# Fish Heart Rate Monitoring by Body-Contact Doppler Radar

Noah Hafner, *Student Member, IEEE*, Jeffrey C. Drazen, and Victor M. Lubecke, *Senior Member, IEEE*

***Abstract*— This paper presents results demonstrating detection of cardiac motion and heart rate monitoring by radar for fish using a contact antenna, as a less-invasive alternative to surgical electrocardiogram (ECG) measurements. Tilapia are used as test subjects with a patch antenna. The frequency of operation, 2.4 GHz, is chosen as a tradeoff between antenna size and propagation. Single lead ECG measurements are used as a reference for comparison with two electrode configurations. The heart rate detected by the radar matched the heart rate detected by ECG. With water temperature near 30 °C, measured heart rates varied with sedation level and over time, in the range of 30–80 bpm.**

***Index Terms*— Biomedical telemetry, Doppler radar, physiology, ultra high frequency technology, underwater technology.**

## I. INTRODUCTION

FISH heart rate is useful for determining metabolic output [1], investigating locomotion and energy budget [2], evaluating the effects of environmental changes on fish [3], and physiological studies. Heart rate is typically used as a correlated measure of metabolic output, but in some cases, cardiac output may vary out of step from heart rate [4]–[6]. Investigation of this has been conducted with cannulae implanted in aortas, veins, and body cavities to measure blood volume as well as pulse rate over a range of swimming speeds [4].

Non-invasive methods of monitoring heart rate, respiration rate, and other physiological signals would obviate the need for survival surgery, a clear refinement in animal care during testing. This improvement would also provide for lower stress levels affecting results, less risk of death for test subjects. Radar can be used as a non-invasive alternative for heart rate monitoring with fish. While the radar system presented here still maintains physical contact with the fish, it is significantly simpler to adhere a patch to the body than surgically implanting electrodes.

Previous work has demonstrated monitoring of cardiopulmonary activity for human subjects using small Doppler radar systems [7]–[10]. Doppler radar has also been successfully used to sense motion underwater [11], to monitor activity levels for fish. A very useful combination of these is non-invasive detection of heart motion for fish. Problems for such measurements include limitations of underwater radio transmission, isolating the subject, and separating heart motion from clutter motion. A simple solution to alleviate most of these is attaching the antenna to the test subject. While no longer non-contact, it is still non-invasive and the attenuation of radio energy in water helps rather than hinders with other issues. The target is right in front of the antenna, other sources of motion are much further away thus isolating the subject from clutter motion in the environment.

A preliminary study of the use of contact radar for measurement of physiological motion in a fish has been reported [12], but no positive means of correlating detected motion to heart activity was included.

While sonar-based sensors are effective for detecting the presence of fish at significant distance, the long-range propagation of sound in water provides a disadvantage when attempting to resolve and isolate close-range motion. For this purpose, radar provides an advantage.

This paper describes experiments investigating fish heart rate sensing with radar. Heart rate is useful in many fish as an analog to metabolic rate in addition to indicating changes in the physical condition of the fish due to health or stress [13], [14].

The experiments described here use a laboratory radar system with the antenna contacting sedated fish with an ECG reference – this setup is specific to the experiment; the application is heart rate sensing of non-sedated fish and additionally non-contact heart rate monitoring for fish. This heart rate sensing can be useful for non-invasive studies involving fish metabolism, aquaculture, and elsewhere.

The remainder of this paper will cover details about the proposed contact radar heart rate sensor. Background information for Doppler radar and underwater radio wave propagation is in the subsequent section, followed by the details of the experiments, the results obtained, and discussion about this sensing technique.

## II. DOPPLER RADAR

Doppler radar provides information about moving objects by comparing transmitted and received frequency. The direct conversion, continuous wave Doppler radar system used for these tests transmits an unmodulated 2.4 GHz radio signal,

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N. Hafner and V. M. Lubecke are with the Electrical Engineering Department, University of Hawaii at Manoa, Honolulu, HI 96822 USA (e-mail: nmh+ieee@nomh.org; lubecke@hawaii.edu).

J. C. Drazen is with the Department of Oceanography, University of Hawaii at Manoa, Honolulu, HI 96822 USA (e-mail: jdrazen@hawaii.edu).

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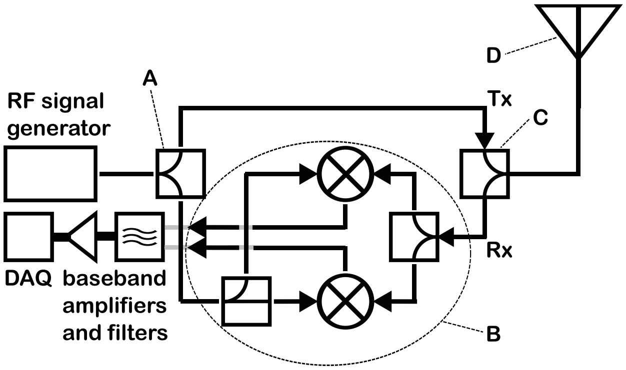


Fig. 1. Doppler radar system used for experiments (not including computer). The generated RF carrier is split by a splitter (A) and sent to the receive section (B) to be transmitted. The receive section uses the carrier to down convert the reflection from the subject. The splitter near the antenna (C) sends the transmit signal to the antenna and the reflected signal to the receive section. The same antenna is used to both transmit and receive because the subject is directly in front of the antenna, and one antenna requires less space than two antennas. Additionally, a quadrature receiver avoids the null point limitation from which single channel radars suffer.

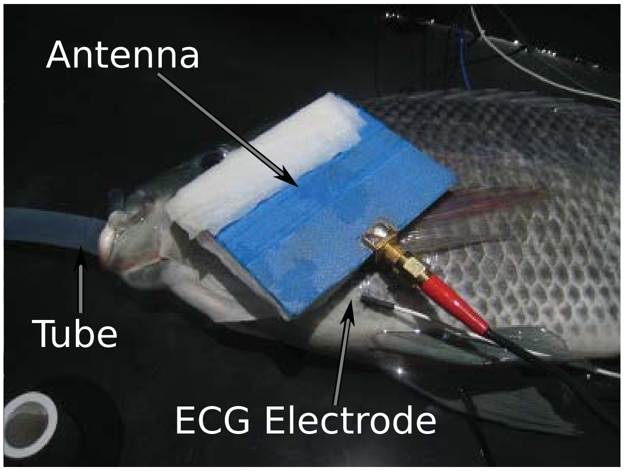


Fig. 2. Photo of fish ready for testing. The antenna is resting on the fish, immediately behind the head and directly over the heart. One of the ECG electrodes can be seen under the antenna; it was located to sense the ECG signals without risk of touching the heart. The tube going to the mouth of the fish provides water for respiration during the test to remove risk of suffocation.

and then mixes the received reflection with the same 2.4 GHz radio signal. This provides an output signal with the motion sensed by the radar system without any additional modulation.

The demodulated signal can be expressed for one of the channels, with simplification, as

$$B_I(t) = cos\left(\theta + \frac{4 \cdot \pi \cdot x(t)}{\lambda}\right) \quad (1)$$

(with the other channel, $B_Q(t)$, offset by $\lambda/4$) [7], [15] using terms: $x(t)$ for subject range, $\lambda$ for wavelength, and $\theta$ for the constant phase offset (all sources). The sources accounted in $\theta$ include: phase shift at reflection, phase delays in the radar hardware) and the phase offset from the constant portion of the radar–subject range simplifying $x(t)$ to the small signal changes in range—the motion of the heart.

The hardware arrangement of the radar is depicted in Fig. 1 with the baseband signals I and Q feeding from the mixers (inside the receiver section labeled B) to the baseband signal processing.

Underwater, radio propagation is limited due to dielectric and conductive properties of water. These vary with salinity, temperature, and radio frequency [16], but generally result in higher propagation loss as compared to air. While this limits the range of operation, it also isolates the system and subject from other motion further away in the environment [11] [16]–[18]. 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

These experiments were conducted with a radar system assembled with connectorised RF components and the fish were sedated and held in place for the experiments.

### A. Tilapia and Testing

Tilapia at the Windward Community College Aquaculture Complex were selected as test subjects for these experiments. At the time the experiments were conducted, the fish were roughly 35 cm in length. Each tested fish was netted from an enclosure and placed in a bucket filled with fresh water and anesthetic [5] for sedation. After sedation, the fish was moved to a shallow bath for testing. This bath was shallow to ease work with the fish but still deep enough to keep the mouth and most of the body submerged as can be seen in Fig. 2.

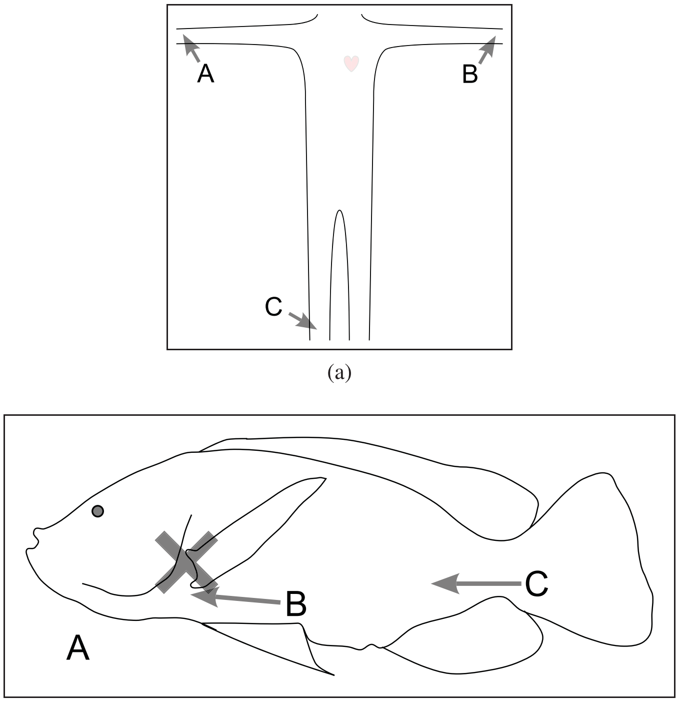
This water level was sufficient to support respiration and hydrate the skin, while still allowing easy placement of the antenna and minimal handling of the fish. After a brief period of testing, the fish would then be returned back into the enclosure. For these tests the fish were heavily sedated. The sedation reduced pain, stress and motion. The fish required heavy sedation to sufficiently reduce body motion. At this level of sedation, natural respiration was undependable, necessitating artificial respiration in the form of forced ventilation (pumping water over the gills). While this effectively provided oxygen to the fish, the pump used to move the water also generated significant electromagnetic noise, which could be separated from the signal (see results below).

### B. Animal Care and Ethics

These experiments were authorized by the Institutional Animal Use and Care Committee and conducted in accordance with an approved protocol.

### C. Safety

Heating from rf energy may be a health and safety concern at high powers, such as inside a 500 W microwave oven [19]. As a comparison, non-specific short range devices have a limit of maximum EIRP of up to 25 mW including at 2.4 GHz [20]. The possible danger from rf exposure presented by the low power radar 5 mW was minimized by limiting the exposure time to short test times. Larger dangers from electrocution and sunburn were minimized by using battery power for the ecg amplifier and using a sunshade for the testing area.



(a)

(b)

Fig. 3. Diagrams of ECG electrode placement on (a) human and (b) fish. The ECG electrodes **A**, **B**, and **C** are located on the fish and used analogously to those used for one-lead ECG measurements for human subjects (a). The large cross close behind the head of the fish indicates the location of the antenna above the heart.

### D. ECG

Standard pad electrodes used with humans would be unsuitable for use on these fish. Some of the issues include wet scale covered skin, mucus displacement, curved shape, available area (near heart – between fins and gill covers). Needle electrodes (used for human Electroencephalogram (EEG) and Electromyogram (EMG) measurements) were the most straightforward replacement (standard practice). Three electrodes were used – two sense electrodes (differential) with one ground reference electrode with one reference electrode close to the tail and two sense electrodes each ventral of a pectoral fin.

The sense electrodes were connected to the inputs SRS SR560 amplifier while the reference electrode was connected to the amplifier ground. The SR560 had the same settings as those used with the radar, but with differential input. The ECG signal was digitized using the same NI USB-6009 as the radar outputs.

This electrode arrangement is depicted in Fig. 3 for human and fish usage. For a one lead human ECG measurement, three electrodes are commonly used with two on the upper extremities (A and B) use for sensing and one on a lower extremity (C) used as a ground reference or displacement current cancellation. The ECG signal is measured differentially across the two sense electrodes.

For fish, the setup is similar to the pictured human single lead ECG and as can be seen in Fig. 3(b), with the two sense electrodes located near the heart (A and B) and the reference electrode is situated near an extremity (C).

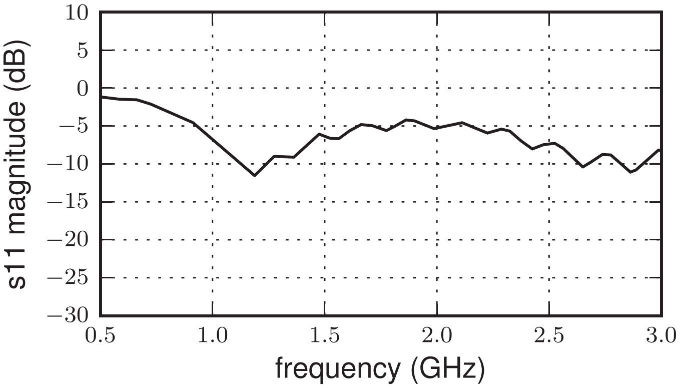


Fig. 4. Return loss for the patch antenna on skin.

### E. Radar

A radar system also used for human physiological motion sensing, similar to that described in [15] and [21], was used for these experiments. This system, depicted in Fig. 1, was assembled from bench equipment and coaxial components including: E4433B RF signal generator, Mini-Circuits ZFSC-2-2500 splitter, Mini-Circuits ZFM-4212+ mixers, Narda 4033C hybrid splitter, SRS SR560 amplifiers, NI USB-6009, and a computer running custom LabVIEW data acquisition software. The RF signal generator was set to output an unmodulated 13 dBm carrier at 2.4 GHz with and the amplifiers settings were: ac coupling, 0.3 Hz to 30 Hz filtering passband, and gain of 5000 V/V.

Operation with a 2.4 GHz carrier frequency offers a reasonable tradeoff of size and motion resolution and additionally leverages commonly available electronics. The baseband signals were lowpass filtered for both antialiasing and to reduce extraneous noise. These signals were also highpass filtered (AC coupled) to allow for higher signal amplification in the face of both constant offset and slow variations in the signal offset; e.g. from the radar system and also a continually changing offset from body motion. Digital filters were also used to clear 60 Hz hum and prepare the signals for analysis (e.g. peak finding).

A printed circuit patch antenna designed for operation in the 2.4 GHz ISM band was fabricated on Rogers 6002 substrate. The return loss of this antenna against skin can be seen in Fig. 4. The antenna location on the fish (indicated by the × in Fig. 3(b)), though larger than the heart, is centered over the heart to sense its motion.

Pad electrodes (for ECG) would be unsuitable, and the radar antenna shares superficial appearances with pad electrodes; but because mode of operation for the radar differs from ECG, some of the problems with using pad electrodes are obviated for the radar due to differences in the two sensing modalities. ECG requires electrical contact—scales or mucus could interfere with this. Radar does not require direct electrical contact, though transmission through various materials can affect the signal. Interference from a thin layer of mucus would be improbable.

### F. Process

For each test the radar antenna was carefully placed on the fish over its heart. With the heart located slightly anterior to

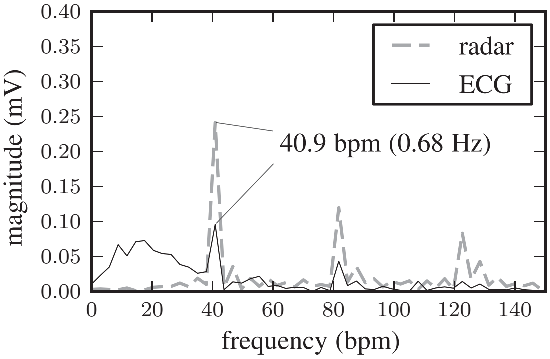


Fig. 5. Plot of radar (in-phase output) and reference (ECG) signals over frequency. The heart rate of 41 bpm is clearly visible, as are the harmonics.

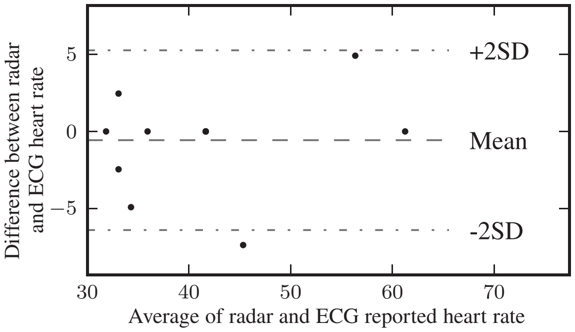


Fig. 6. Bland–Altman plot showing agreement between radar and ECG heart rate measurements for five individuals (with multiple independent tests for some of them). Each point in this plot is from a different test, with the two measurements combined for both of the axes. The distribution showing a mean near zero and closely spaced limits (two standard deviations above and below) indicate that the radar provides a useful alternative to ECG for general heart rate monitoring, though these results indicate that this radar system does not yet provide sufficient accuracy for situations requiring high precision measurement.

the pectoral fins, the antenna rests not only on the skin, but also on the operculum and pectoral fin. For tilapia, the patch antenna provided adequate performance and covered less of the body – though still more than optimal.

In tilapia the heart is located longitudinally between the gills and pectoral fins, vertically at the base of the pectoral fins (near the ventral end of the gills). To better sense heart motion, the antenna was located above the heart – also over the gill cover and pectoral fin, centered as shown in Fig. 3(b). This location was useful for heart monitoring and did not require surgery, but interfered with the gills and pectoral fin on the side of the antenna. It is possible other fish with different body geometries would have more room for locating an antenna, but many, including all members of the extremely diverse order Perciformes, would have similar arrangements to tilapia.

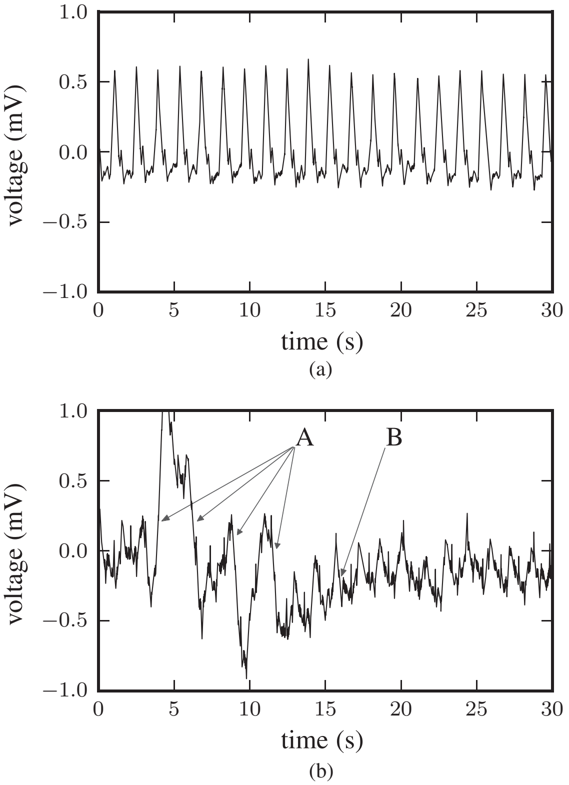
## IV. RESULTS AND DISCUSSION

The same filters were applied to the simultaneously recorded ECG and radar signals to allow more straightforward comparison between the two and to avoid introducing artifacts that cause untoward changes in the results. The 1 kHz sampled signals were used for time domain peak detection of individual heart beats and Fourier transformed for frequency domain analysis. The plot in Fig. 5 is a 20 s section of the trace using a hamming window and with no zero padding. This provides a frequency resolution of about 0.05 Hz or 3 bpm. The rates used for Fig. 6 were determined with a Fourier transform on a 24 s window. Though the radar was run with battery power, the pump providing fresh water to the fish ran off ac power (60 Hz or 3600 bpm) and introduced significant out of band interference. The pump interference did not affect heart rate detection, but did clutter the time plots – the filtered data is easier to inspect visually.

For time domain analysis and also the frequency plot of the radar and reference data, one of the output channels from the was used—$B_I(t)$. This is the projection of a vector with angle proportional to $x(t)$ the real axis. This projection involves some distortion, removable by appropriately combining the two baseband channels $B_I(t)$ and $B_Q(t)$. For these experiments, the distortion did not adversely affect the performance and this signal processing was not required.

For the multiple trial comparison, both radar output channels were used. The average heart rate was individually calculated for each radar channel and the reference. If the ratio of the rate for one radar channel was close to double the rate of the other radar channel, the lower rate was used; otherwise the average of the two rates was used as the radar reported heart rate. As is visible in Fig. 7, the radar provided a clear signal with out extraneous motion and these results show how the periodic motion detected by the radar system matches the heart beats detected by the ECG. The large variations in the ECG data visible in Fig. 7 are a result of large, non-repetitive motion in other muscles while the smaller amplitude, higher frequency signal visible in Fig. 8 likely stems from other body motion such as small twitches in the caudal fin. Moving the ECG electrodes may have improved the appearance of the signal, but the existing placement provided an adequate signal.

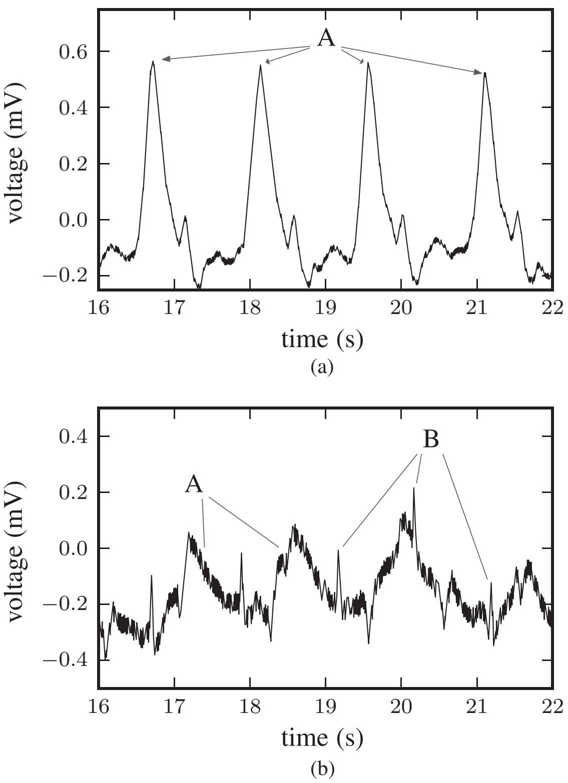
A comparison of the heart beat timing shows the radar and reference data to match closely (see Fig. 5). Plotting the differences against the means for the radar and reference measurements is a graphical alternative to correlation coefficients for assessing the level of agreement between the two. As described by Bland and Altman [22], the correlation coefficient can vary depending on the range of the quantity measured, plotting the data in this manner provides information on the agreement between two methods even when the value measured varies over a wide range. This graphical depiction can be seen in Fig. 6 with the radar and ECG reported heart rates matching within two standard deviations. The heart rate measurements used for this plot were extracted by FFT detection with 24 s long windows. While other plots are from a single test subject, data collected from five individuals were used in this comparison. The fifteen points were discrete sample points—one per test. Multiple tests were performed per test session to reduce the impact of these tests. The ECG electrodes were left in place but the radar antenna was removed then replaced, sometimes with subject orientation changes.



(a)

(b)

Fig. 7. Signals from the radar (7) and the ECG (7) showing the physiological signals of the fish. Though the fish was sedated, the ECG signal shows significant muscle activity in addition to that of the heart. Visible in the plot is both large transients A and the high-pass filter response B following them. (a) Radar. (b) ECG.



(a)

(b)

Fig. 8. Signals from the (a) radar and the (b) ECG over a shorter time span. Both the radar and ECG show 41 bpm waveforms from the heartbeat indicated by A with the ECG showing an extraneous signal, B, at a higher frequency. This signal is also visible in the ECG trace in the frequency plot (Fig. 5) and not in the radar trace.

Realistically, for monitoring heart rate (and not the intervals from one beat to the next), the base line for performance is detecting all the heart beats and the radar is clearly performing above this level. The correspondence in detected heart rate for the radar and reference also can be easily seen in the frequency domain plot, Fig. 5. The peaks for the heart rate is at 41 bpm with harmonics at 82 bpm and 123 bpm – a reasonable rate for fish and comparable to that reported for tilapia at warm temperatures [23]. Also visible in this plot is spectral content in the ECG signal at low frequencies. A large contribution of this is the transient visible in the trace when viewed for a longer time span in Fig. 7.

These data traces show how some of heart beats are obscured by the large transients, but before and after have visible heart beats. While ECG trace in Fig. 7 shows some large transient signals, the radar trace does not show corresponding signals. This may be due, among other possibilities, to the source of the transients in the ECG signal stemming from motion away from the heart and gills or an electrical signal that did not result in motion.

A slightly higher frequency motion is visible in both Fig. 8 (time) and Fig. 5 (frequency) plots. This motion is from muscle activity (involving electrical signaling and motion) and the most likely source is twitching of a fin. Because the fish continued to move its caudal (tail) fin after sedated enough to still its other fins and that fin motion involves large body muscles – easily visible in the ECG even for small twitches – that is likely the motion behind these spikes.

Heart rate monitoring can be useful as an indicator of metabolic output, which is useful for energy strategies and investigating environmental impact. Apart from heart rate, the radar can provide information about body motion which could prove useful in aquaculture.

In addition to applying the radar as a heart rate monitor, the data can be used as an indication of metabolic rate – an important application. Besides just mentioning metabolic rate as an application, you can indicate that such rates are used for studying fish trophic/energy strategies, environmental impact, and fish farming.

For the data collected in these experiments the heart rate is of comparable quality to that provided by the ECG, but the testing still involves handling the fish, sedating it, and restricting its motion. All these affect heart rate and cause stress. Further refinement to eliminate these problems may entail mounting the antenna to a fixture with just enough space for a fish to swim into, a small wearable radar system that can record/transmit heart rate information, or non-contact radar that can sense the heart rate from fish when close to the antenna without requiring contact. Some possible alterations to the radar to improve upon this location include reducing the antenna size to one that would fit between the gill cover and pectoral fin, using the radar to sense motion related to that of the heart in the swim bladder, and mounting the antenna ventrally. Each of these involves different challenges and should be explored. In addition, work to further verify the radar measured heart rate against an ECG reference and expanding refinement to additional species of fish are ongoing.

## V. CONCLUSION

These results demonstrate an advance in physiological sensing with radar. Previous work has demonstrated motion sensing in humans and fish, the results described in this paper are the first to verify fish heart motion sensing with an ECG reference. The preliminary results shown here – fish heart rate measured with radar matching ECG heart rate – are very encouraging. Contact Doppler radar measurements were shown to be at least as effective as ECG, with added suppression of interference from muscle activity not related to heart function.

These experiments used ECG as a reference to verify the performance of the radar system. Used by itself, radar heart monitoring obviates the need for ECG and the consequent invasive surgery. Such non-invasive heart rate monitoring of fish can enable metabolic and efficiency measurements less affected by the stress of surgery for fish. Improved techniques to monitor heart rate without handling can allow physiological monitoring in situations that currently prevent such monitoring, such as deep sea fish in their natural environment.

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**Noah Hafner** (S'00) received the B.S. and M.S. degrees in electrical and computer engineering from Carnegie Mellon University, Pittsburgh, PA, in 2002 and 2003, respectively. He is currently pursuing the Doctoral degree at the University of Hawaii, Manoa.

He was engaged in research with the National Instruments, Austin, TX, and Akustica, Pittsburgh, PA. His current research interests include remote sensing, technological impacts, and security.

**Jeffrey C. Drazen** received the B.A. degree in biology and marine science from the University of San Diego, San Diego, CA, in 1993, and the Ph.D. degree in marine biology from the Scripps Institution of Oceanography, La Jolla, CA, in 2000.

He was a Post-Doctoral Fellow with the Monterey Bay Aquarium Research Institute, before joining the Oceanography Department, University of Hawaii, Manoa, where he is currently an Associate Professor and the Chair of the Biological Oceanography Division. He has been an Affiliate Faculty Member with the Hawaii Institute of Marine Biology, Kaneohe, since 2007. He regularly teaches courses in pelagic ecology and deep-sea biology. His current research interests include feeding ecology, energetic, and physiological ecology of marine fish, particularly those from the deep ocean.

**Victor M. Lubecke** (S'86–M'86–SM'98) received the B.S.E.E. degree from the California Polytechnic Institute, Pomona, in 1986, and the M.S. and Ph.D. degrees in electrical engineering from the California Institute of Technology, Pasadena, in 1990 and 1995, respectively.

He has been with the University of Hawaii, Manoa, since 2003, currently as a Professor of electrical engineering. He was with the Bell Laboratories, Lucent Technologies, Murrray Hill, NJ, where was involved in research on sensing and monitoring technologies for biomedical and industrial applications, and microelectromechanical systems (MEMS) and 3-D wafer-scale integration technologies for wireless and optical communication. From 1987 to 1996, he was with the National Aeronautics and Space Administration, Jet Propulsion Laboratory, La Cañada Flintridge, CA, and from 1996 to 1998, he was with the Institute for Physical and Chemical Research, Sendai, Japan, where his research involved remote sensing and space communication applications, and related MEMS and terahertz technologies. He has authored or co-authored more than 130 peer-reviewed research articles, and holds six U.S. patents with several pending. His current research interests include remote sensing and imaging technologies, biomedical sensors, animal tracking and monitoring, MEMS, heterogeneous integration, and microwave and terahertz radios.

Dr. Lubecke was a co-recipient of the Emerging Technology Award at TechConnect in 2007, and co-founded a start-up company that is now Kai Medical, Honolulu, HI. He was a recipient of the Microwave Prize for the Best Paper presented at the Asia-Pacific Microwave Conference in 2000. He has co-authored student competition papers, which were selected for Honorable Mention at the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium (IMS) in 2001, third place at the IEEE Engineering in Medicine and Biology Society Conference in 2001, first place at the IEEE MTT-S IMS in 2003, and Honorable Mention at the IEEE Radio Wireless Symposium in 2006. He is an Emeritus Distinguished Microwave Lecturer of the IEEE MTT-S from 2006 to 2008. He is a member of the IEEE Engineering in Medicine and Biology and Electron Devices societies and serves on the Technical and Steering Committees of various IEEE and SPIE symposia.