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Combined Doppler/LBL Based Navigation of Underwater Vehicles

Louis L. Whitcomb, Dana R. Yoerger, and Hanumant Singh*

Abstract

This paper first reviews conventional techniques for underwater vehicle navigation, and describes a doppler-based navigation system recently implemented by the authors. Experimental results show that a system combining conventional long-baseline (LBL) acoustic navigation data with doppler navigation data provides superior navigation precision and update rates in comparison to raw LBL or doppler navigation alone. The experiments were conducted during a field deployment in which the new robot navigation system enabled precision acoustic and optical survey, as well as minimally invasive object recovery in the Eastern Mediterranean.

1 Introduction

This paper reports the design, implementation, and field-evaluation of a new navigation system for underwater vehicles. The new system utilized a bottom-lock doppler sonar system to provide significant improvements in the precision and update rates of vehicle position sensing and, in consequence, improved closed-loop vehicle positioning performance.

At present, few techniques exist for reliable three-dimensional position sensing for underwater vehicles. Table 1 summarizes the sensors most commonly used to measure a vehicle's six degree-of-freedom position. While depth, altitude, heading, and attitude are instrumented with high bandwidth internal sensors, X-Y position sensing is usually achieved by acoustically interrogating fixed seafloor-mounted transponder beacons [7, 8].

Ultra-short baseline acoustic navigation systems are preferred for the task of docking a vehicle to a transponder-equipped docking station but are of limited usefulness for general long-range navigation [10, 11]. Inertial navigation systems offer excellent strap-down navigation capabilities, but are of limited utility in the low-speed low-acceleration regime typical for oceanographic robotic vehicles. Moreover, their high cost has generally precluded their widespread use in civilian oceanographic instruments and vehicles. The U.S. sponsored Global Positioning System (GPS) provides superior three-dimensional navigation capability for both surface and air vehicles, and is employed by all U.S. oceanographic research surface vessels. The GPS system's radio-frequency signals are blocked by seawater, however, thus GPS signals cannot be directly received by deeply submerged ocean vehicles. Although recent work suggests that the next generation of acoustic communication networks might provide position estimation [6, 10], no systems providing this capability are commercially available at present.

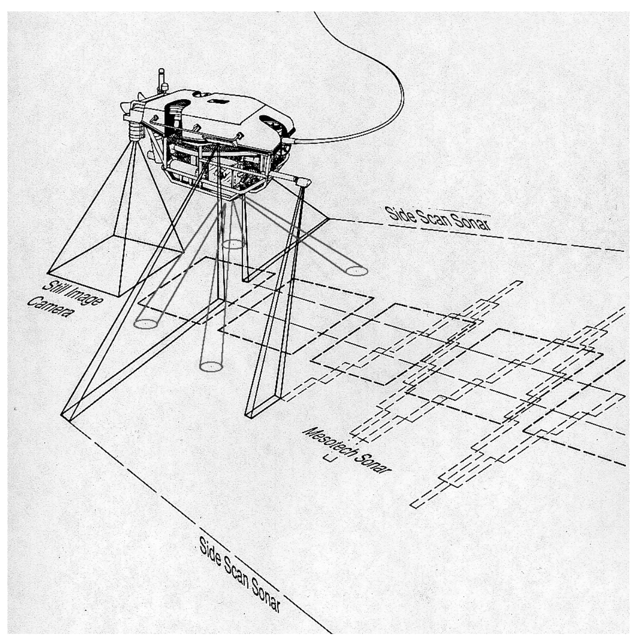

Figure 1: JASON depicted in a survey operation showing electronic-still cameras, video cameras, scanning sonar, sidescan sonar, and doppler sonar beams.

Two problems with existing underwater navigation po-

*Whitcomb is with the Department of Mechanical Engineering, G.W.C. Whiting School of Engineering, Johns Hopkins University, 3400 North Charles Street, Baltimore, Maryland, 21218, email: llw@jhu.edu. Yoerger and Singh are with the Deep Submergence Laboratory, Applied Ocean Physics and Engineering Department, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, email: dyoerger@whoi.edu, hsingh@whoi.edu. We gratefully acknowledge support from the U.S. Navy Office of Naval Research under grant N00014-99-1-0109. This paper is WHOI contribution number 10015.

INSTRUMENT	VARIABLE	INTERNAL?	UPDATE RATE	PRECISION	RANGE	DRIFT
Acoustic Altimeter	Z - Altitude	yes	varies: 0.1-10Hz	0.01-1.0 m	varies	—
Pressure Sensor	Z - Depth	yes	medium: 1Hz	0.0.01%	full-ocean	—
12 kHz LBL	XYZ - Position	NO	varies: 0.1-1.0 Hz	0.01-10 m	5-10 Km	—
Inclinometer	Roll and Pitch	yes	fast: 1-10Hz	0.1° - 1°	$+/-45^\circ$	—
Magnetic Compass	Heading	yes	medium: 1-2Hz	$1-10^\circ$	360°	—
Gyro Compass	Heading	yes	fast: 1-10Hz	0.1°	360°	$10^\circ/hour$

Table 1: Commonly Used Underwater Vehicle Navigation Sensors

INSTRUMENT	VARIABLE	INTERNAL?	UPDATE RATE	PRECISION	RANGE	DRIFT
Bottom-Lock Doppler (1200 KHz)	XYZ - Velocity	yes	fast:1-5Hz	+/-0.2% cm/sec	30m	—
300 kHz LBL	XYZ - Position	NO	1.0-5.0 Hz	+/-0.002 m typ	100 m	—

Table 2: New Sensors employed in JASON's new doppler-based navigation system.

sition sensing techniques severely limit the performance of fine maneuvering: *precision* and *update rate*. On-board depth, heading, and attitude sensors generally offer excellent precision and update rates. XY position sensing is generally instrumented acoustically and, over longer ranges, typically offers poor precision and low update rates.

The standard method for full ocean depth XYZ acoustic navigation is 12 kHz long baseline ("12 kHz LBL") acoustic navigation [7]. 12 kHz LBL typically operates at up to 10 Km ranges with a range-dependent precision of +/-0.1 to 10 Meters and update rates periods as long as 20 seconds [7, 8]. The precision and update rate of LBL position fixes can vary over several orders of magnitude depending on the acoustic frequency, range, and acoustic path geometry. LBL navigation accuracy and precision can be improved to some extent by careful application of Kalman or other filtering techniques [2, 13, 1].

At present, the best method for obtaining subcentimeter XY position sensing is to employ a high-frequency (typically 300 kHz or greater) LBL system. Unfortunately, due to the rapid attenuation of higher frequency sound in water, high frequency LBL systems typically have a very limited maximum range. All absolute acoustic navigation methods, however, require careful placement of fixed transponders (i.e. fixed or moored on the sea-floor [15], on the hull of a surface ship [8], or on sea-ice [3]) and are fundamentally limited by the speed of sound in water — about 1500 Meters/Second.

Figure 2 (top graph) compares JASON vehicle fixes obtained simultaneously using (a) 12 kHz LBL navigation and (b) 300 kHz LBL navigation. The data was obtained during survey operations during JASON dive #250, June 17, 1999, from 18:08Z to 19:34Z. The 12 kHz LBL update rate was 0.16 Hz (one fix every 6 seconds). The 300 kHz LBL update rate was 1.6 Hz (one fix every 0.6 seconds). Figure 2 also shows the corresponding error histogram of X and Y 12 kHz LBL errors in comparison to 300 kHz LBL (bottom graph). The data show the 12 kHz LBL X and Y fixes to have zero mean and a standard deviation of 0.27 meter and 0.21 meter, respectively,

1.1 Doppler-Based UUV Navigation

This section first reviews the technique of bottom-lock doppler navigation (Section 1.1.1), and reviews some relevant previously published work on this subject (Section 1.1.2).

1.1.1 Theory of Operation

Recently available bottom-lock doppler sonars typically work as follows: The doppler transducer unit has four downward-looking beam transducers oriented at about 30° from the instrument vertical axis. A minimum of three beams are required; four are typically used. The resulting narrow beams are depicted in Figure 1.

First, the doppler sensor measures the apparent bottom-velocity (due to the vehicle's motion) along each of the four beams. The velocity measurement in broadband dopplers is performed with an ensemble of one or more discrete "pings" employing the entire set of four beams — this in contrast to some conventional doppler techniques that employ continuous tones. The doppler unit digitally processes the four ping responses to compute a 4×1 vector of velocities, $v_{beam}(t)$, representing the bottom velocity component along the respective beam axes. Single-ping velocity error standard-deviation varies with beam frequency. Velocity error standard-deviations vary with frequency and instrument design — our 1200 kHz unit provides a single-ping beam-velocity error standard deviation of 0.2%.

Second, the 4×1 vector of beam velocities, $v_{beam}(t)$, is converted to the instrument-frame XYZ velocities, $v_{instrument}(t)$, by a linear transformation

$$v_{instrument}(t) = T * v_{beam}(t). \quad (1)$$

The matrix T is a 4×4 constant matrix mapping the four beam velocities into a 4×1 vector of instrument velocities

$$v_{instrument}(t) = \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{z}(t) \\ \dot{e}(t) \end{bmatrix} \quad (2)$$

representing the cartesian velocities $\dot{x}(t), \dot{y}(t)$, and $\dot{z}(t)$, in instrument-frame coordinates, and $\dot{e}(t)$, a least-square measure of the velocity error.

Third, the 4×1 vector of instrument-frame velocities, $v_{instrument}(t)$, is converted to the world-frame XYZ velocities, $v_{world}(t)$, by the linear transformation

$$v_{world}(t) = \begin{bmatrix} R(t)_{3\times3} & 0_{3\times1} \\ 0_{1\times3} & 1 \end{bmatrix} * v_{instrument}(t) \quad (3)$$

where the orthogonal instrument-to-world rotation matrix, $R(t)$, is computed on-line from sensor values of roll, pitch, and heading.

Fourth, the world velocities, $v_{world}(t)$, are integrated to compute bottom track position

$$x_{world}(t) = x(t_0) + \int_{t_0}^{t} v_{world}(\tau) d\tau \quad (4)$$

where $x(t_0)$ is the user's initial position estimate. For a more detailed discussion of the doppler sensor equations and coordinate conversions, the reader is referred to [4, 9].

1.1.2 Previous Work

In [12] Spindel and colleagues report an acoustic navigation system combining LBL navigation techniques with transponder-based doppler velocity sensing. In [4] Brokloff reports a bottom-lock doppler-based dead-reckoning system combining a 300kHz doppler and an inertial navigation unit (for vehicle heading and attitude data) to obtain relative navigation errors of 0.4% of distance traveled over long (five hour) high-speed (five knot) missions. In [5] Brokloff extends the previous results to employ water-lock doppler tracking when the vehicle altitude exceeds bottom-lock range.

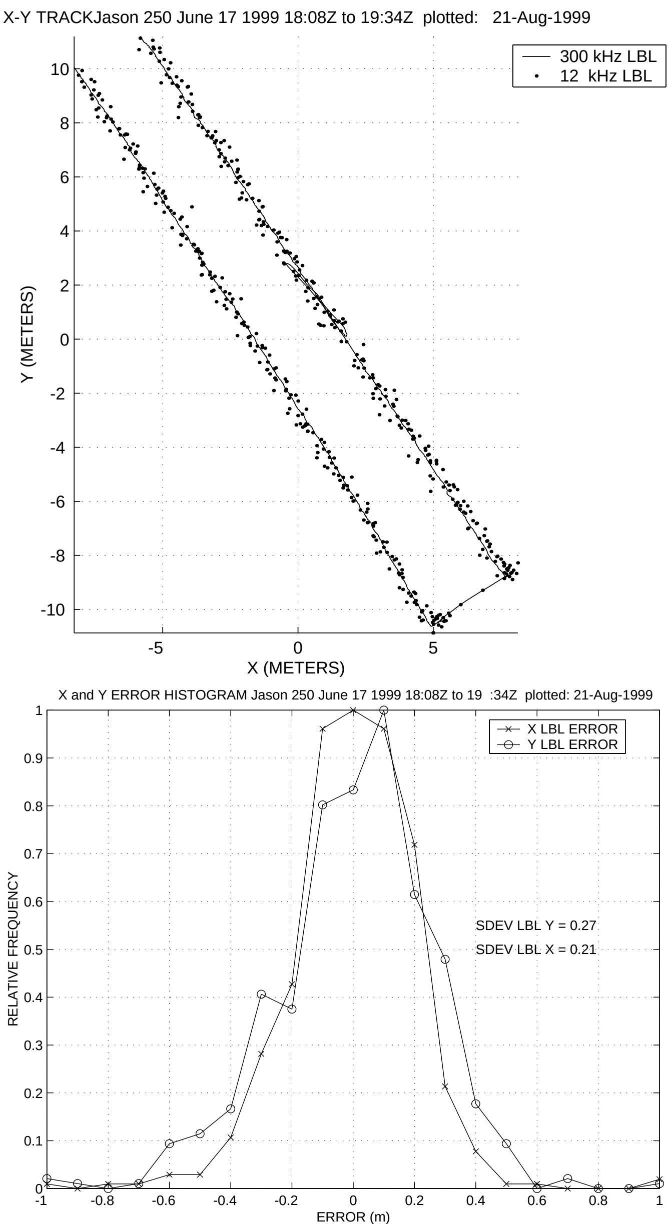

Figure 2: LBL Navigation Precision: X-Y Plot of 12 kHz LBL Jason position fixes (dots) and 300 kHz LBL X-Y fixes (solid line) (top graph). Histogram plot of LBL tracking errors (bottom graph). Data from closed-loop survey operations on JASON dive #250 June 17 1999 18:08Z to 19:34Z.

In [15] the authors report preliminary results from the first deployment of the combined LBL/Doppler navigation system described herein. In [14] the authors identify principal limitations to the bottom-track precision of doppler based navigation systems and analyze the effect of heading-sensor errors on doppler bottom-track precision.

2 Combined Doppler/LBL Navigation

This section reports field trials with the JASON ROV to investigate the X-Y position sensing accuracy of a navigation system comprised of the 1200 kHz bottom-lock doppler sonar and 12 kHz LBL transponder navigation system. To take advantage of the incremental precision of the doppler with the absolute (but noisy) precision of the LBL, we implemented a system utilizing complementary linear filters to combine low-passed LBL position fixes with high-passed doppler position fixes. The system signal flow diagram is shown in Figure 3 The cutoff frequencies for both filters were set to 0.001 Hz. This system employed a conventional magnetic heading compass and conventional gravitational roll/pitch sensors. Note that in normal operation this system requires only standard LBL sea-floor transponders — in contrast to previously reported LBL+doppler systems which utilize additional fixed sea-floor mounted continuous-tone beacons [12].

The experiments were conducted with the JASON ROV during an oceanographic deployment from aboard the *M.V. Northern Horizon* on June 9-20, 1999, at approximately 500 meters depth in the Eastern Mediterranean off the coast of Israel. The authors and collaborators employed JASON, with the navigation system described herein, to perform precise acoustic-bathymetric and photographic image surveys of ancient shipwrecks dating from approximately 750 B.C.

2.1 Experimental Setup

For these experiments, JASON's standard suite of sensors, Table 1, were augmented with new sensors listed in Table 2. JASON's experimental configuration is depicted in Figure 1. The new sensor specifications are as follows:

1. **Doppler Sonar (DVL):** The 1200 kHz bottom-lock, rated to 6000 meter depth, is an RD Instruments "Workhorse Navigator" unit equipped with four acoustic beams, an internal flux-gate compass (+/- 5°), roll/pitch sensors (+/- 2°), and temperature sensor (+/- 0.4°)[1].

2. **300kHz LBL (EXACT):** In order to benchmark actual doppler bottom-track precision, in these experiments we deployed a short-range 300 kHz LBL system called "Exact," developed by the second author and others [16]. This system requires the deployment additional sea-floor transponders. It provides position updates up to about 4 Hz with centimeter accuracy over a maximum range of about 100m.

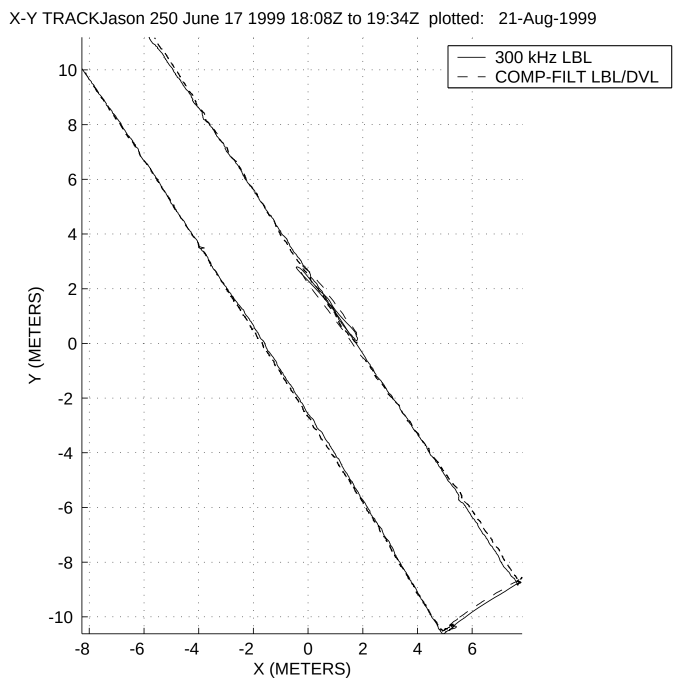

Figure 4: LBL/doppler Navigation Precision: X-Y Plot of LBL/Doppler Jason position fixes (dashed line) and 300 kHz LBL X-Y fixes (solid line). Data from closed-loop survey operations on JASON dive #250 June 17 1999 18:08Z to 19:34Z.

2.2 Combined LBL/Doppler Navigation Performance

Figure 4 compares JASON vehicle navigation fixes obtained simultaneously using the LBL/Doppler system and

[1]The Workhorse Navigator doppler sonar was developed and is manufactured by RD Instruments Inc, 9855 Businesspark Ave., San Diego, CA 92131-1101 phone: 619-693-1178, web: http://www.rdinstruments.com.

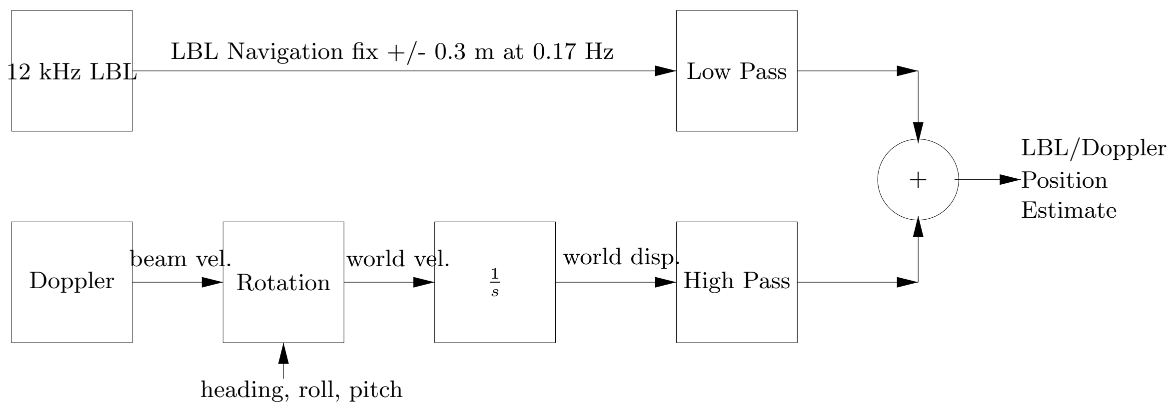

Figure 3: Block Diagram of LBl/Doppler Complementary Filter Navigation System.

the 300 kHz LBL system. The data was obtained during survey operations during JASON dive #250, June 17, 1999, from 18:08Z to 19:34Z. Figure 5 shows histograms of the X and Y navigation errors observed during this vehicle deployment using (a) 12 kHz LBL navigation alone and (b) combined LBL/doppler navigation. The data show the 12 kHz LBL X and Y fixes to have zero mean and a standard deviation of 0.27 meter and 0.21 meter, respectively. The combined LBL/doppler system exhibits X and Y navigation errors with a standard deviation of 0.09 meter. Thus the LBL/doppler system is a factor of three more accurate than the LBL system alone. The LBL/doppler system provides vehicle position fixes every 0.25 second, while the the LBL system provides vehicle position fixes every 6.0 seconds — more than an order of magnitude improvement.

Figure 6 shows the actual LBL fix range error versus time (left graph) and the LBL/doppler fix range error versus time (right graph) for the vehicle tracks depicted in Figure 4. These graphs confirm, in an alternative presentation format, the conclusions obtained from Figure 5.

3 Conclusion

We conclude that the combined LBL/doppler system provides significant improvement in vehicle navigation precision and update rate over 12 kHz LBL alone. The combined LBL/doppler navigation provides navigation precision and update rate necessary for precision closed-loop X-Y vehicle control. In contrast, our experience is that precision closed-loop underwater vehicle control is not possible with LBL alone. Good 12 kHz LBL fixes are essential to LBL/doppler precision; when LBL precision degrades, LBL/doppler precision is proportionally diminished.

This LBL/doppler system is particularly useful for real-world ROV operations — it provides both improved navigation accuracy (in comparison to LBL alone) and enables the use of closed-loop vehicle XY control without requiring the deployment of additional navigation hardware such as additional sea-floor transponders.

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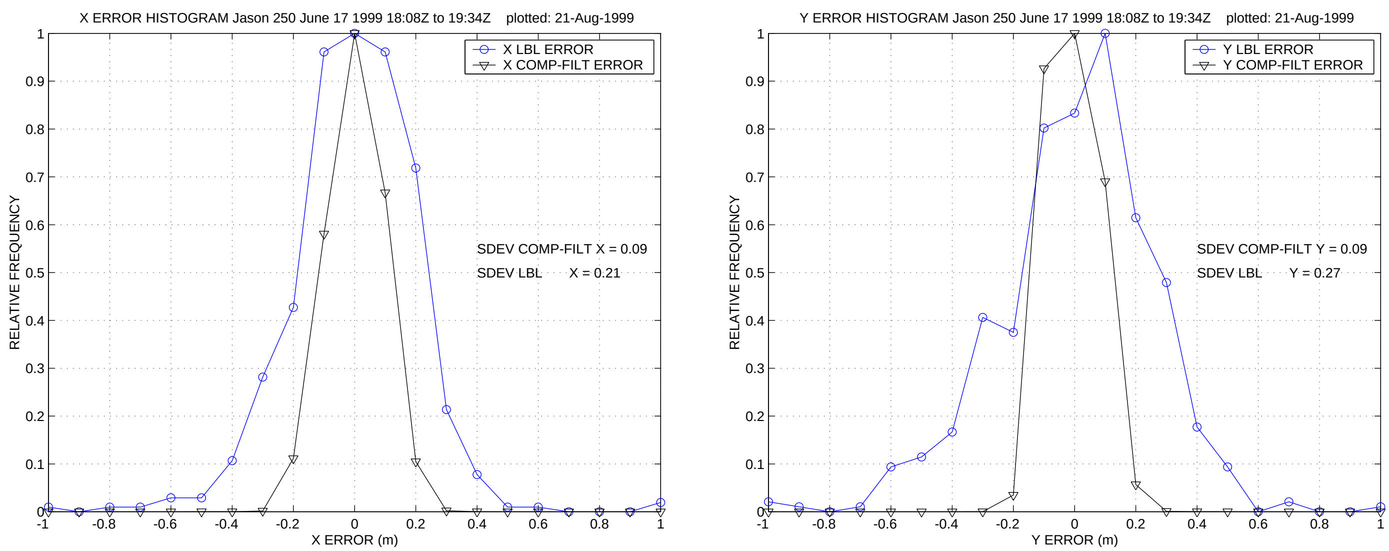

Figure 5: LBL/doppler vs LBL Navigation Precision: Histogram plots of of X and Y tracking errors. Shown are X error histogram (left graph) and Y histogram (right graph). Data from closed-loop survey operations on JASON dive #250 June 17 1999 18:08Z to 19:34Z.

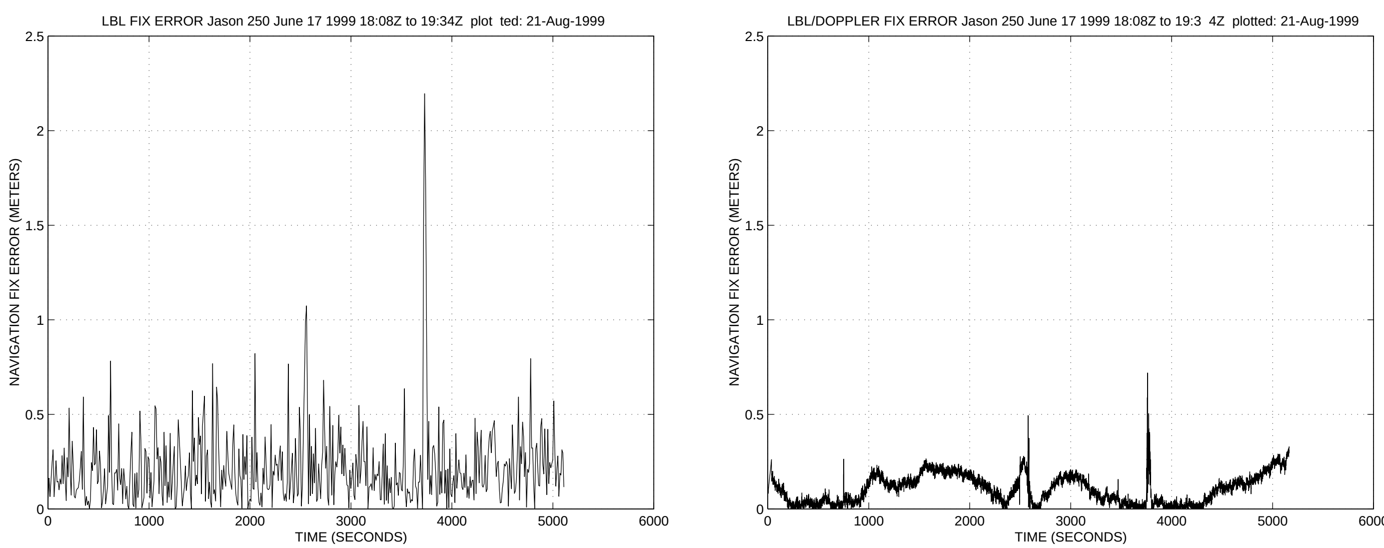

Figure 6: LBL/doppler vs LBL Navigation Precision: LBL fix range error versus time (left graph). LBL/doppler fix range error versus time (right graph). Data from closed-loop survey operations on JASON dive #250 June 17 1999 18:08Z to 19:34Z.

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