shows a rapid response directly after cleaning of the ECO FLNTU sensor as expected in a highly bio-active season (summer). Even in this short time period of 6 days a strong increase and spreading of turbidity values is discernible. Directly after cleaning maximum values are below 5 NTU with a range of 2.2 NTU, already after 3 days the increase started, at the end of this 6-day-period the values spread out to 10 NTU and reach the upper range of the reasonable data for turbidity at nearly 25 NTU.

page 6, line 26-28: This sentence would be good at the beginning of the Conclusion section.

We changed the manuscript accordingly.

Technical corrections

We changed the manuscript for all following comments accordingly.

page 2, line 4: "measurement" instead of measurements"

page 2, line 25: The last sentence of the paragraph could be better placed behind the sentence ending in line 22.

page 2, line 34: Please rephrase the sentence to "At the same time, this approach could contribute to an understanding of..."

page 3, line 5-6: The coordinates could be given without brackets.

page 3, line 9: The abbreviation TSS for Time Series Station Spiekeroog has already been introduced and could be used also here.

page 3, line 16: Maybe rather "Three radiometers continuously measure hyperspectral radiance and irridiance in 5 minute intervals to..."

page 3, line 21: Please rephrase to "...submerged ECO FLNTU sensor (WETlabs,

USA)..."

page 4, line 14: "applied" instead of "implemented" page 4, line 22: "whole" instead of "complete", because this is more related to the following abbreviation (wwc) page 5, line 18: Please rephrase to "Thus, we presume these instruments provide reasonable proxies for the suspended material which are comparable." page 5, line 20: "compare" instead of "compared"

Figure 1: The label "Turbidity Meter" should be placed closer the position of the instrument indicated in red. Furthermore, also the position of the radiometers should be indicated by red symbols to be consistent with the other instruments. Also the same font size should be used for all instrument labels.

Figure 2: The font size of the legend appears to be different. Furthermore, could you provide the units in e.g. brackets? Using a backslash gives the impression of a ratio on the first sight. This applies also to the other figures.

Figure 4: Line colors should be chosen according to the tidal phase to make the figure more clearly (e.g. red for flood, green for ebb etc.). To differentiate between two floods, for example, different shades of the respective color could be used or different types of lines.

Figure 8: Could you explain why the left square is turned? Also, the arrow indicating north should be given on the panel it belongs to.

The left panel is turned because it belong to the arrow which indicates the north.

Anonymous Referee #2

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GENERAL COMMENTS:

The paper presents a novel approach to comparison of different techniques for water transparency measurements using time series data. The purpose of this study was to find correlations between acoustic and optical measurements in order to fill possible gaps in water transparency data when individual instruments fail. This was successfully reached and important conclusions were made. Although, some parts of the text need clarification, I recommend this paper for publication in Ocean Science journal (Special Issue: COSYNA: integrating observations and modeling to understand coastal systems) after some minor revisions specified below.

Thank you for the very encouraging and positive feedback.

SPECIFIC COMMENTS:

P2L25 explain 'SPM' at first mention

We changed the manuscript accordingly.

P3L18 explain NN

NN is the german abbreviation on the mean sea level, which is a national reference height in the geographical height system. Was changed.

P3L19 It will be more clear if you give full reference of 2012, like in P2L10-11.

Yes, you are right. We rewrite and reduce the paragraph.

Hyperspectral radiometers were used to collect and derive remote sensing reflectance (R_{RS}) measurements at 24 m above the seafloor at 5 minute interval continuously. The reflectance measurements, corrected for environmental perturbations, were transformed into Forel-Ule color indices that can be matched to the intrinsic color of water. A submerged WETlabs ECO FLNTU sensor measures turbidity at 12 m above the seafloor at 1 minute interval continuously. The ECO FLNTU sensor samples turbidity data with optical backscattering at a wavelength of 700 nm. Detailed information on the processing of these measurements is presented in an earlier study Garaba et al. (2014).

P3L28 How were these data checked for quality?

The quality control protocol is presented in the JEOS paper Garaba et al. (2014), it was an arbitrary threshold set based on mean turbidity changes just after cleaning. We added an explicit link to this reference in the manuscript.

P3L29 How were they measured? Using the same instrument? Please precise.

These turbidity data were measured with the ECO FLNTU sensor near the surface of the water column at a fixed height above the seabed (see Garaba et al. 2014).

P4L10-12 This sentence doesn't fit here, it should be moved elsewhere (it separates the information about extrapolation), e.g., in L4 before the information on Rmax. Also, there's no need to name plot colors in the text, they are visible on the graph.

We changed the manuscript accordingly.

In different tidal phases (flood, ebb, slack water) the acoustic backscatter signal shows different profiles over depth (Fig. 3). Depending on the current velocity (e.g. at slack water or at maximum velocity), the profiles have similar shapes.

P4L18 Try to make this description more clear. The sentence "The top right graphic shows the extrapolation results" is also true for the left graphic; try to highlight the difference between right and left graphics here, and afterwards explain. Is it the backscatter signal that is highly influenced by strong currents during ebb and flood? Be more precise. I guess, the currents may affect the ADCP backscatter signal as well as the presence of SPM. How do you separate this information? Describe or provide a reference.

The amount of particles within the water column depends on the currents, therefore the backscatter signal is indirectly influenced by the currents.

We changed the manuscript accordingly.

The top graphics show an exemplary profile during low water and one during flood (violet and blue in Fig. 3) with different extrapolations to the surface layer. The top graphics distinguish with the range at which the extrapolation is applied: The extrapolation through the whole water column is shown in the left column. The right graphic shows the extrapolation applied on data where no influence through bottom friction is. Here, the data derived in the near bottom range up to 4 m are excluded since it is highly influenced by strong currents during ebb and flood.

P4L20-21 Can you provide a reference to support this assumption?

Investigations from e.g. Badewien et al. (2009) and van der Hout et al. (2015) showed partially strong vertical gradients in SPM in coastal areas with a reduced variation in the surface concentration signal.

P4L22 Complete or whole? In the description of Fig. 5 you use 'whole' which seems better for the 'wwc' shortcut.

We changed the manuscript accordingly.

P4L24 I suggest to be more precise: 'acoustic backscatter', which 'other parameters' (they are only two, you can list them)?

We changed the manuscript accordingly.

P4L26 Support this assumption with a reference.

See answer for P4L22.

P4L27-28 This is a general statement appropriate for introduction. If you place it in 'Sampling and analysis' section, you should show how you applied this information in your study. Remove or reformulate.

We removed the sentence to the introduction.

P5L9 I would use 'scattering patterns' or 'scattering characteristics' instead of 'scatter behaviour'; the difference is actually in applied method, not in the behaviour of sediments.

We changed the manuscript accordingly.

P5L15 I guess, d stands for 'diameter'. It should be mentioned in the text. In this sentence you speak about sediment concentration and dynamics, but the value you give in brackets is neither one nor the other. Please correct.

We changed the manuscript accordingly.

P5L18 'these' refers to what? It's not clear which instruments you speak about.

We changed the manuscript accordingly.

P5L22-24 You didn't explain here the difference between one day and longer period correlation. Why do you think the results are significantly better for one day data? Is it only for this specific day, or a general trend? More detailed explanation is advised here.

The bio-fouling influence started already in the short six-day time period, therefore correlation values of the shorter one-day time period directly after cleaning of the ECO FLNTU sensor were stronger than the values for the entire time period of six days.

P5L26-27 This sentence is general, it could be good for introduction, but not in a discussion section.

We changed the manuscript accordingly.

P5L24-25 I have the impression that you chose the constant extrapolation only because it gave better results in your study. Can you try to provide a stronger scientific motivation based on other published research?

For further investigations, we used the constant extrapolated acoustic backscatter signal $BS_{Ex,const.}$ This approach corresponded to our assumption of homogeneity of the surface layer.

P5L29 I suggest to say more precisely 'ADCP backscatter signals' or 'acoustic backscatter signals'. It should be clear you don't refer to optical backscattering here.

We changed the manuscript accordingly.

P5L31-33 - P6L1-2 This figure description is not consistent. The first sentence speaks only about the right graph. In the second sentence 'also' seems not appropriate. Please check and reformulate this description.

We changed the manuscript accordingly.

P6L2-3 This information is repeated from P5L30. It is difficult to understand the idea of such repetition.

We changed the manuscript accordingly.

P6L8 This conclusion seems to appear out of nowhere. It is not the result of your study. It seems to be your conclusion/assumption, but in the results and discussion section you don't speak about the possible artefacts of bio-fouling. I suggest to add a short description about the possible influence of bio-fouling on the quality of turbidity data. How long after or before cleaning maintenance was your 5-day study period? Do you assume that the one day study period was less influenced by bio-fouling? Did you receive similar conclusions in your earlier studies quoted in this paper, where you linked turbidity to Forel-Ule index?

We changed the manuscript accordingly.

Turbidity time series (Fig. 2) shows a rapid response directly after cleaning of the ECO FLNTU sensor as expected in a highly bio-active season (summer). Even in this short time period of 6 days a strong increase and spreading of turbidity values is discernible. Directly after cleaning maximum values are below 5 NTU with a range of 2.2 NTU, already after 3 days the increase started, at the end of this 6-day-period the values spread out to 10 NTU and reach the upper range of the reasonable data for turbidity at nearly 25 NTU.

P6L11 ’is’ seems to strong in this place; I would say ’can be’ - looking at the correlation test results.

We changed the manuscript accordingly.

P6L12-13 This sentence should be in discussion section, and the results of Schultz et al. (2015) should be described briefly in comparison to your current results.

We changed the manuscript accordingly.

Our results regarding the correlation between acoustic backscatter signal and turbidity agree well with investigations of Schulz et al. (2015). The data sets of the in-water sensors showed moderate to strong correlations, especially the counter wise strengths of the signals during the tidal signal are found again.

P6L13 Be careful with conclusions that go too far. Which responses do you call linear in your study? Spearman rank test doesn’t prove linear correlation, but a monotonic correlation (which can be non-linear). Only some of your results show very strong or strong correlation; most of correlations is moderate or weak. I suggest simply to show your best and worse result with appropriate comments.

We changed the manuscript accordingly.

P6L18 Avoid citation in conclusions.

We changed the manuscript accordingly.

P6L20 powerful tool to do what? Be more precise.

We changed the manuscript accordingly.

On a qualitative level, using the Forel-Ule-Index, as derived from radiometer measurements, is a powerful tool for exchangeable estimations of water transparency as much as data sets derived from ADCP measurements.

Citations: 17 out of 41 references are authors’ self-citations (which is more than 40%). I have the impression that some paper are quoted unnecessarily, giving three or four references to support one thesis is too much. If you see their findings are essential for your study, point them precisely in separate sentences.

This paper is based on a series of dedicated research activities from the authors over the last decade and it is part of a special issue on COSYNA summing up the work of a multi-year project. It is therefore our aim to link the advances presented to this body of work and provide the reader with the appropriate references.

To prevent overloading and doubling, we checked the references and indicated them at the specific sentences. In total the number of references and self-citations was reduced.

All figures: the units in text are presented in a rectangular brackets. Please use the same way on figures and their descriptions.

We changed the figures accordingly.

Fig. 3. Description: add short information about the device and location Fig. 4. The same. Can you add another LW profile plot? The graph makes a reader wonder why all examples are double except of LW. Height and depth - choose one way to describe this quantity.

We changed the description and figures accordingly.

Fig. 3-7,10-11. I suggest to add ’acoustic’ or ’ADCP’ backscatter in the figures’ description.

We changed the descriptions accordingly.

Fig. 8. description: ’schematic’ or ’scheme’?

We decided to choose ‘schematic’.

Why the right graph of Fig. 9 contains much less points than the corresponding graph of Fig. 10? Both figures’ descriptions show the same five-day period. Please explain and/or correct.

We selected time periods which we can assign to the phases of the tidal signal and averaged them.

LANGUAGE COMMENTS:

We changed the manuscript for all following comments accordingly and had an expert English speaker additionally reviewing the manuscript.

Although English is not my first language I see some minor grammar, punctuation and syntax errors. I recommend to use a professional English correction service, and in particular please check the following sentences/phrases:

P1L2-3 I suggest to continue the sentence in past tense: determined, demonstrated

P1L4 is=comes

P4L4 ...one of such... P2L20 comma needed P3L29 can be?

P4L8 "between ... and ..." or "from ... to ..."

P4L34 ’earlier’ or ’previous’

P5L20 compare

P6L13 sensor

P6L14 agree

P6L26 was=were

Acoustic and optical methods to infer water transparency at the Time Series Station Spiekeroog, Wadden Sea~~(southern North Sea)~~

Anne-Christin Schulz[1], Thomas H. Badewien[1], Shungudzemwoyo P. Garaba[2], and Oliver Zielinski[1]

[1]Institute for Chemistry and Biology of the Marine Environment, Carl von Ossietzky University of Oldenburg, Schleusenstr. 1, 26382 Wilhelmshaven, Germany.

[2]Department of Marine Sciences, Avery Point Campus, University of Conneticut, 1080 Shennecosset Road, Groton, CT 06340, USA.

Correspondence to: Anne-Christin Schulz (anne.c.schulz@uni-oldenburg.de)

Abstract. Water transparency is a ~~key~~ primary indicator of optical water quality that is driven by suspended particulate and dissolved material. ~~In this study we carried out an intercomparison~~ A data set from the operational Time Series Station Spiekeroog located at a tidal inlet of the Wadden Sea was used to perform (i) an inter-comparison of observations related to water transparency, ~~determine correlations among the~~ (ii) correlation tests among these measured parameters and ~~demonstrate~~ to (iii) explore the utility of both acoustic and optical tools in monitoring water transparency. ~~The data set used here is from the operational Time Series Station Spiekeroog located at a tidal inlet of the Wadden Sea.~~ An Acoustic Doppler Current Profiler was used to ~~obtain acoustic measurements~~ derive the backscatter signal in the water column. Optical observations were ~~determined using a set of three radiometers above water to collect radiometric quantities and a turbidity sensor within the water column~~collected using above-water hyperspectral radiometers and a submerged turbidity meter. Bio-fouling ~~was identified as a source of anomaly in turbidity measurements~~on the turbidity sensors optical windows resulted in measurement drift and abnormal values during quality control steps. We observed significant correlations between ~~in-situ optically measured turbidity and derived turbidity from above water color sensing and acoustic backscattering strength~~turbidity collected by the submerged meter and that derived from above-water radiometer observations. Turbidity from these sensors was also associated with the backscatter signal derived from the acoustic measurements. These findings ~~underline~~ suggest that both optical and acoustic measurements can be reasonable proxies of water transparency with the potential to mitigate gaps and increase data quality in long-time observation of marine environments.

Keywords: Acoustic backscatter, turbidity, ~~Forel-Ule-Index~~Forel-Ule-index, Time Series Station, remote sensing reflectance.

1 Introduction

Over the ~~last years, the importance of~~ past decades, scientists, policy makers and the public have become more aware of issues of environmental concern such as water quality (WFD, 2000; OECD, 1993; Borja et al., 2013). To better understand the dynamics of water quality~~and environmental awareness has risen for the public, scientists and policy makers (WFD, 2000; OECD, 1993; Bo~~ ~~In order for us to better understand water quality~~, it is ~~important to gather environmental information from different tools on~~

platforms at varying necessary to use different platforms and tools, which allow for collecting data over a broad range of temporal and spatial coverage scales (Zielinski et al., 2009; Pearlman et al., 2014). The information from these different tools ought to be comparable for a better understanding of environmental dynamicsthat drive water quality. However, water quality is an abstract term that is used widely to describe comprehensive and reliable view of these dynamics. Water quality in general is the state of water according to its a water body parameterized according to predefined thresholds typically grouped according to ecological, chemical, optical or morphological properties; each of these having a set of related variables that are used as indices. One of the key indicators for water quality is the water transparency (CRWN, 2012). Two main aspects of water clarity (Davies-Colley and Smith, 2001) or water transparency (Wilson, 2010) are the light penetration and the visual clarity (Kirk, 1988). Both are strongly affected by dissolved and suspended material within the water (Kirk, 1985) and the optical properties of the water. Optical water transparency . Water transparency is determined from optical observations that involve using the human eye as a tool or methods that replicate the human eye sensing approach (Moore et al., 2009). In general, water transparency Optical water quality has been determined for decades as the tools needed are easy to use, fast, inexpensive and robust. Typical Common optical observations provide information about the light availability in the water column, which can be translated into water transparency. Turbidity is one such measurements which refers measurement referring to a relative index of water cloudiness influenced by the inherent dissolved and particulate material (Kirk, 1985; Moore, 1980). Remote sensing Another parameter derived from ocean color remote sensing is remote sensing reflectance (R_{RS}) , also known as an essential climate variable, . R_{RS} is a proxy for the intrinsic apparent color of water and driven by optically active constituents of water (Garaba et al., 2015; Garaba and Zielinski, 2013; GCOS, 2011; Watson and Zielinski, 2013)(Garaba et al., 2015; Garaba and Zielinski, 20
The natural color of water, driven by the optically active constituents of water and environmental conditions, can be distinguished using a standard Forel-Ule color comparator scale. The Forel-Ule color scale numerically categorizes natural waters assigns numbers to the color of a natural water body, ranging from 1 (indigo-blue) to 21 (cola brown), and this . This information can also be derived from R_{RS} information (Garaba et al., 2014; Wernand and van der Woerd, 2010; Garaba et al., 2015)(Garaba et al., 201
In more recent years, acoustic backscatter has been Over the past decades, measurement methods based on acoustic backscatter have been increasingly used to estimate the abundance and distributional patterns of suspended matter (Thorne and Hanes, 2002; Deines, 19
Acoustics (Deines, 1999; Thorne et al., 1991). Indeed, acoustics is one of a number of those technologies advancing our capabilities to probe sediment processes (Thorne and Hanes, 2002; Voulgaris and Meyers, 2004). Acoustic backscatter The acoustic backscatter signal is used to quantitatively determine suspended matter and therefore relates to turbidity (Deines, 1999; Lohrmann, 2001; Sc
Therefore, acoustic backscatter signals provide information about the suspended material in a given water body and enable to record the changes over a long time scale. An Acoustic Doppler Current Profiler (ADCP), for example, measures non-intrusive and three-dimensional, making it a very powerful tool for examining small-scale sediment transport processes (Thorne and Hanes, 2002; Schulz et al., 2015).

In coastal and estuarine regions, the The composition and concentration of suspended material is highly variable in coastal and estuarine regions (Winter et al., 2007; Fugate and Friedrichs, 2002). Fragile flocculants change their characteristics over short and over long time scales due to hydrodynamic forcing conditions among them such as currents, turbulence and tides (Vousdoukas et al., 2011; Fugate and Friedrichs, 2002; Burchard and Badewien, 2015). Depending on whether optical methods

~~(White, 1998; Sutherland et al., 2000) or~~ (Vousdoukas et al., 2011; Burchard and Badewien, 2015). Optical (White, 1998; Sutherland et al. acoustic methods (Voulgaris and Meyers, 2004; Fugate and Friedrichs, 2002) ~~are used, the~~ typically reveal different scattering properties of ~~sediment differ. Optical measurements are more sensitive to fine sediment, while acoustic measurements are more sensitive to coarser material, depending on the operating frequency (Gartner, 2004).~~ the sediment. Thus Winter et al. (2007) concluded that the combination of different instruments reveal different aspects of ~~SPM dynamics. Comparisons of acoustic and optical sensors for measurements of suspended sediment concentrations performed under laboratory conditions showed that most in-water sensors have a linear response under bimodal and randomly sorted suspended sediments (Vousdoukas et al., 2011).~~ suspended particulate matter (SPM) dynamics.

~~In this work , we therefore aim~~ The aim of this work is to find out ~~if the information from optical water quality variables is related to the backscatter signal. The assumption is based on the fact that~~ whether measurements of acoustic backscatter can be reliably related to optical water properties. As all these observations provide information about the inherent suspended particulate and dissolved material~~and therefore can be~~ , these should also be suited as practical indicators of water transparency and thus quality. We also evaluate ~~to which extent combining~~ the utility of acoustic and optical ~~techniques are suited for environmental monitoring . We discuss additionally, whether~~ technology in environmental monitoring to gather qualitative and quantitative ~~information gathered at operational long time series observatory platforms helps identifying~~ indicators of change within natural waters ~~. Comparing different tools for analysing water quality may also prove valuable for assessing precision as well as accuracy of measurements. At the same time, this approach also helps, understanding associations~~ taking advantage of operational long time series observatory platforms. The goals of this study will be towards (i) inter-comparison of measurements from different tools, (ii) understanding correlations among the observed variables~~. This in turn may enable to close~~ , and (ii) developing methods geared at closing gaps in relevant information ~~concerning dynamics of suspended material in~~ about variability in water transparency in the water column such as when individual instruments fail.

2 Materials and methods

2.1 Study area

The Time Series Station Spiekeroog (TSS, Fig. ~~**??**) is an operational multidisciplinaryautonomous observatory located (53° 45.016' N, 007° 40.266' E)~~ 1) is a multidisciplinary, autonomously operating observatory located in a tidal channel between the islands of Langeoog and Spiekeroog ~~(Badewien et al., 2009)~~at 53° 45.016' N, 007° 40.266' E (Reuter et al., 2009). These islands are part of an island barrier system in the East Frisian Wadden Sea, southern North Sea, which belongs to the UNESCO World Natural Heritage sites. The region is part of an extended North Sea tidal flat system with shallow water depths ranging from 0 to 20 ~~m. The typical water depth is~~ m, with current velocities of up to 2 m s^{-1}. The tidal cycle is semi-diurnal. The water depth at the TSS Spiekeroog is about 13.5 ~~m~~ m, with tidal range of about 2.7 ~~m at the site of the Time Series Station Spiekeroog (Holinde et al., 2015). Usual current velocities during ebbing and flooding periods reach values of up to 2 m/s. The~~ m (Holinde et al., 2015). Here, the distribution of suspended particulate inorganic and organic material is strongly influenced by ~~the semi-diurnal~~ tidal currents as well as ~~waves driven by wind (Bartholomä et al., 2009; Reuter et al., 2009; Badewien et al., 2009).~~

These by wind-driven waves (Bartholomä et al., 2009; Badewien et al., 2009). Because of these strong and rapid dynamicsaround TSS make it a valuable study area for , the area at the TSS is well suited for studying the biogeochemical and physical investigations in transitional waters from land processes occurring at the transition from the coast to the open sea.

2.2 Sampling and analysis

Three radiometers (TriOS, Germany) continuously measure with a 5 minute interval, hyperspectral radiance (2 x RAMSES ARC) and irradiance (1 x RAMSES ACC) to assess Hyperspectral radiometers were used to collect and derive remote sensing reflectance (R_{RS}) . The radiometers are mounted to the TSS data at 24 m m above the seafloor (approx. 12 m above NN). The radiometric quantities are at 5 minute interval continuously. The reflectance measurements, corrected for environmental perturbations(Busch et al., 2013; Garaba et al., 2015, 2012) and are , were transformed into Forel-Ule color indices that can be matched to the intrinsic color of water(Wernand, 2011). Detailed information on the processing of these measurements is presented in an earlier study (Garaba et al., 2014). A submerged ECO FLNTU (WETlabs, USA) sensor continuously measures . A submerged WETlabs ECO FLNTU sensor measured turbidity at 12 m m above the seafloor with at 1 minute interval continuously. The ECO FLNTU sensor samples turbidity data with optical backscattering at a wavelength of 700 nm. The sensitivity of the sensor is 0.01 NTU and the typical range of turbidity is between 0 NTU and 25 NTU. Because of problems associated with bio-fouling, turbidity measurements at the TSS might not be at all times reliable. In order to compare optical data to other variables, data were taken from a period directly after cleaning the ECO FLNTU sensor (low water, 28 August 2013) from bio-fouling. Figure **??** shows the turbidity data in NTU over a time period from 28 August 2013 until 02 September 2013. The blue points show the in-situ raw data, limited between 0 NTU and 25 NTU.The red points represent quality checked turbidity data. These turbidity data were measured near the surface of the water column at a fixed height above the seabed, therefore these data can directly used for the comparison.nm. Detailed information on the processing of these measurements is presented in an earlier study Garaba et al. (2014).

A bottom-mounted (1.5 m m above the seafloor), upward looking 1200 kHz kHz ADCP (Teledyne RD Instruments Workhorse Sentinel, USA) estimates was used to estimate the current velocity using the Doppler effect in three dimensions. The ADCP is installed at a distance of about 12 m towards North-north-west from the pole m north-north-west of the station's pole. We receive data over the entire water depth with a vertical resolution of 0.20 m m (bin size) and a temporal resolution of 5 minutes (measurements are averaged over 45 pings in 5 minute bursts). The shape of the depth profiles derived from the backscatter data (Fig. 2) vary depending on the tidal phase (flood, ebb, slack water). Those phases with similar current velocity also result in similar shapes of the backscatter profiles. Because the ADCP has a beam angle of 20° and a tilted orientation with pitch a pitch of $\sim$ 19.39° and roll a roll of $\sim$ 17.96°, the maximal maximum range R_{max} $m$in m of acceptable data is given by

$$R_{max} = D\cos(\phi) \tag{1}$$

where D is the distance from ADCP to between the ADCP and the surface in mm, and ϕ is the angle in ° of the beam relative to vertical °the vertical. The resulting blank space near the surface reached values between 3.0 m m to 3.5 m m (see Fig. **??**).

In order to fill this gap, we extrapolated the acceptable backscatter data from R_{max}-depth 3). To compare the data at nearly the same sampling target, we extrapolate the acoustic backscatter signal to the sea surface layer. In different tidal phases (flood, ebb, slack water) the backscatter signal shows different profiles over depth. Figure **??** displays that the profiles at slack water (high / low water - light blue, orange, violet)have similar shapes. Also, the profiles at maximum velocity (flood / ebb - green, blue, dark yellow, brown) show similar shapes.To extrapolate the backscatter data to the surface layer, area (details of the sampling areas of the different sensors are shown in Fig. 4), using the acceptable acoustic backscatter data until R_{max}-depth. To do so, we applied various curve fitting techniques using MATLAB R2015a, Curve Fitting Toolbox (MathWorks, USA)were implemented. These methods were (i) the exponential fitting method ('exp', equation: $a \cdot exp(b \cdot x)$), (ii) the polynomial fitting method ('poly', equation: $p1 \cdot x + p2$, basically linear), (iii) the power fitting method ('power', equation: $a \cdot x^b$) and (iv) constant extrapolation (using the last reliable data value as the surface value). Comparisons between Applications of these methods are shown in Fig. **??**5. The top left graphic shows a profile graphics show profiles, which are exemplary for data obtained during low water (violet in Fig. **??**) and and one during flood (violet and blue in Fig. **??**2) with different extrapolations to the surface layer. The top right graphic shows the extrapolation results. Here, the data These graphics also demonstrate the different ranges, which were used for extrapolating: Data were extrapolated using measurements obtained within the entire water column (left panel). In an alternative approach, extrapolation of data was based solely on measurements not affected by bottom friction - that is data derived in the near bottom range up to 4 m are excluded since it is highly influenced by strong currents during ebb and flood. m were excluded (right panel). In this range, the impact of ebb and flood-induced currents is strong. The bottom panel shows the summary of all R^2 obtained from the different extrapolation methods on the entire data set. We assume that the distribution of suspended matter near the surface layer is homogeneous nearly homogeneous (e.g. Badewien et al. (2009); van der Hout et al. (2015)) because of turbulence and wind influence.

The best results for extrapolation over different existing data sets (extrapolation with complete (wwc) and reduced water column (rwc)) are given by the exponential extrapolation ('exp') resulted in the best fits for all data sets and extrapolation ranges. The R^2 values over the entire period are good with $R^2 > 0.99$ (see Fig. **??**5, bottom). Figure **??** shows the resulting signals at the surface layer. To compare Therefore, to compare acoustic backscatter data with the other parameters, the exponential fitting method and the extrapolations with constant values ($BS_{Ex,exp}$ and $BS_{Ex,const}$) were used. The latter was used to fulfil based on the assumption of homogeneity in the top layer of the water column. The acoustic backscatter signal is used to quantitatively determine suspended matter and therefore relates to turbidity (Deines, 1999; Lohrmann, 2001; Schulz et al., 2015). One aim of this study is the inter-comparison of measurements from different tools to understand correlations among the observed variables and to mitigate gaps in relevant information concerning changes in suspended material or water transparency in the water column, e. g. when instruments fail (Oehmcke et al., 2015). Vousdoukas et al. (2011) found a linear response between SPM data obtained by optical and acoustic sensors in laboratory conditions under various suspended sediment conditions. Our early investigations estimated a linear relation between turbidity and Forel-Ule-Index (Garaba et al., 2014) and apolynomial function of second order between turbidity and acoustic backscatter signal (Schulz et al., 2015). For this study, we consider for the first time

3 Results

Turbidity time series (Fig. 6 displayed data obtained from 28 August 2013 until 02 Septemper 2013) shows a rapid response directly after cleaning of the ECO FLNTU sensor as expected in a highly bio-active season (summer). Even in this short time period of six days a strong increase and spreading of turbidity values is apparent. On 27 August 2013, the ECO FLNTU sensor was cleaned. Directly after cleaning, the values were below 5 NTU with a range of 2.2 NTU. After three days, the values increased and reaching maximum values of up to 25 NTU with spreading out to 10 NTU at the end of the 6-day-period. These values indicate that the upper limit of reliable measurements had been reached. Figure 7 presents a closer look at the variables of the acoustic and optical measurements obtained on 29 August 2013. Visual inspection of data (Forel-Ule-index, turbidity and the acoustic backscatter) suggested that there was a moderate correlation. As expected, the highest values of the variables investigated were during periods with high current speeds, i.e. when the water level rises or falls. Because of the measurement principle the Forel-Ule-index was restricted to a time span between 6 a.m. to 6 p.m. resulting from daytime and the reflectance of the sunlight. The signals of both the Forel-Ule-index FUI and the turbidity TRB were stronger during ebb tide than during flood tide. The acoustic backscatter signals, which were extrapolated using constant values $BS_{Ex,const}$, were nearly equal strength during ebb and flood tide, whereas $BS_{Ex,exp}$ exhibited stronger ebb signal. However, during slack water the values were slightly decreasing. Thus, the dynamics of all data sets ~~of the different measurement approaches (acoustic and optical, in-water and above water) to evaluate their utility for environmental in-situ monitoring of information on water transparency variables. In order to confirm correlations, we apply the~~ corresponded well to the observed tidal signal.

Results of the Spearman rank correlation for one day (29 August 2013, directly after sensor cleaning) and for a longer period (six days) are shown in Table 1. As described above, we extrapolated the acoustic backscatter signal towards the sea surface to be able to compare these acoustic measurements with the optical approaches. Two of these extrapolated variables ($BS_{Ex,const}$ and $BS_{Ex,exp}$) were used for the Spearman rank correlation test.

4 ~~Results and discussion~~

~~A time series~~ The correlation coefficient between the data sets increased from moderate ($\rho_{Spearman} > 0.4$ and $\rho_{Spearman} < 0.6$) to strong ($\rho_{Spearman} > 0.6$ and $\rho_{Spearman} < 0.8$). In general, the correlation values of the shorter time periods were higher, than the values for the longer time period, especially for the comparison of the acoustic ~~and optical measurements from the 29.08.2013 is presented in Fig. ??. Visual inspection of the data suggested that there was a moderate correlation . We assume it is because of the position of~~ backscatter signal and the ~~sensors,~~ turbidity. The correlation between FUI and TRB was also very good ($\rho_{Spearman} > 0.8$). The comparison of the two different time periods showed nearly the same values. For further investigations, we used the constant extrapolated acoustic backscatter signal $BS_{Ex,const}$. For this approach, we assumed a homogenous surface layer (see above).

Table 2 shows a comparison between the constantly extrapolated ADCP backscatter signal $BS_{Ex,const}$ and the Forel-Ule-index and the turbidity data separated into different tidal phases: ebb, flood, high waters, low waters. The data cover the time period from 28 August 2013 until 02 September 2013. The correlations between the acoustic backscatter data $BS_{Ex,const}$ and FUI

ranged from a weak correlation of $\rho_{Spearman}$ = 0.34 during high tide to a strong correlation during low tide of $\rho_{Spearman}$ = 0.81. In between, the methods correlated mostly moderate ($\rho_{Spearman} > 0.4$ and $\rho_{Spearman} < 0.6$). The correlations between acoustic backscatter data $BS_{Ex,const}$ and TRB were weak at high tide and flood and otherwise strong ($\rho_{Spearman} > 0.6$ and $\rho_{Spearman} < 0.8$).

4 Discussion

The time series of turbidity data shown in Fig. 6 indicate the strong influence of bio-fouling on the sensors during the bio-active seasons spring and summer even during shorter time periods of several days. Thus, it is vital to regularly check and, if necessary, clean sensors to reduce the impact of bio-fouling on data quality. The merely moderate correlation between the acoustic backscatter data $BS_{Ex,const}$ and the Forel-Ule-index and turbidity (seen in Fig. 7 and Table 1) presumably results from the fact that the sensors had different positions, namely above the sea surface, submerged near the sea surface and submerged near the seafloor (an overview of the fields of view is shown in Fig. ~~??~~4). Additionally, the lack of a strong correlation may be due to ~~the different scatter behaviour~~ different scattering characteristics of suspended sediment ~~(White, 1998; Sutherland et al., 2000; Voulgaris and Meyers, 2004; Fugate and Friedrichs, 2002)~~ (White, 1998; Sutherland et al., 2000; Vo on whether optical or acoustic methods are applied. Comparisons of acoustic and optical sensors for measurements of suspended sediment concentrations performed under laboratory conditions showed that most in-water sensors have a linear response under bimodal and randomly sorted suspended sediments (Vousdoukas et al., 2011). Optical measurements are more sensitive to fine sediment and are wavelength dependent, while acoustic measurements are more sensitive to coarser material, depending on the operating frequency (Gartner, 2004). Both depend on the amount of suspended sediment in the water column. Badewien et al. (2009) measured a range of particle sizes from 1.25 µm to 26.9 ~~µm~~ µm (radius) at the same site. Therefore, mainly fine sediment concentrations are expected. A modelling study by Stanev et al. (2007) showed different sediment concentrations and dynamics for fine SPM (mud, ~~d_{mud}~~ d_{mud} = 63 ~~µm~~µm; d: diameter) and sand (~~d_{sand}~~ d_{sand} = 200 ~~µm~~µm) for this Wadden Sea area. Depending on the specific location, the dynamics of the different sediment types (fine or coarse) ~~acted~~ act differently dependent on the tidal signal. ~~The dynamics of~~ Concentrations of coarser material usually clearly peak at maximum flow velocities (flood and ebb). The concentration of fine sediments is highest during ebb, although the peak is broader. The peak during flood is less pronounced. In this study, the dynamics observed in all data sets correspond well to the observed tidal signal ~~. Furthermore, we presume these instruments provide a reasonable proxy for the~~ (Fig. 7). As shown in Schulz et al. (2015) the remaining shear currents in the surface layer kept particles within the water column at slack water times. Thus, we assume that the instruments used in this study provide reasonable proxies for suspended material which is comparable ~~. In order to confirm the correlations we applied the Spearman rank correlation test (for two time periods of different length). Results of the Spearman rank correlation are shown in table 1. To compared the data at nearly~~ in size.

To be able to compare the data obtained by different methods at about the same sampling ~~target, we extrapolated the~~ site, we had to extrapolate the acoustic backscatter signal towards the sea surface ~~area~~as described above. Two of these extrapolated variables ($BS_{Ex,const}$ and $BS_{Ex,exp}$) ~~are~~ were used for the Spearman rank correlation test as shown in Table 1 and 2. The correlation coefficient between the data sets increases from moderate ($\rho_{Spearman} > 0.4$ and $\rho_{Spearman} < 0.6$) to strong($\rho_{Spearman} > 0.6$ and $\rho_{Spearman} < 0.8$). The correlation between Forel-Ule-Index increased from moderate to strong. These differences may result from the different scattering characteristics and dynamics of the kinds of sediment, which occur in this location. The bio-fouling influence started already in the short six-day time period. Therefore correlation values derived from the data of the shorter one-day time period directly after cleaning of the ECO FLNTU sensor were stronger than the values for the entire time period of six days. The correlation between the Forel-Ule-index FUI and the turbidity TRB is was even very good ($\rho_{Spearman} > 0.8$). For further investigations, we use the constant extrapolated backscatter signal $BS_{Ex,const}$. The Forel-Ule color scale is an inexpensive and longstanding tool used to determine intrinsic color of water (Garaba et al., 2015; Garaba and Zielinski, 201 the comparison of the two different time periods showed nearly the same values. This indicates that both optical measurements (above and in-water) detect the same type of sediment. In a previous study it was shown that the Forel-Ule-Index (FUI) Forel-Ule-index can be used to accurately derive turbidity (Garaba et al., 2014). We therefore evaluate evaluated its potential in providing information about suspended material, which in turn can be compared to information derived from acoustic backscatter signals. Our results regarding the correlation between the acoustic backscatter signals (Fig. ??). We made comparisons with data obtained from different tidal phases (ebb, flood and slack water periods) and observed correlations between $\rho_{Spearman} = 0.34$ (for high tide) and $\rho_{Spearman} = 0.81$ (low tide) (all results are shown in table 2). Figure **??** shows a comparison between the backscatter signal and the turbidity data, which are separated into the tidal phases: ebb (green), flood (red), high waters (dark blue), low waters (light blue). The Fig. shows also the comparison between the backscatter signal from the ADCP which was constantly extrapolated to the sea surface $BS_{Ex,const}$ versus Forel-Ule-Index FUI on the left and $BS_{Ex,const}$ versus turbidity data TRB on the right. Spearman rank correlation tests were also applied to signals at different tide phases (ebb, flood and slack water periods) and results are presented in table 2. The correlations between backscatter data $BS_{Ex,const}$ and Forel-Ule-Index FUI are weak at high tide ($\rho_{Spearman} = 0.34$) and mostly moderate ($\rho_{Spearman} > 0.4$ and $\rho_{Spearman} < 0.6$). The correlations between backscatter data $BS_{Ex,const}$ and turbidity TRB are weak at high tide and flood and otherwise strong ($\rho_{Spearman} > 0.6$ and $\rho_{Spearman} < 0.8$). turbidity agree well with investigations of Schulz et al. (2015). The data sets of the in-water sensors correlated moderately to strongly. In particular, the counter wise strengths of the signals during the tidal cycle could be identified. In summary, our results on the correlation of the different sensor types agree well with previous results from laboratory investigations (Vousdoukas et al., 2011).

5 Conclusions

The The goals of this study was to perform an inter-comparison of measurements from different tools, to understand correlations among the observed variables, and to develop methods geared at closing gaps in relevant information about variability in water transparency in the water column when individual instruments fail.

The results of this study show that bio-fouling decreases the data quality of in-water optical measurements of turbidity within short time periods. Hence, it is important to find an approach to improve the monitoring over time and increase the robustness of the turbidity results. This study demonstrates that bottom-mounted ADCP measurements, which are hardly influenced by bio-fouling, is can be a suitable alternative to overcome the problem. We found that using the acoustic backscatter signal and Forel-Ule-Index the Forel-Ule-index both yield reliable results, thus broadening the work of Garaba et al. (2014). Our results regarding the correlation between backscatter signal and turbidity agree well with investigations of Schulz et al. (2015). The linear responses between the different sensors types found in this study agrees with previous results from laboratory investigations (Vousdoukas et al., 2011)On a qualitative level, using the Forel-Ule-index, as derived from radiometer measurements, is a powerful tool for exchangeable estimations of water transparency as much as data sets derived from ADCP measurements. We have also shown that data sets from different measurement principles (optical and acoustic) are comparable and complementary. This is despite of the position of the sensors , even though the different sensors reveal different scattering properties of particles and are positioned in different ways, i.e. above the sea surface, submerged near the sea surface and submerged near the seafloorand the well-known fact that the scattering properties of particles derived from both methods differ (White, 1998; Sutherland et al., 2 Thus, our study strongly suggests that combining these methods can be utilized as an affordable tool and from different platforms an effective tool to monitor environmental processes . On a qualitative level, using the Forel-Ule-Index, derived from radiometer measurements, is a powerful tool as much as data sets derived from ADCP measurements. Our investigations also underline that long term observatories are key in understanding the marine environment because short-term studies only allow for a limited view on the considered dynamics.Summarizing we found out that the information from optical water quality variables is related to the acoustic backscatter signal. We also evaluated the utility of acoustic and optical technology in environmental monitoring to gather qualitative and quantitative indicators of change within natural waters taking advantage of operational as a part of long time series observatory platforms. The goals of this study was to perform an inter-comparison of measurements from different tools, to understand correlations among the observed variables, and to develop methods geared at mitigating gaps in relevant information about changes in water transparency in the water column when instruments fail. observatories.

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References

Badewien, T. H., Zimmer, E., Bartholomä, A., and Reuter, R.: Towards continuous long-term measurements of suspended particulate matter (SPM) in turbid coastal waters, Ocean Dynamics, 59, 227–238, 2009.

Bartholomä, A., Kubicki, A., Badewien, T. H., and Flemming, B. W.: Suspended sediment transport in the German Wadden Sea-seasonal variations and extreme events, Ocean Dynamics, 59, 213–225, doi: 10.1007/s10236-009-0193-6, 2009.

Borja, A., Elliott, M., Andersen, J. H., Cardoso, A. C., Carstensen, J., ao G. Ferreira, J., Heiskanen, A.-S., ao C. Marques, J., ao M. Neto, J., Teixeira, H., Uusitalo, L., Uyarra, M. C., and Zampoukas, N.: Good Environmental Status of marine ecosystems: What is it and how do we know when we have attained it?, Marine Pollution Bulletin, 76, 16–27, 2013.

Burchard, H. and Badewien, T. H.: Thermohaline residual circulation of the Wadden Sea, Ocean Dynamics, pp. 1–14, doi:10.1007/s10236-015-0895-x, 2015.

Busch, J. A., Hedley, J. D., and Zielinski, O.: Correction of hyperspectral reflectance measurements for surface objects and direct sun reflection on surface waters, International Journal of Remote Sensing, 34, 1–17, dOI: 10.1080/01431161.2013.804226, 2013.

CRWN: Colorado River Watch Network Water Quality Monitoring Manual, 2012.

Davies-Colley, R. J. and Smith, D. G.: Turbidity, Suspended Sediment, and Water Clarity: A Review, Journal of the American Water Resources Association, 37, 1085–1101, 2001.

Deines, K. L.: Backscatter Estimation Using Broadband Acoustic Doppler Current Profilers, in: Current Measurement, 1999. Proceedings of the IEEE Sixth Working Conference on, pp. 249–253, doi:10.1109/CCM.1999.755249, 1999.

Fugate, D. C. and Friedrichs, C. T.: Determining concentration and fall velocity of estuarine particle populations using ADV, OBS and LISST, Continental Shelf Research, 22, 1867–1886, 2002.

Garaba, S. P. and Zielinski, O.: Comparison of remote sensing reflectance from above-water and in-water measurements west of Greenland, Labrador Sea, Denmark Strait, and west of Iceland, Optics Express, 21, 15 938–15 950, doi: 10.1364/OE.21.015938, 2013.

Garaba, S. P. and Zielinski, O.: An assessment of water quality monitoring tools in an estuarine system, Remote Sensing Applications: Society and Environment, 2, 1–10, doi:10.1016/j.rsase.2015.09.001, 2015.

Garaba, S. P., Schulz, J., Wernand, M. R., and Zielinski, O.: Sunglint Detection for Unmanned and Automated Platforms, Sensors, 12, 12 545–12 561, doi: 10.3390/s120912545, 2012.

Garaba, S. P., Badewien, T. H., Braun, A., Schulz, A.-C., and Zielinski, O.: Using ocean colour products to estimate turbidity at the Wadden Sea time series station Spiekeroog, Journal of the European Optical Society, 9, 1–6, doi: 10.2971/jeos.2014.14020, 2014.

Garaba, S. P., Voß, D., Wollschläger, J., and Zielinski, O.: Modern approaches to shipborne ocean color remote sensing, Applied Optics, 54, 3602–3612, doi: 10.1364/AO.54.003602, 2015.

Gartner, J. W.: Estimating suspended solids concentrations from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay, California, Marine Geology, 211, 169–187, 2004.

GCOS: The Global Climate Observing System - Systematic Observation Requirements for Satellite-based Data Products for Climate: 2011 Update GCOS-154, 2011.

Holinde, L., Badewien, T. H., Freund, J. A., Stanev, E. V., and Zielinski, O.: Processing of water level derived from water pressure data at the Time Series Station Spiekeroog, Earth Syst, Sci. Data, 7, 289–297, doi:10.5194/essd-7-289-2015, 2015.

Kirk, J. T. O.: Effects of suspensoids (turbidity) on penetration of solar radiation in aquatic ecosystems, Hydrobiologia, 125, 195–208, doi: 10.1007/BF00045935, 1985.

Kirk, J. T. O.: Optical Water Quality-What Does it Mean and How Should We Measure It?, Water Pollution Control Federation, 60, 194–197, 1988.

Lohrmann, A.: Monitoring Sediment Concentration with acoustic backscattering instruments, nortek technical notes/October15, 2001/Document No. N4000-712, 2001.

Moore, C., Barnard, A., Fietzek, P., Lewis, M. R., Sosik, H. M., White, S., and Zielinski, O.: Optical tools for ocean monitoring and research, Ocean Science, 5, 661–684, 2009.

Moore, G. K.: Satellite remote sensing of water turbidity / Sonde de télémesure par satellite de la turbidité de l'eau, Journal of the European Optical Society - Rapid Publications, 5, 407–421, 1980.

Morel, A.: In-water and remote measurements of ocean color, Boundary-Layer Meteorology, 18, 177–201, doi:10.1007/bf00121323, 1980.

OECD: CORE SET OF INDICATORS FOR ENVIRONMENTAL PERFORMANCE REVIEWS - A synthesis report by the Group on the State of the Environment, Organisation for Economic Co-operation and Development, Paris, 1993.

Oehmcke, S., Zielinski, O., and Kramer, O.: Event Detection in Marine Time Series Data, Conference: KI 2015: Advances in Artificial Intelligence, pp. 1–8, doi:10.1007/978-3-319-24489-1_24, 2015.

Pearlman, J., Garello, R., Delory, E., Castro, A., del R´io, J., Toma, D. M., Rolin, J. F., Waldmann, C., and Zielinski, O.: Requirements and approaches for a more cost-efficient assessment of ocean waters and ecosystems, and fisheries management, in: 2014 Oceans - St. John's, pp. 1–9, doi:10.1109/OCEANS.2014.7003144, 2014.

Reuter, R., Badewien, T. H., Bartholomä, A., Braun, A., Lübben, A., and Rullkötter, J.: A hydrographic time series station in the Wadden Sea (southern North Sea), Ocean Dynamics, 2009.

Schulz, A.-C., Badewien, T. H., and Zielinski, O.: Impact of currents and turbulence on turbidity dynamics at the Time Series Station Spiekeroog (Wadden Sea, southern North Sea), IEEE, Current, Waves and Turbulence Measurement (CWTM), 2015 IEEE/OES Eleventh , doi: 10.1109/CWTM.2015.7098095, 2015.

Stanev, E. V., Brink-Spalink, G., and Wolff, J.-O.: Sediment dynamics in tidally dominated environments controlled by transport and turbulence: A case study for the East Frisian Wadden Sea, Journal of Geophysical Research, 112, 1–20, doi: 10.1029/2005JC003045, 2007.

Sutherland, T., Lane, P., Amos, C., and Downing, J.: The calibration of optical backscatter sensors for suspended sediment of varying darkness levels, Marine Geology, 162, 587–597, 2000.

Thorne, P. D. and Hanes, D. M.: A review of acoustic measurement of small-scale sediment processes, Continental Shelf Research, 22, 603–632, 2002.

Thorne, P. D., Vincent, C. E., Hardcastle, P. J., Rehmann, S., and Pearson, N.: Measuring suspended sediment concentrations using acoustic backscatter devices, Marine Geology, 98, 7–16, 1991.

van der Hout, C. M., Gerkema, T., Nauw, J. J., and Ridderinkhof, H.: Observations of a narrow zone of high suspended particulate matter (SPM) concentrations along the Dutch coast, Continental Shelf Research, 95, 27 – 38, doi:10.1016/j.csr.2015.01.002, 2015.

Voulgaris, G. and Meyers, S. T.: Temporal variability of hydrodynamics, sediment concentration and sediment settling velocity in a tidal creek, Continental Shelf Research, 24, 1659–1683, 2004.

Vousdoukas, M., Aleksiadis, S., Grenz, C., and Verney, R.: Comparisons of acoustic and optical sensors for suspended sediment concentration measurements under non-homogeneous solutions, Journal of Coastal Research, 64, 160–164, 2011.

Watson, J. and Zielinski, O.: Subsea optics and imaging, Woodhead Publishing (Elsevier imprint), 2013.

Wernand, M. R.: Poseidons paintbox: historical archives of ocean colour in global-change perspective, phD Thesis (Utrecht University), 2011.

Wernand, M. R. and van der Woerd, H. J.: Spectral analysis of the Forel-Ule Ocean colour comparator scale, Journal of the European Optical Society - Rapid Publications, 5, 10 014s, doi: 10.2971/jeos.2010.10014s, 2010.

WFD: European Water Framework Directive, Directive 2000/60/EC of the european parliament and of the council, Official Journal of the European Union, L327, 1–72, 2000.

White, T. E.: Status of measurement techniques for coastal sediment transport, Coastal Engineering, 35, 17–45, 1998.

Wilson, P. C.: Water Quality Notes: Water Clarity (Turbidity, Suspended Solids, and Color), department of Soil and Water Science, UF/IFAS Extension, SL314, 2010.

Winter, C., Becker, M., Ernstsen, V. B., Hebbeln, D., Port, A., Bartholomä, A., Flemming, B., and Lunau, M.: In-situ observation of aggregate dynamics in a tidal channel using acoustics, laser diffraction and optics, Journal of Coastal Research, 50, 1173–1177, 2007.

Zielinski, O., Busch, J. A., Cembella, A. D., Daly, K. L., Engelbrektsson, J., Hannides, A. K., and Schmidt, H.: Detecting marine hazardous substances and organisms: sensors for pollutants, toxins, and pathogens, Ocean Sci. Discuss., 6, 953–1005, 2009.

Table 1. Spearman rank correlation results of the backscatter data from the ADCP $BS_{EX,const}$ and $BS_{EX,exp}$ for one day and for a longer time period (29 August 2013-02 September 2013) as well as the estimated Forel-Ule-index FUI and the turbidity TRB.

variables	$\rho_{Spearman}$ one day	$\rho_{Spearman}$ longer period	p-value one day	p-value longer period
$BS_{EX,const}$ vs. TRB	0.78	0.50	<0.001	<0.001
$BS_{EX,exp}$ vs. TRB	0.67	0.42	<0.001	<0.001
$BS_{EX,const}$ vs. FUI	0.58	0.52	<0.001	<0.001
$BS_{EX,exp}$ vs. FUI	0.48	0.44	<0.001	<0.001
FUI vs. TRB	0.88	0.85	<0.001	<0.001

Table 2. Spearman rank correlation results of the backscatter data from the ADCP $BS_{EX,const}$, the estimated Forel-Ule-index FUI and the turbidity TRB with separation into tidal phases.

variables	tide phase	$\rho_{Spearman}$	p-value
$BS_{Ex,const}$ vs. FUI	ebb	0.45	<0.001
	flood	0.52	<0.001
	high tide	0.34	0.06
	low tide	0.81	<0.001
$BS_{Ex,const}$ vs. TRB	ebb	0.71	<0.001
	flood	-0.34	<0.001
	high tide	0.40	0.0014
	low tide	0.77	<0.001

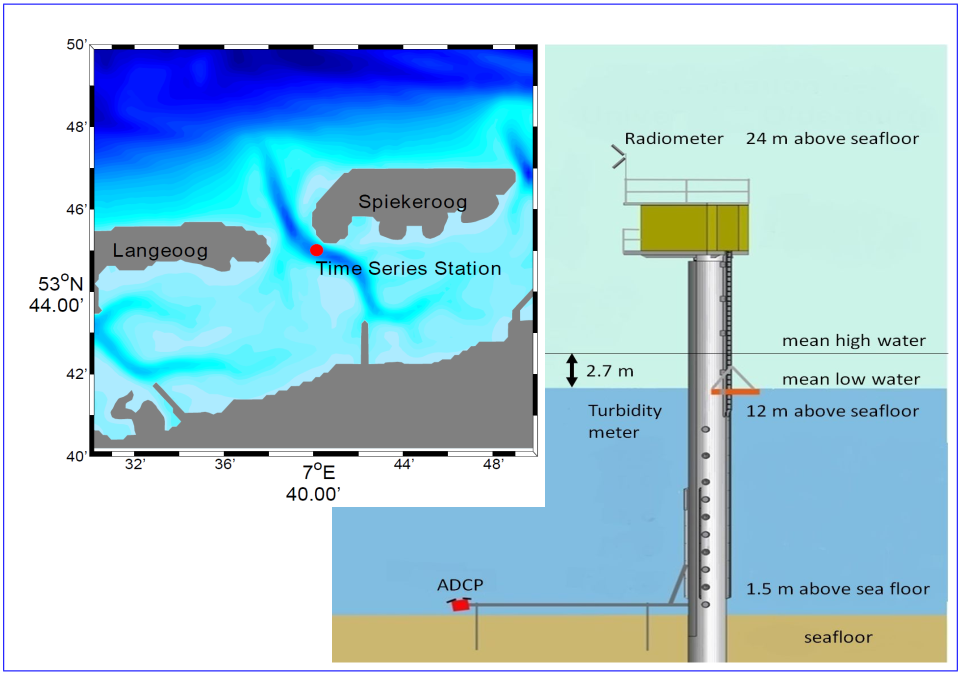

Figure 1. Schematic of the Time Series Station Spiekeroog showing the position of the radiometers (24 m), the turbidity meter (12 m) and the ADCP (1.5 m above the seafloor). The typical water depth is 13.5 m with tidal range of about 2.7 m between mean high and low water. The insert shows the location of the Time Series Station where the colors indicate the water depth at high water.

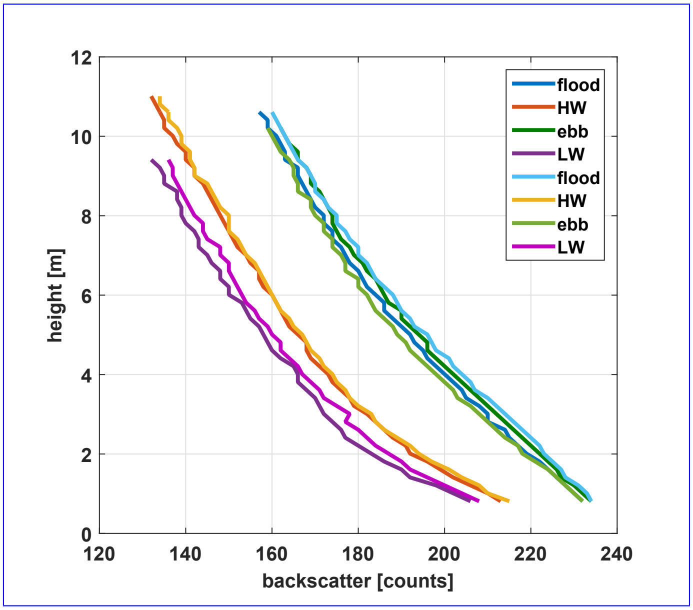

Figure 2. Example acoustic backscatter profiles measured from ADCP over height in counts observed on 29 August 2013 at different tidal phases: flood, ebb, slack water (high water (HW), low water (LW)).

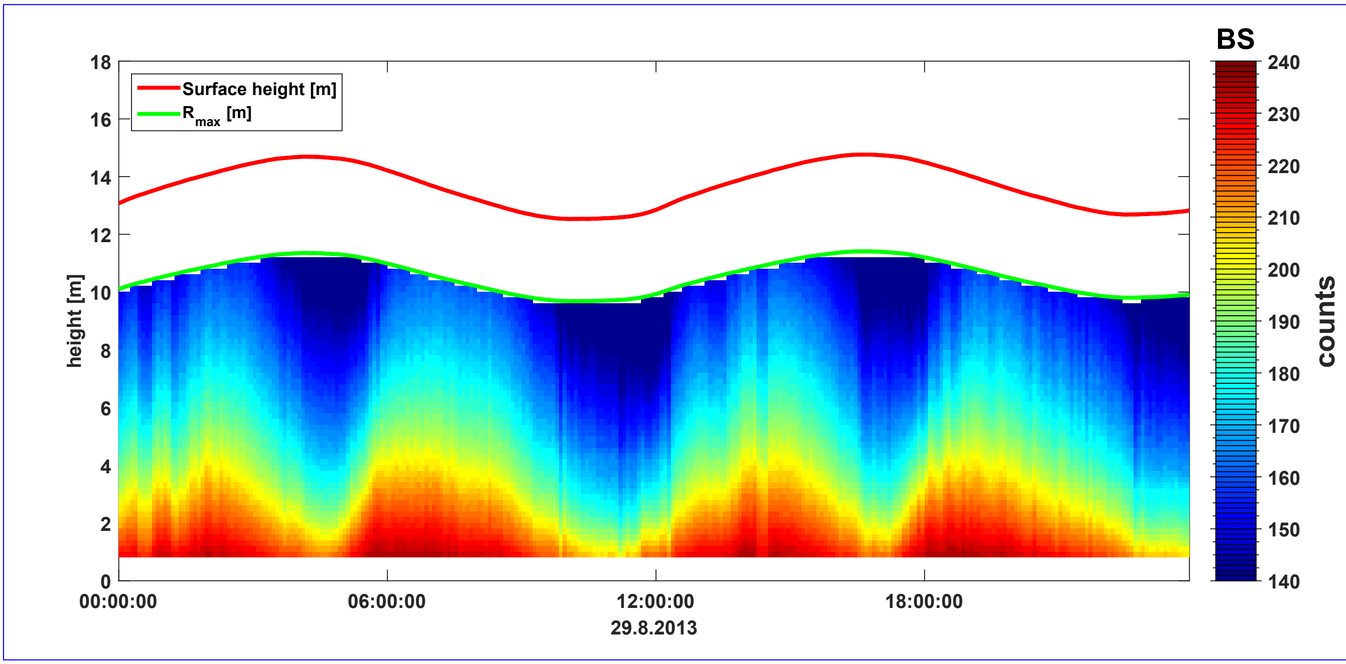

Figure 3. An example of acoustic backscatter signal in counts measured with the ADCP (from the seafloor upwards through the water column), acceptable backscatter data until R_{max}. Green line: R_{max}-depth in m; red line: sea level (height in m) observed on 29 August 2013.

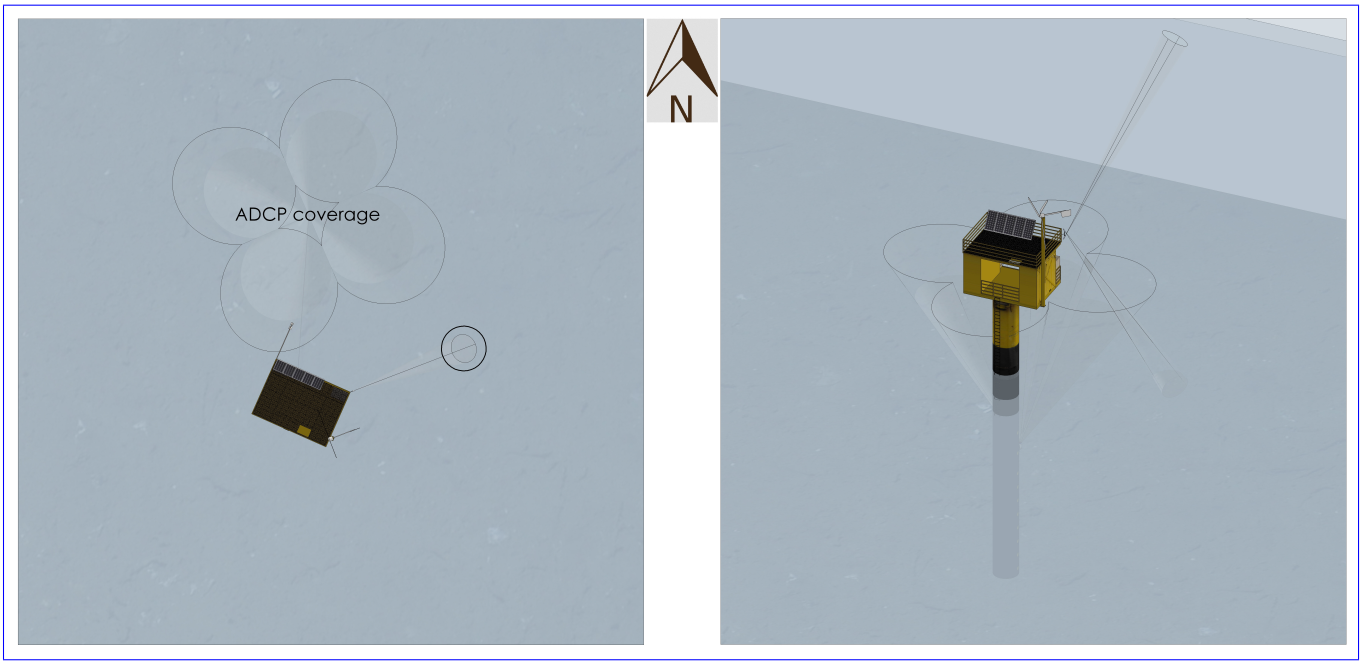

Figure 4. Schematic of the different measurement fields of view (FOV) of the sensors at the Time Series Station Spiekeroog at high water. Left panel: top view; right panel: perspective from south (provided by Nick Rüssmeier).

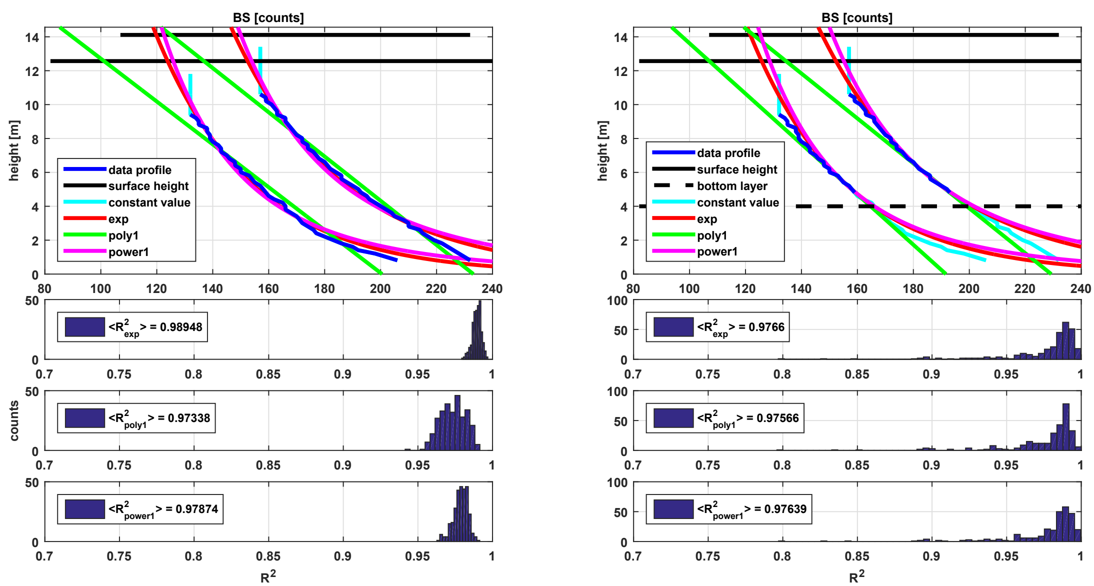

Figure 5. Selected acoustic backscatter profiles during low water and during flood; top left: extrapolation through the whole water column; top right: extrapolation through the reduced water column. The colored profiles show the results of the different extrapolation methods (cyan: constant extrapolation; red: exponential extrapolation; green: polynomial extrapolation; magenta: power extrapolation). Black line: surface layer and black dotted line: lower layer. Bottom graphics: histograms of the corresponding R^2 values (from every profile) for the entire period; left: for the whole water column, right: for the reduced water column.

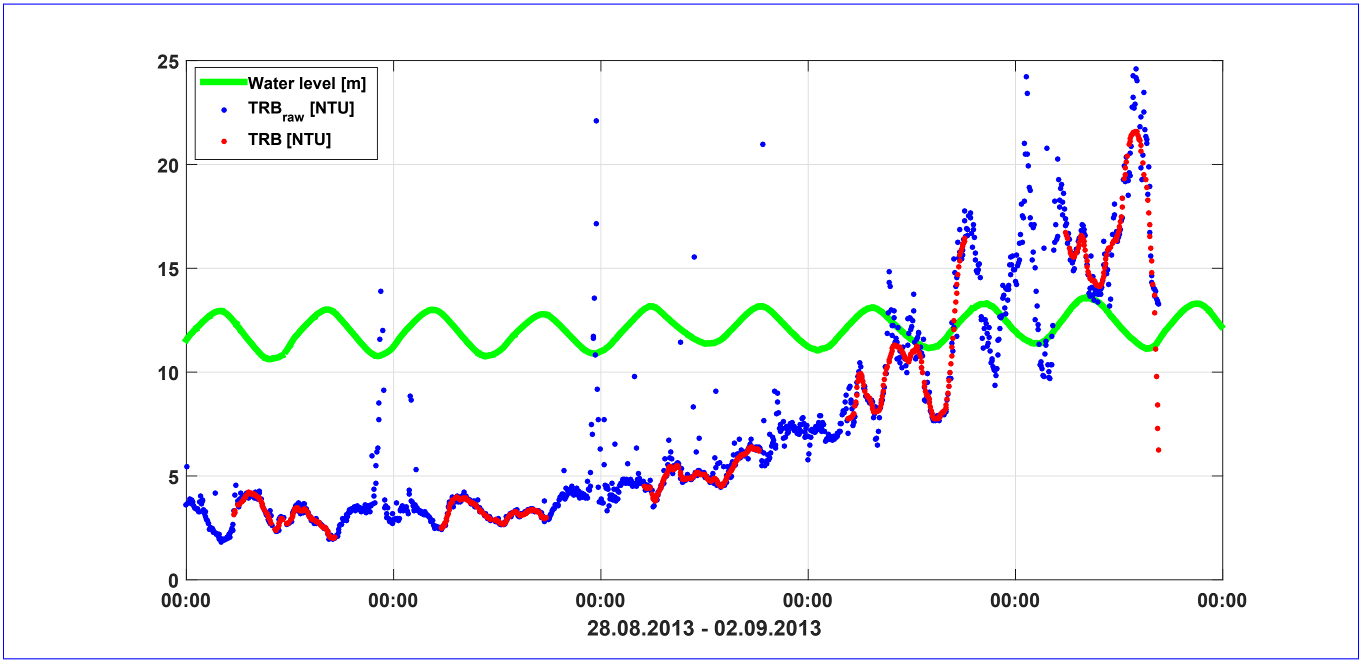

Figure 6. Turbidity data in NTU from 28 August 2013 until 02 September 2013, limited in range (0-25 NTU), blue: raw data, red: quality checked data and green: water level in m.

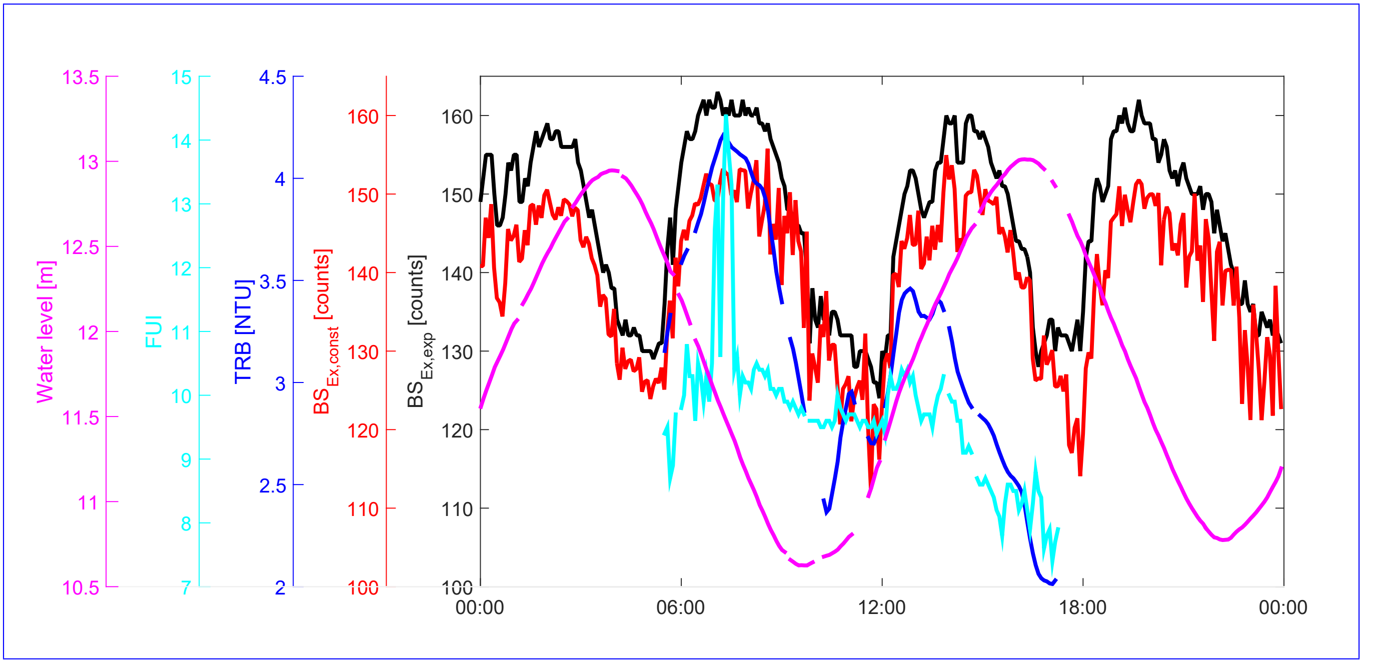

Figure 7. Time series observations on 29 August 2013 of Forel-Ule color index (FUI, cyan), backscatter signal (BS, constant extrapolation: red, exponential extrapolation: black), turbidity (blue) and water level (magenta).