Sensing the Underwater Acoustic Environment with a Single Hydrophone Onboard an Undersea Glider

Brian G. Ferguson[1], Kam W. Lo[1] and Joshua D. Rodgers[2]
Defence Science and Technology Organisation
[1]Maritime Operations Division, Australian Technology Park, Eveleigh 1430 NSW Australia.
[2]Maritime Platforms Division, 506 Lorimer Street, Fishermans Bend, VIC 3207 Australia.

Abstract- **Undersea gliders are autonomous vehicles that propel themselves through the ocean by changing their buoyancy. Acoustic platform noise (or self-noise) generation occurs only briefly (and predictably) when the buoyancy change and trim adjustment mechanisms are activated on these quiet platforms. Also, hydrodynamic flow noise is minimal due to the slow (≤0.5 m/s) travel speed of the glider. This paper demonstrates the utility of a single hydrophone onboard a glider that samples the underwater acoustic environment in space and time for the purpose of detecting human activity during a glider mission. In May 2009, acoustic sensor data from a single hydrophone onboard a Slocum glider were recorded during the glider's deployment in a shallow water environment. Time-frequency signal analysis of the underwater acoustic data results in the detection of a helicopter, a surface vessel and the presence of tone burst transmissions from an underwater sound beacon. In addition, echolocation sound pulses (or clicks) emitted by the biological sonars of dolphins permeate the data. Cepstrum analysis of the acoustic data containing the surface vessel's radiated noise (as the signal) provides an estimate of the time delay between the direct path and multipath arrivals of the vessel's broadband acoustic energy at the hydrophone. Given the multipath time delay estimate, along with the known (measured) water depth, hydrophone depth, and sound speed in water, a single hydrophone multipath passive ranging method is able to estimate the instantaneous range of the surface vessel from the glider. The variation with time of the range estimates provides the distance and occurrence time of the closest point of approach of the vessel to the glider. The onboard underwater sound sensor, coupled with the passive ranging method, provides the glider with a self-protection capability in that the separation distance between an encroaching maritime vessel and the glider would indicate the likelihood of the vessel encountering the underwater vehicle, which could adversely affect the operation of the glider.**

I. INTRODUCTION

Undersea gliders propel themselves by changing their buoyancy. A change in buoyancy leads to platform motion in the vertical (depth) direction, while forward motion in the horizontal direction results from the addition of a pair of wings to the torpedo-shaped platform hull. The wings and hull body provide lift, which in turn, allows the glider to move horizontally while it simultaneously moves vertically (upward direction for positive buoyancy; downward for negative buoyancy). These two (vertical and horizontal) orthogonal motions result in the glider following a sawtooth trajectory (in the vertical plane), which is periodic due to the vehicle completing repetitive descent-ascent trim cycles. Wing lift balances the across-track buoyant force, while the drag balances the forward buoyant force [1].

Undersea gliders are attractive to the oceanographic community because a fleet of small inexpensive gliders appears to be the best approach to solving the core oceanographic observational problem of sampling the properties of the oceans on a range of spatial scales that extend from ocean basins, through mesoscale eddies, down to the microscales on which turbulent dissipation occurs [1]. Traditionally, a global array of small profiling floats has been used to measure ocean currents (by tracking displacement) as well as variations with depth of sea temperature and salinity. However, the horizontal sampling capability of moving gliders is a fundamental advance over float technology. The periodic sawtooth trajectory traced by the glider's motion enables onboard sensors to sample the ocean both vertically and horizontally. Similarly, undersea glider fleets appeal to defence forces because of platform stealth, operational endurance, and sensing profiles that enable both vertical and horizontal sampling of the physical, chemical and biological properties of the underwater medium. Undersea gliders are capable of submerged transits over the horizon to remote areas, collecting environmental data and transmitting tactical information via satellite to a central command and control facility for intelligence and decision making purposes. For example, optical sensor suites onboard gliders can be used to determine underwater visibility conditions in littoral areas (characterized by shallow coastal waters) in advance of deployed assets [2]. The clarity of the seawater is important for divers, when they are required to undertake mine counter measures, and for estimating bathymetry using airborne laser depth sounders. Also, it has been proposed that gliders act as mobile nodes in distributed autonomous sensor networks for surveillance of the undersea environment to deny quiet diesel-electric threat

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submarines unmonitored movement in focal areas [3]. This approach uses gliders in littoral waters as both sensing nodes and low-observable acoustic-satellite communication gateways to relay tactical data for other nodes (such as fixed bottom-mounted sensors) in the network. An autonomous undersea sensor network could be covertly deployed in days, operate for weeks to months, and adapt to *in situ* conditions to provide a capability for the detection, classification, localization, and tracking of subsurface threats.

In May 2009, acoustic sensor data from a single hydrophone onboard a Slocum glider were recorded during the glider's deployment in a mock undersea surveillance mission outside the entrance to Jervis Bay (35°S07', 150°E50'), New South Wales. This shallow water environment, which has a typical depth of 90 m, was characterized by good acoustic propagation conditions and low ambient sea noise levels. Post processing of the data resulted in the detection of a helicopter, a surface vessel and the presence of tone burst transmissions from an underwater sound beacon. The data also contained echolocation clicks emitted by *Tursiops aduncus* dolphins that frequent the area [4]. In the case of airborne acoustic sources, the application of time-frequency signal analysis methods to single hydrophone data has been shown previously by the authors to provide tactical information such as speed, altitude and rotor/propeller blade rates of transiting air vehicles (helicopters and turboprop aircraft) [5]. Section II contains spectrograms that show the acoustic characteristics of a slowly moving helicopter as well as two different transmission frequencies for an underwater sound beacon operating in the area. In Section III, cepstrum analysis [6, 7] of the acoustic data provides an estimate of the multipath time delay between the direct path and multipath arrivals of the surface vessel's radiated noise at the hydrophone. This multipath time delay estimate, along with the known (measured) water depth, hydrophone depth, and sound speed in water form the inputs for a single hydrophone multipath passive ranging method [8]. The variation with time of the range estimates provides the distance and time of the closest point of approach of the vessel to the glider. In addition, waveforms of underwater sound pulses emitted by local dolphins are presented in Section IV, with Section V containing the conclusions.

II. TIME-FREQUENCY SIGNAL ANALYSIS

A. Underwater Sound Beacon Transmissions

The output of the single hydrophone onboard the glider is sampled every 10 μs, that is, at a sampling rate of 100 kHz. For the detection of tone burst transmissions from an underwater sound beacon, the data are down sampled to 15 kHz. Figure 1 is the spectrogram showing the presence of two different sequences of tone burst transmissions from the beacon at frequencies of 4.8 kHz and 6.0 kHz respectively. The lower frequency tone bursts occur at 13 s, 31 s, 38 s and 44 s, while the higher frequency tone bursts occur at 6 s, 23 s and 55 s. All of the tone bursts transmissions have the same half-second duration.

B. Helicopter Transit

For the detection of helicopters and turboprop aircraft, the data are down sampled to 1 kHz. Figure 2 is the spectrogram showing the presence of a slowly moving helicopter, for which there are two harmonic series of spectral lines (horizontal linear features in the spectrogram): one has the main rotor blade passing frequency as its fundamental; while the other (with the lower signal-to-noise ratio) has a fundamental frequency that corresponds to the tail rotor blade passing frequency. The helicopter flies past the glider at a time of 27 s. If the helicopter passes directly over the glider, then tactical information (helicopter speed and altitude, as well as the rest frequencies for the main and tail rotor blade passing rates) can be extracted from the hydrophone data using signal processing methods described previously by the authors in the scientific literature [5]. The vertical stripes in the spectrogram at 15 s, 32 s and 53 s are due to spectral leakage from the tone bursts emitted by the underwater beacon. Other sources of acoustic interference are associated with activation of the buoyancy change pump and trim compensation mechanism on the undersea glider. This platform machinery-generated noise is observed as (less pronounced) vertical stripes in the spectrogram and includes those features with a 4 s periodicity (e.g. 36 s, 40 s, 44 s, 48 s) in Fig. 2.

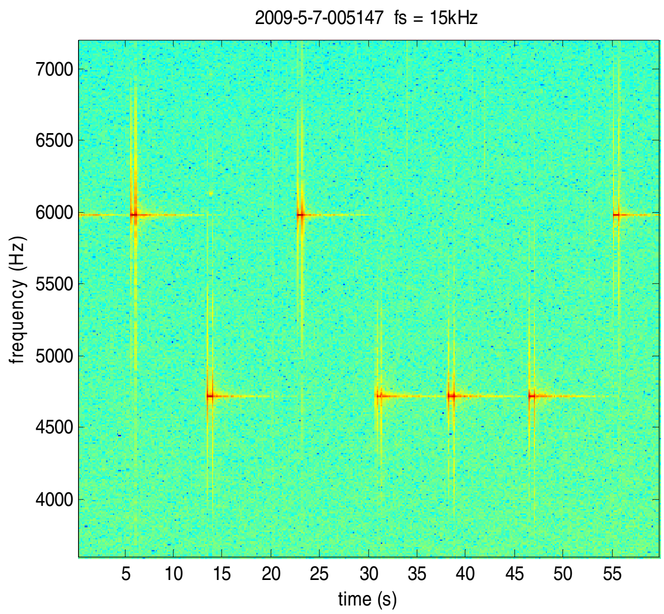

Figure 1. Spectrogram of the hydrophone output showing the presence of two different sequences of tone burst transmissions.

III. CEPSTRUM ANALYSIS

A.. Surface Vessel Transit

After down sampling to a frequency of 10 kHz, time-frequency signal analysis methods are applied to the hydrophone data recorded during a surface vessel transit. A spectrogram of the data is shown in Fig. 3. The observed periodic structure in this time-frequency distribution is attributed to the acoustical Lloyd's mirror effect [9]. For broadband sources in motion (like jet aircraft in air or surface vessels in water), multipath propagation results in the occurrence of an interference fringe pattern in the time-frequency distribution of an acoustic sensor's output [10].

The cepstrum is the inverse Fourier transform of the logarithmic power spectrum [6]. It differs from the autocorrelation function only by virtue of the logarithmic scaling of the original power spectrum shown in Fig. 3. The cepstrum is able to detect periodic structures in the logarithmic spectrum such as families of harmonically-related spectral lines or, of particular relevance here, an acoustic Lloyd's mirror interference pattern. In the present case, the cepstrum is applied to the time-frequency distribution in Fig. 3 to form the cepstrogram shown in Fig. 4. Each peak in the cepstrum corresponds to a rahmonic and the position of the first rahmonic along the quefrequency (time lag) axis gives the multipath time delay estimate. The variation with time of the instantaneous multipath delay is indicated by the black line in Fig. 4. These multipath delay estimates, which are plotted in Fig. 5, are extracted automatically from the time varying quefrency curve for the first rahmonic shown in Fig. 4.

C. Passive Ranging of Surface Vessel

Given the multipath time delay estimate, along with the known (measured) values for the water depth, hydrophone depth, and sound speed in water, a single hydrophone multipath passive ranging algorithm is invoked to provide estimates of the instantaneous range of the surface vessel from the glider. This algorithm has been applied previously to localizing active sonar transmissions in shallow water [8]. The variation with time of the range estimates provides the distance (940 m) and time (48 s) of the closest point of approach of the vessel to the glider – see Fig. 6. The radial velocity of the high-speed vessel is about 18 m/s.

The passive ranging capability of the glider could be readily adapted for a self-protection application where the glider would be able to monitor the instantaneous range of the vessel to determine if the vessel is continuing to approach or if it has passed the closest point of approach. If the vessel continues to close in range, the glider could elect to remain deep while the vessel transits past the glider.

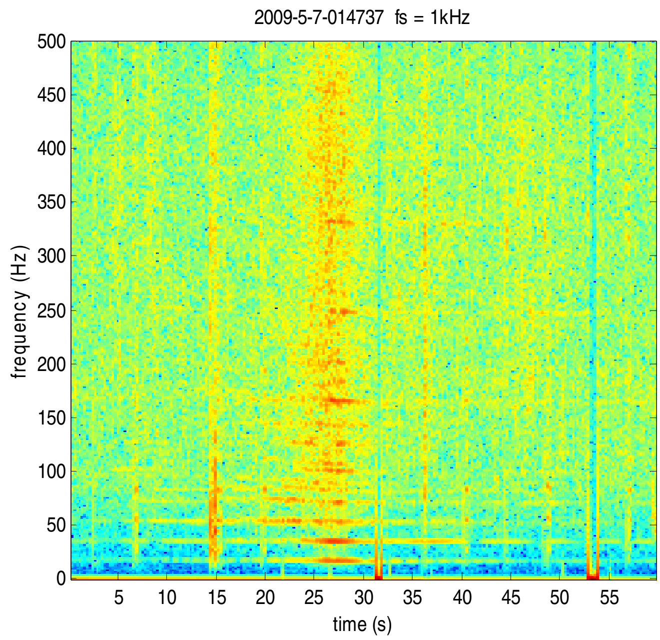

Figure 2. Spectrogram showing the variation with time of the frequency components of the hydrophone output. A helicopter passes over the glider at 27 s. Strong interference events (vertical stripes) occurring at 15 s, 32 s and 53 s are due to spectral leakage from the presence of strong tone burst transmissions at 4.8 kHz and 6.0 kHz.

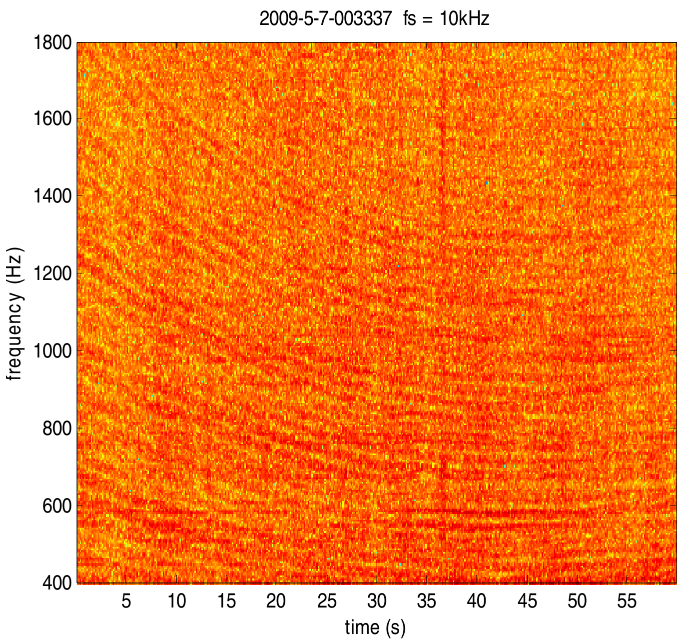

Figure 3. Variation with time of the output power spectrum of the hydrophone onboard an undersea glider during the passage of a surface vessel past the glider.

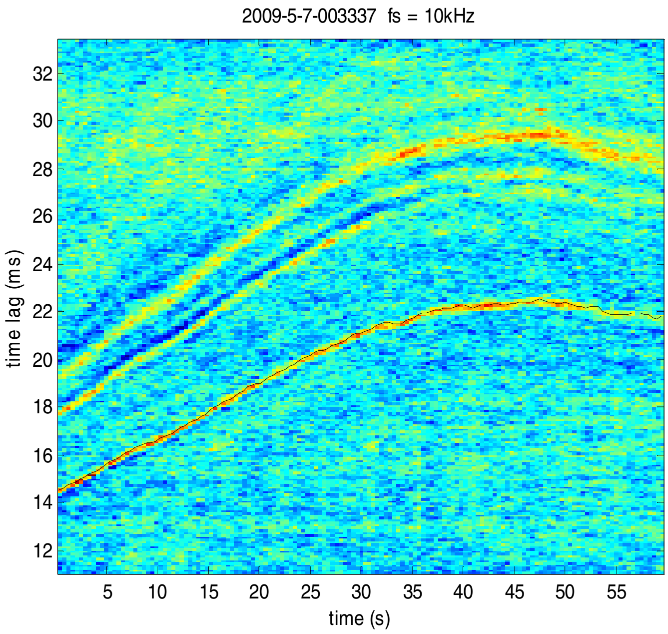

Figure 4. Cepstrogram showing the variation with time of the cepstrum during a surface vessel transit. The vertical axis corresponds to the quefrency (time lag) variable of the cepstrum and the horizontal axis represents time.

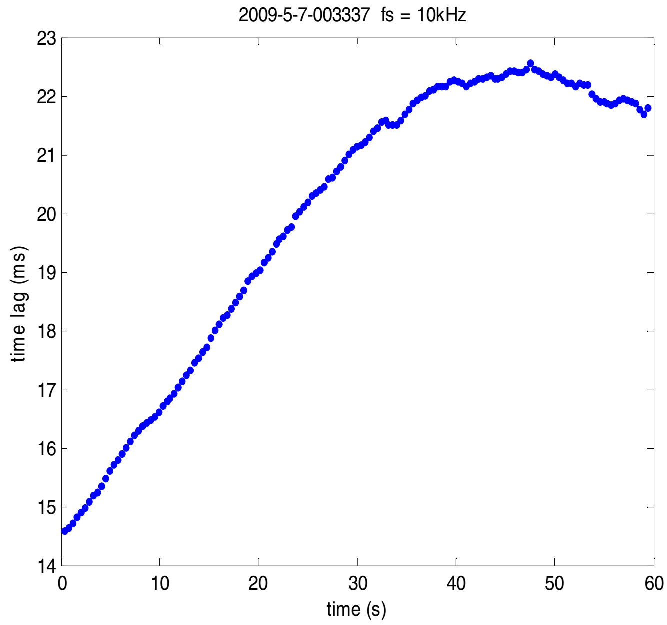

Figure 5. Temporal variation of the time lag (or time delay) between the direct path and multipath arrivals of the signal at the hydrophone.

IV. DOLPHIN BIOSONAR ECHOLOCATION WAVEFORMS

The hydrophone onboard the undersea glider also sensed the presence of strong underwater acoustic transient signals, which were identified as being of biological origin [4]. Two of these biological transient signals are reproduced in Figs 7-8. Although the reception of these two biosonar transmissions are well-separated in time (by 17 s), the waveforms display a close match. These transient signals are echolocation sound pulses (or clicks) emitted by Indo-Pacific bottlenose dolphins (*Tursiops aduncus*), which inhabit Jervis Bay and its seaward approaches [4].

V. CONCLUSIONS

The addition of a single hydrophone sensor onboard an autonomous undersea glider provides a capability for surveillance of the underwater acoustic environment and the extraction of tactical information for transiting surface vessels and aerial vehicles. It also enables the detection of underwater sound projector transmissions and biological sonar echolocation pulses, most notably Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) active biosonar transmissions. A single sensor passive ranging capability onboard an undersea glider could be adapted to sense encroaching surface vessels.

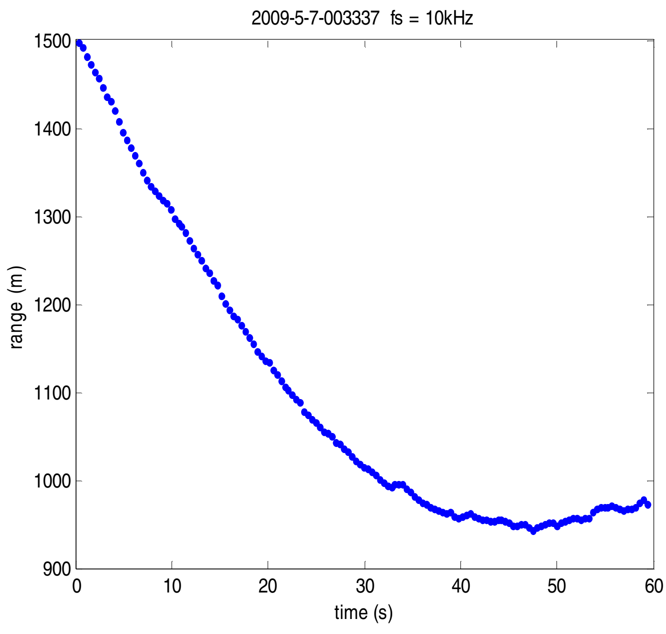

Figure 6. Variation with time of the range of a transiting surface vessel from the undersea glider.

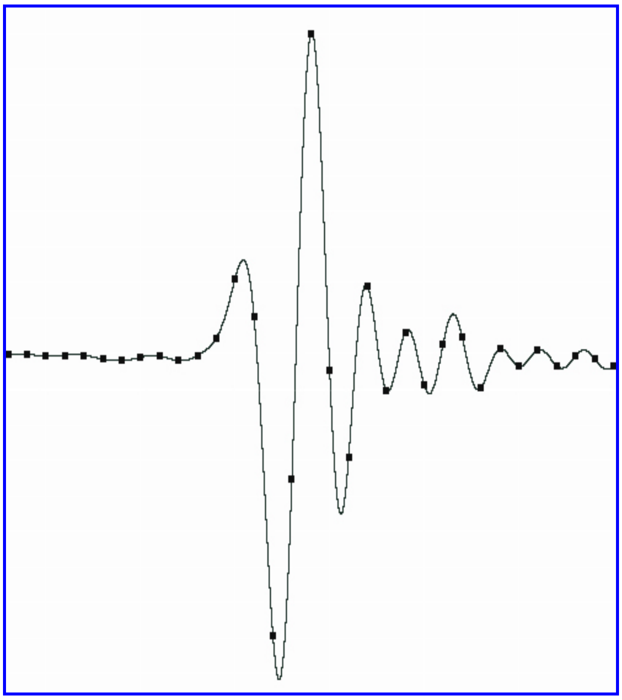

Figure 7. Waveform of a dolphin biosonar echolocation click transmission. The time interval between sampling points is 10 μs.

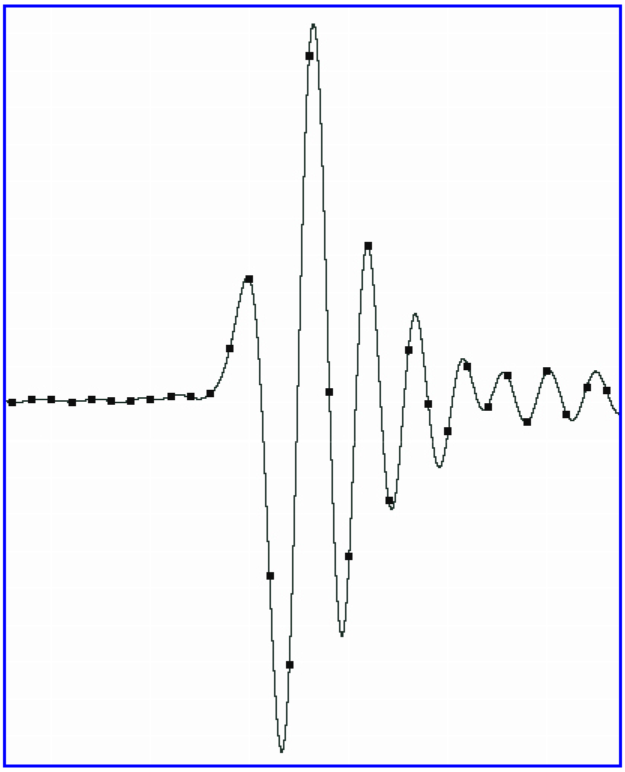

Figure 8. Similar to Fig. 7 but for a dolphin click received 17 s later.

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