An Autonomous Underwater Vehicle Towed Array for Ocean Acoustic Measurements and Inversions

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***Abstract*— A novel experimental method involving an autonomous underwater vehicle (AUV) with a towed hydrophone array has been developed to measure the single path interaction from the surface, bottom and volume of the shallow water waveguide. The system is designed to operate from the low (~ 100 Hz) to the mid frequencies (≤ 10 kHz) with a directional source. The effects of surface, volume, and bottom scattering on the coherency of direct and direct-reflected signals are difficult to measure and a mobile directional receiver provides an adaptive capability. For example, the quantification of the role micro-bubble layers near the surface and in surface ship wakes plays on the coherency and scattering of sound could be measured with this device. In addition, an AUV with a hydrophone array can be easily and rapidly deployed and because of its mobility can provide area wide characterization. However, AUV radiated noise measurements indicated vehicle noise would limit the ability of hull-mounted or interior hydrophone arrays and thus suggested the use of a low noise towed array. The AUV discussed here is the Remus[1] vehicle, a tested as well as a readily-available tow platform for a small low drag array. To demonstrate the ability of Remus to act as a low noise tow vehicle, radiated noise measurements were made on the vehicle at Dodge Pond[2] acoustic test facility. The vehicle was rotated on a shaft at a depth of 8 meters and calibrated noise levels measured at 13 meters distance. At the maximum RPM of the AUV, the $1/3^{\mathrm{rd}}$ octave noise level, when converted to source level by the calibrated transmission factor, was 130 dB re 1μPa at 1m. This would represent the radiated noise source level for a vehicle moving at 3 knots. A small-diameter (2.8 cm O.D.) fluid-filled hydrophone array has been developed with 6 channels spaced evenly at 0.75 meters, each channel having a receiving sensitivity of -174 dB re 1μPa/V from 100 Hz to 10 kHz. The recording system consisted of three commercial off-the-shelf (COTS) battery powered mini-disc recorders with a 20 kHz band pass, sampling frequency of 44 kHz and a 16 bit analog to digital converter providing storage capability of 90 minutes of raw data. The prototype system was deployed in a "proof-of-concept" test at the Dodge Pond test facility. The vehicle was programmed to navigate along paths that provided straight courses as well as several turns to determine the operational characteristics of the system. Results on capabilities of the vehicle with the towed system are presented including vehicle and array noise, beamforming, and element localization.**

I. INTRODUCTION

For sound scattering and transmission experiments in the ocean, one typically needs to know and control the angle of incidence from the surface and bottom, as well as the range, depth and bearing of the receiver. To conduct a transmission experiment in the ocean, the simplest experimental system would consist of a single source and a single receiver, each of which could be stationary or mobile. The factors determining which configuration will actually be implemented, among other things, includes the often prohibitive cost of ship time. The lowest cost one can achieve without resorting to a stationary source and receiver is a single ship experiment, but this allows for only a moving source and stationary receiver or vice-versa. Since sources are often inefficient, it is desirable to keep the source on the ship and deploy a stationary receiver, which is a well proven experimental technique (see for example [1]). If instead of a moored receiver, the receiver is placed on an autonomous underwater vehicle (AUV), then the full versatility of a moving source and moving receiver experiment can be realized without the expense of a second ship.

The idea of attaching a sensor to an AUV in order to make it a mobile sensor is not new. Considering an acoustic sensor, one can easily attach a hydrophone to an AUV and place a source in the water which has been demonstrated most readily by the acoustic communications community. However, in the low to mid frequency ranges where wavelengths can be of the order of the length of the vehicle, acoustic sensors that are constrained by the vehicle length would not be very directional, a property which is essential in separating the effects of the boundaries and the volume. Further, in the measurement of the effects of the surface, bottom and volume of the water column on sound transmission in this frequency regime signal levels are often very low and sensors mounted on the AUV would be plagued by vehicle noise. Thus, a novel approach to allow for wide area characterization of effects that require directional discrimination is to attach a towed hydrophone array behind an AUV and use a steered directional parametric source to further increase the ability to discriminate effects. By deploying a parametric source from a ship and steering the main difference

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[1] The Remote Environmental Monitoring UnitS (Remus) vehicle was developed a the Woods Hole Oceanographic Institution and is commercially available from Hydroid Inc., Pocasset, MA.

[2] NUWC Division Newport Detachment, 6 Dodge Court, Niantic CT 06357

frequency beam at the surface or bottom, as the array navigates away from the ship, it will pass through the direct path and then single path reflected beams. The beam response of the array coupled with the AUV navigation system will allow for determination of the angle of incidence. The volume effects are thus determined by the direct path signal, and by varying the steering angle of the source, the angular dependant effects of the boundaries are determined from the single reflection path.

Since parametric array technology is well established (see [2]) the remaining hardware issue is the AUV towed hydrophone array. The rest of this paper will discuss experimental results intended to show the feasibility of conducting the above experiment towing a fluid filled hydrophone array with an AUV, the Remus vehicle.

II. PROTOTYPE ARRAY

In order to test the ability of an AUV to tow a hydrophone array in a straight, stable path, a prototype hydrophone array was constructed. Because the vehicle has limited available thrust and its endurance decreases with increased drag, it was desirable to minimize the diameter of the towed array as much as possible and limit the surface area and consequently drag. Thus, the array was constructed from a 9.2 m (30 ft) long Kevlar reinforced tube with an outer diameter of 2.8 cm (1.1 inches). The hydrophones were connected in groups and each group was attached to a preamplifier, all of which was encased in the tube. The tube was then filled with mineral oil in order to be neutrally buoyant. The hydrophone groups were separated by 0.75m which is one half wavelength ($\lambda/2$) for a design frequency of 1000 Hz. There were 6 total channels and each channel was calibrated to be -174 ± 1.5 dB re 1μPa/V over the range 100 Hz to 10 kHz.

Rapid integration of the array onto the vehicle was achieved by use of a recording system made of 3 commercial off-the-shelf (COTS) mini-disc recorders. These recorders were housed in a water-tight cylindrical enclosure with a nose cone strapped to the outside of the vehicle. An approximately neutrally buoyant 10 m cable served as both the tow cable and data cable connecting the array to the recorder enclosure. The only other adaptation made to the otherwise standard Remus vehicle was that a shroud was strapped to the back of the vehicle to protect the tow cable and array from the propeller on the vehicle. Fig.1 shows the recording system and enclosure attached to the vehicle as well as the tow cable leading to the hydrophone array.

III. NOISE TESTS

As the radiated noise of the AUV was brought up as a major concern for an acoustic towed array, the radiated noise of the Remus AUV was measured at the Dodge Pond facility. This was done in two ways. First, the vehicle was suspended below the floating acoustic test platform on a rigid test shaft. The shaft was lowered until the vehicle was at mid-water depth, 8 m, and calibrated hydrophones were lowered to depths of 4, 8 and 12 m. The vehicle was then run at motor speeds ranging from 0 to 1400 RPM (full power). The positioning shaft was rotated in 10° increments between 0° and 180° (180° corresponding to directly aft of the vehicle). At each angular position, recordings were made for the vehicle operating at 0, 25, 50, 75 and 100 % of max RPM. This resulted in a maximum radiated noise in 1/3 octave band levels for the vehicle of 130 dB re 1μPa at 1m directly aft of the vehicle for a center frequency of 1000 Hz. During this test non-essential sensors were turned off in the vehicle so that the noise recorded was created only by the vehicle processor and/or propulsion system. The major noise components were essentially omni-directional with less than 3 dB variation of level with bearing.

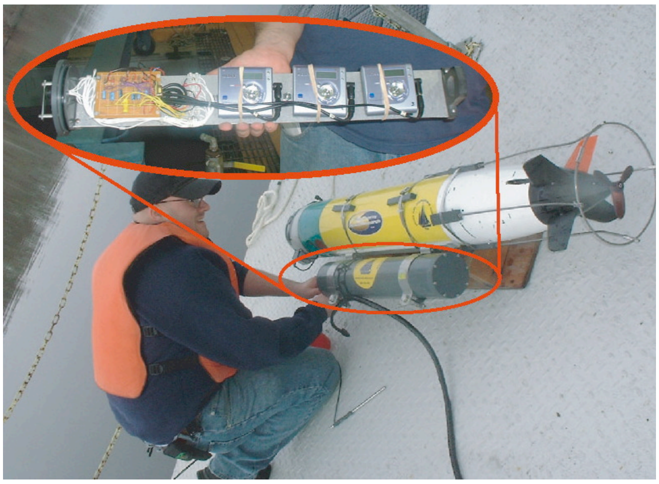

Fig. 1. Image showing the recording system and enclosure as attached to the AUV

Vehicles typically radiate less noise in free operating conditions than in tethered conditions, so the second method for measuring the radiated noise of the vehicle was to examine the power spectral density of the noise as recorded on the hydrophone array as it was towed behind the vehicle. A description of this deployment test follows in the next section, but essentially the noise of the vehicle was recorded on the array hydrophone while the vehicle was towing the array in a straight path. Because the vehicle control system had to compensate for extra drag, there were a few instances of the vehicle RPM dropping to zero. Examination of the power spectral density of the recorded signal and the RPM versus time showed the RPM dependent radiated noise in the aft direction. Fig. 2 shows the radiated noise as received on channel 1 at a distance of 14.6 m behind the vehicle.

It should be noted that the results of both noise measurement methods showed a radiated noise level for the Remus comparable in level to other vehicles [3] .

IV. DEPLOYMENT TEST

After initial noise testing in the tethered position, the towed array prototype and recording system were attached to the AUV and deployed at the Dodge Pond test facility. A 10 m long rope drogue was attached to the back end of the array

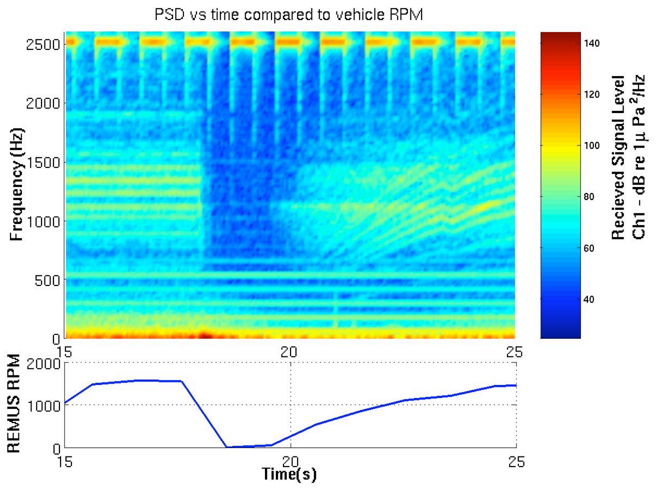

Fig. 2. Power Spectral Density as recorded on array channel 1 and vehicle RPM vs. time. The signal at 2500 Hz is a source with 500 ms repetition rate.

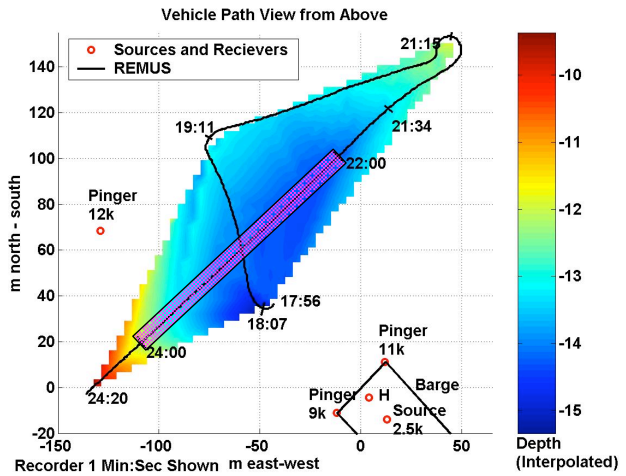

Fig. 3. Vehicle path for Dodge Pond mission number 04120901. The highlighted section on the path corresponds to the region of the time line in Fig. 4. The depth contour is interpolated from vehicle bathymetry data.

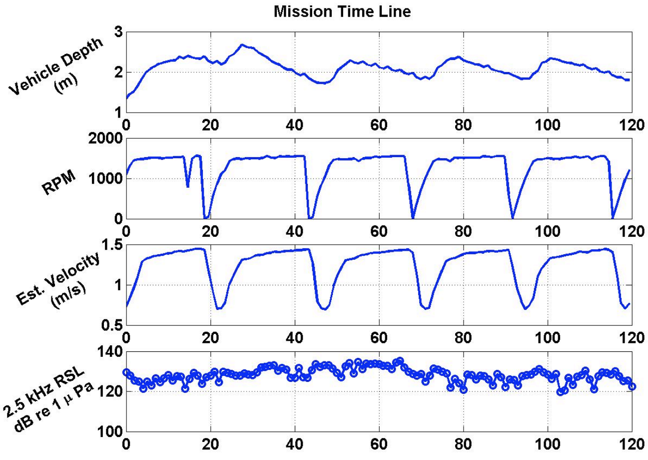

Fig. 4. Mission time line for Dodge Pond mission number 04120901.

to add drag in order to keep the array straight and stable. This increased the combined length of the cable, array and drogue to approximately 30 m. The vehicle was programmed to navigate along a predetermined path using dead reckoning from on-board Doppler speed over bottom estimates. The vehicle path consisted of a turn of approximately 10m radius followed by a turn of approximately 5m and then a straight tow path on the order of 100 m. Three acoustics pingers with different frequencies (9, 11, and 12 kHz) and repetition rates of about 4 s were placed at the corners of the test facility barge and on a float approximately 100 m away from the barge. Below the barge was deployed an acoustic projector controlled by a signal generator that was set to transmit 500 ms bursts of continuous wave signals at 750 or 2500 Hz. Due to the winter weather, the water column for the test was characterized by an iso-velocity sound speed profile measured at 1430m/s over a thick, soft mud bottom. The vehicle path as well as the mission time line which includes data from the array and the vehicle are shown in Figs. 3 and 4.

In order to beamform well, the array must be towed in a straight and stable path. Using recorded receptions of the pingers, the position of each hydrophone relative to the first hydrophone was determined. This analysis was performed by finding the time lag between channels using cross correlation. For a plane wave and constant sound speed, a plot of hydrophone position versus time lag would yield a straight line. By fitting the data with a least squares fit, the deviation of each time lag from the best fit time lag is an indication of the geometry of the array. From this, it was determined that the array was deformed from a straight line causing a slight phase deviation (equivalent to a time lag) from the expected linear phase difference between each channel and channel 1 on the order of 10°. Further, the standard deviation of the phase deviation from linear was about 5° for the design frequency. Considering the distance from the source, assuming a deformation in the vertical direction, this corresponds to a bow on the order of 0.10m over the acoustic section length of 3.75m with a standard deviation of position of about 0.05m. This indicates a rather straight tow that was stable.

The beamforming capability of the array was tested by using a simple time delay algorithm. Defining the broadside bearing angle from the array as 90° for forward end fire, 0° for broadside and -90° for backward end fire, for a plane wave propagating from the direction θ, the time delay between the array center and a sensor at position x_i is given by

$$\Delta t_i = \frac{x_i}{c} \sin\theta$$

where c is the speed of sound. Since the data is discrete, time delays amount to sample delays and the number of samples to delay each channel is given by rounding $\Delta t_i/FS$ where FS is the sampling frequency (44.1 kHz in this case). By applying the appropriate time delay to each channel,

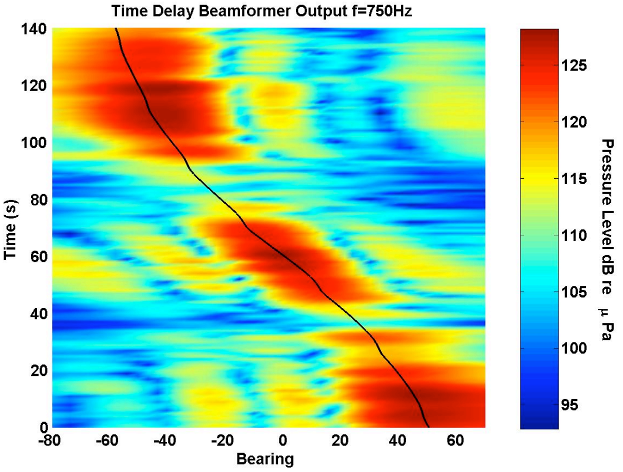

Fig. 5. Beamformed array output as the vehicle drives by the 750 Hz source. The black line represents the theoretical bearing from vehicle velocity and position

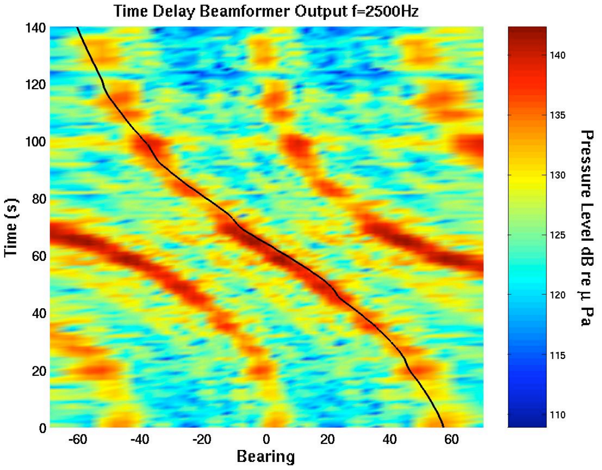

Fig. 6. Beamformed array output as the vehicle drives by the 2500 Hz source. The black line represents the theoretical bearing from vehicle velocity and position

coherently summing and finding the mean square measured pressure, the array is beamformed. Results of this analysis for the 750 Hz case and 2500 Hz case are shown in Figs. 5 and 6. Since the array was constructed with 6 sensors spaced at 0.75 m (approximately $\lambda/2$ for 1000 Hz) one would expect to see side lobes in the beamformer output and grating lobes of equal magnitude to the main lobe for frequencies above 1000 Hz. These effects are clearly evident in Figs. 5 and 6. Further, knowing the path of the vehicle and its approximate velocity from the Doppler velocimeter, the theoretical target bearing versus time was found, which agreed well with the main lobe target bearing versus time shown for both cases.

Due to the small diameter of the array, flow noise was a primary concern. However, at a tow speed of approximately 2-3 knots, the array was ambient noise limited in the range of 500 Hz to 10 kHz for the sea-state 0 conditions of Dodge Pond.

V. CONCLUSIONS

The purpose of this paper was to outline a new experimental technique and show that an AUV could act as a quiet platform to tow a short hydrophone array. The results of noise testing of the Remus vehicle showed that with some noise reduction it will serve well as a quiet platform. Deployment tests of a prototype hydrophone array showed that a small diameter, low noise, AUV towed array is achievable. Further, the AUV was able to tow the array at speeds of about 2-3 knots in a stable configuration. The excellent coherent beamforming results observed in the small Dodge Pond clearly show that this system is a feasible and valuable acoustic measurement tool.

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