Diversity-based acoustic communication with a glider in deep water (L)

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The primary use of underwater gliders is to collect oceanographic data within the water column and periodically relay the data at the surface via a satellite connection. In summer 2006, a Seaglider equipped with an acoustic recording system received transmissions from a broadband acoustic source centered at 75 Hz deployed on the bottom off Kauai, Hawaii, while moving away from the source at ranges up to ~200 km in deep water and diving up to 1000-m depth. The transmitted signal was an m-sequence that can be treated as a binary-phase shift-keying communication signal. In this letter multiple receptions are exploited (i.e., diversity combining) to demonstrate the feasibility of using the glider as a mobile communication gateway.

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I. INTRODUCTION

Ocean sampling has traditionally been carried out by ships and moorings. While remote sensing techniques from satellites and airplanes provide useful data, they do not penetrate very far below the ocean's surface. To gain insight into the temporal and spatial processes below the ocean surface, alternative sensing techniques such as subsurface floats, remotely operated vehicles, and autonomous underwater vehicles have emerged over the last decade to complement the existing sensing techniques. In particular, autonomous underwater gliders[1] represent a rapidly maturing technology with a substantial cost savings over traditional ocean sampling techniques for sustained, almost real-time measurements. In this letter, we explore the possibility of using the gliders as mobile communication gateways.

The primary use of underwater gliders is to collect oceanographic data within the water column (e.g., temperature and conductivity) and transmit their data to shore while periodically downloading instructions at the surface via a satellite connection. However, the mission of gliders has expanded lately into acoustics. Send *et al.*[2] reported the successful deployment of Spray Gliders equipped with a commercial acoustic modem for data retrieval from subsurface moorings and seafloor systems installed with a similar modem in deep water. The gliders navigated within a few km of the moorings and the acoustic link with subsurface moorings was established while the gliders were at the surface. Several tests of acoustic communications between gliders and between gliders and other platforms have also taken place at a few km ranges in shallow water to demonstrate the capability of gliders for global observation programs such as Ocean Observatories Initiative.[3]

Separately, gliders equipped with an acoustic recording system (ARS) can be used for passive monitoring, for example, to collect marine mammal data during an experiment in Monterey Bay in 2006.[4] In another mission off the Hawaiian Island of Kauai, a Seaglider recorded transmissions from a 75 Hz bottom mounted acoustic source [part of the Acoustic Thermometry of Ocean Climate (ATOC)/North Pacific Acoustic Laboratory (NPAL) project].[5] Coherent signal processing with near theoretical gain was achieved with positive ray identification, demonstrating the potential of using gliders as mobile tomography receivers in deep water performing acoustic tomography on 700 km scale. More recently, GPS-based surface positions have been combined with subsurface position estimates derived from acoustic signals that were transmitted for the purpose of performing acoustic tomography.[6]

This letter explores the potential of using the gliders with a single hydrophone for long-range acoustic communication in deep water. This is motivated by the recent demonstration of basin-scale acoustic communication[7] which exploits either (a) spatial diversity provided by a vertical array or (b) temporal diversity provided by the time-varying ocean itself with a single stationary receiver. The gliders are in constant motion diving to depths of ~1000 m and traveling horizontally at about 0.25 m/s (half a knot) for several hours during a dive, naturally inducing a combination of spatial and temporal

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[a)] Author to whom correspondence should be addressed. Electronic mail: hcsong@ucsd.edu diversity that can be utilized for acoustic communication. Previously, similar spatial/temporal diversity was investigated for synthetic aperture communications[8] exploiting the relative motion between a source and receiver where the moving source was confined to only horizontal motion (i.e., constant depth). To achieve the objective, we revisit the Seaglider experiment conducted around the 75 Hz Kauai source where the transmitted m-sequence can be treated as a binary-phase shift-keying (BPSK) communication signal with an information rate of 37.5 bits/s.[7,9] The long-range and duration capabilities of gliders coupled with acoustic communication will enable them to serve as mobile communications gateways.

II. KAUAI EXPERIMENT WITH A SEAGLIDER

In summer 2006, a Seaglider equipped with an ARS (SG023) was deployed in the vicinity of Kauai, Hawaii where one of the active ATOC transmitters was located 14.8 km north of Haena Point, Kauai as depicted in Fig. 1(a).[4] The bottom-mounted Kauai source (22° 20.949′N, 159° 34.195′W) was 811 m deep. During the experiment, the Kauai source transmitted two sets of signals: (1) a 2-h long pseudorandom m-sequence once per day except Friday and (2) a 20-min long coded message six times each Friday (every four hours). While both signals can be useful, in this letter we focus on the 300-s probe signal contained in the precursor of (2) for acoustic communications with a mobile platform. The probe signal was a 1023-digit m-sequence repeated 10 times with each digit consisting of 2 cycles of 75 Hz (37.5 Hz bandwidth). The entire 1023-digit sequence lasted 27.28 s. The source level was gradually ramped up over approximately five minutes preceding the normal transmission time, from 165 dB to 195 dB re 1 μPa at 1 m, in accord with requirements of the various authorizations for the operation of the source.[5]

The Seaglider with a hydrophone mounted in the flooded tail section is shown in Fig. 1(b). It was deployed from a small boat on 30 August 2006, just a few km south of the Kauai source. Over the next 40 days it traveled about ~200 km in the northeast direction toward Point Sur, California, turned around, and was recovered 10 October on the south side of Kauai after making 166 dives. In the next section, we describe the communication processing and performance of source signals captured during dives 53, 74, and 75 at approximate source-to-glider ranges of 100 and 200 km, respectively, as marked in Fig. 1(a). After a few initial shallow dives off the coast of Kauai, the glider was programmed to dive to 1000 m depth. The glider profile is illustrated in Fig. 1(c) where highlighted segments indicate glider positions at the times of source signal reception: 450, 800, and 400 m, respectively. Note that the profiles of dives 74 and 75 are almost identical.

III. COMMUNICATION PERFORMANCE

To evaluate the communication performance with the Seaglider in motion at various ranges, we analyze receptions made during dives 53, 74, and 75. The ARS on the glider collected acoustic data from a single hydrophone at a sampling rate of 5 kHz. However, the ARS real-time clock drifted during the data acquisition and had to be synchronized to GPS at each surfacing. Based on the difference between the clocks, the effective sampling rate was estimated as 4993.8 Hz with a slight variation from dive to dive. Consequently, the overall Doppler is due to both mismatch in sampling frequency (i.e., 6.2 Hz) and horizontal motion of the glider at the time of reception.[10] For Doppler estimation, a single period of 1023-digit m-sequence (27.28 s) was used for resampling and then correlated with the data, searching for the frequency shift that yielded the best match. Assuming a sampling frequency of $f_s = 5$ kHz, the estimated total Doppler relative to 75 Hz was 0.072, 0.090, and 0.085 Hz, respectively. After taking into account the frequency shift due to the clock drift, the corresponding radial velocity was consistent with the rather crude velocity estimate based on the glider path.

After resampling of the data with the corresponding Doppler estimate, channel estimation was carried out using the adaptive least mean square algorithm[11] and the known sequence of symbols (i.e., training mode) as shown in Fig. 2. A few interesting observations follow. First, the channel delay spread is approximately 3 s which corresponds to

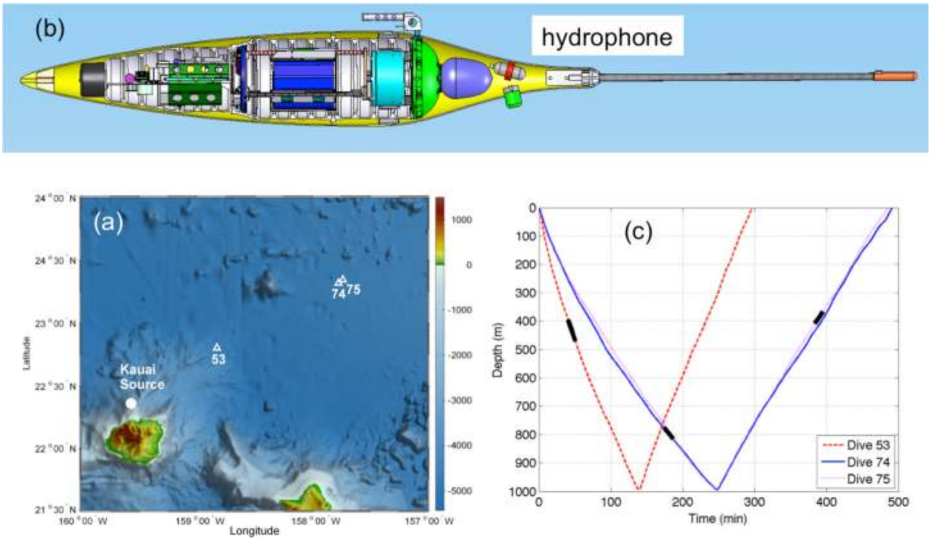

FIG. 1. (Color online) (a) The Kauai source (filled dot) is bottom-mounted off Kauai, Hawaii. Triangles indicate GPS positions of the glider at the beginning of each dive at the surface. (b) The acoustic Seaglider. The hydrophone is in the tail cone at the top. (c) Glider positions at the time of receptions (highlighted segments) superimposed on the profile of dives 53, 74, and 75. Note that dive 75 is almost identical to dive 74.

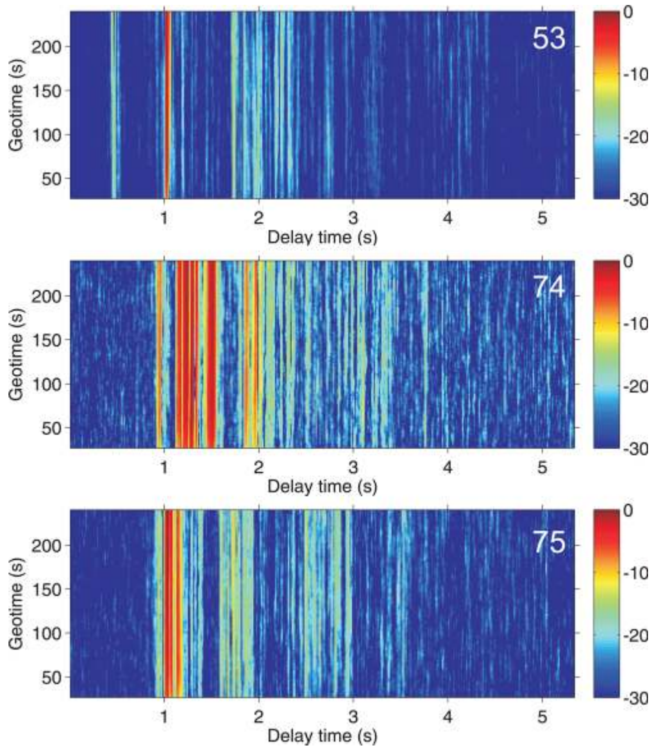

FIG. 2. (Color online) Channel impulse responses during dives 53, 74, and 75. The color scale is in dB.

intersymbol interference of about 100 symbols for the symbol rate of $R = 1/T = 37.5$ symbols/s. Second, the channel is slowly time-varying over 300-s, requiring periodic channel updates when channel-estimate-based equalization is applied.[10] Third, the sparsity of the channel is noticeable in particular at a closer range (dive 53). The sparsity will be exploited by the matching pursuit (MP) algorithm for channel estimation below.[12] Fourth, at a similar range for dives 74 and 75 (∼200 km), the channels at different depths (i.e., 800 and 400 m) and different times (several hours apart) are distinguished from each other, indicating the spatial/temporal diversity generated by the glider movement.[7] Finally, significant energy is carried by the early arrivals even at the depth of 800 m during dive 74 close to the sound channel axis (1000-m). This is in contrast with typical ATOC/NPAL basin-scale receptions where early visible, weak arrivals are followed by later arrivals containing most of the energy.[7]

There are two common approaches to channel equalization in underwater acoustic communication in the literature: (1) multichannel decision-feedback equalizer[13] (M-DFE) and (2) time reversal (TR) combining followed by a single channel DFE (TR-DFE).[14] While both approaches theoretically provide similar performance in terms of output SNR, it is found that a block-based TR-DFE with MP consistently outperformed a M-DFE. Thus here we report the results using the TR-DFE.[14] While channel estimation was carried out by a MP algorithm exploiting channel sparsity, the single channel equalizer employed the adaptive recursive least squares algorithm[11] with a forgetting factor of $\lambda = 0.999$. A fractionally spaced DFE (two samples per symbol) was applied to the DFE feedforward filter, and the number of feedforward and feedback filter taps was 100 and 50, respectively. The number of training symbols for equalization and block size for channel update both were a single period of the m-sequence, i.e., $N_T = N_B = 1023$.

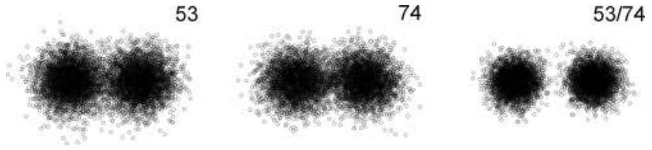

FIG. 3. Performance of BPSK communications for two individual receptions during dives 53 and 74 (left two panels). The output SNR is about 5 dB for both cases with a bit error rate of 2%. The performance enhancement due to diversity combining (53 and 74) is evident in the rightmost panel with an output SNR of 8 dB. A TR-DFE with MP is employed for multichannel equalization.

The performance of BPSK communications for individual receptions (dives 53 and 74) is shown in Fig. 3 as a scatter plot. The output SNR is 5 dB for both cases with a bit error rate of about 2%. The output SNR is comparable to the input SNR. Although not shown, dive 75 yields the worst performance with an output SNR of 3.5 dB due to its lower input SNR. The two receptions (dives 53 and 74) can be combined coherently.[15] The performance enhancement due to diversity combining is clearly evident in Fig. 3 (rightmost) with an output SNR of 8 dB, achieving a 3-dB increase from individual cases (5-dB). Further combining all three receptions (dives 53, 74, and 75) leads to an error-free performance with a 9 dB output SNR. It should be mentioned that error correcting codes can be introduced to further improve the communication reliability at the expense of data throughput.[16]

IV. SUMMARY

The concept of diversity combining was demonstrated for receptions made during different dives at different ranges and depths. This was done because the scheduled signal transmissions were intermittent during the Kauai experiment. In practice, a glider can capture a number of transmissions at various depths (up to 1000 m) and different times for several hours during a single dive, providing spatial/temporal diversity which can be utilized for performance improvement even when individual receptions have low SNR. The decrease in effective data rate due to diversity combining is not a major concern for mobile gliders which will remain underwater for several hours before surfacing. On the other hand, the benefit of diversity combining is to increase the range coverage of the gateway and reliability of the communication link along with error correcting codes. At the surface, the glider can relay the decoded messages to shore via a satellite connection acting as a mobile communication gateway.

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