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UW215. Localization of small surface vessels through acoustic data fusion of two tetrahedral arrays of hydrophones

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Detection and tracking of vessels is important in confined areas such as marine parks or harbors. Nowadays, the presence of ships can be accurately monitored either by radar or via AIS system, while small vessels, which have weak radar signature, may be easily missed. The paper presents the detection and localization algorithms optimized for small- and mid-sized boats and based on data either from a single underwater sensor station of four hydrophones, or from data fusion between two hydrophone volumetric arrays. Each platform hosts a sparse tetrahedral array of broadband hydrophones and pan, tilt, compass and depth sensors. Both acoustic and non-acoustic data from the two stations are transferred to shore, where they are stored and processed on a PC. The basis of localization algorithm is the cross-correlation between pairs of hydrophones along time (crosscorrelogram). The wavevector estimation of a vessel from each tetrahedron is achieved through Least Mean Square method. Adequate data association algorithms allow the fusion of estimates obtained from each array in order to provide precise and robust tracking of each vessel. At-sea results demonstrate the system capability for detecting and localizing small vessels in a shallow-water harbor environment. [Work partially funded by EU within ARGOMARINE Project]

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1 INTRODUCTION

Detection and tracking of surface vessels is important in confined areas such as marine parks or harbors, where maritime traffic needs to be carefully monitored. Our “targets” to detect and localize are surface vessels of any kind, from small inflatable boats to work-boats, from luxurious leisure boats to ferries and ships. Nowadays, the presence of large ships can be accurately monitored either by radar or via the Automatic Identification System (AIS), while small vessels, in particular inflatable boats, which have very weak radar signature, may be easily missed by usual monitoring systems.

The paper presents the detection and localization algorithms optimized for small- and mid-sized boats and based on data either from a single underwater sensor station of four hydrophones, or from data fusion between two hydrophone volumetric arrays. Each platform hosts a sparse tetrahedral array of four broadband (up to 70 kHz bandwidth) hydrophones and an integrated pan, tilt, compass and depth sensor package for monitoring its attitude. Both acoustic and non-acoustic data from the two stations are transferred through electro-optic cables to shore, where they are stored and processed on a PC.

Various methods of Direction Of Arrival (DOA) estimation can be found in literature for passive underwater acoustic applications [1,2,3]. The selected approach is suitable to work with broadband signals using relatively small arrays and exploits the time coherence of signal of interest among the array elements; it is based on the computation of the cross-correlation between pairs of hydrophones along time (namely, X-correlogram) [3]. The 3D wavevector estimation of a vessel from each tetrahedron is achieved through a Least Mean Square method (LMS) among the tracks extracted from a minimum of three X-correlograms. Adequate data association algorithms allow the fusion of estimates obtained from each sensor station in order to provide precise and robust 3D localization and tracking of each vessel along time. At-sea results demonstrate the system capability of automatic detection and localization of small vessels in a shallow-water harbor environment, and the improvement achieved by fusing the positioning results obtained from each station separately

2 VESSEL LOCALIZATION USING ONE TETRAHEDRON

2.1 Analysis of signal of interest: boat-radiated underwater acoustic noise

The signal of interest is the underwater acoustic emission by motorboats and ships, generated by the engine, the shaft, the propeller and the hull interacting with the sea surface along movement. Generally speaking [4-6], the most significant noise components come from the engine and propeller turns (giving rise to spectral lines at low frequency - up to few kHz at most - in the vessel's frequency signature) and from the cavitation generated by the propeller (giving rise to a very wideband, diffuse noise having significant level up to high frequencies, even well beyond 50-60 kHz). In any case it can be classified as a continuous signal, and it is generally very complicated to model and characterize.

2.2 Basic TDOA (Time-delay-based Direction Of Arrival) estimation method

Noise radiates from the vessel and propagates away. In general we can assume that our measurement system (each volumetric array of hydrophones) is always in the far field of the noise source, hence receives noise as a plane wave.
First it is assumed to work with a single underwater sensor station (one tripod) which hosts a volumetric array of four hydrophones located at the vertices of a regular tetrahedron. The length of the tetrahedron side strongly affects the localization performance; it should be selected in such a way that signals received by different sensors maintain high coherence in time, but are as separated as possible in order to increase the achievable angle resolution. Given also operational problems of deployment, the selected tetrahedron has 1.6m-long sides, which allows a theoretical angle resolution of 0.3^{o} using the proposed algorithm, under the assumption of 192 kHz of data sampling frequency.
For a surface vessel, in theory the knowledge of azimuth and elevation are sufficient to achieve the estimate of the range too (hence a 3D localization), given the depth of the tetrahedron center,. However in the selected shallow-water operational conditions the estimation precision of the elevation angle dramatically decays at pretty short range (less than about 150 m) from the sensor station, preventing beyond that range the 3D localization, but allowing only a rough azimuth (hence DOA) estimate, not adequately compensated by the elevation correction. In this latter case, localization can be obtained only by fusion with another sensor station (by standard triangulation, given two known azimuth angles).
Under the plane wave assumption, and given just one pair of hydrophones, the emitted noise reaches separated sensors with a delay ΔT, which is a function of the direction α of the noise source with respect to the axis of the sensor pair, on the slant range plane defined by the noise source and the sensors' axis (see Fig.1). Hence time-delay DOA algorithm exploits time coherence of acoustic signals received by the array elements.
The fundamental step of the proposed processing for DOA estimation is the measurement of this delay through cross-correlation (or one of the generalized cross-correlation methods [3]) applied to the data received by the two hydrophones of a pair. In the presence of a vessel, the cross-correlation presents a peak at a time lag corresponding to the delay of arrival of the signal on the hydrophones, which is related to the bearing angle α by a simple trigonometric formula, shown in Fig. 1, where d is the hydrophone spacing and c_w the sound speed in water. If one plots a waterfall image of correlation signals obtained by dividing the raw time series into adjacent windows of N samples, the so-called X-correlogram is obtained (time vs. time-lag – or bearing angle), which shows the tracks of all the noise sources present in the measurement area as continuous lines of energy. The selection of the window duration depends on the stationarity of the signal of interest. In this case it is of the order to tens of milliseconds. This data representation allows not only to achieve the basis for DOA estimation and localization, but to separate noise sources, as each line on the X-correlogram represents one vessel (or generally one noise source). One X-correlogram is computed for each hydrophone pair of our volumetric array.
Each energy line is then automatically detected and localized on each X-correlogram domain. An innovative, refined algorithm based on the application of various mathematical morphology operators (closures and apertures) is developed in order to automatically:

1) delete or minimize spurious noise blobs (false alarms) and
2) extract each track line,

by enhancing the signal to noise ratio and the continuity of the track lines even in case of interference.
The final image processing step is a skeleton extraction. Then each line is organized in a tree structure

where simple algorithms based on the prediction of line direction are applied in order to join line segments into the same vessel tracks even when holes of several pixels occur. The general block diagram of track extraction is shown in Fig. 3 along with an example of analyzed data. Only the line with the superimposed red track in image (3) is extracted and stored. The example emphasizes the capability of the algorithm to neglect spurious energy blobs present in the original X-correlogram image (image 1) and to join segments of lines remained separated after the application of the threshold-based detection algorithm (image 2).

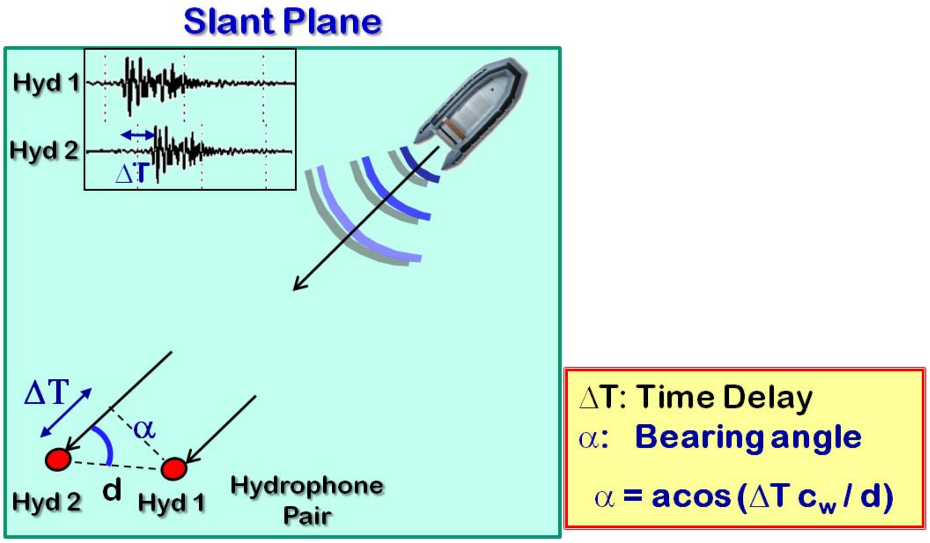


Figure 1. Sketch of the basic principle of bearing angle estimation from acoustic data by using one pair of hydrophones.

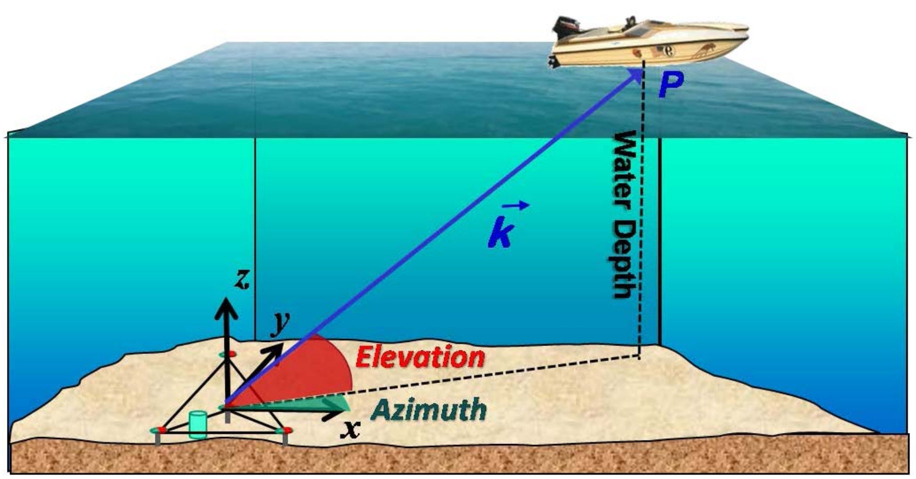


Figure 2. 3D cartoon of the geometry of the localization problem with one tetrahedron.

2.1.1 Localization algorithm

Tracks extracted from the analysis of each pair of receivers are fused together in order to get an estimate of the wave-vector ***k*** of the noise source as time varies, by applying the pseudo-inverse method, based on an LMS algorithm [7].

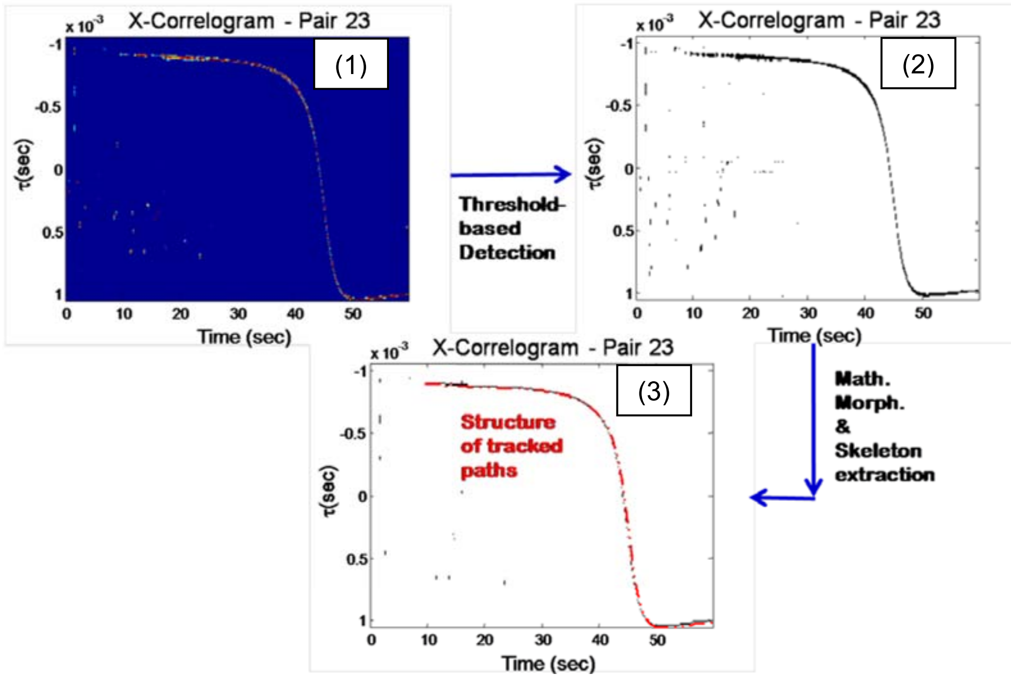


Figure 3. Block diagram of extraction of vessel tracks from a X-correlogram plane.

In ideal noise-free conditions the only difference between the signal received by two different sensors *i* and *m* is the time delay ΔT_{im} corresponding to the propagation of sound between the two, as the direction of propagation is identical (given the abovementioned far field assumption):

$$\Delta T_{im} = \mathbf{k}^T(\mathbf{x}_i - \mathbf{x}_m) = \mathbf{k}^T \mathbf{x}_{im}, \tag{1}$$

where $\mathbf{x}_{im}$ is called sensor vector. The wavevector can be estimated via LMS method as a solution of the equation:

$$\mathbf{t}_M = \mathbf{V}_M \mathbf{k}, \tag{2}$$

where *M* is the number of time delays used in the estimation, i.e. is the dimension of the vectors, and $\mathbf{V}_M = \begin{bmatrix}\mathbf{x}_{i_1m_1} & \mathbf{x}_{i_2m_2} & \dots & \mathbf{x}_{i_Mm_M}\end{bmatrix}^T$, $\mathbf{t}_M = \begin{bmatrix}\Delta T_{i_1m_1} & \Delta T_{i_2m_2} & \dots & \Delta T_{i_Mm_M}\end{bmatrix}^T$.

The solution is:

$$\mathbf{k} = \left(\mathbf{V}_M^T \mathbf{V}_M\right)^{-1} \mathbf{V}_M^T \mathbf{t}_M . \tag{3}$$

The three components of ***k*** defined in the body-frame reference system of the tetrahedron allow the estimation of azimuth θ and elevation ϕ of the source with respect to the array center, according to the following trigonometric expression:

$$\mathbf{k} = -\begin{bmatrix}\cos\theta\cos\phi & \cos\phi\sin\theta & \sin\phi\end{bmatrix} \tag{4}$$

As anticipated, at relatively short range azimuth and elevation estimates are precise enough for allowing the 3D localization of a surface vessel.

Body-frame localization is then transformed into the geographical reference system thanks to the measurement of the geographical (GPS) position (Lat-Lon or UTM) of the sensor station and its orientation (roll, pitch yaw, provided by an appropriate sensor rigidly connected and integrated on the underwater station) with respect to the Local Level frame.

In this paper experimental results will be shown in the case of fusion among various pairs of receivers in the presence of only one strong noise source, in order to make data association straightforward; however, the algorithm is capable to make data association of the same vessel among various pairs by comparing the spectral content of data around each detected correlation peak of the different X-correlograms.

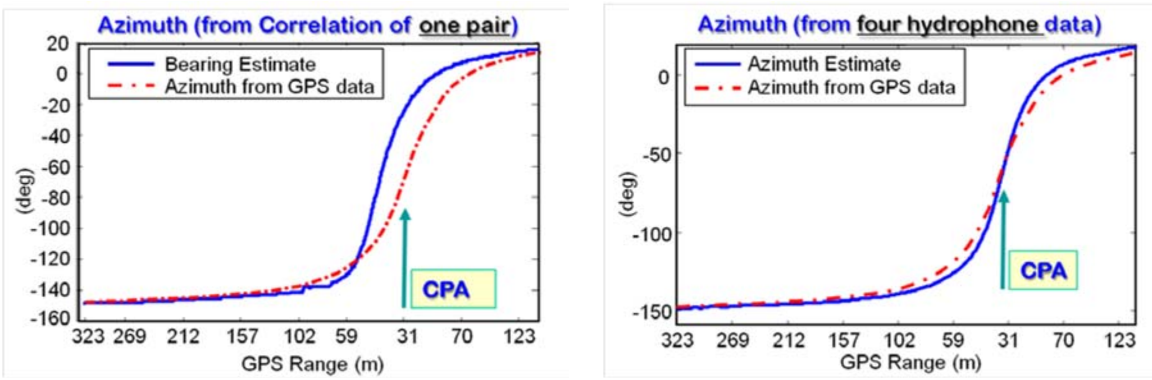
3 3D LOCALIZATION USING TWO TETRAHEDRA

The 3D localization of a vessel crossing the monitored area can be improved by fusing data from two distributed sensor stations deployed underwater on the seabed. In the first measurement tests, in order to cover an area of several hundred meters (up to various kilometers in the case of big ships), but in order to be sure to have simultaneous insonification of the two stations by the same vessel even in hard environmental conditions of a very noisy, commercial harbor, the two tetrahedral arrays are deployed at 100m of distance. Although the two arrays are able to collect acoustically synchronous data (hence in principle cross-correlation might be applied on pairs of hydrophones belonging to different stations), this distance is such that signal coherence decays significantly, hence time coherence between two hydrophones belonging to different tetrahedral is not exploited. Data fusion is applied at a higher level, i.e., on the estimates of angles (and possibly positions) by each of the stations.
As mentioned above, data fusion between the two stations is particularly useful when a vessel is so far from both arrays, that localization by means of a single station is not feasible due to the poor elevation estimate. At short range data fusion is expected to refine the localization precision.

4 EXPERIMENTAL RESULTS AND DISCUSSION

A selection of results is presented in order to show the method capabilities and start to quantify the precision of the algorithm. Acoustic measurements of ambient noise and passages of surface vessels were conducted in April 2012 in the very shallow, highly anthropic environment of the La Spezia harbor. This environment is characterized by a muddy seabed with smooth, flat bathymetry (water depth between 7 and 12 m). Two underwater sensor stations each hosting one 1.6m-long-side tetrahedron of hydrophones were deployed on the seabed, at about 450m and 600m of distance from the shore lab respectively, in 10.5m of water. Technological details on the measurement systems designed and developed at the NATO Center for Maritime Research and Experimentation (CMRE) can be found in [5-6]. As anticipated, the distance between the two stations was about 100m. Their GPS positions were measured during deployment.
For validating and assessing the performance of the developed algorithms of detection, direction of arrival, localization and data fusion, a controlled set of experiments were conducted. An inflatable, rigid-hull boat conducted various runs by crossing the area of measurements along pre-determined tracks in different directions and at different speeds. It was equipped with a GPS antenna sending its instantaneous position via radio-link in real time to shore, where GPS data could be recorded and integrated into the acoustic data files along each passage of the boat itself. Also the roll, pitch and yaw sensor measurement were integrated in the data; this allowed a straightforward post-processing comparison between ground-truth measurement and acoustic-based localization result in geographic, absolute coordinates.
Figure 4 shows the comparison between the precision in estimate of direction of arrival one can obtain by using the basic cross-correlation computation between one pair of hydrophones at the basis triangle of one tetrahedron (a), and by integrating all pairs of hydrophone of the same tetrahedron (b). In the first case the estimate can be only of the bearing angle on the slant plane containing the hydrophone pair and the noise source (assumed point-like); in the second case the elevation-corrected estimate of azimuth is achieved. The advantage achieved by data fusion among the four hydrophones of the array is evident, due to elevation correction. On the x axis the range of the vessel from the array center is

shown, based on GPS measurements of the vehicle position. Minimum range corresponds to the vessel Closest Point of Approach (CPA) with respect to the array.



(a) (b)

Figure 4. Comparison of azimuth estimate accuracy achieved by using the basic cross-correlation between one pair of hydrophones (a) and by integrating all pairs of one tetrahedron array (b). The green arrow localizes the vessel CPA.

An example of 3D localization result one can achieve by using one tetrahedron is shown in Fig. 5, where the true (GPS measurement) and estimated tracks are shown in the XY plane (Local Level system). In this case the environment was very favorable, ambient noise was low, and even using one tetrahedron allows one to obtain excellent positioning accuracy at short range, generally in the order of 150 m, as anticipated in Section 2.2. Beyond that limit, elevation accuracy dramatically degrades and cannot be used, preventing the localization by single tetrahedron. At shorter ranges, where elevation-based compensation of azimuth is fundamental (as shown in Fig. 4), an error in elevation of few degrees causes a significant error in positioning: this is evident in the left side of Fig. 5, where elevation error with respect to GPS-based measurement was about 3^o maximum.
When background ambient noise is higher and the environment more complex, single localization estimates are not so good, and their fusion may improve the positioning accuracy, as shown in Fig. 6 where the groundtruth position measurement is compared to the separate estimates and the fusion of the two. The estimated horizontal range with respect to one of the tripods (namely, Tripod 1) is shown in Fig. 7, and compared to GPS groundtruth. The CPA of the boat with respect to tripod 1 occurred at 29 m of range. From this preliminary data processing and analysis, the maximum error in positioning (Euclidean distance) obtained from data fusion of the two acoustic sensor stations is about 18 m within a maximum range of 250 m between the vessel and one of the two stations.
An overall performance evaluation will be conducted on a statistical basis after a large set of data have been collected at sea under controlled conditions in the next experimental phases of the project.

5 CONCLUSIONS

This work has addressed the problem of detection and localization of a surface vessel by means of underwater acoustic data collected by one or two hydrophone regular tetrahedra. A new algorithm of automatic detection and extraction of vessel tracks from the X-correlogram of each pair of hydrophones is proposed. On a single tetrahedron, the compensation of azimuth by elevation computation (by fusing data from all the hydrophones) provides a significant improvement in the estimate accuracy, particularly at short range. However a small error in elevation causes a significant error in positioning at short range. Hence the advantage of fusing localization results from the two arrays is emphasized, especially when the ambient noise is high and the environment is complex. From preliminary data analysis, the maximum position error obtained from data fusion is about 7% within a range of 250 m between the vessel and one of the two stations.

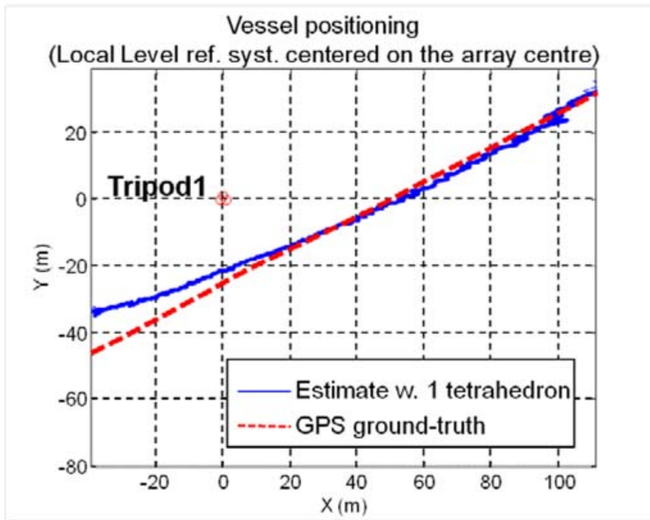


Figure 5. Example of localization result on the horizontal plane (Local Level centered on the tetrahedron center) obtained through one tetrahedron array. The vessel is in the near field of the array. During this run the boat was running at about 18kn speed.

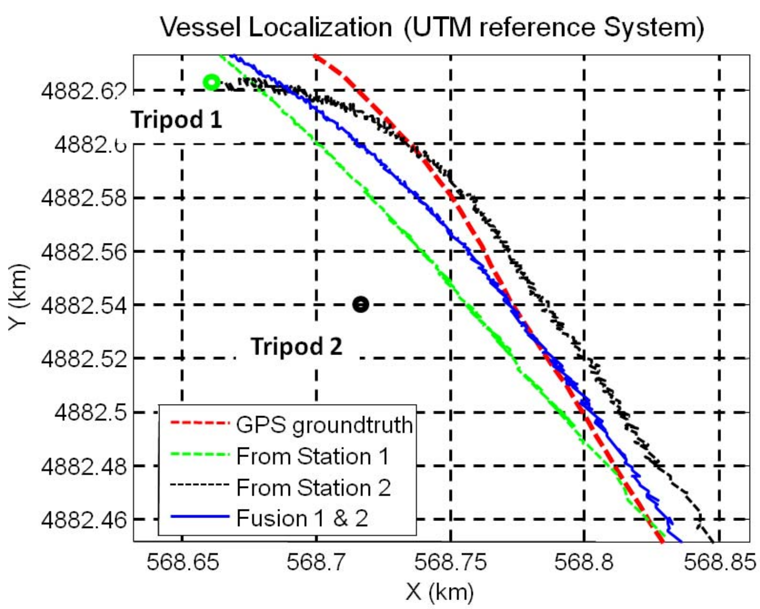


Figure 6. Comparison of localization results in geographical coordinates (UTM) obtained through the two tetrahedral separately and after data fusion (reference: the ground-truth GPS measurement as dashed red line). During this run the boat was running at about 12kn speed.

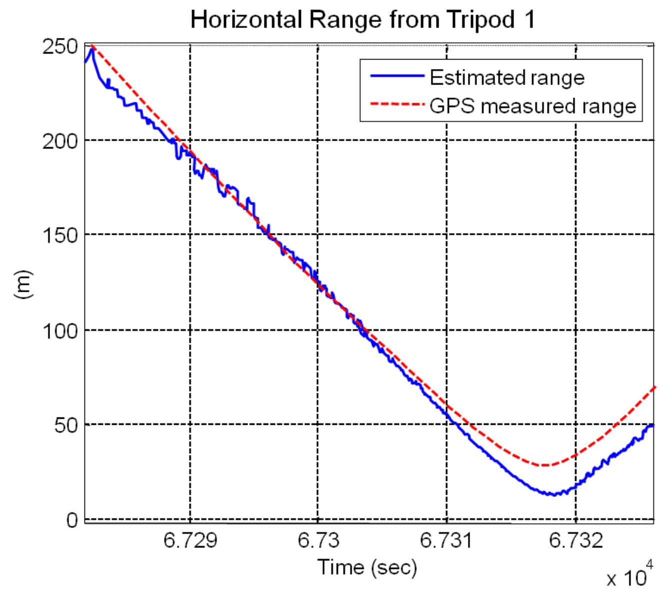


Figure 7. Estimation of horizontal range with respect to Tripod 1 position, derived from data fusion of the two stations, compared to GPS groundtruth.

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