Author comments on

"Automated gas bubble imaging at sea floor – a new method of in situ gas flux quantification"

by K. Thomanek et al.

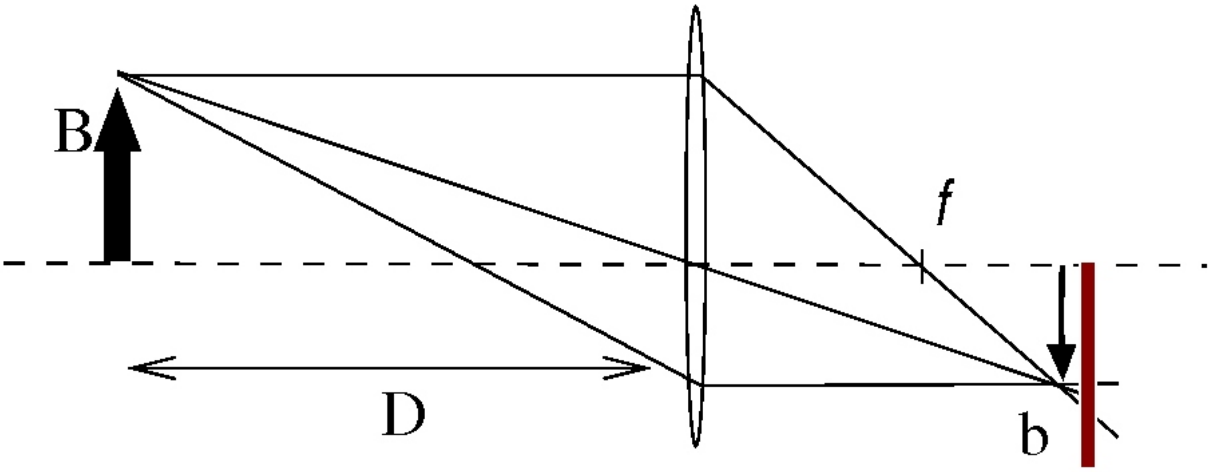
We thank the reviewers for their positive evaluation of the manuscript and appreciate their very helpful comments and proposed modification on further improving this manuscript. The following lists the reviewer's comments together with the modifications to the manuscript.

1) *The paper is well written but perhaps a little too long. The authors could make some efforts to shorten the paper by perhaps removing small details not critical to the main results.*

It is true to say, the manuscript is not a short review. Indeed it combines four separate parts of the process. However, the length is due to the fact that this work describes a unique system which in this form had not existed before. In order to demonstrate its functionality the setup and method of measurement had to be described. While proving the systems capability of measuring bubbles and construing image data the results returned were unexpected. As such these results had to be verified for physical consistency as opposed to computing errors. Finally we felt the importance of demonstrating the system's ability of deployment under deep-sea condition, thus completing the development process from laboratory towards a field operating device. However, we have revised the manuscript and removed less significant and technical parts in order to address this issue.

2) *Fig 1 is not very informative. I would like see an optical layout for the instrument (even though this might be simple).*

Figure 1 is intended as a simplified sketch showing the system in its components. This way we hope to assist the reader in comprehending the critical parts as the manuscript continues to describe each component. For simplicity the optical layout is drawn below.



In linear optics light is refracted at the lens in such a way that the Bubble-object 'B' is mapped onto the Bubble-image 'b' at the sensor chip of the camera (red bar). The distance between bubble and lens is 'D'. In Figure 1 of the manuscript the bubbles rise in the volume of observation confined between illumination (1) and box (2). 'f' denotes the focal length and has an impact on the size of the observed volume.

3) *P298, L15 – to my mind a "notebook" will for ever be something with paper between covers!! And you can't connect a camera to it. Please use term "notebook PC" or "laptop".*
   also:
   p298, line 15, notebook IBM compatible computer?

The expression 'notebook' has been successfully converted into 'laptop PC'

4) *Something about the wavelength of LEDs and bandwidth would be useful.*

The wavelength of the LEDs used is Gaussian distributed with a peak at μ=524nm and deviation of σ=10nm which has been added to the manuscript.

5) *How does transparent oil increase buoyancy?*

Special oil is used as hydraulic medium. Its density is ρ=0.97 g/cm^3 and thus less than the average density of sea water, i.e. $\rho_{av.}$=1.034 g/cm^3. Once the box is filled with oil and submerged in seawater it produces an upward force of approximately 100N. Oil with high transmission coefficients i.e. τ>0.9 reduce losses in light intensity opposed to those oils with low transmission coefficients. Both characteristics being a non critical minor detail have been combined in a single sentence for the sake of shortening the manuscript.

6) *P303, L22 – "bubbles oscillated during acend causing.." should be replaced*

Manuscript modified as suggested.

7) Authors use fps instead of Hz throughout - SI recommends Hz

SI-Unit 'Hz' is applicable for technical applications with pulse frequencies or for the transmission of electromagnetic waves. The repetition at which each semiconductor sensor is actuated on a camera chip for example may be best described as frequency denoted in 'Hz'. In digital imaging, however, there is a variety of periodical reoccurring events which are subject to the previously mentioned repetition frequency but yet must be clearly distinguished. Semiconductor sensors may be repeatedly triggered forming lines of image. Subsequent lines may be combined forming images. Single images may be combined forming time sequences. These tempo-spatial parameters are generally adjustable and thus, we fell must be clearly verbally distinguished from the technically fixed pulse frequency. Moreover, using this terminology we are in accordance the general terminology used in digital image processing. See for example: Bernd Jähne, Digital image processing: concepts, algorithms and scientific applications, Springer-Verlag, London, 1991

8) *Technical corrections P298 throughout P332*

We are particularly thankful for the careful reading and appreciate the corrections proposed for the manuscript. Where applicable, errors have been eliminated. (P298, 299, 300, 303, 304, 305, 309,

311) Proposed corrections which indicated lacking explanation have been revised and modified. (P304, 305, 308) The layout and figures have been revised too.

9) *On the other hand, the technical developments are significant as they enable methane gas bubble fluxes up to 10 L/min to be quantified to within ± 33% for the worst case scenario. However, this value of 33% seems rather large to me, although no doubt a significant improvement on a total lack of data or error bars. I think the readership would benefit from a statement on the most likely level of accuracy for typical deployments or flow rates seen in situ in the abstract and discussion section, as presumably, this is generally much better than ± 33%?*

We agree with the reviewer that the proposed maximum error of ± 33% may initially not be all too exciting. However, we would like to point out that the parameters in the laboratory were deliberately chosen to represent the worst case scenario. One of the initial objectives during development was to determine the operational parameter limiting. We therefore know now, that we can determine the flow rate even if the flux is as high as 10L/min and even when recorded close to the vent opening in water with only few surface active substances. Luckily, in deep sea conditions the magnitudes of critical parameters observed are in favor for the Bubblemeter, i.e. very low flux (sometimes in the order of ml/min only), high viscosity, high concentration of surface active substances, buoyancy driven bubble rise and the absence of plume effects. On page 316 we described the in-situ deployment together with the result as well as the associated error, i.e. ϕ=140±10ml/min. This yields an error of approx. 7% only. The computed results are in accordance with an independent volume measurement by means of a physical gas capturing method which was carried out at the same vent. Finally we would like to conclude that even a method with an error of 33% for the worst may be useful in the absence of efficient alternatives.

10) *I found the literature review to be excellent, except in one regard: they have not compared the advantages and disadvantages of using optical probes against their chosen imaging method (see, for example, A. Cartellier, "Simultaneous void fraction measurement, bubble velocity and size estimate using a single optical probe in gas-liquid two phase flows", Review of Scientific Instruments , vol. 63, pp. 5442-5453, 1992.).*

We are thankful for the positive feedback on our literature review and regret not having considered the method of optical probes so. In his paper Alain Cartellier describes a combined method of optical probe and visual image acquisition in order to measure void fraction, bubble velocity and bubble size. The latter two are also important parameters determining the fate of methane gas rising from the seep sites in deep sea. However, any gas measuring system intended for being deployed at deep sea has to cope with the hydrate stability field. That is, methane gas emerging in that depth i.e. pressure-temperature field, will solidify instantly upon contact with a solid probe. This would causes rapid ice formation and a malfunction of the device. Therefore, for the development which lead to the Bubblemeter it was of utmost importance using none-intrusive methods.

11) *it is reasonable to expect the bulk fluid velocity to be a strong function of gas flux. But changing the gas flux by a factor of two had very little effect on the bulk water velocity.*

We appreciate the thorough understanding of this topic and agree that one indeed would expect a much higher rise velocity due to the increased upwelling effect. As a consequence we verified that this similarity in rise velocity was not a computational error. Being of physical nature its origin had to be investigated, in order to provide waterproof evidence of the systems functionality and to avoid justified critics on lacking verification work. Unfortunately, this introduced a complete new chapter in the manuscript increasing its length even further.

12) *As the authors state, a decreasing velocity gradient profile (in the horizontal) in the bulk fluid of the plume could explain this. However, were this the case, I would expect the shape of the bubble velocity probability density distribution (PDF) to become more narrow as the gas flux rate increased. A decrease in the velocity gradient profile implies that more bubbles throughout the plume horizontal cross-section are moving at the same speed. However, Fig. 7 does not show any particular indication of a change in the shape of the bubble rise velocity PDF as a function of gas flux.*

This scenario is true in case the plume is a completely isolated body of mass with no interface interactions whatsoever. If the plume was confined in a tube the phenomenon of near-nil horizontal velocity gradient and a narrow peak velocity distribution might be observed. Although even then conservation of mass would cause backflow with some small gas bubbles actually travelling downwards. At the same time the reviewer suggests an explanation as to why the PDF does not change as much as one might expect...

13) *An alternative explanation is that the additional drag introduced by the increased number of bubbles in the higher flux case goes into entraining more fluid into the two-phase plume, rather than an increase in the plume velocity across the entire plume width. Did the authors observe the overall cross-section of the plume (at a fixed height) to increase with increasing gas flux?*

It has been observed that the horizontal plume diameter increased with increasing gas flux. While increasing the flux the increased potential energy converted into turbulences which spread over an increasing cross sectional area.

14) They could apply the same reasoning to identify bubble clusters, by looking at the derivative of the bubble size distribution at the large end of the bubble spectrum. Since these clusters contribute a significant fraction of their total error, they may be able to identify and remove bubble clusters and so improve their estimates of gas flux.

The derivative of the bubble axis was used to identify same bubbles in successive images. There are straight forward ways of identifying bubble clusters and possibilities of excluding them from computation. However, as stated on P309 Line 12-21, bubbles large enough to form clusters on a two dimensional projection transport 30%-90% of the total gas volume. By excluding them, the ellipsoid model precision would be significantly better, yet the accuracy of flux estimation would drop to an unacceptable level.

15) *Is there any way to assess the contribution of bubbles cut-off at the edge of the images to the overall gas flux and bubble size distribution errors?*

Yes and the condensed results were reported on page 309 i.e. 30%-90%

16) *Specific comments: P298-P312*

Modifications and recommendations have been implemented as suggested by the reviewers.