33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Noise and Range Considerations for Close-Range Radar Sensing of Life Signs Underwater

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***Abstract*— Close–range underwater sensing of motion-based life signs can be performed with low power Doppler radar and ultrasound techniques. Corresponding noise and range performance trade-offs are examined here, with regard to choice of frequency and technology. The frequency range examined includes part of the UHF and microwave spectrum. Underwater detection of motion by radar in freshwater and saltwater are demonstrated. Radar measurements exhibited reduced susceptibility to noise as compared to ultrasound. While higher frequency radar exhibited better signal to noise ratio, propagation was superior for lower frequencies. Radar detection of motion through saltwater was also demonstrated at restricted ranges (1–2 cm) with low power transmission (10 dBm). The results facilitate the establishment of guidelines for optimal choice in technology for the underwater measurement motion-based life signs, with respect to trade offs involving range and noise.**

I. INTRODUCTION

Heart rate is an important vital sign, useful for physiological monitoring and also as a proxy for metabolic output. It can also be used for tracking the status of divers or monitoring stress levels of marine mammals. Measuring the heart rate of aquatic animals is particularly difficult, with current techniques involving invasive procedures. The safest and least invasive is surgical Electrocardiogram measurement, which still requires needle electrodes to be inserted subcutaneously.

Non-contact sensing offers many advantages, in addition to non-invasive monitoring with reduced stress on the subject, it can be used outside the laboratory setting for remote or automated sensing – possibly also for animal detection. Sonar is typically used for underwater sensing, but standard sonar systems lack sufficient resolution for detecting heart motion. Radar systems have been used for non-contact heart rate monitoring [1], but radio waves suffer from poor underwater propagation. Fish heart rate monitoring via radar has been demonstrated with the antenna touching the fish [2], sidestepping the issue of propagation – this is interesting, but remote sensing has much wider use.

For the initial investigation, simplified test cases will provide easier to analyze data and reduce the amount of testing for live subjects to techniques that have already been refined.

II. BACKGROUND

Doppler radar operation involves transmitting a radio signal towards a target, receiving the reflected signal, and comparing the two. For continuously moving targets (e.g. an automobile), the speed of the target can be measured by comparing the frequency of the received signal to that of the transmitted signal. For oscillating targets (e.g. a mover in an aquarium, or later, a heart), the variation of phase difference from the transmitted to the reflected signal will be more useful for detecting the target motion. For a continuous wave system with a target postion of $x(t)$ over time, the demodulated signal can be expressed as:

$$B_I(t) = A_B cos\left(\theta + \frac{\pi}{4} + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)\right) \tag{1}$$

for one of the channels (with the other offset by $\lambda/4$).

Underwater, radio propagation is limited due to dielectric and conductive properties of water. The relative permittivity of water, ε_r, at frequency ω is

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}, \tag{2}$$

with the relative permittivities at zero and infinite frequencies (respectively) ε_s and ε_∞. The conductivity (γ) depends on frequency (ω), relative permittivity (ε_r), and relative permeability (μ_r)

$$\gamma = \frac{j\omega}{c}\sqrt{\varepsilon_r \mu_r} = \alpha + j\beta. \tag{3}$$

While this limits the range of operation, it also isolates the system and subject from other motion further away in the environment [3]–[5].For example, the radar may sense motion at a range of 0.5 m in the presence of significant clutter motion 2 m from the antenna.

III. EXPERIMENTAL SETUP

The testing involved a measured amount of water in an aquarium with a mover controlling the position of a plastic sphere in the water. The clear plastic sides of the aquarium allowed visual monitoring of the antenna and mover. Tap water was added for the first set of tests (freshwater), then salt was added for the second set of tests (salt water). A powered mixer was used to evenly distribute the salt through the water volume.

The mover used in place of a live test subject provided simple, controlled, repeatable motion along a straight line to the antenna. A small plastic sphere with a metal cover was used as the radar visible target – without the metal cover, the ball and supporting rod were effectively invisible to the radar

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This work was supported in part by the National Science Foundation under Grant ECS0702234.

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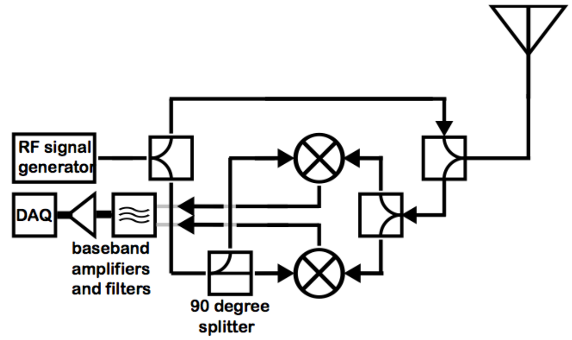


Fig. 1. Doppler radar system used for experiments (not including computer). A quadrature receiver avoids the null point limitation from which single channel radars suffer.

system. Rather than using a submersible motor, a standard servo actuated the ball through a linkage of control rods and bel cranks. Control for the servo was provided by a small microcontroller – both amplitude and frequency of motion were run without computer interaction. The settings used for all tests were a frequency of 78 bpm (1.3 Hz) and an amplitude of 5 mm.

A radar system for these experiments was assembled from coaxial components with the LO power supplied by an HP 83640B, a diagram of which is presented in Fig. 1. The amplitde of the transmitted signal was only 10 dBm and the frequency of operation ranged from 600 MHz to 3600 MHz.

The baseband signals were filtered and amplified by SR-560s and then digitized with a NI USB-6009 multifunction DAQ device. The signals were recorded on a computer using software written in LabVIEW. Software written in Python aided in post-test analysis and visualization.

For comparative testing between radar and sonar sensing of small motion at close range, an ultrasonic heart rate monitor was modified to access the mixer output directly to provide a similar output to that of the radar system. The mixer output was sent to an SR-560 for amplification and then digitized with the radar outputs.

IV. RESULTS

The consistent motion of the mover can be observed as consistent oscillations in the time (Fig. 2) and sharp spikes in the frequency (Fig. 3) plots. While the mover follows a pattern of $sin(t)$ along its axis of motion, the radar output has an appearance closer to $abs(sin(t) + 0.3)$ as can be seen in Fig. 2.This is due to the range of motion exhibited by the mover and the large angel traced out by its movement can be easily found in Fig. 4. These three plots, from a signal recorded in freshwater, show very clean signals with negligible clutter.

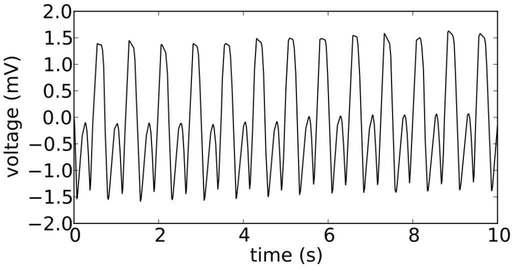


Fig. 2. Short plot of radar output over time showing repetitive motion of sphere.

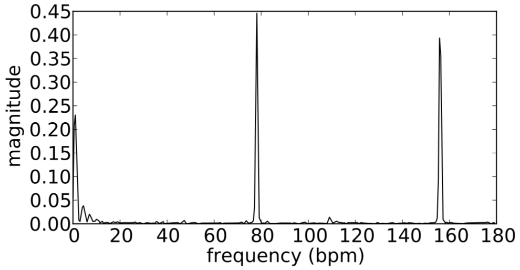


Fig. 3. Frequency plot of radar output showing clear spikes at 78 bpm and 156 bpm from the oscillation of the sphere moving with a constant period.

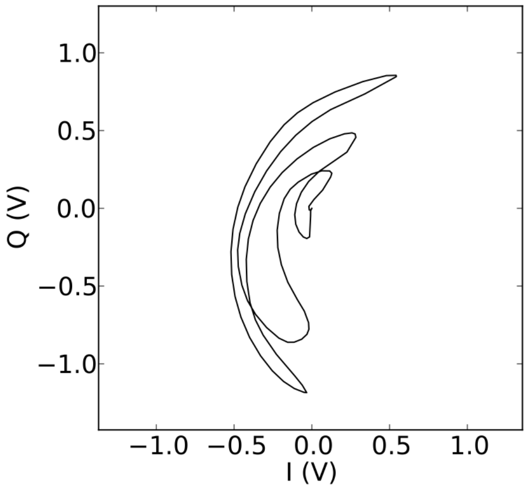
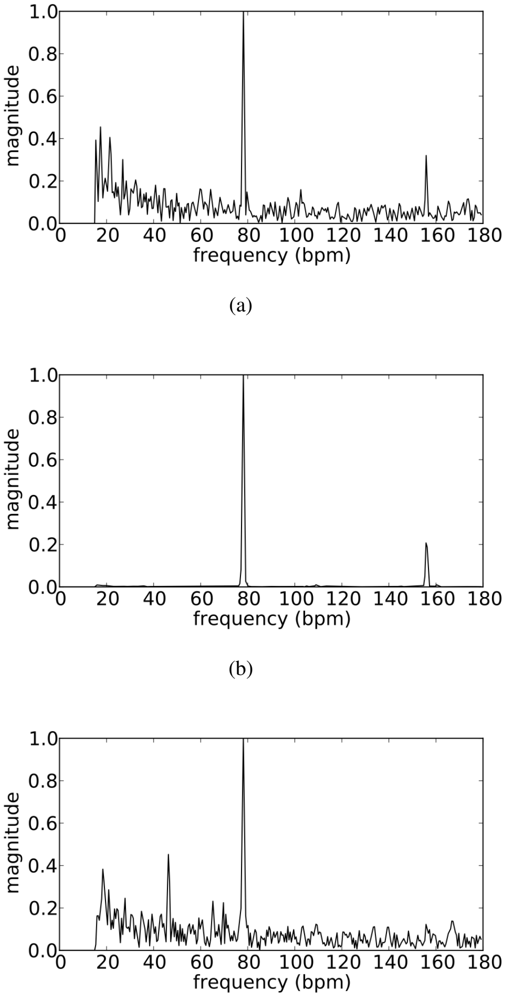


Fig. 4. IQ plot showing the large angle of motion. The I channel shows twice the oscillating frequency of the Q channel due to the range and phase offset.

The three plots in Fig. 5 show the radar output for the two higher frequencies of operation – 2400 MHz to 3600 MHz. They have been scaled so that the value of the frequency with the maximum magnitude is unity. This is to allow a visual inspection of the comparative noise from 15 bpm to 180 bpm (0.25 Hz to 3 Hz). The noise spectrum in Fig. 5a (2400 MHz in salt water) is similar in amplitude to that in Fig. 5c (3600 MHz in tap water) relative to the signal from the mover while the signal to noise ration for operation at 2400 MHz in tap water (Fig. 5b) is much higher. This relation can be seen compactly in Fig. 8.

The plots in Fig. 5 show the data used to generate Fig. 8. They are normalised to facilitate judging the relative signal

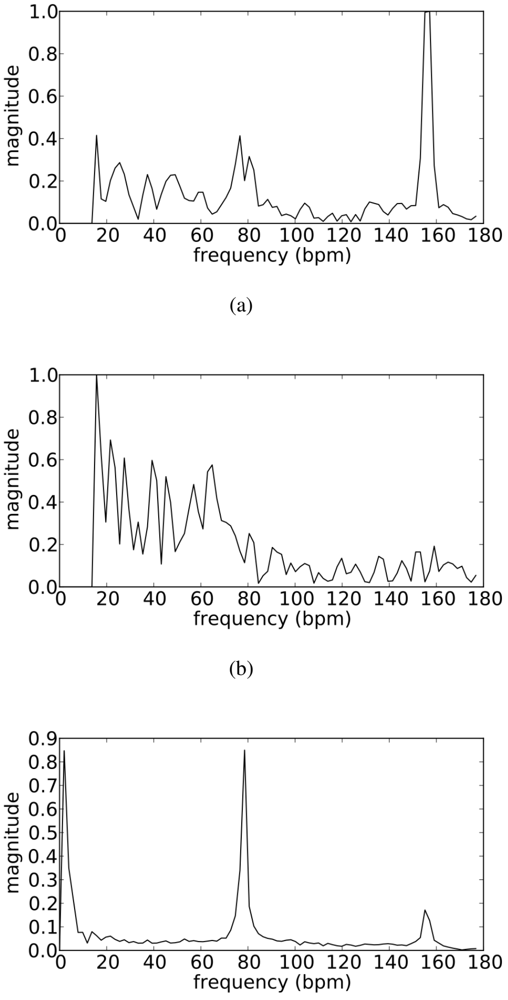


(a)

(b)

(c)

Fig. 5. Frequency plots of the radar output for multiple frequencies of operation. The plots have been scaled to normalize the signal level to ease comparison of signal to noise ratios by observing the noise levels. The plots are: (a) 2400 MHz in salt water, (b) 2400 MHz in tap water, and (c) 3600 MHz in tap water. Visual inspection shows that operation in salt water at 2400 MHz and tap water at 3600 MHz, (a) and (c) respectively, have similar levels of signal compared to noise while 2400 MHz operation in tap water (b) exhibits significantly lower noise relative to the signal.



(a)

(b)

(c)

Fig. 6. Frequency plots of sonar and radar output in tap water. (a) shows the sonar output signal with no additional clutter or noise added. Compared with Fig. 5a, or with the radar output in the presence of noise (c), the sonar output exhibits much more noise. (b) also shows the sonar output, in this case water was poured into the tank during the test to add background noise. (c) shows radar with the same noise source (water pouring into the tank) for comparison of noise susceptibility. An example of the radar output without the added noise can be seen in Fig. 5b – the noise can be seen by looking closely near the frequency axis at f==20.

to noise ratios by comparing the noise levels given constant signal levels. The example plots include two signals recorded in tap water, and two recorded with an operating frequency of 2400 MHz Un-normalised peaks at 80 bpm are:

- Fig. 5a: 0.05 for 2400 MHz in salt water
- Fig. 5b: 0.58 for 2400 MHz in tap water
- Fig. 5c: 0.25 for 3600 MHz in tap water

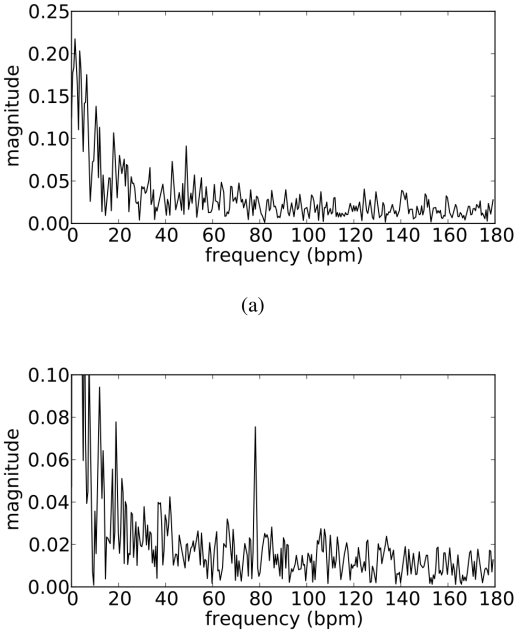
but the noise for the 3600 MHz signal is correspondingly higher than the noise for the salt water signal, leading to similar ratios between the signal and noise for the two.

The radar outputs for 3600 MHz and 600 MHz at a range of 20 cm to the mover are plotted in Fig. 7. Both signals show a fair amount of noise, but the signal (when operating at 3600 MHz is attenuated before it returns to the radar system.

The radar was also compared to sonar by testing the capability of an ultrasound heart monitor to sense the mover. Fig. 6 shows the output of the sonar with no added clutter or noise as well as both the sonar and radar outputs in the presence of added noise (in the form of water pouring into the tank away from the mover).

V. DISCUSSION

The ratios of signal to noise for 600 MHz to 3600 MHz in water with and without salt are plotted in Fig. 8. The pattern formed is higher signal returns for tap water (less attenuation) and lower returns for the highest frequency (3600 MHz), but for the lower frequencies, it is not as clear. Both show lower relative signal power at 1200 MHz, but lower frequencies appear to offer more benefit in tap water than salt water.



(b)

Fig. 7. Frequency plots for the radar detection of motion at long range for (a) 3600 MHz and (b) 600 MHz. The signal in (b) has at least as much noise as the signal in (a), but the mover's oscillating motion can clearly be seen above the noise in (b) – and not in (a).

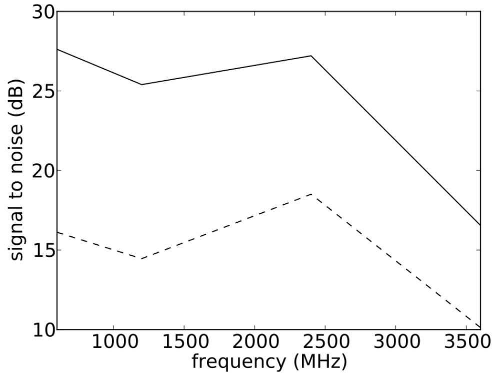


Fig. 8. Plot of signal to noise ratio of radar output over frequency in tap water (solid line) and salt water (dashed line). The signal is reduced at high frequencies in both tap and salt water, but for lower frequencies, there is less of a pattern - though the radar return is much stronger in tap water than salt water.

For short range operation, UHF frequencies (<3 GHz) offer better transmission in both salt water and fresh water than microwave frequencies (>3 GHz). Much lower frequencies (<1 MHz) may offer improved transmission loss, but require significantly larger antennas which could be difficult to transport, situate, or steady underwater. For a hand portable monitoring system, the antenna should probably be about the size of a notebook computer, to minimize mounting or transport problems.

Comparative tests between the radar and sonar systems showed the sonar to provide greater range, without adverse effect from saltwater. In the course of testing the sonar did, however, show a propensity for sensing noise. Tests with possible noise sources showed this to be a significant problem, as can be seen in Fig. 6. While the sonar detects the target motion in a quiet environment, the noise of water pouring into the tank adversely affects the sonar motion detection while the radar shows little to no change with the acoustic noise and vibration.

Increased range can be accomplished simply by transmitting at higher power levels, but operation in water will still be limited to very short ranges – for long ranges, sonar is a better choice. Some uses for short range sensing include: monitoring fish in conjunction with video recording, especially when bait is used to attract fish to the cameras; and monitoring fish in constricted spaces such as fish ladders or elevators, or even inside a baited fish trap (which can release the fish after measuring it).

VI. CONCLUSION

Non-contact heart rate sensing can improve physiological monitoring for aquatic animals and help asses stress from environmental changes, energy usage, and can metabolic output in a field setting. These results show radar can be used for underwater heart rate monitoring without requiring contact with the animal. Such non-contact monitoring can also allow physiological sensing in situations that currently prevent such monitoring, such as deep sea fish in their natural environment.

ACKNOWLEDGMENTS

The authors would like to thank Donald Ho and Aditya Singh for their assistance.

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