AUV swath bathymetric sensor data fusion for Rapid Environment Assessment

Ridha Fezzani[a] , Benoit Zerr[a], Michel Legris[a], Ali Mansour[a], Yann Dupas[b]

[a]Lab-STICC UMR CNRS 6285, ENSTA Bretagne/Ocean Sensing and Mapping
2 rue François Verny, 29806 Brest Cedex 9, France
[b]SHOM/DOPS/HOM/DEV, 13 rue du Chatellier, CS 92803, 29228 Brest Cedex 2, France

ridha.fezzani@ensta-bretagne.fr ; benoit.zerr@ensta-bretagne.fr; michel.legris@ensta-bretagne.fr; mansour@ieee.org; yann.dupas@shom.fr

Tel: +332.98.34.88.84
Fax: +332.98.34.87.50

Abstract: *Nowadays, Autonomous Underwater Vehicles (AUVs) become significant contributors to Rapid Environment Assessment (REA). Indeed, a variety of acoustic sensors can be mounted on AUVs allowing a complete seafloor representation (images, 3d data, video, sub-bottom layers, etc.). The AUV DAURADE platform is a new generation of AUVs. It can acquire bathymetry simultaneously with two acoustic sensors: a multibeam echo sounder (MBES) and an interferometric sidescan sonar (ISSS).*
In this paper, we propose a framework to fuse the bathymetric data coming from the two swath bathymetric sensors using the theory of belief functions. Here in after, obtained results on actual data are discussed.

Keywords: *AUV, multibeam, interferometric sidescan, fusion, bathymetry, seafloor, REA, belief functions, DTM.*

1. Introduction

In the last decade, autonomous underwater vehicles (AUV) equipped with a wide variety of acoustic sensors or sonar systems have been deployed to conduct REA. AUVs are also capable of covert introduction into the area of operations.

In many AUV survey missions (such as detecting and mapping submerged wrecks, rocks and obstructions), side-scan sonar imagery is a commonly used tool to make observations at high resolutions in close proximity to the seafloor. In the other hand, the multibeam echosounder is known to be the accurate sonar system for bathymetric data collection. For full area coverage when operating in shallow water, MBES survey is time consuming and strongly limited by the AUV battery autonomy. Thus, the operational mission configuration is always a trade-off among a number of considerations. When the AUV is also equipped by an interferometric sidescan sonar with large coverage capability and less accurate soundings, an important question arises: can this redundancy and complementarities be used to generate a more accurate digital terrain model (DTM)?

The remainder of this article is organized as follows: Section 2 describes the DAURADE AUV and the two swath bathymetric sonars. In Section 3, MBES versus ISSS bathymetric data quality are discussed. Section 4 describes the bathymetric data fusion model. Experimental results and conclusion are given in section 5.

2. The DAURADE AUV

The Daurade vehicle [1] is built by ECA Company for the benefit of the French hydrographic and oceanographic service (SHOM) and the Atlantic undersea studies group (GESMA). It is a multi-purpose experimental AUV for Rapid Environment Assessment (REA), it can perform hydrography, oceanography and mine detection missions. The vehicle is 5m length and has 10 hours autonomy at 4 knots. It contains a PHINS Inertial Navigation System, GPS receiver and Doppler Velocity Log which improve navigation accuracy and allow full autonomous operation. Daurade also comes with a navigation post-processing system (DELPH INS), which can increase the navigational integrity and maximize the position accuracy using GPS surface fix.

The DAURADE AUV carries four hydrographic systems (Fig. 1): A Klein 5500 SSS, a Reson 7125 MBES, an Atlas DESO 35 SBES and an Edgetech 2200 SBP. In our study, we are only interested by swath bathymetric sonars. The MBES is characterized by: 512 beams of width 0.5°x 1° ; a total aperture of 128°; a frequency of transducer 400 kHz; 512 equidistant beams; 300 m max range; depth resolution of 5 mm. The interferometric sidescan has a frequency of transducer 455 kHz, baseline spacing 6.5 wavelengths and 75m-150m range.

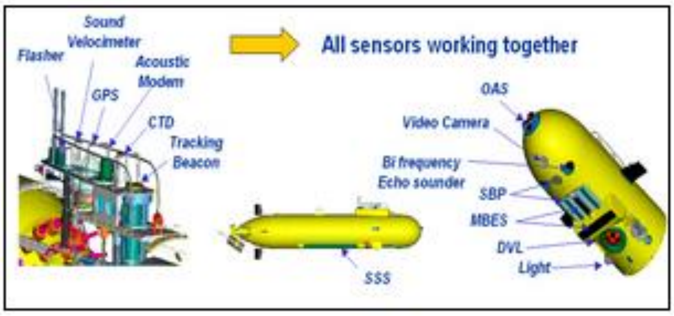

Fig1. The DAURADE AUV sensors.

3. MBES vs ISSS

Employing a number of sensors to simultaneously collect bathymetric data requires an operator skill in the planning of complex multi-sensor missions. Indeed, the various sensors typically work best at different altitudes, speeds *etc*. In shallow water and for full coverage area survey, the two most used systems are the multibeam echo sounder (MBES) and the interferometric sidescan sonar (ISSS). The MBES is considered as the reference system for an accurate hydrographic survey. Unfortunately MBES on AUV navigating close to the seafloor suffers from its limited angular coverage. With such limitation, a full coverage is time consuming and not compatible with the battery autonomy. Therefore ISSS can advantageously be used in this case. An ISSS has a swath width over 10-times the altitude of the sonar and produces high resolution bathymetry across track. The latter propriety helps significantly reducing the time of the survey for a full coverage. On the other hand, such system suffers from

several drawbacks: The geometry of ISSS transducer does not allow gathering data in nadir area, it has a limited bathymetric accuracy about 2-3% of water depth, and it is penalized by the baseline decorrelation and the shifting footprint effect [5]. In spite of these significant disadvantages, recent developments in system electronics and processing algorithms have improved ISSS performance.
To quantify the sounding quality of each swath system, Lurton et *al.* have proposed a model describing the sounding uncertainty for a swath system based on the signal to noise ratio [4, 6]. Their proposed quality factor is defined as:

$$\mathrm{QF} = \log_{10} \frac{z}{\delta z} \tag{1}$$

Where z and δz are respectively the sounding value and its standard deviation. The sounding error estimation depends on the detection method applied to received signals. In case of MBES, the center of gravity (COG) of the amplitude envelope is used in near nadir ranges and the zero phase difference instant estimation (ZDI) for far ranges. For the ISSS, the quality factor is estimated throw the phase difference direction (PDD). Fig.2 shows a ping quality factor for the Reson and the Klein on actual data.

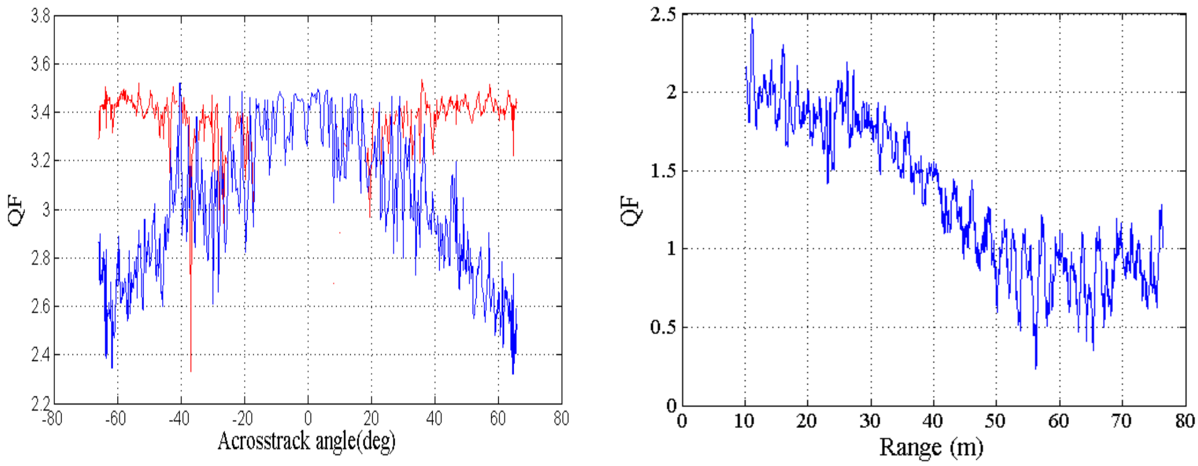

Fig2. Example of an estimated quality factor for on ping. (Left) MBES QF for amplitude (blue) and phase (red). (Right) ISSS QF (one side).

4. MBES-ISSS bathymetric data fusion model

In radar community, the most used fusion algorithm to combine DTMs (SAR interferometry, LIDAR, etc.) is a weighted average of inputs in each grid cell. As the weight factors are not usually available, data accuracies are estimated from DTM (roughness, slope, etc...). To be robust against blunders, other methods are used by representing local patches as a sparse combination of basis patches [10]. These algorithms cannot integrate a prior knowledge about the precision and reliability of sensors which can vary with time and environment conditions. In order to overcome limitations of each DTM, an intelligent fusion considering uncertainty and reliability of each sensor becomes necessary. To deal with such kind of measurements, many theories have been proved suitable for modelling the uncertainty. It is worth mentioning that imprecise probability, possibility theory and theory of belief functions are widely used in the literature. The theory of belief functions, also known as Dempster-Shafer Theory (DST), was initiated by the work of Dempster on imprecise probabilities and developed by Shafer [7]. Actually, it is a popular approach to handle uncertainty for data fusion and it is often considered as a generalized model of the probability and possibility theory. The basic of this theory is not recalled here. Interested readers can find sufficient interpretations of evidence theory in the literature ([2], [7]). In our application, inputs are the sounding z_i with a known position y_i and a standard deviation σ_i obtained from MBS and ISSS quality factor. We are aiming to improve the accuracy of z_i values by combining the outputs of the sonars. In [8], Petit-Renaud and Denoeux propose an evidential regression (EVREG) analysis of imprecise and uncertain data. In their model, evidential theory are extended to fuzzy sets where focal elements are fuzzy variables. Their basic idea is to construct a fuzzy belief assignment (FBA) in two steps: discounting FBA's m_i according to a measurement of dissimilarity among input vectors, and the combination of a discounted FBA's [8]. In our previous works, this algorithm was applied in [6] on simulated data and showed good results compared to the simulated terrain model. In the following section, we applied the same method to an actual data and using the same measurement (quantiles of the pignistic probability [6] and nonspecificity measurement [10]) to qualify the fused bathymetry.

5. EXPERIMENTAL RESULTS

The study area is located in Brittany (north-western France), in the north of Douarnenez Bay. The water depth of the area ranges from 21 to 26 meters. The seabed presents a sand ripple area and a rocky area. Two east/west survey lines spacing of 130 m were used. This provided a little data overlaps for the interferometric sonar and no overlapping for MBS soundings. The AUV depth was maintained to about 15 m during the survey. The area covered by the two ISSS lines is about 270 by 600 meters. For the survey the klein 5500 was run on a range scale of 75m per channel (the other range scales are very noisy). Bathymetric data is measured using the so-called Vernier Method which consists of estimating a unique receiving angle by combining pairs of stave measurements. The final soundings were de-spiked for gross outliers. Bathymetric soundings from MBS are calculated from the raw formed beam data using a center of gravity approach for the amplitude data and a zero-phase difference instant estimation for the phase difference data. For purpose of MBS-ISSS bathymetry fusion, we gridded the area covered by ISSS. Gridding was carried out to a 0.2 m pixel resolution. Following gridding, 5 nearest neighbors soundings from each sonar were employed to estimate the fused sounding. Reliability p_i is set to 1, so only sounding uncertainty derived from quality factor is used in fusion process. Fig.3 and Fig.4 present the bathymetric data to be fused. A blind zone can be observed on the nadir of the ISSS bathymetry and the noisy outer beams. Fig.5 presents outcomes of our algorithm i.e the obtained bathymetry. We can notice that the overlapped area of the two passes (middle of Fig.5) still noisy because it's the area of outer beams witch is very noisy and also because no sound velocity profile was available to correct the ray bath in the water column.

To have an idea about the quality of the fused bathymetry Fig.6 presents the estimated depth along a cross profile and the 0.1 and 0.9 quantiles of the pignistic probability, as a confident interval. We can notice that the presence of MBS data makes the confident interval very narrow. In addition, the *bow tie* effect is clearly in the end of across swath due to the noisy outer beams of the interferometric sidescan sonar. In spite of the use of data not corrected with water column celerity profile, the fusion method allows us to obtain a bathymetric data with quality factors very useful for Rapid Environment Assessment (REA). The fusion process depends on AUV navigation (horizontal position) and all common sounding corrections.

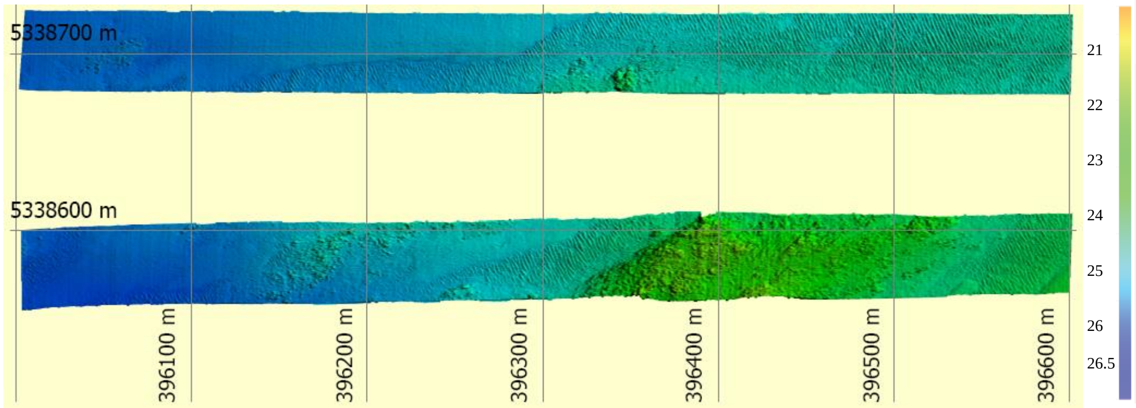

Fig.3 Gridded Reson 7125 bathymetry on two parallel lines.

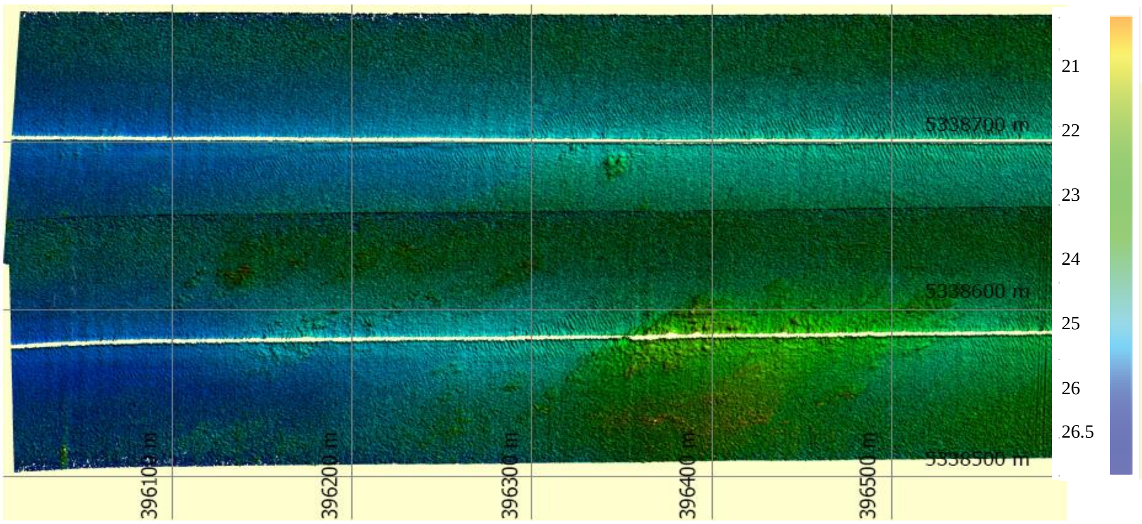

Fig.4 Gridded Klein 5500 bathymetry on two parallel lines

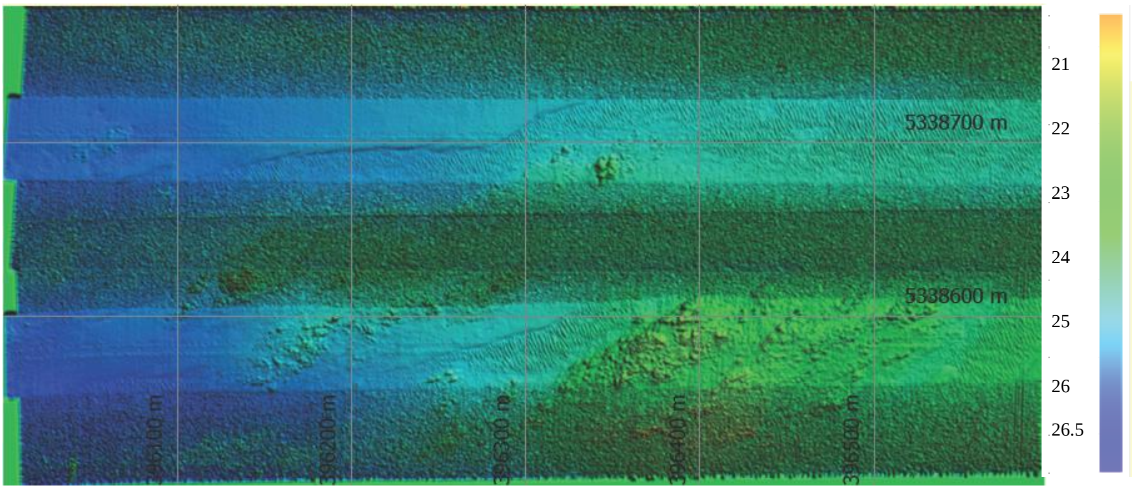

Fig.5 Gridded fused bathymetry

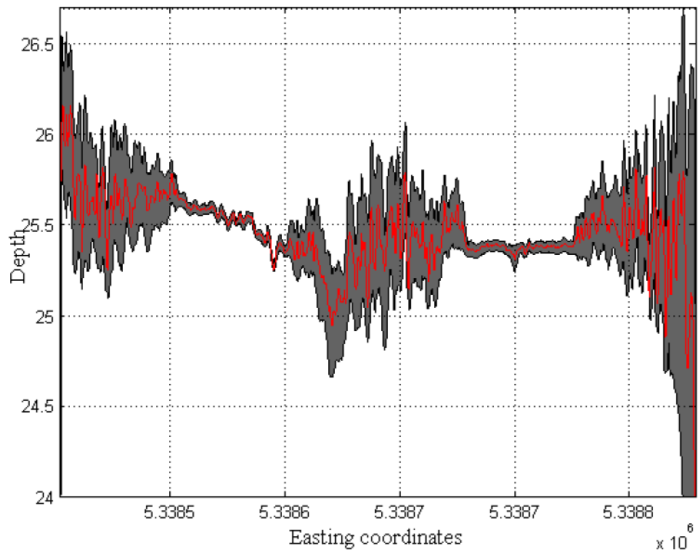

Fig. 6. A cross profile of a single grid line. First and ninth deciles of the pignistic probability (grey area). Estimated depth (red line)

Our future work consists in applying the fusion process to a corrected bathymetric data and to define an optimum adaptive survey. This is can be achieved by adapting the AUV survey route based on a quality factor (it's can be quantiles of the pignistic probability or a measurement of non-specificity) observed in the fused bathymetry.

REFERENCES

[1] **J. Meyrat**, "DAURADE: an AUV for REA", In *Proceedings of inmartech*, 2008.

[2] **R. Yager and L. Liu**, *Classic works of the Dempster-Shafer theory of belief functions*. Springer Science & Business Media, 2008, vol. 219.

[3] **X. Lurton, Y. Ladroit and J. M. Augustin**, *A quality estimator of acoustic sounding detection.* International hydrographic review, November 2010, Pages 35-45.

[4] **X. Lurton,** *Swath bathymetry using phase difference: theoretical analysis of acoustical measurement precision*. IEEE Journal of Oceanic Engineering, Vol.25, NO.3, July 2000.

[5] **Y. Ladroit, X. Lurton, C. Sintès, J. M. Augustin, R. Garello.** *Definition and application of quality estimator for multibeam echosounders.* In *Oceans, 2012-Yeosu*. IEEE, 2012. p. 1-7.

[6] **R. Fezzani, B. Zerr, M. Legris, A. Mansour, Y. Dupas.** « *The fusion of digital terrain models measured from multiple acoustic sensors .Application to the DAURADE autonomous underwater vehicle* ». 2nd International Conference and Exhhibition on Underwater Acoustics. Rhodes, Grèce, 22-27 Juin, 2014.

[7] **G. Shafer.** *A mathematical theory of evidence.* princeton university press, 1976.

[8] **S. Petit-Renaud, T. Denoeux,** *Nonparametric regression analysis of uncertain and imprecise data using belief functions.* International Journal of Approximate Reasoning 35:1-28. 2004.

[9] **H. Papasaika, E. Kokiopoulou, E. Baltsavias, K. Schindler, D Kressner.** *Fusion of digital elevation models using sparse representations.* In Photogrammetric Image Analysis. Springer Berlin Heidelberg, 2011. p. 171-184.

[10] **D.Dubois, H. Prade**. *A note of measures of specificity for fuzzy sets.* International Journal of Central Systems, 10(4): 279-283, 1985.