III. Testing Procedure and Results

An experimental setup with a single antenna and a coaxial power splitter was used to make the measurements discussed below, and is shown in Fig. 2. A Mini-Circuits power splitter, part ZFSC-2-2500, provided 17 dB of isolation between input and output signals. A commercially available Antenna Specialists ASPPM2988 1900 MHz patch antenna with 65° by 80° beam width was used. Measurements were performed at 1892 MHz, which required a VCO tuning voltage of 12 V. The subject was seated at a varying distance, d, fully clothed, facing the antenna, and breathing normally (Fig. 2(b)). A finger pressure pulse sensor (UFI-1010 pulse transducer) was used during the measurements to provide a reference signal for heart activity. The IF output was filtered with Stanford Research Systems Model SR560 Low Noise Amplifiers, which both amplify and filter the signal. The resulting voltage waveforms were digitized with an HP Infinium digital oscilloscope.

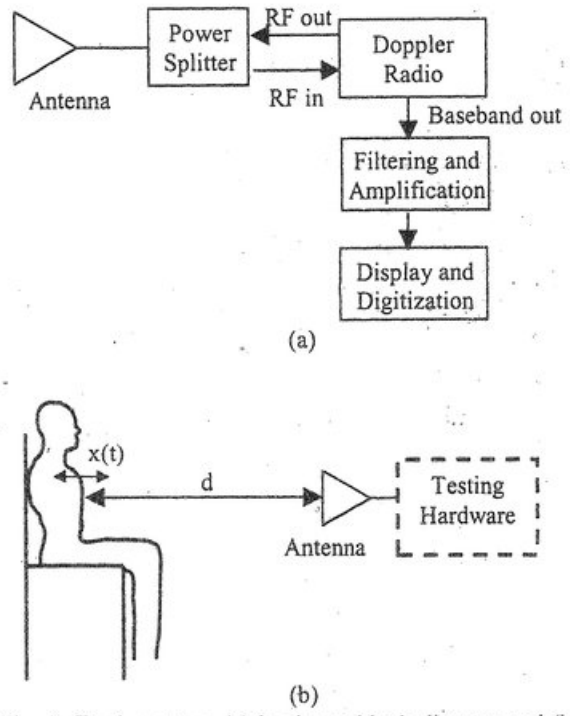

Fig. 2. Testing setup: (a) hardware block diagram and (b) placement of target.

The baseband signal was initially filtered with a band-pass filter between 0.03 Hz and 10 Hz, to remove the DC component and minimize out of band noise and aliasing error. The respiration signal was clearly visible after this filtering stage, but it could be better resolved with an additional low-pass filter. The heart signal was isolated using a 6 dB roll-off 1 Hz to 3 Hz band-pass filter. The first filtering stage provided most of the amplification, which was adjusted to produce the clearest output signal.

The measurement was made in two ways, using the on-board VCO, and using a modified board with an external LO from a signal generator with the same 5 mW output power. This made it possible to determine the contribution of noise from the VCO, and to independently evaluate the rest of the board. At distances less than one meter using the on-board VCO, the interval between "beats" in the heart signal was clearly evident and corresponded to that of the pulse reference, indicating that heart rate could be determined accurately using this Doppler radio. Signals obtained using the on-board VCO with the subject one half meter from the antenna are shown in Fig. 3. The mixer output was filtered and amplified to produce voltage waveforms representing respiration (top trace) and heart (middle trace) signals, with a reference (bottom trace) signal from the finger pulse sensor included for comparison.

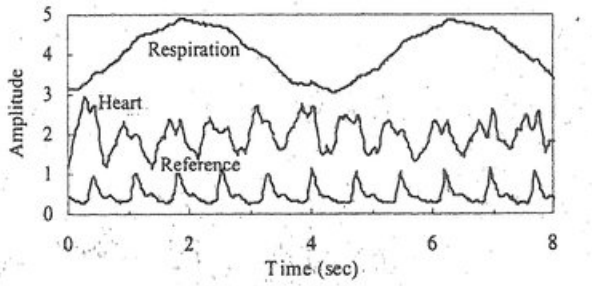

Fig. 3. Respiration (0.3-10 Hz), heart (1-3 Hz), and pressure pulse reference signals (voltage waveforms) with the subject one half meter from the antenna and a VCO as the local oscillator.

At distances of one meter and beyond, the signal to noise ratio decreased due to increased free space loss, and it was more difficult to extract the heart data when using the on-board VCO. The data obtained with the subject one meter from the antenna using the signal generator, and on-board VCO, is shown in Fig. 4(a) and (b), respectively. The top trace corresponds to the pre-filtered signal containing both breathing and heart information, the middle trace to the band-pass heart signal, and the bottom trace to the pressure pulse reference. In both cases, periodic heart activity is evident in the top traces, however it is noisier when the on-board VCO is used (Fig. 4(b)). After band-pass filtering, the heart signal (middle trace) shows the same number of intervals between beats as the reference signal (bottom trace), in both cases. This indicates that although the signal from the VCO has higher noise, it is still possible to extract the heart rate at