

Arctangent Demodulation With DC Offset Compensation in Quadrature Doppler Radar Receiver Systems

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Abstract—Direct-conversion microwave Doppler radar can be used to detect cardiopulmonary activity at a distance. One challenge for such detection in single channel receivers is demodulation sensitivity to target position, which can be overcome by using a quadrature receiver. This paper presents a mathematical analysis and experimental results demonstrating the effectiveness of arctangent demodulation in quadrature receivers. A particular challenge in this technique is the presence of dc offset resulting from receiver imperfections and clutter reflections, in addition to dc information related to target position and associated phase. These dc components can be large compared to the ac motion-related signal, and thus, cannot simply be included in digitization without adversely affecting resolution. Presented here is a method for calibrating the dc offset while preserving the dc information and capturing the motion-related signal with maximum resolution. Experimental results demonstrate that arctangent demodulation with dc offset compensation results in a significant improvement in heart rate measurement accuracy over quadrature channel selection, with a standard deviation of less than 1 beat/min.

Index Terms—Arctangent demodulation, biomedical monitoring, biomedical signal detection, dc offset, direct conversion receiver, Doppler radar.

I. INTRODUCTION

DIRECT-CONVERSION microwave Doppler radar has been introduced for noncontact detection or monitoring of human cardiopulmonary activity [1]–[3]. These functions can be a promising tool for health care, emergency, military, or security applications if reliable and robust sensing can be provided. One challenge in providing robust sensing is detection sensitivity to target position due to the periodic phase relationship between the received signal and local oscillator (LO), resulting in “optimum” and “null” extreme target positions. A quadrature Doppler radar receiver with channel selection has been proposed to alleviate this problem [3]. This method selects the better of the quadrature (I and Q) channel outputs, and is thus limited to the accuracy of a single channel. A frequency tuning technique with double-sideband transmission has also been proposed for *Ka*-band radar [4]; however, this

technique requires more complex hardware with a tunable intermediate frequency. In this paper, we propose to combine quadrature outputs using arctangent demodulation with dc offset compensation. Arctangent demodulation overcomes position sensitivity issues while removing the small-angle limitation on the range for phase deviation detection, which can be significant in single-channel systems operating at high frequencies. The use of dc offset compensation ensures that unwanted dc components produced by receiver imperfections and clutter reflections are removed, while dc information required for accurate arctangent demodulation is preserved.

Typically, a Doppler radar motion sensing transceiver transmits a continuous wave signal, and phase demodulates the signal reflected from a target [1]. A stationary human body presents two independent time-varying sources of motion with zero net velocity, resulting from respiration and cardiac activity, and the largest reflection of incident RF power occurs at the body surface. In terms of phase demodulation, the two extreme cases, i.e., “null” and “optimum,” occur periodically for target positions at each $\lambda/4$ interval from the antenna with $\lambda/8$ separation between null and optimum points [4]. The mathematical basis for Doppler radar sensitivity to a target’s position has been introduced with supporting experimental results [5]. For the optimum case, the demodulated phase variation is linearly proportional to chest displacement, assuming the target displacement is small compared to λ . However, in the null case, the demodulated heart and respiration related phase data can be self-coupled or mutually coupled, resulting in large detection errors [5].

This paper will present relevant quadrature receiver theory, followed by experimental results demonstrating expected signal distortion in “null” cases. Arctangent demodulation will then be introduced as a means of overcoming this issue, thus providing a more robust sensing system. Before arctangent demodulation can be performed, quadrature channel imbalance and dc offset issues must be addressed. Both of these issues are well known in direct conversion receivers for radar [6] and communications applications [7]–[10]. With known channel imbalance factors, the Gram–Schmidt procedure can be used to correct imbalance errors [11]. Several dc offset compensation techniques have been proposed for communications receivers [8], [12], [13], where all of the dc signal is assumed to be undesired. The simplest solution for dc offsets is to remove them by using a high-pass filter. However, several modulation methods, such as the phase modulation method in this paper, contain critical “dc information,” which must be distinguished from unwanted

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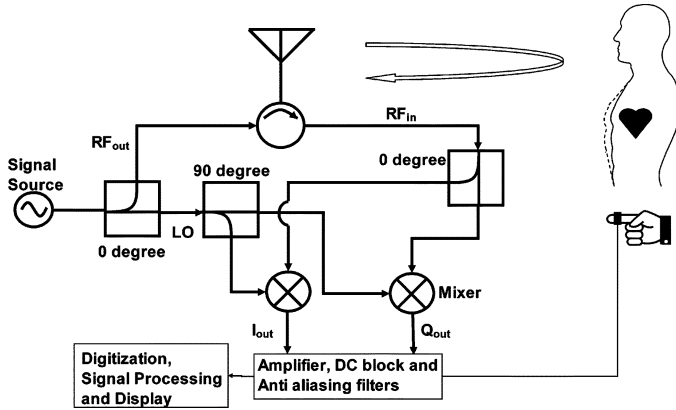


Fig. 1. Block diagram of a quadrature Doppler radar heart rate measurement system. The LO signal is divided by a two-way 90° power splitter to get two orthonormal baseband signals (I and Q), which can be combined to minimize sensitivity to target position. Processed I and Q channels are compared with a wired finger pulse sensor reference.

“dc offsets” caused by imperfections in circuit components and reflections from stationary objects. The dc information component, associated with target position in Doppler radar, is typically several orders of magnitude larger than the amplitude of the periodic baseband signal related to heart activity, making it impractical to simply digitize the full signal with reasonable resolution. Thus, this paper explores techniques for isolating dc offset, dc information, and the ac motion signal to overcome dynamic range limitations for pre-amplifiers and analog-to-digital converters (ADCs) without discarding important components of the desired data. The results of arctangent demodulation experiments with a target at several different positions are described here, demonstrating proper preservation of cardiopulmonary-related motion information, and verifying accuracy insensitivity to target position. In each case, the heart rate obtained from combined quadrature outputs agreed with a wired reference, with a standard deviation of less than 1 beat/min. For the same measurements, the standard deviation of data from each in-phase (I) or quadrature (Q) channel varied from 1.7 beats/min in the optimum case, to 9.8 beats/min in the null case, with the additional problem of heart rate tracking drop-outs in the latter case.

II. QUADRATURE RECEIVER

Fig. 1 shows the block diagram of a quadrature Doppler radar system. A single signal source provides both the RF output and LO signals. The LO signal is further divided using a 90° power splitter to provide two orthonormal baseband outputs. Assuming that heart and lung motion is given by $x(t)$ and $y(t)$, the quadrature baseband outputs can be expressed as

$$B_I(t) = \sin \left[\theta + \frac{4\pi x(t)}{\lambda} + \frac{4\pi y(t)}{\lambda} + \Delta\phi(t) \right] \quad (1)$$

and

$$B_Q(t) = \cos \left[\theta + \frac{4\pi x(t)}{\lambda} + \frac{4\pi y(t)}{\lambda} + \Delta\phi(t) \right] \quad (2)$$

where $\Delta\phi(t)$ is the residual phase noise, and θ is the constant phase shift related to the nominal distance to the subject including the phase change at the surface of a target and the phase delay between the mixer and antenna.

The null and optimum extreme cases for the output signal with respect to θ can be observed in (1) and (2). When θ is an odd multiple of $\pi/2$, the baseband signal of the Q channel is at an optimum point, while that of the I channel is at a null point. On the other hand, when θ is an integer multiple of π , the baseband signal of the I channel is at an optimum point, while that of the Q channel is at a null point. Assuming that both $x(t)$ and $y(t)$ are much smaller than $\lambda/4\pi$ (the small angle approximation) and that they can be simplified as sinusoidal waves of frequency f_1 and f_2 , with θ , an integer multiple of π , (1), and (2) become

$$B_I(t) \approx A \sin 2\pi f_1 t + B \sin 2\pi f_2 t + \Delta\phi(t) \quad (3)$$

$$B_Q(t) \approx 1 - [A \sin 2\pi f_1 t + B \sin 2\pi f_2 t + \Delta\phi(t)]^2 \quad (4)$$

where $f_1 \ll f_2$ and $A \gg B$. Note that the small angle condition becomes more challenging as λ decreases. In this case, the “optimal” I channel output is linearly proportional to chest motion, and it should be possible to obtain the desired data accurately with appropriate filtering. The “null” Q channel output given by (4) can be expanded and rearranged as

$$\begin{aligned} B_Q(t) &\approx 1 - \frac{1}{2} [(A^2 + B^2) - A^2 \cos 4\pi f_1 t - B^2 \cos 4\pi f_2 t \\ &\quad - 2AB(\cos 2\pi(f_2 + f_1)t - \cos 2\pi(f_2 - f_1)t) \\ &\quad + 2\Delta\phi(t)(2A \sin 2\pi f_1 t + 2B \sin 2\pi f_2 t + \Delta\phi(t))]. \end{aligned} \quad (5)$$

Several problematic phenomena can be observed for this “null” case from (5). There is a significant dc component present at the output, and the output is no longer linearly proportional to displacement. The square terms result in signal distortion either by doubling the signal frequency or by mixing heart and respiration frequencies, while the linear terms are multiplied by the residual phase noise, thus degrading the SNR. The above described phenomena were confirmed by experimental measurements using a custom direct conversion quadrature-receiver Doppler system, like that shown in Fig. 1 [5], and looking at each output channel independently. A commercially available Antenna Specialists ASPPT2988 2.4-GHz patch antenna was used, with a gain of 7.5 dBi, an E -plane range of 65° , and an H -plane range of 80° . A Mini-Circuits JTOS-2700 V voltage-controlled oscillator (VCO) was used as the signal source, which delivered 0.8 dBm at 2.4 GHz to the antenna port. A Mini-Circuits RPS-2-30 was used for each two-way 0° power splitter, and a Mini Circuits QCN-27 was used for the two-way 90° power splitter. A Mini-Circuits SKY-42 was used for each mixer. As the measurement setup shown in Fig. 1 indicates, the baseband output signals were amplified ($\sim 1000\times$) and bandpass filtered (0.03–10 Hz) with SR560 low-noise amplifiers (LNAs), and then digitized with a DT9801 ADC card. Heart and respiration rates were extracted in real time with custom software based on an autocorrelation algorithm described in [14], and heart rate was compared with

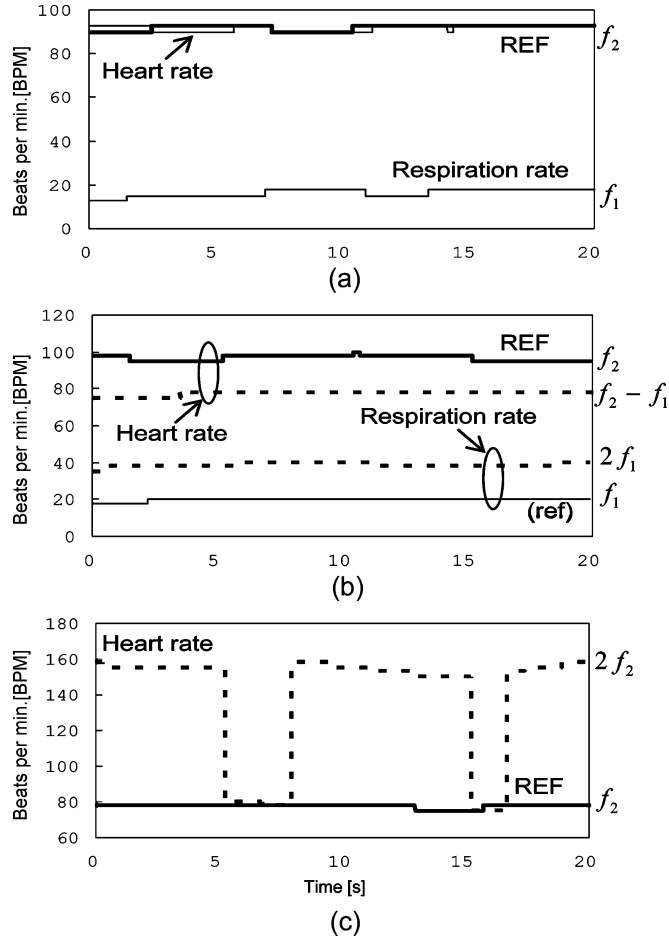


Fig. 2. Rate measurement history data for both respiration (f_1) and heart (f_2) with a receiver output at either the: (a) optimum or (b) and (c) null points. At the optimum point, the Doppler measured heart rate corresponds closely to the reference for all f_2 . At the null point during continuous breathing (b), the Doppler measured heart rate and reference differ by the respiration reference frequency f_1 , while with breath-holding (c), it jumps between either double or equal to the actual frequency. The respiration “(ref)” signal in (b) is that measured from the other quadrature (not null) channel. Data from [5].

that obtained from a wired finger pressure pulse sensor (UFI 1010) used as a reference. Measurement results are shown in Fig. 2, and the distortion cases discussed above were observed. In Fig. 2(a), corresponding to the “optimum” case, the baseband data is linearly proportional to the actual signal resulting in an output that corresponds well with the reference. Fig. 2(b) and (c) shows the “null” case data taken both during continuous breathing and breath holding, respectively. As predicted in (5), Fig. 2(b) shows the detected heart rate decreased by an amount equal to the respiration rate, and a doubled respiration rate is also evident. Fig. 2(c) shows the heart rate doubling effect.

III. ARCTANGENT DEMODULATION CHALLENGES

The single receiver-channel Doppler radar system limitations previously described can be eliminated by using a quadrature receiver system like the one shown in Fig. 1 with both channels considered simultaneously. A quadrature receiver provides two orthonormal outputs, thus ensuring that when one channel is in a

“null” position the other will be in an “optimum” position. Furthermore, by combining the two channels, accurate phase demodulation can be achieved regardless of the target position or displacement amplitude, the latter being restricted to the small angle deviation condition for even the optimum case in a single channel receiver. As shown in (1) and (2), the I and Q outputs are the cosine and sine of a constant phase delay caused by the nominal distance to a target with a time varying phase shift that is linearly proportional to the chest displacement. By applying the arctangent operation to the I and Q output data ratio, accurate phase demodulation can always be obtained regardless of the target’s position as

$$\phi(t) = \arctan\left(\frac{B_Q(t)}{B_I(t)}\right) = \arctan\left(\frac{\sin(\theta + p(t))}{\cos(\theta + p(t))}\right) = \theta + p(t) \quad (6)$$

where $p(t) = 4\pi(x(t) + y(t))/\lambda$ is the superposition of the phase information due to respiration or heart signals.

However, quadrature channel imbalance and dc offset act as a linear transform on the I and Q components, thus modifying (6) to

$$\begin{aligned} \phi'(t) &= \arctan\left(\frac{B_Q(t)}{B_I(t)}\right) \\ &= \arctan\left(\frac{V_Q + A_e \sin(\theta + \phi_e + p(t))}{V_I + \cos(\theta + p(t))}\right) \end{aligned} \quad (7)$$

where V_I and V_Q refer to the dc offsets of each channel, and A_e and ϕ_e are the amplitude error and phase error, respectively. Correction for a known phase and amplitude imbalance is straightforward using the Gram–Schmidt procedure [6]. The dc offset issue is more complex, however, due to the fact that the total dc signal contains dc information required for accurate demodulation. The dc offset is caused by two main sources: reflections from stationary objects (clutter) and hardware imperfections. Hardware imperfections include circulator isolation, antenna mismatch, and mixer LO to RF port isolation, resulting in self-mixing, which produces a dc output. On the other hand, as indicated by (5), dc information associated with the target’s position is also part of each baseband signal. The magnitude of this dc level is dependent on the target’s position, such that the dc level is higher for target positions closer to the “null” case. Consequently, before arctangent demodulation is performed, the dc information must be extracted from the total dc output, and preserved.

A coaxial quadrature radar system, also as shown in Fig. 1, was used to examine arctangent demodulation issues. The same antenna, baseband pre-amplification, and data acquisition and heart rate extraction systems were used as previously described. An HP E4433B signal generator was used as the LO and divided into RF and LO signals by a Mini-Circuits ZFSC-2-2500 signal splitter. A Narda 4923 circulator was used to isolate transmit and receive signals with the circulator RF to LO isolation measured to be -22 dB. The LO signal was further divided by a hybrid splitter (Narda 4033C) to provide quadrature outputs. A Mini-Circuits ZFM-4212 was used for the mixer in each channel. Amplitude and phase imbalance factors for this coaxial radar system were determined to be 1.013° and 1° , respectively, using the measurement method described

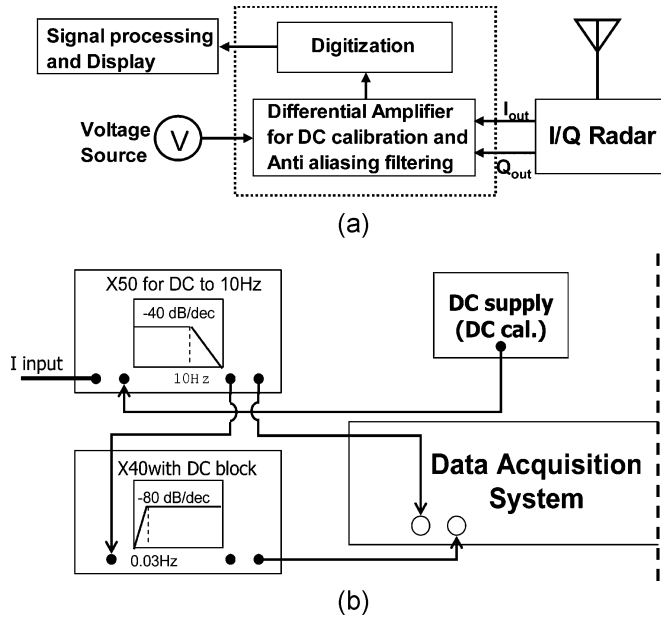


Fig. 3. Measurement setup for dc compensation. Overall radar setup is shown (a) with data acquisition [dashed region in (a)] details provided for the I channel (the Q channel is exactly the same) (b). The clutter and circuit based dc offset measured with no target present is reproduced (dc supply) and subtracted from the response for a human subject so that the heart motion signal (which includes a dc component) can be digitized with maximum resolution.

in [15]. The dc offset caused by hardware imperfections was measured by terminating the antenna port with a $50\text{-}\Omega$ load. The main contribution to this dc offset is caused by self-mixing with circulator leakage power, dependent on the phase difference between the LO and antenna feed line. By connecting a phase shifter between the LO feed line and varying the phase delay, the dc offset range for each channel can be measured at the corresponding mixer's IF port. This was determined to be 19.4 mV for the I channel and 19.8 mV for the Q channel with an LO power of 0 dBm . The dc offset due to reflections was estimated by putting a large metal reflector at a distance of 1 and 2 m from the radar with a half-wavelength position variation used to find the maximum and minimum dc values. The dc offset range for the I and Q channels from a reflector at a 1- or 2-m distance are 3 and 3.4 mV and 0.6 and 0.8 mV , respectively. As expected, experimental results show that the dc offset is dominated by the contribution from imperfections in the circuit components rather than from clutter located 2 m away from radar.

IV. EXPERIMENTAL RESULTS

The measurement setup for dc compensation is shown in Fig. 3. The coaxial radar described in Section III was used to collect data from a seated subject facing the antenna at a distance of approximately 1 m. A wired finger pressure pulse sensor was used to provide the reference for heart rate. Once the dc offset components were determined, as described above, they could be subtracted from the output signal. The remaining challenge was to preserve the relatively large dc information level while sufficiently amplifying the weak time-varying heart-related signal. In this coaxial radar system, the maximum dc information, which occurs at the null case, reaches approximately 3.8 mV , while peak-to-peak voltage for heart motion

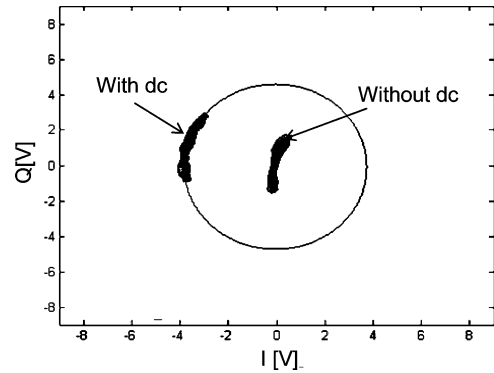


Fig. 4. Polar plot of I/Q data. The I/Q data with dc preserved forms a portion of a circle centered at the origin, verifying preservation of all phase information, while the I/Q signals without dc information form a line near the center for which phase information cannot be accurately recovered.

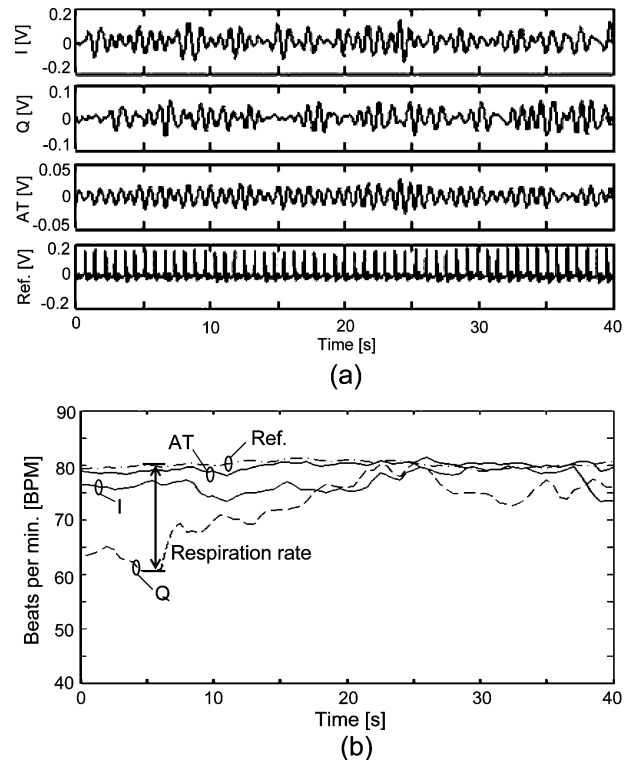


Fig. 5. Heart rate measurements for both channels in an intermediate position. Bandpass filtered ($0.9\text{--}2\text{ Hz}$) Doppler radar I and Q signals are shown along with the combined arc tangent demodulated output (AT) and a wired finger pulse reference (a). Heart rate history (using autocorrelation) is also shown (b), where the Q channel data is at times off by the respiration rate value, as predicted. Standard deviation is less than 1 beat over the full 40-s interval for the AT data, while it is 3.9 and 9.8 beats for the I and Q channels, respectively.

typically results in less than $25\text{ }\mu\text{V}$. In other words, the dc information is 2–3 orders of magnitude larger than the signal amplitude. This makes it difficult to amplify the signal associated with heart displacement sufficiently for high-resolution digitization without saturating the amplifiers or the ADC.

Details for the method used for achieving high amplification without saturation is shown in Fig. 3(b). With no object within 1 m in front of the radar, the internally or externally induced dc offset of each channel could be measured. These dc offsets were then calibrated by using differential amplifiers, each with

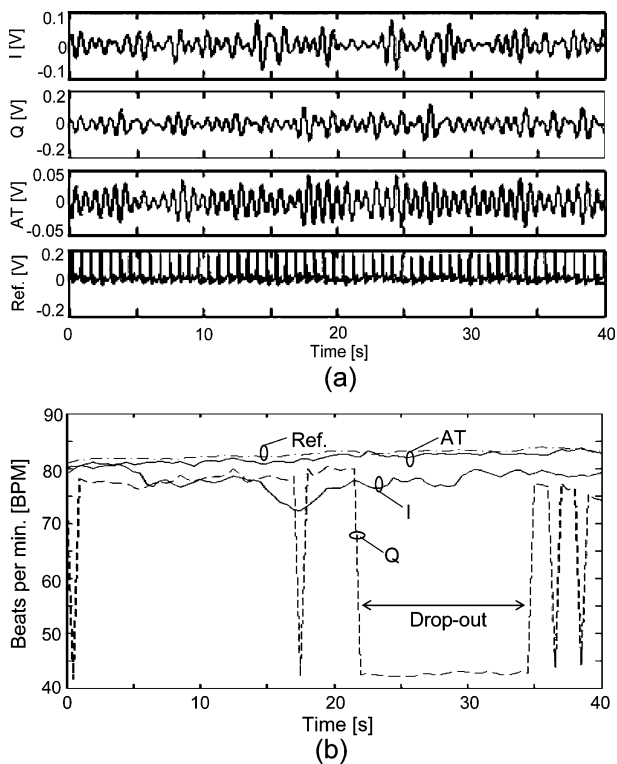


Fig. 6. I, Q, and arctangent (AT) demodulated signals (a) measured for a position where the Q channel is close to a null condition. The Q channel rate (b) shows drop-out regions (in 35% of the interval) when the SNR is insufficient for digitization, as occurs with the squaring effect when in the null position. Excluding drop-outs, the I and Q channels have errors of 4.8 or 5.2 beats, respectively, over the same 40-s interval where the AT data has an error of only 0.9 beats.

one input port connected to a dc power supply. The dc supplies were then used to generate the same voltage as the dc offset of each channel, thus producing a zero dc level at the output. While preserving this condition, a human subject was then located at a distance of approximately 1 m from the radar. In this experiment, the full dc level, including the heart motion signal, was detected at each channel. To achieve sufficient amplification of the signals, three amplifiers were used at the baseband stage of the I and Q channels. The first one was a differential amplifier with a gain of 50 that amplified both the dc and heart motion signal, and calibrated the dc offset. Subsequently, the output of the first amplifier was divided into two outputs, one of which was saved in the data acquisition system and the other was saved after the dc was removed and the ac content was amplified. Two amplifiers were used for the dc blocking filter with a cutoff frequency of 0.03 Hz and gain settings of 20 and 2, respectively, in order to obtain a high- Q (-80 dB/dec) and, thus, a sharp cutoff.

Arctangent demodulation was performed using these signals with and without dc content using MATLAB software. The signal with dc content was multiplied by 40 in the MATLAB code before summation with the ac signal that was pre-amplified before the ADC. At the same time, the ac-only signal was filtered with a Butterworth filter that passed frequencies between 0.9–2 Hz to eliminate the still-detectable low-frequency component due to respiration and, thus, avoid including this effect twice when summing with the dc-included signal. Consequently, a high-resolution heart motion signal combined with a virtual dc com-

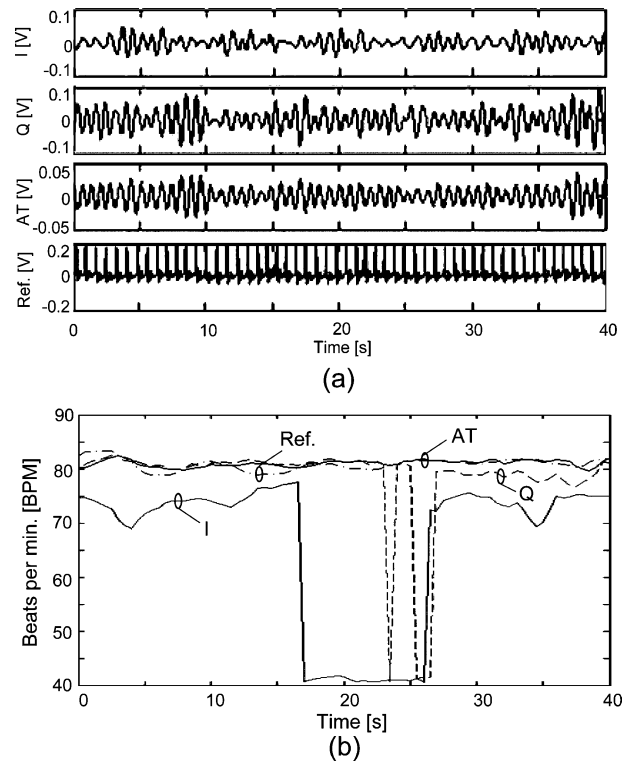


Fig. 7. I, Q, and arctangent demodulated signals (a) measured for the I channel close to a null position. Data drop out regions occur for both I (23% of the interval) and Q (5%) channels. Standard deviation is 7.5 or 1.7 beats for the I and Q channels, respectively, and only 0.6 for the arctangent output.

ponent was created. Without this procedure, the dc component would saturate the amplifiers before the smaller heart motion signal could be sufficiently amplified for recording.

To verify that the dc information was properly preserved, I/Q data after imbalance and dc offset compensation was plotted on a polar plot. Two orthonormal sinusoidal functions of the same phase information will compose part of circular trace centered at the origin, corresponding to the phase information. As shown in Fig. 4, the I/Q baseband signals dc information form a part of an almost perfect circle centered at the origin, confirming that the dc information was correctly accounted for (it would be a circle for two orthonormal sinusoids). The same measurement with the dc portion removed is also shown, appearing at the origin where the phase information cannot be recovered with the same certainty.

Figs. 5–7 show the I, Q, and arctangent demodulated signals obtained using the measurement setup shown in Fig. 3 for the subject in an intermediate position for both channels (Fig. 5), close to a null position for the Q channel (Fig. 6), and close to a null position for the I channel (Fig. 7). The null and optimum positions cannot be set exactly for heart rate measurements as the nominal distance (and associated phase) varies as a result of respiration and effects rate data accordingly. To examine the effectiveness of arctangent demodulation, standard deviation was used to provide a quantitative comparison of accuracy. As shown in Figs. 6 and 7, a drop-out region occurs at the null point due to degradation in signal power, and this region is excluded when calculating standard deviation. In Fig. 5, the Q channel heart signal is affected by the presence of the

respiration signal, which is around 20 beats/min, at the beginning of the measurement interval. The I and Q channels show an error of 3.9 or 9.8 beats, respectively, during the 40-s time interval, while the arctangent combined output has an error of only 0.95 beats. In Fig. 6, 35% of the Q channel data could not be acquired or, dropped out, and the rest has an error of 4.8 beats. The more stable I channel data still has an error of 5.2 beats, while the arctangent combined output has an error of only 0.9 beats. In Fig. 7, both I and Q channels drop out for 23% and 5% of the total time interval, respectively. The I channel data has an error of 7.5 beats and the Q channel data has an error of 1.7 beats, while the arctangent combined output has an error of only 0.6 beats. From the measurement results described above, it is evident that arctangent demodulation results are significantly more accurate than any single channel output, with an error that is consistently less than 1 beat in standard deviation over the 40-s monitoring interval, and when using this data, there is no drop-out region. Thus, arctangent demodulation produces robust and accurate data for rate tracking regardless of a target's position without need for channel selection.

V. CONCLUSION

Single channel Doppler radar systems for detecting cardiopulmonary activity are subject to a systematic functional limitation in that their accuracy is highly dependant on exact target position, and limited by the small angle approximation of motion amplitude for even the optimum target position. By combining output signals in a quadrature receiver system using arctangent demodulation, robust and accurate output data can be obtained regardless of the target's position and motion amplitude. Unwanted dc offset was successfully eliminated while dc information was correctly preserved, even when measuring ac signals with amplitudes that were several orders of magnitude smaller. The effectiveness of arctangent demodulation has been demonstrated for several subject positions illustrating theoretical worst case positional scenarios. Arctangent combined output data did not result in drop-out intervals and maintained an error rate of less than 1 beat over the 40-s test intervals, while individual I and Q data was subject to drop-out during up to 35% of the interval with rate errors up to 9.8 beats for the remainder of the interval. While the arctangent demodulation demonstrated here was processed separately after recording, the technique can be transferred to real-time processing with an appropriate dc tracking and compensation scheme. This could be implemented on chip, complete with low-pass filtering, using techniques such as those described in [16].

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REFERENCES

- [1] J. C. Lin, "Microwave sensing of physiological movement and volume change: A review," *Bioelectromagnetics*, vol. 13, pp. 557–565, Dec. 1992.
- [2] V. M. Lubecke, O. Boric-Lubecke, G. Awater, P.-W. Ong, P. Gammel, R.-H. Yan, and J. C. Lin, "Remote sensing of vital signs with telecommunications signals," presented at the World Congr. Med. Phys. Biomed. Eng., Chicago, IL, USA, Jul. 2000.
- [3] A. D. Droitcour, O. Boric-Lubecke, V. M. Lubecke, J. Lin, and G. T. Kovacs, "Range correlation and I/Q performance benefits in single chip silicon Doppler radars for noncontact cardiopulmonary monitoring," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 3, pp. 838–848, Mar. 2004.
- [4] Y. Xiao, J. Lin, O. Boric-Lubecke, and V. M. Lubecke, "Frequency tuning technique for remote detection of heartbeat and respiration using low-power double-sideband transmission in *K a*-band," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 5, pp. 2023–2032, May 2006.
- [5] B.-K. Park, S. Yamada, V. M. Lubecke, and O. Boric-Lubecke, "Single-channel receiver limitations in Doppler radar measurements of periodic motion," in *IEEE Radio Wireless Symp.*, San Diego, CA, 2006, pp. 99–102.
- [6] R. Moraes and D. H. Evans, "Compensation for phase and amplitude imbalance in quadrature Doppler signals," *Ultrasound Med. Biol.*, vol. 22, pp. 129–137, 1996.
- [7] A. A. Abidi, "Direct-conversion radio transceiver for digital communications," *IEEE J. Solid-State Circuits*, vol. 30, no. 12, pp. 1399–1410, Dec. 1995.
- [8] R. Svitec and S. Raman, "DC offsets in direct-conversion receivers: Characterization and implications," *IEEE Micro.*, vol. 6, pp. 76–86, Sep. 2005.
- [9] L. Noor and A. Anpalagan, "Direct conversion receiver for radio communication systems," *IEEE Potentials*, vol. 24, no. 5, pp. 32–35, Dec. 2005.
- [10] C. Masse, "2.4 GHz direct conversion transmitter for Wimax application," presented at the IEEE RFIC Symp., 2006.
- [11] F. E. Churchill, G. W. Ogar, and B. J. Thompson, "The correction of I and Q errors in a coherent processor," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-17, no. 1, pp. 131–137, Jan. 1981.
- [12] A. Mashhour, W. Domino, and N. Beamish, "On the direct conversion receiver—A tutorial," *Microw. J.*, vol. 44, no. 6, pp. 114–128, Jun. 2001.
- [13] B. Matinpour and J. Laskar, "A compact direct-conversion receiver for *C*-band wireless applications," in *IEEE RFIC Symp. Dig.*, 1999, pp. 25–28.
- [14] B. Lohman, O. Boric-Lubecke, V. M. Lubecke, P. W. Ong, and M. M. Sondhi, "A digital signal processor for Doppler radar sensing of vital signs," presented at the IEEE Eng. Med. Biol. Conf., Istanbul, Turkey, Oct. 2001.
- [15] B.-K. Park, S. Yamada, and V. M. Lubecke, "Measurement method for imbalance factors in direct-conversion quadrature radar systems," *IEEE Microw. Wireless Compon. Lett.*, to be published.
- [16] S. Solis-Bustos, J. Silva-Martinez, F. Maloberti, and E. Sanchez-Sinencio, "A 60-dB dynamic-range CMOS sixth-order 2.4-Hz low-pass filter for medical applications," *IEEE Trans. Circuits Syst. II, Analog Digit. Signal Process.*, vol. 47, no. 12, pp. 1391–1398, Dec. 2000.



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