Ambient Noise Imaging Through Joint Source Localization

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***Abstract*—Underwater Ambient Noise Imaging (ANI) systems rely on the acoustic illumination produced by natural noise sources to image an object of interest. Snapping shrimp are a dominant natural source of illumination in tropical waters and their snaps occur randomly. Hence incoherent energy detection methods, which require no knowledge of the source locations, are usually employed to form images of the objects. This approach, although simple, only produces images when the anisotropy in ambient noise is conducive. Even in anisotropic noise, some sources 'illuminate' the target while others obscure it. In this paper we describe a different approach. We use a snap detection algorithm to estimate the locations of the noise sources on the sea-bottom and then use the sound from these sources to passively range and form images of the objects. By using only the noise from sources that provide us good illumination and rejecting undesirable sources, we improve the image quality. The feasibility of this approach has been experimentally demonstrated with the data collected during a recent deployment of ROMANIS, an ANI camera developed in Singapore.**

I. Introduction

The concept using ambient noise in the ocean to produce images of submerged objects was first described in 1992 [1], [2]. An ambient noise imaging (ANI) camera called ADONIS was built at the Scripps Institute of Oceanography and tested successfully near San Diego in 1995 [3], [4]. The results obtained from field deployments of ADONIS formed images of static underwater objects at range of about 40 m, thus demonstrating that ANI was indeed feasible. By the virtue of its design, ADONIS provided beam-formed, incoherent output that reduced the computational complexity of the data processing, but limited the processing algorithms that could be used. The Acoustic Research Laboratory (ARL) at the National University of Singapore (NUS) built a digital broadband second generation ANI camera called ROMANIS, to get around this limitation. It consisted of 508 broadband acoustic sensors spanning a 1.4 m diameter aperture. The camera was integrated and first tested in the waters of Singapore in 2003 and images of underwater stationary objects were formed at a range of about 70 m [5]. The ROMANIS system was re-engineered in 2009 to improve its reliability in the field and also to achieve near real-time data processing [6]. The system operated in the frequency band of 25 kHz to 85 kHz. It was deployed again in 2010 and a large amount of high quality data was collected. ANI experiments with both mobile and stationary objects were conducted. Remarkable underwater images/videos were obtained with various imaging techniques. In this paper, we present one such technique where we locate dominant noise sources and use them to coherently image underwater objects.

II. ANI with Joint Source Localization

In warm shallow waters, such as Singapore, one of the most dominant noise sources that contribute to the persistent ambient noise is the snapping shrimp [7]. By rapidly closing its large claw, the shrimp makes a loud sound or 'snap'. When these shrimp snap in large numbers, the superposition of these sound leads to sustained impulsive background noise (Fig. 1). As these impulsive snaps are compact but sparse in time, and arrive randomly, conventional techniques such as energy averaging in beams do not consistently produce good images. An alternative approach is to detect and localize individual snaps and then use these sources of opportunity as if they were deterministic sources at known locations to produce images. The approach can be thought of as a bi-static sonar with random sources of opportunity.

For ANI in Singapore waters, these shrimp snaps are the prime source of acoustic illumination. If a snap occurs within the view of the sensors on ROMANIS, we can detect the snap, locate its origin and then use energy of the snap to produce images. Once the individual snaps are localized with respect to ROMANIS, they can be treated as active sources for range estimation as well as imaging.

A. Snap Detection

Although complex snap detection algorithms exist, simple threshold detection techniques [8], [9] work remarkably well for our application. The threshold for snap detection was set as multiple of the standard deviation σ of the sensor noise. A blanking interval after each detection was used for snap detection because each snap was followed by a significant amount of oscillation and reflections. Fig. 2 shows a large amplitude snap after which there is a period of oscillation that exceeds 3 ms beyond the main impulse of the snap.

To reduce the probability of false detection, snap detection was performed on five sensors of the imaging array. A snap filter combined these outputs and declared the occurrence of the snap if all the snap detectors (SD) detected the snap within the short time window. Fig. 3 shows the complete snap detection scheme. The snap detection could have been performed on all the sensors with a voting scheme, but the computation load for that would have been significantly higher.

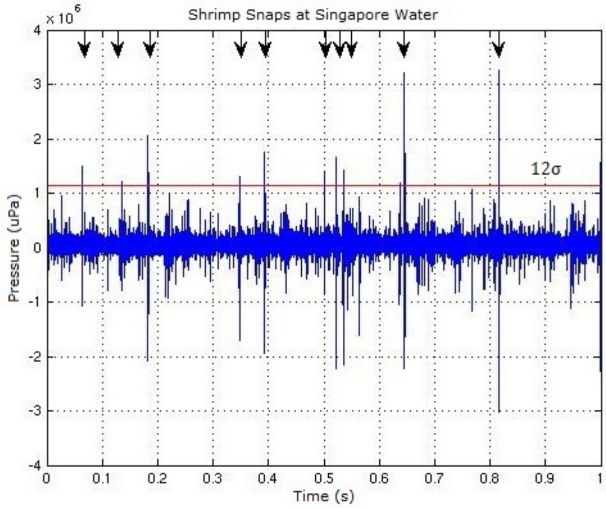

Fig. 1. Shrimp's snap detection with 12σ

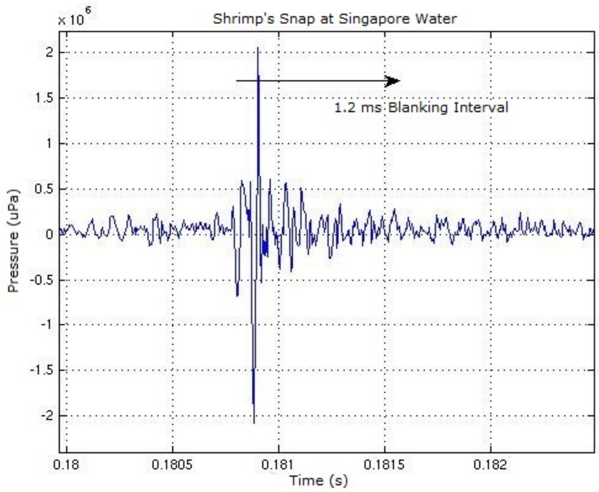

Fig. 2. Shrimp's snap and its decay

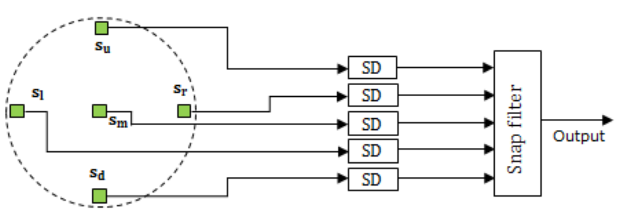

Fig. 3. Snap detection scheme

B. Snap Localization

Once a snap was detected, then the next step was to locate the snap for both imaging and ranging purposes. A snap may have arrived from surface, bottom, near field and far field. Surface arrivals are usually the reflections of snap produced by snapping shrimps, which usually lives on the bottom (unless there are structures around that offer homes to these shrimp). So one can judiciously eliminate the surface

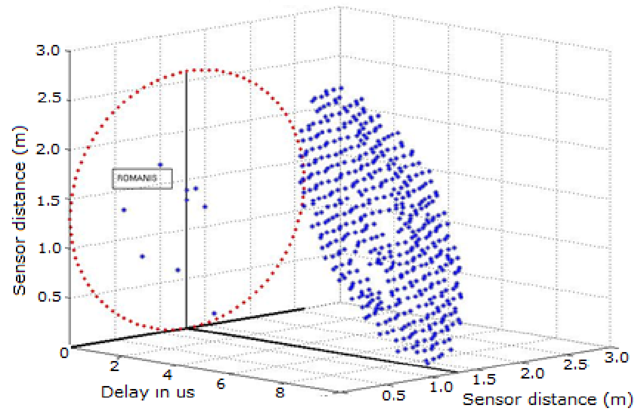

Fig. 4. Example snap arrival (surface)

and far-field arrivals and process only near-bottom snaps. Far field snaps indeed back illuminate the objects, but acoustic image processing techniques with back illumination have not been considered here. An example of surface arrival snap plane (sensor position vs time delay) is shown in Fig. 4. The location of the snap was estimated by computing the azimuth θ_a and elevation θ_e of the arrival, and then intersecting a ray along that direction with the sea bottom (assuming a flat bathymetry and constant sound speed profile over the range of interest). Once the snap location was known, the snap occurrence time was easily calculated.

The azimuth θ_a and elevation θ_e were obtained by solving the mean-square minimization problem:

$$(\theta_e, \theta_a) = \underset{\theta_e', \theta_a'}{\operatorname{argmin}} \sum_{i=1}^{N-1} \left[\tau_i - f_i\left(\theta_e', \theta_a'\right) \right]^2 \tag{1}$$

where τ_i are the measured time delays at sensor i with respect to a center reference sensor (see Fig. 5), and $f_i\left(\theta_e', \theta_a'\right)$ represents the computed time delay for sensor i if the arrival direction is given by (θ_e', θ_a'). If d_{xi} and d_{yi} are the x and y distances of sensor i with respect to the reference sensor and c is the speed of sound in water, then

$$f_i\left(\theta_e', \theta_a'\right) = \frac{m_x \times d_{xi} + m_y \times d_{yi}}{c} \tag{2a}$$

$$m_x = \cos\left(\theta_e'\right) \times \cos\left(\theta_a'\right) \tag{2b}$$

$$m_y = \sin\left(\theta_e'\right) \tag{2c}$$

Once the angle of arrival was known, using the geometry shown in Fig. 6, the location of the snap with respect to the array was computed:

$$x_s = h \times \tan(\theta_e) \times \sin(\theta_a) \tag{3a}$$

$$y_s = h \times \tan(\theta_e) \times \cos(\theta_a) \tag{3b}$$

The range r_{as} and the time t_{as} of snap occurrence were also

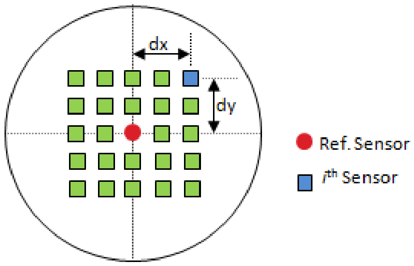

Fig. 5. Sensor Position

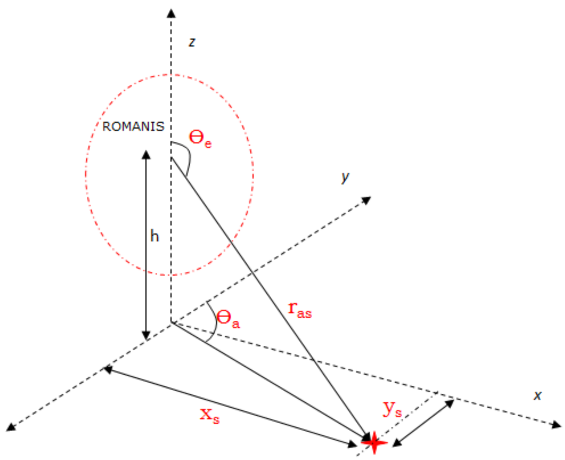

Fig. 6. Snap localization

calculated:

$$r_{as} = \sqrt{x_s^2 + h^2} \tag{4a}$$

$$t_{as} = \frac{r_{as}}{c} \tag{4b}$$

C. Passive Ranging

The beamformer used with ROMANIS produces 24×12 beams spanning a $17^o \times 8^o$ field of view [10]. For every snap that was located, we processed the beamformed data within a window length (determined by the maximum range of interest) to find potential reflections (increase in beam energy) from a target. By making a static target assumption, we were able to identify likely targets where we consistently received an increased energy in a beam after every snap. This detection was performed at low end of the ROMANIS frequency band (25 kHz) because the target reflection is expected to be less directional at lower frequencies.

As shown in Fig. 7, the time of travel t_d from the snap location to the target and then to ROMANIS is given by:

$$t_d = \frac{r_{st} + r_{at}}{c} \tag{5}$$

Once t_d was measured for a target, the range r_{at} of the target

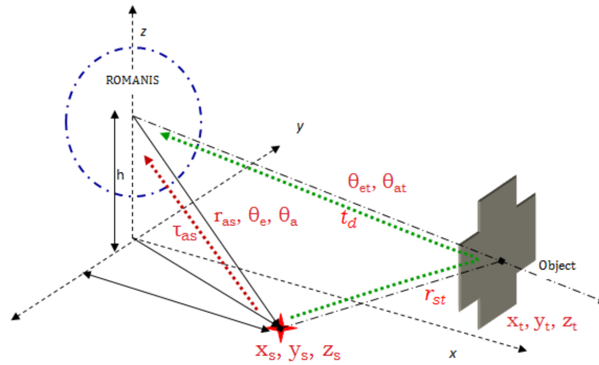

Fig. 7. Passive Ranging

was computed using the mean square minimization:

$$r_{at} = \underset{k}{\operatorname{argmin}} \left[c \times t_d - g(k)\right]^2 \tag{6a}$$

$$g(k) = \sqrt{(x_s - x_{tk})^2 + (y_s - y_{tk})^2 + (z_s - z_{tk})^2} \tag{6b}$$

$$x_{tk} = k \times \sin(\theta_{et}) \times \sin(\theta_{at}) \tag{6c}$$

$$y_{tk} = k \times \sin(\theta_{et}) \times \cos(\theta_{at}) \tag{6d}$$

$$z_{tk} = h - \cos(\theta_{et}) \tag{6e}$$

where $g(k)$ represents the time of travel from the snap location to the target if the target were at a range k from ROMANIS.

D. Passive Imaging

The image resolution is better at higher frequency as the beams are narrower. Hence a 50–65 kHz frequency band was selected for imaging. Once the range information of the target was calculated, then the image of the target was formed using the following steps. From each detected snap we computed the distance to the target and the expected time t_{ex} of reflection from the target. We then extracted the relevant data section from the beamformed output. Since the locations of snaps vary, not all snaps illuminate the object completely. However, by combining the information from various snaps by simply averaging the individual images, we were able to obtain a good image of the target.

III. Experimental Results

During April-May 2010, we performed an experiment in Singapore waters to test the imaging capability of ROMANIS. We present the results from one of the data sets (Apr-11-2010 17:05:27) recorded during this experiment.

The ROMANIS array was deployed at the GPS coordinates 1^o 12.968' N, 103^o 44.373' E. A target (Fig. 8) was deployed at GPS coordinates 1^o 12.932' N, 103^o 44.367' E. The estimated distance based on the GPS coordinates between ROMANIS and the target was 67 m. The details of one of the snaps in the data set are given in Table. I. Using this data, the range obtained from (6a) was 67.4 m, very closely agreeing with the estimate from the GPS coordinates.

Fig. 9 shows an acoustic image obtained using the passive imaging technique. This image is from a single frame where

TABLE I
EXPERIMENT DATA FOR RANGING

Parameters	Data
Experiment date	Apr-11-2010
Experiment time	17:05:27
Target bearing $(\theta_{at}, \theta_{et})$	85.4 deg, 89.5 deg
Snap detection time	1.8584 s
Snap range (r_{as})	47.03 m
Snap location $(x_s, y_s, z_s = 0)$	47.01 m, -3.3 m
Snap occurrence time	1.8234 s
Reflection time from target	1.87202 s
Time delay (t_d)	0.04862 s

Fig. 8. Test Frame

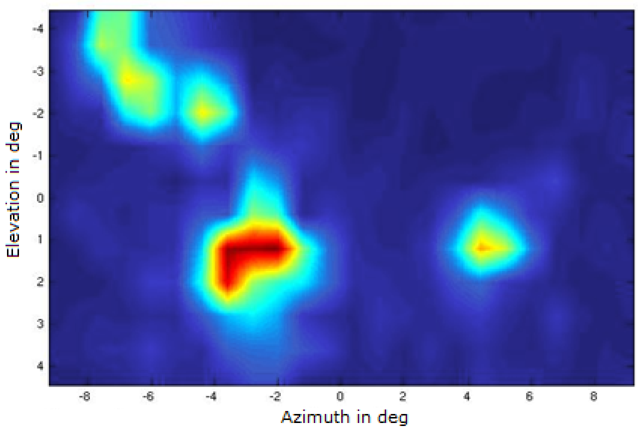

Fig. 9. Passive Imaging with source localization

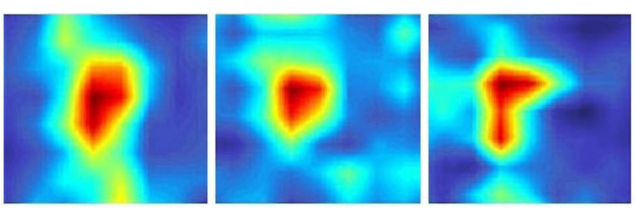

Fig. 10. Images with single snap

the illumination was favorable. Fig. 10 shows images obtained after processing individual snaps where only part of the target was clearly visible. Fig. 11 shows a complete image of the target obtained by averaging the images with partially visible target.

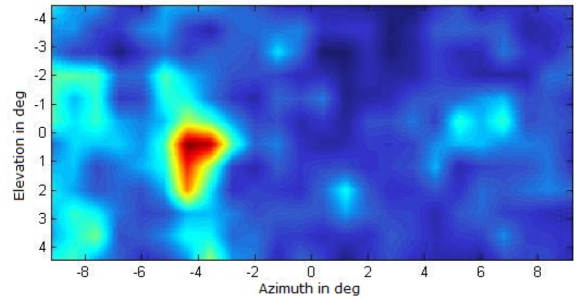

Fig. 11. Joint Source Imaging

IV. CONCLUSION

In this paper, we presented a novel ANI technique using joint source localization. The technique works by first detecting a snap on several sensors in the imaging array. The snap is then localized by using the time of arrival of the snap at all the sensors in the array and assuming that the snap originates near the sea bottom. Once the snap is localized in time and space, it is used as a known source in a bi-static sonar system to detect and locate a target. After a target is detected, an image can be formed using the beamformer output from the sensor array. Finally, multiple images of a target can be combined to produce a high quality image. This technique is able to not only produce high quality images of a passive target using ambient noise due to snapping shrimp, but also able to estimate the range to the target. The solution has been experimentally demonstrated in Singapore waters with a target deployed at a range of 67 m.

ACKNOWLEDGMENT

We would like to express our gratitude to Mr. Shailabh Suman, Dr. Costas Pelekanakis and Dr. Edmund Brekke for providing valuable suggestions during development of this algorithm. We would also like to thank Mr. Amogh Raichur, Mr. Unnikrishnan, Mr. Jaiwin, Ms. Tan Soo Pieng, Mr. Mohanan and numerous other colleagues at ARL for their support in the development of ROMANIS and during the field experiments. Finally, we would like to acknowledge Dr. John Potter, who initiated and led the ROMANIS project for many long years.

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