Proceedings of the Eighth European Conference
on Underwater Acoustics, 8th ECUA
Edited by S. M. Jesus and O. C. Rodríguez
Carvoeiro, Portugal
12-15 June, 2006

UNDERWATER ACOUSTIC POSITIONING SYSTEMS BASED ON BUOYS WITH GPS

A. Alcocer, P. Oliveira, and A. Pascoal

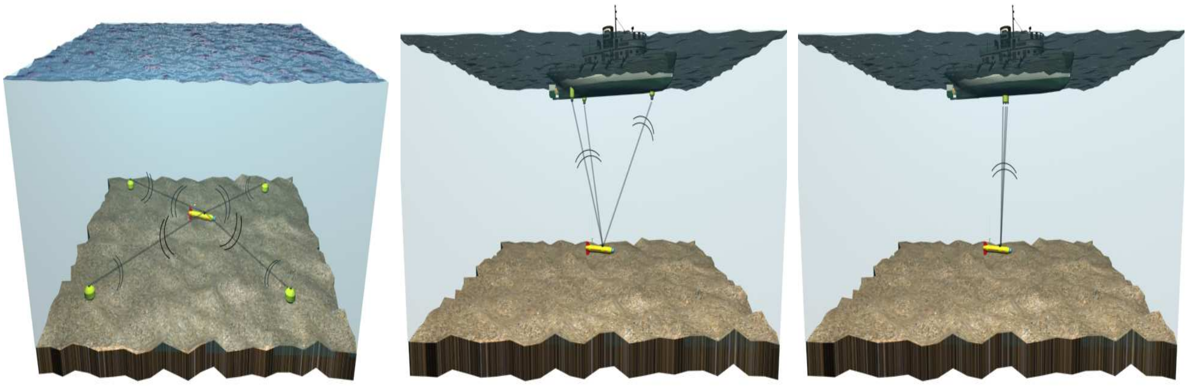
Institute for Systems and Robotics (ISR), Instituto Superior Técnico (IST)
Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal
email: {`alexblau,pjcro,antonio`}`@isr.ist.utl.pt`

Abstract: *The paper addresses the general problem of estimating the position of an underwater target carrying an acoustic emitter by measuring the times of arrival (TOAs) of the acoustic signals at a set of surface buoys equipped with submerged hydrophones and GPS receivers. Examples of underwater targets of interest include AUVs (Autonomous Underwater Vehicles) and ROVs (Remotely Operated Vehicles) as well as manned submersibles, divers, and even marine animals. When compared with classical systems, the class of underwater acoustic positioning systems considered in this paper is far more versatile and portable and the costs of operation are greatly reduced. This justifies the increasing interest that such systems have received over the past few years, both from a theoretical and practical standpoint. Research and development in this area have progressed to the point where a commercial product made its appearance in the market: the so-called GIB (GPS Intelligent Buoys). However, much work remains to be done towards the development of operational systems capable of yielding adequate performance in the presence of multi-path effects and acoustic outliers. The paper gives a brief overview of this area of research and discusses theoretical and practical issues that arise in the development and operation of acoustic positioning systems at sea.*

1. INTRODUCTION

The last decade has witnessed the emergence of Ocean Robotics as a major field of research. Remotely Operated Vehicles (ROVs) and, more recently, Autonomous Underwater Vehicles (AUVs) have shown to be extremely important instruments in the study and exploration of the oceans. Free from the constraints of an umbilical cable, AUVs are steadily becoming the tool *par excellence* to acquire marine data on an unprecedented scale and, in the future, to carry out interventions in undersea structures. Central to the operation of these vehicles is the availability of accurate navigation and positioning systems. The first provide measurements of the angular and linear positions of a vehicle and are therefore crucial to platform stabilization and control. The latter include, but are not restricted to, systems that are designed with the sole purpose of tracking the evolution of an underwater platform from a surface ship. There is a clear connection between the two systems, because positioning systems are often used to complement information provided by a navigation system resident on-board the vehicle when a reliable acoustic communications link can be established between the surface and the underwater units. This paper focuses on the positioning problem only.

Classical approaches to underwater vehicle positioning include Long Baseline (LBL), Short Baseline (SBL), and Ultra-Short Baseline (USBL) systems, to name but a few (Fig. 1). See [8], [9], [10], [16], [17] and the references therein for an introduction to this challenging area. More recently, triggered by fast development in GPS technology, new underwater acoustic positioning systems have arisen that are based on buoys equipped with GPS receivers and acoustic communication capabilities (see for instance [7]). One of such systems has actually been implemented and is available commercially: the so-called GPS Intelligent Buoys (GIB) [1], [13]. The system is designed to track the position of an underwater target equipped with an acoustic emitter by measuring the times of arrival of the acoustic signals at a set of surface buoys equipped with submerged hydrophones and GPS receivers. Because of its innovative characteristics, in this paper we select GIB as the representative of a class of promising acoustic positioning systems and discuss theoretical and practical issues that must necessarily be taken into account during its operations at sea. The discussion is rooted in the results of actual experiments carried out by ISR/IST.



(a) LBL (b) SBL (c) USBL

Fig.1: Classic underwater acoustic positioning systems. (a) Long Baseline LBL system. (b) Short Baseline SBL system. (c) Ultra-Short Baseline (USBL) system.

2. SYSTEM DESCRIPTION

The GIB system consists of four surface buoys equipped with DGPS receivers and submerged hydrophones. Each of the hydrophones receives the acoustic impulses emitted periodically by a synchronized pinger installed on-board the underwater platform and records their times of arrival (TOA). The buoys communicate via radio with a central station (typically on-board a support vessel) where the position of the underwater target

(a) (b) (c)

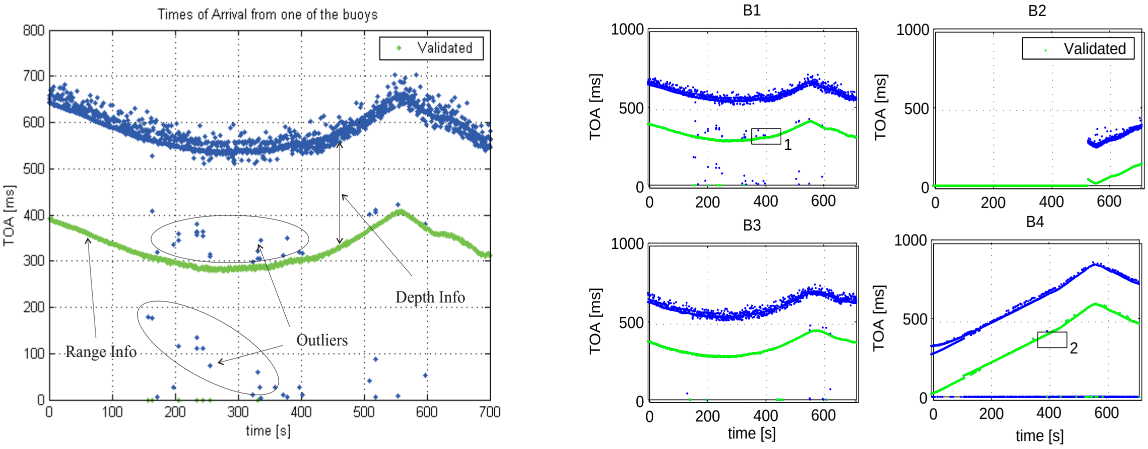
Fig.2: Underwater acoustic positioning system based on surface buoys with GPS like the GIB (GPS Intelligent Buoys). (a) GIB system. (b) GIB buoys before deployment. (c) GIB pinger.

is computed and displayed (see Fig. 2). The depth of the target is also available from the GIB system by coding that info in the acoustic emission pattern. The pinger emits two successive acoustic pulses during each emission cycle, the time delay between the two pulses being proportional to the pinger depth (see Fig. 3).

The times of arrival can be translated into ranges (or distances) between the buoys and the pinger if the sound of speed in the water is assumed to be known. It is common to assume a constant value for the speed of sound which greatly simplifies the treatability of the problem. Fig. 3 shows typical TOA data obtained by the authors with a GIB-based system. The measured TOA data contains range and depth information as well as numerous outliers. Acoustic multiple paths are the major source of spurious data. It is a critical issue for this kind of systems to be able to identify and properly reject acoustic outliers. See [15] for a treatment and discussion on this challenging topic.

3. ALGORITHMS - OVERVIEW

Most underwater acoustic positioning systems rely on the measurements of the ranges from an underwater vehicle to a set of beacons (with known positions), given indirectly by the times of arrival of the acoustic signals emitted by the moving platform. If enough number of ranges are available, an instantaneous position solution can be obtained by triangulation or by using more sophisticated algorithms. This problem is usually referred to as spherical positioning, as the position solution is the intersection of a set of spheres centered at the receivers with radius equal to their corresponding ranges. When the emitter and the receivers are not synchronized, there is an additional unknown time synchronization error that needs to be estimated. This can be avoided by performing differences among the range measurements. The resulting observations are referred to as range differences and the corresponding problem as hyperbolic positioning. What follows is a brief formulation and overview of spherical positioning algorithms. For more details, see for instance [5], [6] [11], [12] and the references therein.



(a) (b)

Fig.3: (a) Times of arrival (TOA) of acoustic pulses. Depth information is coded in the time between two consecutive pulses in each emission cycle. Validated range data is shown in a lighter tone. (b) Times of arrival at each of the buoys during an experiment.

3.1 Instantaneous positioning algorithms

It is possible to roughly differentiate among two basic kind of algorithms: the instantaneous and the filtering algorithms. The instantaneous algorithms compute a position fix given a set of ranges corresponding to a single instant of time. This is what is commonly refereed to as triangulation (see for instance [12]). Common algorithms include Maximum Likelihood and simple Least Squares (LS), which are based on transforming the original nonlinear problem into a linear one by squaring the range observations. An outline of the LS estimator is as follows. Let $\mathbf{p} = [x\ y\ z\ ]^T \in \mathbb{R}^3$ denote the position of the target with respect to some inertial reference frame. Let $\mathbf{p}_{Bi} = [x_i\ y_i\ z_i\ ]^T\ ; i = 1, \ldots, m$ (where m is the number of buoys) denote the position of the hydrophone at the buoy i. Further let $\mathbf{d} = [d_1\ \ldots\ d_m]^T \in \mathbb{R}^m$ be a vector containing the distances between the target and the buoys, i.e.

$$d_i = \|\mathbf{p} - \mathbf{p}_{Bi}\| = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}. \tag{1}$$

Assuming that the pinger is synchronized with the buoys and that the speed of sound v_s is constant and known, the measured times of arrival τ_i can be converted to distance's through $r_i = v_s \tau_i = d_i + w_i$, where w_i is assumed to be a Gaussian, zero mean, disturbance. Stacking the observations and disturbances into vectors $\mathbf{r} = [r_1\ \ldots\ r_m]^T$ and $\mathbf{w} = [w_1\ \ldots\ w_m]^T$, respectively the observation equation can be written in compact form as

$$\mathbf{r} = \mathbf{d} + \mathbf{w}, \quad \mathrm{E}\left\{\mathbf{w}\mathbf{w}^T\right\} = \mathbf{R} \in \mathbb{R}^{m \times m}. \tag{2}$$

Note that by taking the square of $r_i s$, a linear equation in the unknown vector $\mathbf{p}$ is obtained except for a term $\|\mathbf{p}\|^2$, i.e., $r_i^2 = \|\mathbf{p}\|^2 + \|\mathbf{p}_{Bi}\|^2 - 2\mathbf{p}_{Bi}^T \mathbf{p} + \xi_i$, where the new disturbance $\xi_i = w_i^2 + 2w_i d_i$ is approximately Gaussian zero mean when $d_i >> w_i$. Now stacking all the m squared ranges observations we obtain

$$\underbrace{\begin{bmatrix} 2\mathbf{p}_{B1}^T \\ \vdots \\ 2\mathbf{p}_{Bm}^T \end{bmatrix}}_{\mathbf{A}} \mathbf{p} = \underbrace{\begin{bmatrix} \|\mathbf{p}_{B1}\|^2 - r_1^2 \\ \vdots \\ \|\mathbf{p}_{Bm}\|^2 - r_m^2 \end{bmatrix}}_{\mathbf{b}} + \underbrace{\begin{bmatrix} \xi_1 \\ \vdots \\ \xi_m \end{bmatrix}}_{\xi} + \|\mathbf{p}\|^2 \mathbf{1}_m \tag{3}$$

Multiplying both sides of (3) by a matrix $\mathbf{M} \in \mathbb{R}^{m-1 \times m}$ which has $\mathbf{1}_m$, that is, a vector of m ones in its null space (for instance the usual differencing matrix $\mathbf{M} = [\mathbf{1}_{m-1} \mid -I_{m-1}]$), yields the linear system $\mathbf{MAp} = \mathbf{Mb} + \mathbf{M}\xi$. Now if the matrix $(\mathbf{MA})^T(\mathbf{MA})$ is invertible, a LS estimate can be obtained through $\widehat{\mathbf{p}} = \mathbf{Wb}$, where $\mathbf{W} = (\mathbf{MA})^+\mathbf{M}$, and $\mathbf{A}^+ = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T$ is the matrix pseudo-inverse. The covariance of the resulting estimate can also be easily computed. Defining $\mathbf{D} = \operatorname{diag}(\mathbf{d})$, a matrix with the distances d_i in the diagonal, and under the assumption that $d_i >> w_i$, we have $\mathrm{E}\left\{\xi\xi^T\right\} \approx 4\mathbf{DRD}$. Finally, the LS estimation error covariance becomes $\mathrm{E}\left\{(\mathbf{p} - \widehat{\mathbf{p}})(\mathbf{p} - \widehat{\mathbf{p}})^T\right\} \approx 4\mathbf{WDRDW}^T$. Note that the procedure described can be easily modified to include the case when the pinger depth z is known.

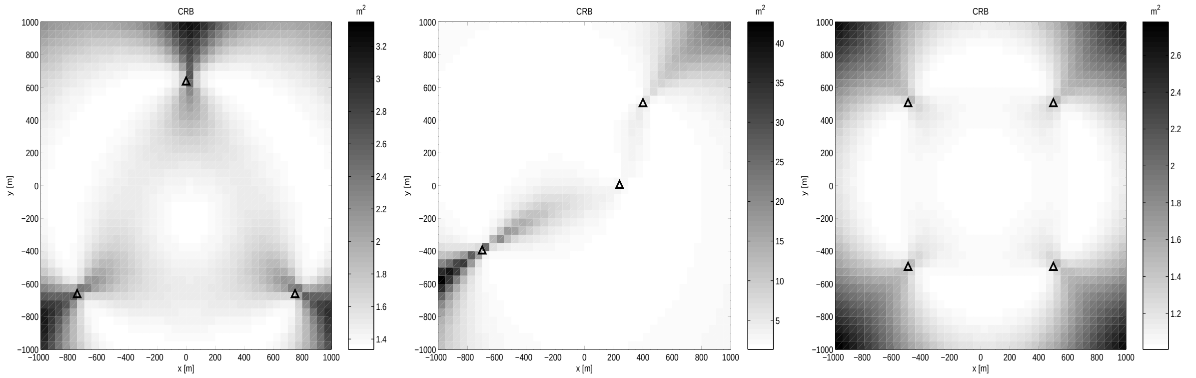
3.2 Filtering (dynamic) algorithms

In contrast with positioning algorithms, filtering algorithms use also observations from past instants of time and involve a kinematic or dynamic model of the target. The Extended Kalman Filter (EKF) is the basis for most of this kind of algorithms (see for instance [3], [2]). Outlier rejection is of utmost importance in this algorithms since a single outlier can have tremendous performance degradation consequences. Another issue to be taken into account when designing a filtering algorithm is the fact that the acoustic signals (emitted by a single source) are received at the different transducers at different instants of time and with a range-dependent delay. An algorithm that explicitly addresses the latter problem was proposed in [2], where the reader will also find an extensive list of references.

4. BUOY GEOMETRY - ACCURACY ANALYSIS

The geometry of the buoys with respect to the pinger affects tremendously the achievable performance of the positioning system. It is important to be able to asses *a priori* the performance of a given configuration, for instance as a way to help in the design of favorable buoy geometries. An analytical lower bound on the accuracy of the position estimates can be obtained through the Cramér-Rao bound (CRB) [14], [6]. Consider the estimation setup where the pinger is synchronized with the buoys, and its depth z is assumed to be known. Let $\varepsilon = [\tilde{x}\ \tilde{y}\ ]^T = [x - \hat{x}\ \ y - \hat{y}\ ]^T \in \mathbb{R}^2$ denote the vector of (horizontal) position estimation errors that are expected to be obtained with an unbiased estimator based on the observations (2). For the problem at hand, the CRB states that the variance of the estimation error satisfies

$$\operatorname{var}\{\varepsilon\} := \operatorname{tr}\left(\mathrm{E}\left\{\varepsilon\varepsilon^T\right\}\right) \geq \operatorname{tr}\left(\left[\mathbf{C}^T\mathbf{R}^{-1}\mathbf{C}\right]^{-1}\right), \qquad \mathbf{C} := \begin{bmatrix} \frac{x-x_1}{d_1} & \frac{y-y_1}{d_1} \\ \vdots & \vdots \\ \frac{x-x_m}{d_m} & \frac{y-y_m}{d_m} \end{bmatrix} \tag{4}$$



(a) $m = 3$ buoys (b) $m = 3$ buoys (c) $m = 4$ buoys

Fig.4: Cramér-Rao bound (CRB) for different buoy geometries. The lower bound on the variance $\mathrm{tr}\left([\,\mathbf{C}^T\mathbf{R}^{-1}\mathbf{C}\,]^{-1}\right)$ *is coded in grayscale. In all the cases the covariance was set to* $\mathbf{R} = \sigma I_m$ *where* m *is the number of buoys and* σ *= 1 m. The hydrophones depth were set to* z_i *= 0 for all the buoys, and the target depth was* z *= -50 m.*

where $\mathrm{tr}\,(\cdot)$ is the matrix trace operator. The CRB for different buoy configurations is illustrated in Fig. 4. Interestingly enough, this circle of ideas can be extended to another class of problems in which not only the position but also the attitude of the underwater vehicle needs to be estimated [4].

5. EXPERIMENTAL RESULTS

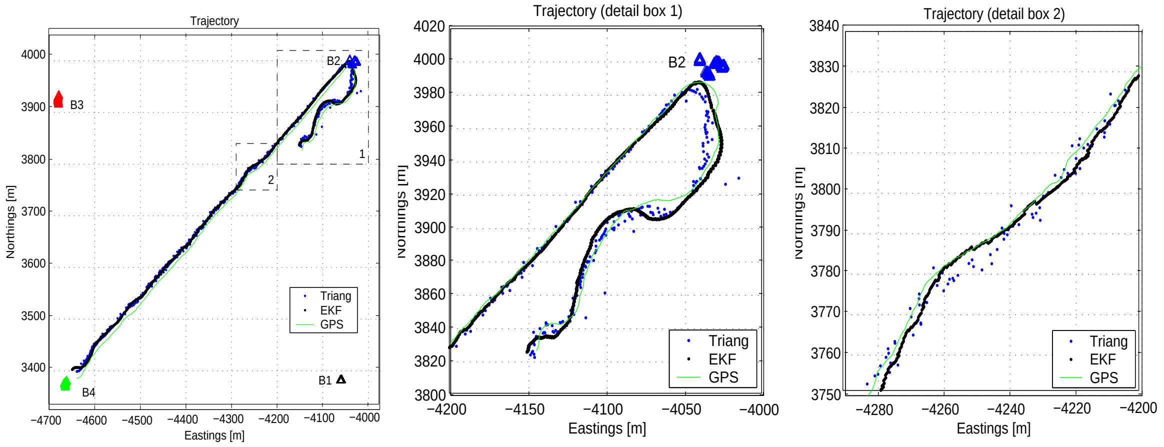
In Fig. 5 experimental data obtained with a commercial GIB system and two different positioning algorithms are illustrated. The figures show the trajectory of a pinger that was installed on a platform able to provide position estimates with centimetric accuracy manoeuvred from a surface vessel. Estimated trajectories are shown using the instantaneous LS positioning algorithm (triangulation) and an EKF based filtering algorithm described in [2].

6. CONCLUSIONS AND SUMMARY

The paper gave an overview of underwater acoustic positioning systems based on surface buoys equipped with GPS receivers. Theoretical and practical issues that arise in the development and operation of such systems were briefly summarized and discussed. Experimental data from sea tests illustrated the scope of the problems that must be addressed to develop positioning systems that can perform reliably in the presence of multi-path effects and acoustic outliers.

ACKNOWLEDGEMENTS

We thank M. Rufino, L. Sebastião, J. Alves, and G. Libório for their valuable help in setting up and operating the GPS and GIB equipments at sea. We are also indebted



(a) (b) (c)

Fig.5: (a) Trajectory of the manoeuvred pinger during the experiment. The figure shows the actual position of the pinger (given by post-processed GPS and the IRIS platform [2]) and the estimated position given by an EKF and LS triangulation algorithms. (b) Detail of box 1. (c) Detail of box 2.

to Prof. C. Silvestre for making available for the tests at sea the IRIS platform that was developed under the MEDIRES project.

This work supported in part by the Portuguese FCT (Foundation for Science and Technology) POSI Programme under framework QCA III, by project MAYA-Sub of the AdI, and by projects DREAM, MAROV, and RUMOS of the FCT. The work of the first author was supported by a PhD scholarship of the FCT.

REFERENCES

[1] ORCA ACSA. *Trajectographe GIB Manuel Utilisateur*, 1999.

[2] A. Alcocer, P. Oliveira, and A. Pascoal. Study and Implementation of an EKF GIB-Based Underwater Positioning System. Accepted for publication in *Control Engineering Practice*, 2006.

[3] A. Alcocer, P. Oliveira, and A. Pascoal. Study and Implementation of an EKF GIB-Based Underwater Positioning System. In *Proc. of the IFAC Conference on Control Applications in Marine Systems (CAMS'04), Ancona, Italy.*, July 2004.

[4] A. Alcocer, P. Oliveira, A. Pascoal, and J. Xavier. Estimation of Attitude and Position from Range only Measurements using Geometric Descent Optimization on the Special Euclidean Group. In *Proc. of the 9th International Conference on Information Fusion*, July 2006. Submitted.

[5] Y. T. Chan and K. C. Ho. A Simple and Efficient Estimator for Hyperbolic Location. *IEEE Transactions on Signal Processing, vol. 42, Issue: 8*, pages 1905–1915, August 1994.

[6] M. Deffenbaugh, J.G. Bellingham, and H. Schmidt. The relationship between spherical and hyperbolic positioning. In *Proceedings of MTS/IEEE Conference OCEANS '96, Fort Lauderdale, FL, USA*, volume 2, pages 590–595, September 1996.

[7] L. Freitag, M. Johnson, M. Grund, S. Singh, and J. Preisig. Integrated Acoustic Communication and Navigation for Multiple UUVs. In *Proceedings of MTS/IEEE Conference OCEANS '96, Fort Lauderdale, FL, USA.*, pages 59–64, 1996.

[8] M. B. Larsen. *Autonomous Navigation of Underwater Vehicles.* Ph.D. Dissertation, Department of Automation, Technical University of Denmark, February 2001.

[9] J. Leonard, A. Bennett, C. Smith, and H. Feder. Autonomous underwater vehicle navigation. MIT Marine Robotics Laboratory Technical Memorandum 98-1. 1998.

[10] P. H. Milne. *Underwater Acoustic Positioning Systems.* Gulf Publishing, Houston, 1983.

[11] J. O. Smith and J. S. Abel. Closed-form least-squares source location estimation from range-difference measurements. *IEEE Transactions on Acoustics, Speech, and Signal Processing, vol. ASSP-35 Issue: 12*, pages 1661–1669, December 1987.

[12] J. O. Smith and J. S. Abel. The spherical interpolation method of source localization. *IEEE Journal of Oceanic Engineering, vol. 12, Issue: 1*, pages 246–252, January 1987.

[13] H. G. Thomas. GIB buoys: An interface between space and depths of the oceans. In *Proceedings of IEEE Autonomous Underwater Vehicles, Cambridge, MA, USA*, pages 181–184, August 1998.

[14] H. L. Van Trees. *Detection, Estimation, and Modulation Theory (Part I).* John Wiley and Sons, 1968.

[15] J. Vaganay, J. Leonard, and J. Bellingham. Outlier Rejection for Autonomous Acoustic Navigation. In *Proceedings of IEEE International Conference on Robotics and Automation, Minneapolis, MN, USA*, pages 2174–2181, 1996.

[16] K. Vickery. Acoustic positioning systems. A practical overview of current systems. In *Proceedings of the 1998 Workshop on Autonomous Underwater Vehicles., Fort Lauderdale, FL, USA.*, pages 5–17, August 1998.

[17] L. L. Whitcomb, D. R. Yoerger, and H. Singh. Combined Doppler/LBL Based Navigation of Underwater Vehicles. In *Proceedings of the 11th International Symposium on Unmanned Untethered Submersible Technology, Durham, New Hampshire, USA*, August 1999.