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Title: Monitoring compliance with fuel sulfur content regulations of sailing ships by unmanned aerial vehicle (UAV) measurements of ship emissions in open water

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Referee Report: Jan Duyzer

General comments:

This is an interesting paper on an important issue. Sulphur compliance monitoring at sea. The method using drones is rather new and the paper shows details that could help other researchers in this area. Especially the verification measurements presented in the paper and the experiences with the on-board verification attempts are important. Worldwide readers will be interested in the results of the measurements but also in the experiences with on-board inspections.

The paper reads well and although it is only a small contribution, I think it deserves publication paying attention to some of the points below. I would like to see a more detailed and perhaps more quantitative treatment of the way the measured data are handled and converted to FSC and when they are rejected.

I have only a few small comments on the English (see below). Other more general comments:

- The qualifications *poor* and *good* are recognizable. We use that as well in our monitoring. Yet I would like to challenge the authors to come up with a more objective assessment of the quality of each measurement or at least some description as to why some measurements are considered *poor*. It could be difficult to find objective measures, but it seems needed before the method will become a true enforcement tool.
- The S-content is now derived from the “fluctuating” signal presented in figure 5. It is not entirely clear why the 10 s averaged data would lead to a better result. I can hardly see the difference. Please show why this is better
- It should be noted that the signal is not noisy but simply reflects the incomplete mixing of the exhaust gas with clean air. The peaks represent the air that is exhausted from the funnel i.e. only in the peaks you will find the ratio between SO₂ and CO₂ that is a direct measure of the fuel composition. The highest peak is probably the best choice but could still be a result of mixing of clean air with exhaust air and lead to bias in the result. Or is this negligible? I would welcome a discussion showing that the peak height is a good measure.
- Why not convert table 1 and table 2 into x-y graphs? Perhaps if combined?
- Our enforcement contacts tell us that ship owners will normally use fuel with a Sulphur content just below the limit. If I look at all the individual samples, I don't see that. Is there an uncertainty that is missed or are the vessels changing from one fuel to the other at the time of the sampling?

More specific comments:

Abstract:

Line 12 Emissions of CO₂ and SO₂ are not measured if I am correct. S content (S%) is measured.

Line 13: I don't think the costs of this method are presented or discussed explicitly in this paper. The cost of a vessel capable of operating in open sea seems neglected. In our country that is *not low cost*. This is also rather costly.

Line 17 *According to the monitoring results*: I suggest changing to: Based upon the online monitoring results

Line 69: low cost but doesn't include the cost of sailing

Line 90 precision of 5 % at full range (is 10 ppm) or 0.5 ppm. Is that correct? Please mention. And how high is that compared to the observed values? What is the Sulphur content of the example presented in figure 5? Please add.

Line 90 etc. Could some details or results of the calibration procedure be presented as well.

Line 107 "measure the concentration of SO₂ and CO₂". Change to: Measure the concentration of SO₂ and CO₂ *in the plume*

Line 124 *EF* has no unit or? I wonder why equation 1 is mentioned. I think it is a bit confusing.

Line 132: What is *sampling rate*? Electronically? And why are the SO₂ and CO₂ sensors not synchronized? In the graphs it looks like *a delay*. And you could just shift them a little. Why is that not done? And why is the 10 s averaged data better. I don't see that.

Figure 5 Please use equal y-scales in the right and left panel. This is confusing.

Line 137: The 10 sec averages hardly differ from 1 sec data. How could that happen?

Line 140 What is meant by the *calculated function*? Not just the average measurement value?

Line 160: What would be objective criteria to tell whether it's a poor-quality plume?

Line 167 Is this correct 20% (m/m)? I would expect 20% uncertainty with no units. So I suggest to leave (m/m) out.

Line 168 and 169. Unclear what is meant here (after *therefore*)? It could be interesting for the reader interested in enforcement to mention (even in the abstract) how many of the Non Compliants were detected and how many were missed (i.e. ships that were not identified as Non Compliants but had an FSC above the limit.

Line 189: perhaps the word *optimistic* is not the right word. Perhaps it should be: The uncertainty in the assessment is not small but the results so far, do not lead to optimism with respect to the FSC used by ships sailing in the area.

Line 210: It is only a small sample isn't it, but still convincing looking at figure 6. Please mention that.

Page 15: Number of digits in the given numbers are large (such as 40913 ppm, I suggest changing that to 4.1 %)

Page 15 Why are the results of the sampling by the maritime authority not given in the table

English:

Line 15 ships → vessels

Line 45 and 66 supervise or supervision → enforce and enforcement

Line 46 Several studies have suggested monitoring methods or similar. Otherwise I understood wrong but then the sentence is not very clear.

Line 54 and 65 navigation → navigating (?)

Line 60: airplane → aircraft

Line 65 inaccurate → non representative

Line 67 Suggestion: leave *therefore* out

Line 85 extracts gas? → draws air

line 108: approximately a few hundred meters. This is double: a few hundred meters is already an expression showing that it is an approximate value. Suggest leaving the word *approximately* out.

Page 13 legends to figure 4: the enlarged UAV is shown in the top **left** corner (and it is in the right corner: a detail)

NB: I have two versions of the text. Also, one with an appendix including two figures:

Figure A2 The Chinese text could be difficult to read for non-Chinese readers. Perhaps add some explanation of the Chinese text.