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DEVELOPMENT OF AN EM-BASED LIFEFORM MONITOR

Second Annual Technical Report

Project A-3273

March 1984

Research Contract No. N00014-82-C-0390

By

Joseph Seals, Steven M. Sharpe and
Michael L. Studwell

Prepared for

NAVAL MEDICAL RESEARCH AND DEVELOPMENT COMMAND
National Naval Medical Center
Bethesda, Maryland 20014

By

BIOMEDICAL RESEARCH DIVISION
Electronics and Computer Systems Laboratory
Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

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FOREWORD

This annual technical report summarizes research efforts performed on this program from 1 May 1983 to 31 January 1984 by personnel of the Biomedical Research Division in the Electronics and Computer Systems Laboratory of the Engineering Experiment Station at the Georgia Institute of Technology, Atlanta, Georgia. The program is sponsored by the Naval Medical Research and Development Command contracting through the Office of Naval Research. Within the Navy, the program is identified as Contract No. N00014-82-C-0390 and it is designated by Georgia Tech as Project A-3273. Dr. Elliot Postow of the Naval Medical Research and Development Command is serving as Program Monitor. Mr. Joseph Seals of the Biomedical Research Division is serving as Project Director. Staff members from the Biomedical Research Division that are assigned to this program include Dr. Steven M. Sharpe and Mr. Michael Studwell.

Respectfully submitted,

Joseph Seals

Joseph Seals,
Project Director

APPROVED:

J. C. Toler

J. C. Toler, Chief
Biomedical Research Division

SECTION I
INTRODUCTION

Georgia Tech is currently conducting a program to develop an electromagnetically-based lifeform monitor capable of evaluating the medical status of battlefield casualties from extremely long ranges (10-100 meters). This lifeform monitor operates by measuring and analyzing scattered electromagnetic fields to detect respiratory-related and cardiac-related body motions in the casualty being evaluated. Because antenna-based techniques are used to perform the required scatttered field measurements, the instrumentation being developed on this program achieves true remote operation. That is, personnel being evaluated do not wear or carry a biomedical transducer or any other type of auxillary device. This fact greatly enhances the attractiveness and potential usefulness of this approach.

A number of applications can be envisioned for a device which functions as an extremely sensitive, non-contact, indicator of personnel-related motion (e.g., intruder detection, location of hidden personnel, etc.). However, the instrumentation being developed on this program is primarily intended to be used for battlefield triage and diagnostic applications such as

- Rapid evaluation and prioritizing of casualties when casualties are dispersed over a broad battlefield rea,
- Preliminary long-range evaluation of casualties isolated by distance, chemical agents, weapons fire, dangerous terrain, or other threats,
- Evaluation of casualties wearing protective clothing or equipment that interferes with the operation of conventional medical instrumentation (e.g., chemical warfare suits), and
- Evaluation of casualties that have suffered burns or other trauma requiring that patient contact or movement be minimized.

Development of an electromagnetically-based lifeform monitor with the required long-range capability presents a significant challenge. Electromagnetic (EM) fields scattered by a casualty's body are extremely weak (especially when the casualty is lying on the ground) and measurements easily can be contaminated by the effects of numerous types of noise and clutter. To meet this challenge, an intensive effort has been made to thoroughly analyze factors that affect the performance of EM-based measurement techniques and to develop methods for effectively overcoming identified range-limiting problems. These efforts have led to the development of a prototype EM-based lifeform monitor that incorporates a number of unique operational features.

These features, which are discussed in more detail in Section II, include (1) a 35-GHz operating frequency to enhance motion sensitivity and achieve high antenna directivity using a compact antenna size, (2) a sophisticated frequency modulation scheme to permit implementation of quadrature detection channels and improve rejection of both clutter (through range-gating) and internal system noise (through frequency sidestepping), and (3) a homodyne demodulation scheme that makes it possible to achieve excellent receiver performance using a simple system configuration. Based on preliminary results, the combined performance improvements resulting from use of these features will make it possible to achieve the long-range detection capabilities that are the objectives of this research program.

The current version of the prototype EM-based lifeform monitor has been tested under a number of field conditions. Performance of the prototype system in these tests has greatly exceeded expectations. For example, it initially was estimated that EM-based techniques could be used to detect the relatively large body motions produced by respiration from ranges extending to approximately 30 meters. However, the prototype system already has been used to detect subtle heartbeat-related motion from ranges exceeding 30 meters while more profound respiration-related motion has been detected from ranges up to 50 meters. Further improvements in range are predicted. In fact, with implementation of a number of planned system improvements (particularly in the area of signal processing), it is estimated the range of the prototype EM-based lifeform monitor eventually can be extended beyond 100 meters.

In addition to achieving greater range than initially estimated, the respiration- and cardiac-related information provided by the prototype system has been of a higher quality than anticipated. In many instances, it appears that information quality is sufficient to permit actual casualty diagnosis. The higher information quality is a result of the relaxed filtering requirements made possible by the excellent overall performance of the prototype system. In addition to improving information quality, the relaxed filtering bandwidth requirements also permit detection over a greater range of breathing and heartbeat rates. This is significant since the vital signs of wounded personnel are likely to exhibit considerable variation.

As indicated by the preceding description, efforts during the first 21 months of this program to develop an EM-based lifeform monitor have been quite successful. In addition, plans are now underway to implement a number of system improvements that should significantly extend the range of the current prototype system. Because of the proven success of past program efforts and the evident potential of efforts planned for the remainder of this program, it is respectfully requested that this program be continued in accordance with the basic conditions specified in the attached business statement. Specific tasks planned for the remaining months of this second year and for the requested third year are briefly reviewed in Section III. The following section contains a summary of progress made during the initial nine months of this second program year.

SECTION II

REPORT OF TECHNICAL PROGRESS

A. Summary

A number of challenging problems must be solved in order to implement an EM-based lifeform monitor capable of long-range detection of the minute body motions associated with respiratory and cardiac functions. Problems capable of severely limiting the range of the EM-based lifeform monitor include (1) internal receiver noise, (2) AM and FM transmitter noise, (3) external noise or clutter, and (4) range-dependent motion sensitivity. In the first Annual Technical Report [1] submitted on this program (dated January 1983), a number of techniques potentially useful for solving these range-limiting problems were identified and discussed.

During the past 12 months, significant advances have been made in incorporating the most promising of these techniques as well as a number of other improvements into a 35-GHz prototype EM-based lifeform monitor. Specific accomplishments during the past year include

- Extensive analysis of the operation and capabilities of a variety of FM-CW techniques,
- Implementation of a sophisticated FM-CW system that has quadrature detection and range-gating capabilities,
- Analysis and testing of the operation of single-ended mixers and detectors,
- Implementation of a high-performance receiver that uses a simple but versatile homodyne demodulation scheme,
- Design and fabrication of two dielectric lens antennas (six- and nine-inch diameters) and a custom scalar feed horn,
- Fabrication and/or purchase of a number of compact millimeter-wave components that have significantly reduced the size of the prototype system's RF section,
- Battery powering of the prototype system, and
- Field testing of the prototype EM-based lifeform monitor from ranges of 30, 40, and 50 meters.

Key aspects of the most relevant of these accomplishments are reviewed in the following discussions.

B. FM-CW Subsystem

One of the most important features of the EM-based lifeform monitor is its use of frequency modulation. The sophisticated FM-CW scheme being utilized in the current prototype system (1) aids receiver performance by reducing the effects of flicker noise, (2) permits implementation of the quadrature detection channels necessary to eliminate range-dependent motion sensitivity problems, and (3) enables range-gating, a key to minimizing the effects of clutter. In addition, since the required frequency modulation is being applied at a conveniently low frequency, the prototype frequency modulated system is only slightly more complex than an unmodulated CW system.

1. Flicker Noise Reduction Using FM-CW

The reduction of flicker noise is one valuable result of using frequency modulation. Flicker noise, which is due to semiconductor effects in the mixer and to demodulated AM transmitter noise, is very large near baseband but decays in an approximately linear manner with increasing frequency [2, 3, 4, 5]. This effect can be observed by examining Figure 1 which shows the measured noise spectrum of the mixer being used in the current prototype system. With unmodulated CW systems, the respiratory- and cardiac-related information contained in the received return signal is directly translated to baseband where it can be masked by flicker noise. Signal amplification at this point would be of little help in reducing flicker noise effects since both the desired information and the undesired flicker noise would be equally amplified.

Problems due to flicker noise can be effectively treated in a number of ways. One solution would be to amplify the return signal prior to demodulation. By amplifying at the system's high operating frequency (or RF), the information of interest can be amplified independently of the undesired flicker noise. However, several potential problems associated with using RF amplifiers as receiver front-ends should be noted. One problem is that low-noise amplifiers that have suitable gain and are capable of operating at gigahertz frequencies can cost thousands of dollars. In addition, the power consumption of these RF amplifiers is usually high (typically 1-5 watts). It may also be necessary to null out any strong reflections such as those from

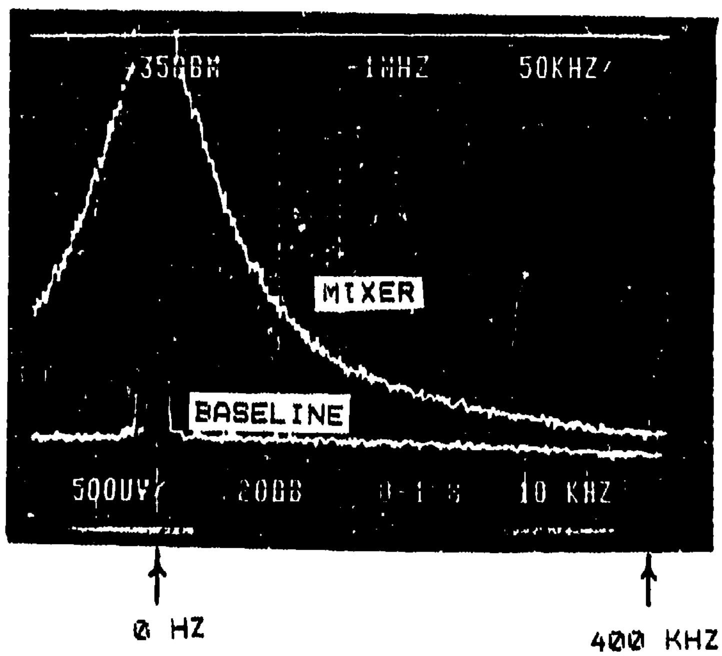


Figure 1. Photograph of measured noise spectrum of the single-ended mixer being used in the prototype EM-based lifeform monitor. Zero input power; 50 microamps bias current.

the antenna or from the ground in order to avoid amplifier saturation. This could be accomplished using feed-through nulling techniques at a cost of increased system complexity.

Another way to combat flicker noise is to use a balanced detection scheme. When carefully designed, balanced detectors or mixers can be very effective in cancelling the effects of flicker noise due to demodulated AM noise from the local oscillator (or from the reference signal if a homodyne approach is being used). However, noise from any signals that leak into the signal channel (e.g., reflections from the antenna or from the ground) will not be cancelled and can still cause problems. In addition, balanced detection schemes require separate input ports for the local oscillator signal and the target return signal. This latter fact can be troublesome when using waveguide as a transmission medium.

A third technique for reducing flicker noise involves translating the target return signal to an intermediate frequency (IF) prior to final detection. The selected IF should be high enough to avoid any existing flicker noise but low enough that signal amplification is convenient and economical. With adequate IF amplification, the information of interest again can be made stronger than the existing flicker noise when the final translation to baseband is made. Translation to a suitable intermediate frequency is usually made by using superheterodyne techniques. However, superheterodyne techniques can be cumbersome since they require coherence between a local oscillator and the transmitter. Translation to a suitable IF can also be achieved using frequency modulated techniques. With FM-CW, the modulating parameters (modulating frequency and frequency deviation) can be selected so that following demodulation, the information of interest is at either the modulating frequency, or a harmonic thereof, instead of at baseband [6]. If the modulating frequency is greater than a few kilohertz, flicker noise effects will be greatly reduced as was shown in Figure 1.

The demodulated signals outputted by the current prototype system are at a frequency of approximately 28 kHz. Tests have shown that, at this frequency, the system signal-to-noise ratio is 25-30 decibels better than that of a comparable CW system employing direct baseband detection. This level of improvement can be used to increase system range (by a factor of four to five when the limiting factor in system performance is internal noise) or to achieve equivalent range using significantly lower transmitted power levels. Currently, the use of even higher modulating frequencies is being considered.

2. Quadrature Channel Detection using FM-CW

A second advantage resulting from the use of FM-CW techniques is the ability to implement quadrature detection channels. The use of quadrature detection channels is important since the problem of range-dependent motion sensitivity arises if only single channel detection is used. As explained in the first Annual Technical Report [1], this problem results from the fact that the desired motion information is only indirectly available as the argument of a sinusoidal term. Because of the periodic nature of this sinusoidal term, the motion sensitivity of the EM-based lifeform monitor is periodic with range. This effect is dependent on the operating wavelength, and regions of minimum and maximum motion sensitivity repeat at range intervals of one-eighth wavelength. In this application, the range to the target casualties cannot be controlled. Therefore, the existence of ranges of minimum motion sensitivity (or critical ranges) makes it extremely difficult to reliably detect small motions such as heartbeat or shallow breathing. In addition, motions detected for more pronounced events such as normal or deep breathing can be distorted. It would be desirable to avoid any signal distortion since the effectiveness of some of the signal processing algorithms being considered for use could be degraded.

When quadrature detection is used, two detection channels are available. One channel contains the cosine and the second channel contains the sine of the desired motion information. There are never critical range problems when detecting small motions using quadrature channels since the sensitivity of one channel is at a maximum if the sensitivity of the second channel is at a minimum. In addition, larger motions can be detected without distortion because the sine-cosine channels can be processed to directly obtain the desired motion-related information.

A number of techniques can be used to implement quadrature detection channels. One method described in the first Annual Progress Report [1] involved implementing the quadrature channels at the RF level. However, this can prove difficult because of the additional RF hardware needed and the requirement that the relative phases of numerous RF signals be carefully controlled. Quadrature channels can also be implemented at the IF level if a superheterodyne approach is being used. However, as noted previously, superheterodyne techniques can be cumbersome.

With FM-CW techniques, quadrature detection channels can be implemented without requiring the use of complex RF or IF instrumentation. This is accomplished by frequency modulating the transmitter in a manner that essentially causes the locations of the points of minimum and maximum sensitivity to vary with time. With appropriate demodulation, this permits the generation of the desired sine-cosine channels. An analog switch-based correlator is being used to perform the needed demodulation in the current prototype system. It should be noted that some knowledge of the target range is required in order to derive the desired sine and cosine channels. However, the required range information is automatically provided as a result of the range-gating scheme being used in the prototype system. Range-gating is discussed in the next part of this report.

3. Range-Gating using FM-CW

An ability to reduce the effects of close-in clutter was a benefit of using FM-CW techniques that was discussed in the first technical report. However, this capability has been greatly refined during the past year and the current FM-CW system actually permits an effective level of range-gating. That is, the current system is able to selectively examine targets located at specific ranges. This capability significantly improves the potential clutter rejection capabilities of the prototype system since return signals received from objects at ranges different than the target will be strongly attenuated.

Range-gating is accomplished by comparing the target return signal (which has been delayed by an amount of time proportional to the target range) with a suitable reference signal and processing only those returns having the proper delay and thus the proper range. This requires that some type of timing mark be placed on the transmitted signal. A suitable timing mark can be placed by using a pulse modulation approach, a frequency modulation approach, or a combination of these two approaches. When a frequency modulation approach is used, the length of the range cells that can be selected (i.e., range resolution) is determined by the amount of frequency deviation. The frequency deviation required to obtain various levels of range resolution are shown in Table 1. Review of various product literature indicates that 35-GHz solid-state oscillators capable of deviating over a frequency range of 500 MHz are currently available. With 500 MHz of frequency deviation, Table 1 shows that a range resolution of ± 0.15 meters could be obtained.

Measurements with the voltage tunable 35-GHz oscillator being used in the current prototype system indicate that it can be electronically tuned over a frequency range as large as 40 MHz. Therefore, the prototype system has a potential range resolution capability of ± 1.9 meters. A frequency deviation of only 20 MHz is currently being used. However, the ± 3.8 meter range resolution resulting from 20 MHz of deviation has proven adequate in most field tests. In addition, the smaller deviation simplifies system operation since higher range resolution would require the target's range to be known with greater precision. An excellent demonstration of the range-gating capabilities of the current prototype system is given in the discussion of experimental results presented later in this report.

TABLE 1

RANGE RESOLUTION BANDWIDTH REQUIREMENTS

FREQUENCY DEVIATION (MHZ)	RANGE RESOLUTION (METERS)
1000	± 0.075
500	± 0.15
100	± 0.75
50	± 1.5
40	± 1.9
20	± 3.8
10	± 7.5
1	± 75

C. Homodyne Receiver

A homodyne demodulation approach is being employed in the receiver in the prototype EM-based lifeform monitor. Homodyne approaches are convenient since they permit a single RF source to be used for both the transmitter signal which is beamed at the target and the reference (or injection) signal which is mixed with the target return signal for demodulation and information recovery. The use of a single RF source is beneficial since it results in coherent operation if the source is phaselocked. Even with unlocked RF sources, near-coherence can be maintained for return signals from nearby targets since the phase-noise terms of the return signal and the reference signal will be nearly identical and will therefore mutually cancel.

Because the frequency modulation scheme being employed in the prototype system greatly reduces flicker noise, a convenient single-ended mixer is being used for demodulation instead of the balanced mixer configurations normally required with unmodulated CW approaches. As previously noted, the demodulated information output by this mixer will be at a harmonic of the modulating frequency. Therefore, a low-noise amplifier was built and attached to the mixer's output port. Because of the high gain of this amplifier, it does little to degrade the noise figure of the homodyne receivers and receiver performance is largely dependent on the performance of the front-end mixer. Since the receiver performance is determined by the front-end mixer, a great deal of effort has been made to learn about factors that affect the performance of single-ended mixers.

One simple but important fact is that the performance of single-ended mixers can be accurately controlled by adjusting either the reference signal level or the applied bias current level. Notably, with selection of a suitable bias current, near-optimal mixer performance can be achieved using relatively low reference signal levels. By employing a low reference signal level, the amount of output power required from the transmitter can be reduced (which improves system efficiency, an important consideration for battery-powered systems). Often, this also means that the amount of power transmitted at the target can be reduced. The use of lower transmitted power levels is of course extremely desirable from the viewpoint of personnel safety.

Efforts to develop a high-performance homodyne receiver on this program have progressed well. For example, the excellent performance of the receiver in the current prototype system permits an effective transmitted power level of only 0.31 milliwatts to be used for tests performed from a target range of 50 meters. With further improvements in the mixer biasing techniques currently being employed, it is possible this figure can be lowered to 0.1 milliwatts. These low power levels should result in extremely safe system operation, even at close ranges.

D. Lens Antennas

A considerable effort has gone into the design and development of the lens antennas being used in the prototype system. The performance of these antennas is critical since they control the target area scanned by the EM-based lifeform monitor. Ideally, the scanned target area should be minimized to reduce the effects of clutter from grass, trees, and other clutter sources. This requires that the system antennas have a narrow beamwidth (i.e., high directivity) and low sidelobe radiation.

The lens antennas being utilized in the prototype system are highly efficient scalar feed horn/dielectric lens configurations arranged as shown in Figure 2. The scalar feed horn, which was designed at Georgia Tech, was electro-formed at a custom-fabrication house. The beam from this feed horn has extremely low sidelobe radiation but has a relatively wide 3-dB beamwidth (approximately 20 degrees) due to its small one-inch aperture. However, the diverging beam from the scalar feed horn is collimated or "corrected" by refraction produced by the dielectric lens. The scalar feed horn has been designed so the illumination pattern at the outside edge of the dielectric lens is approximately 20 dB below the main beam. This results in an extremely well-collimated beam that also has low-sidelobe radiation (typically 20-30 dB below the main beam) [7].

Two different dielectric lenses (six- and nine-inch diameter) have been designed and fabricated in-house. Each lens is compatible with the single scalar feed horn. The six-inch lens has a measured 3-dB beamwidth of approximately 3.5 degrees while the nine-inch lens has a computed 3-dB beamwidth of approximately 2.3 degrees [8]. Examples of the target areas that would be scanned at different ranges using the six- and nine-inch lenses are shown in Figure 3. The six-inch lens has been used in the field tests conducted on this program. The maximum range used in these field tests has been 50 meters. At this range, the beamwidth of the six-inch lens appears to be adequate. However, as the range is increased to 90-100 meters, the bottom diagram in Figure 3 shows that a typically-sized person would occupy a smaller portion of the beam produced by the six-inch lens and it may prove necessary to use the nine-inch lens when operating at longer ranges.

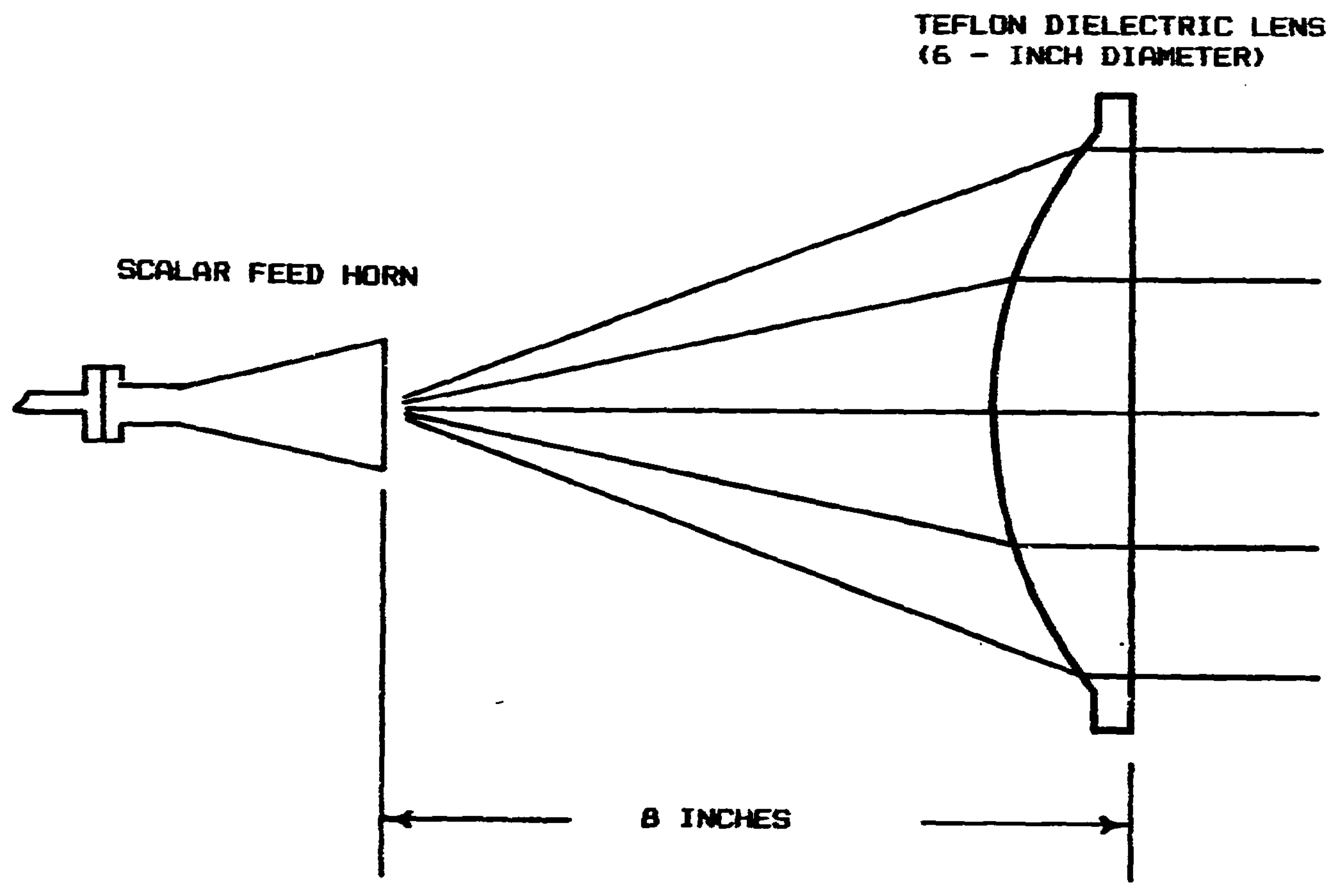


Figure 2. Scalar feedhorn and dielectric lens configuration comprising antenna being employed in prototype EM-based lifeform monitor.

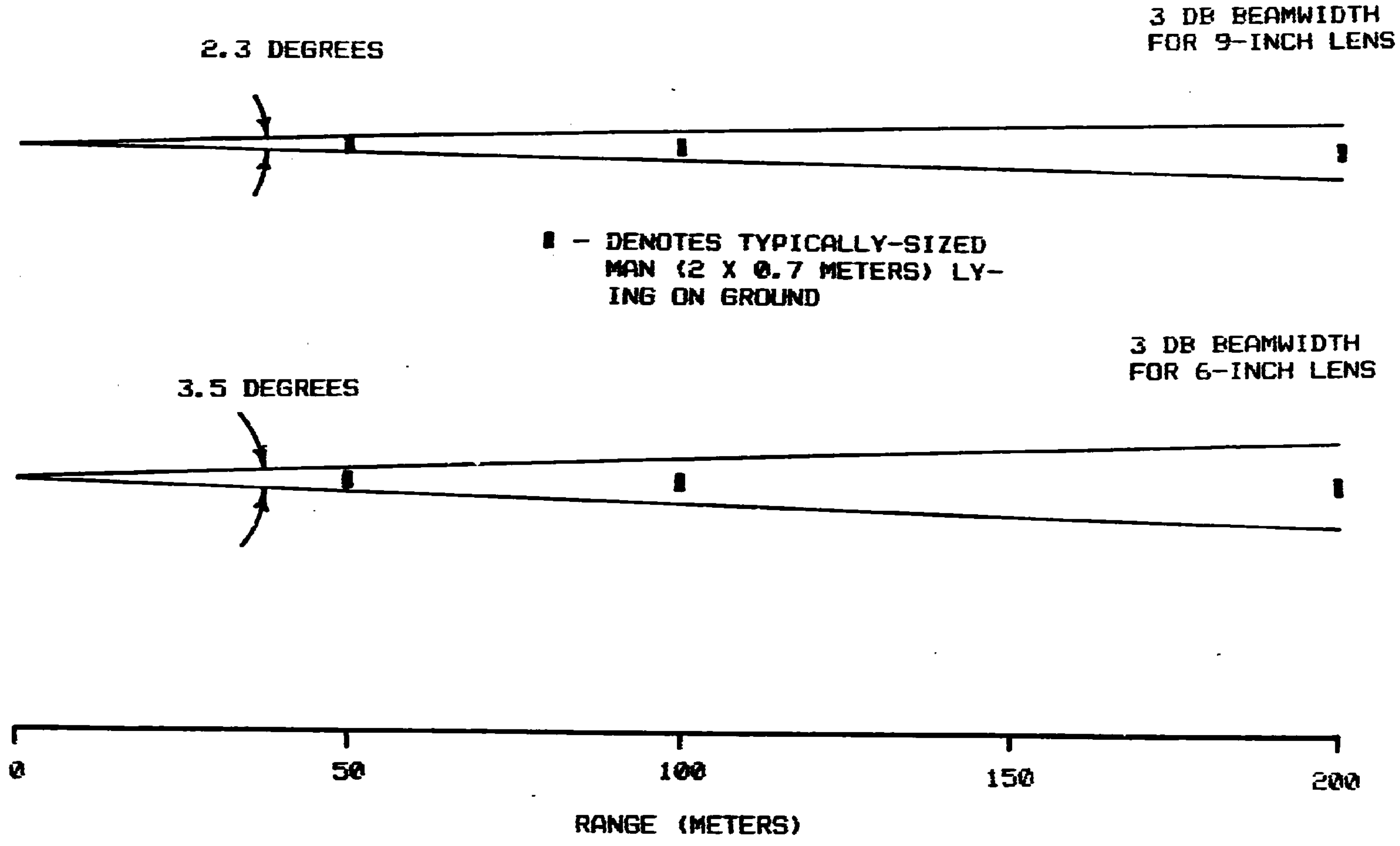


Figure 3. Overhead view of 3-dB beamwidths for six- and nine-inch lens at 35 GHz.

The lens antenna is the largest single component in the prototype system. If the antenna size required to achieve the narrow beamwidths necessary for longer-range detection becomes prohibitive, it may be desirable to consider using a higher operating frequency. For example, at 94 GHz, a six-inch diameter lens would produce an extremely narrow 3-dB beamwidth of approximately 1.3 degrees if a suitable feedhorn were employed. If a decision is made to change to a higher operating frequency, it should be noted that the existing lenses and lens housings have been designed so they could be used at significantly higher frequencies by simply changing to a higher frequency feedhorn.

E. Description of Prototype EM-Based Lifeform Monitor

The current prototype EM-based lifeform monitor is a compact, battery powered system that operates at a millimeter-wave frequency of 35 GHz. The high operating frequency enhances motion sensitivity (shorter wavelengths result in improved motion sensitivity) and makes it possible to achieve high antenna directivity using small antennas. The prototype system also uses a FM-CW scheme that (1) significantly reduces the degrading effects of flicker noise, (2) allows derivation of quadrature detection channels, and (3) enables an effective level of range-gating.

A block diagram of the prototype system is presented in Figure 4. The transmitter depicted in this figure is a 35-GHz voltage tuned oscillator (VTO) with an output power level of 50 milliwatts. Frequency modulation is achieved by inputting a suitable signal from the modulator into the VTO's varactor tuning port. Range-gating is achieved by appropriately adjusting the parameters of the modulating waveform. Various types of modulating waveforms including sinusoids, ramps, and modified ramps, are currently being investigated. The frequency of the modulating signal is extremely stable since it is referenced to a 1 MHz crystal.

The frequency modulated 35-GHz signal outputted by the VTO is passed through the attenuator shown in Figure 4 to achieve the desired transmitted power level. A typical setting for this attenuator is 22 dB which would result in a transmitted power level of approximately 0.31 milliwatts. The attenuated signal then passes through the junction circulator with only minor insertion loss (less than 0.5 dB). This circulator is a compact, 3-port device that isolates the mixer from any signals traveling in the forward direction (i.e., from the transmitter to the antenna) but efficiently couples into the mixer all signals traveling in the reverse direction (i.e., from the antenna to the transmitter).

After leaving the circulator, the transmitter signal passes through the oscillator injection network. This network reflects a small portion (typically 5-10 percent) of the transmitter signal back into the 3-port junction circulator. The circulator couples this reflected signal into the mixer where it serves as a reference signal for demodulation of received

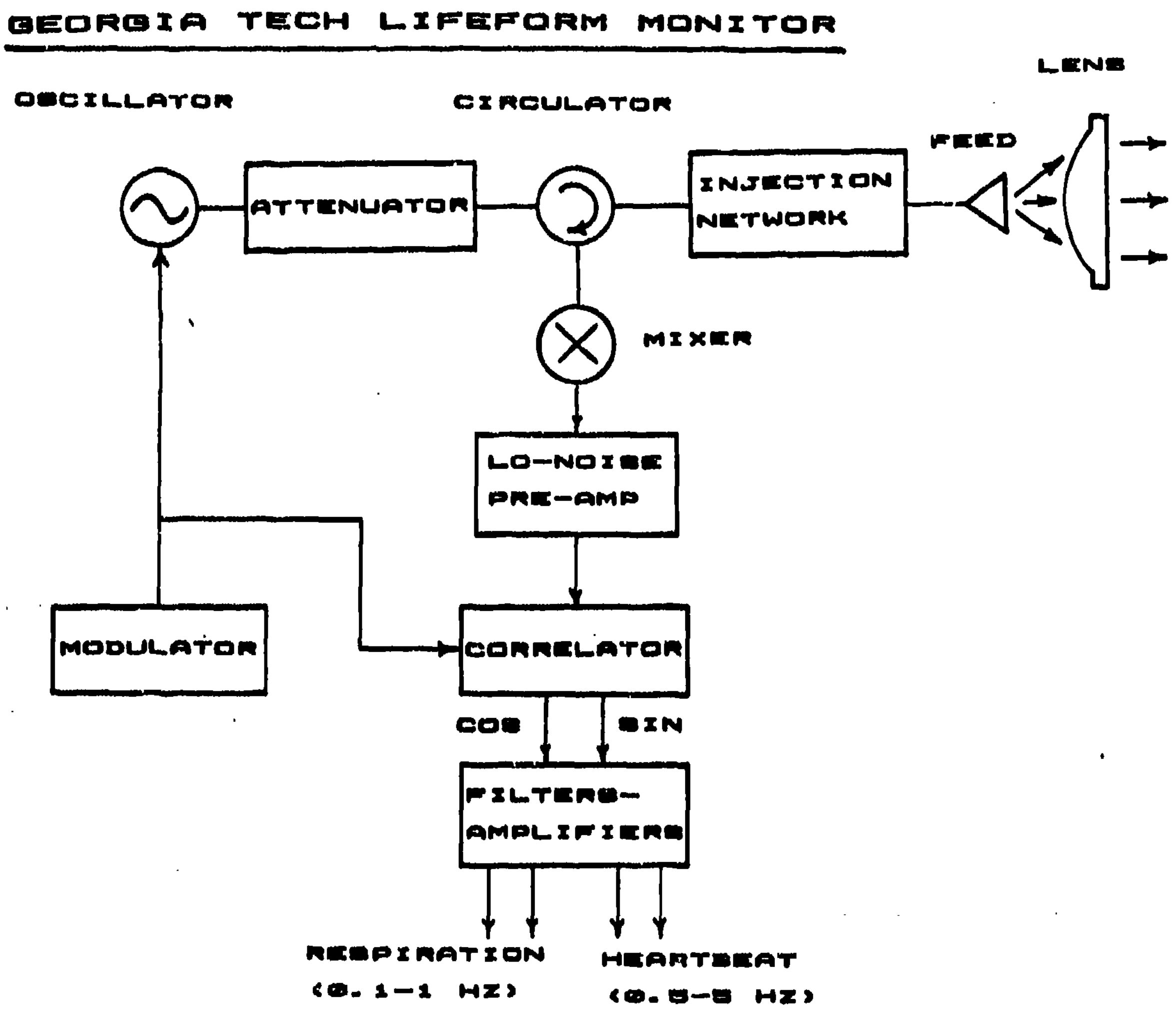


Figure 4. Block diagram of 35 GHz prototype EM-based lifeform monitor developed at Georgia Tech.

return signals. The unreflected transmitter signal passes through the oscillator injection network to the lens antenna from which it is beamed at the target of interest.

Any motions associated with the target will cause phase modulation of the signal scattered by the target (see equation 8 in the first Annual Technical Report). A portion of this phase-modulated signal will reflect back at the lens antenna where it will be received and then coupled through the junction circulator to the mixer where homodyne demodulation takes place. The demodulated information from the mixer will be at a harmonic of the modulating frequency. The eighth harmonic (28 kHz) is being used in the current prototype system. Because of the unique nature of the modulating waveform being used, the demodulated signal can be synchronously detected in the correlator in a manner that permits sine-cosine channels to be derived. The reference signal required for synchronous detection of the demodulated signal is provided by the crystal-referenced modulator network. The range information required to achieve sine-cosine channels is automatically provided as a result of the range-gating that is being performed.

The sine-cosine channels outputted by the correlator each contain respiratory- and cardiac-related parameters. As shown in Figure 4, these parameters are being separately processed by passing the sine-cosine channels from the correlator through appropriate amplifiers and filters. The desired respiratory- and cardiac-related motions are then observed on a strip-chart recorder or storage oscilloscope. A more detailed diagram of one of the filter-amplifier networks being utilized is shown in Figure 5. This network essentially passes the sine-cosine channels through selected bandpass filters. The filter characteristics (cutoff frequencies and filter roll-offs) used in these networks were selected using the information shown in Figure 6. This information indicates the selected filter characteristics should be adequate for a wide range of normal and abnormal respiratory and cardiac rates.

It may be noted that the filter bandwidths being used for heartbeat are five times wider than that being used for respiration. It is the combined effect of the wider filter bandwidths (which results in more noise) and weaker signal strengths (the cardiac signals appear to be 5-10 times weaker than the

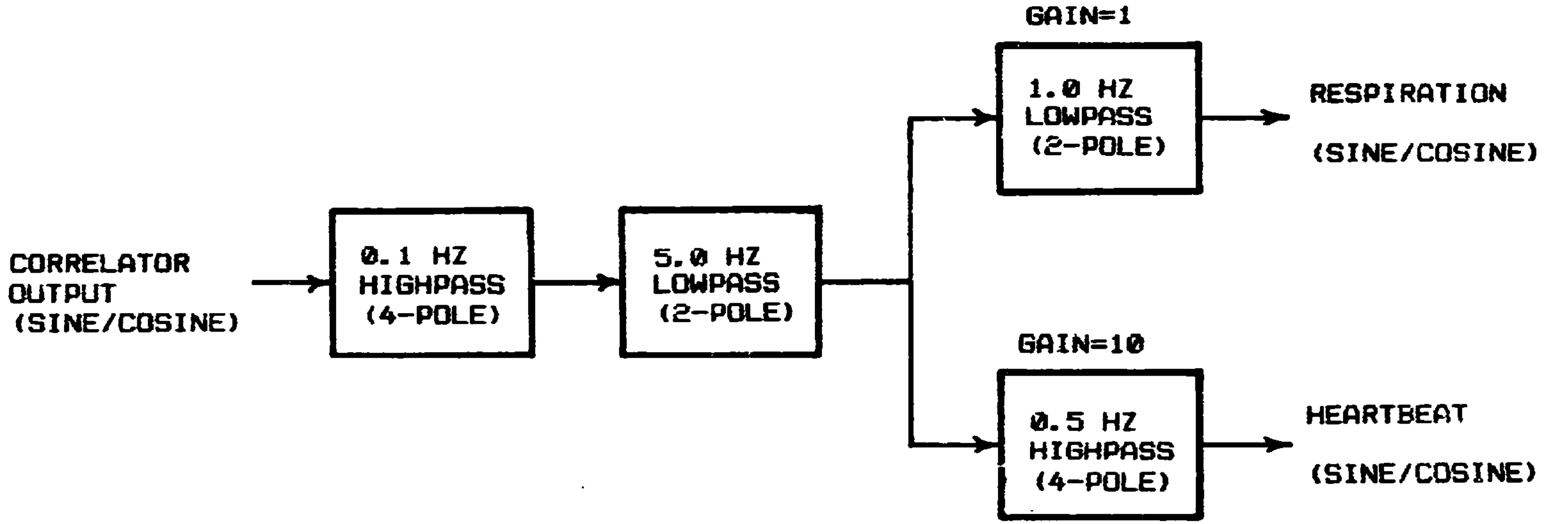


Figure 5. Block diagram of one of the amplifier-filter networks being used to process respiration and heartbeat signals. Respiration signals are bandpass filtered from 0.1 - 1.0 Hz. Heartbeat signals are bandpass filtered from 0.5 - 5.0 Hz.

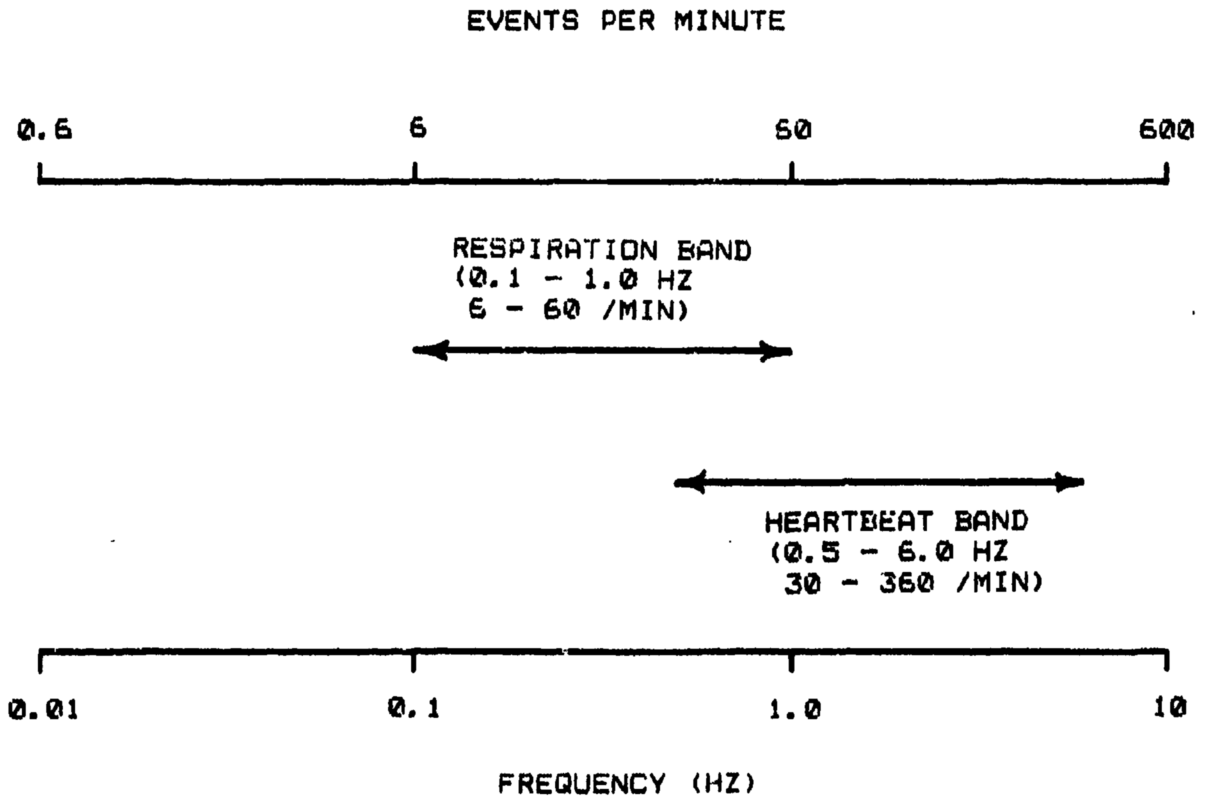


Figure 6. Time-domain and frequency-domain factors considered for selection of filter characteristics.

respiratory signals) that makes heartbeat more difficult to detect than respiration. However, factors such as faster, more periodic signatures should enhance the ability to detect heartbeat once a more effective signal processing system is implemented. With implementation of a suitable signal processing system, the degree of filtering shown in Figure 5 will not be necessary. However, some degree of filtering will likely be maintained to enable real-time, manual observation of data and to provide some signal conditioning for the final signal processor.

F. Experimental Results

During the first 21 months of this program, the range capability of the prototype EM-based lifeform monitor has been steadily increased from an initial limit of only 5 meters to the current maximum tested range of 50 meters. A graph showing the improvements made in system performance as well as the technical advancement responsible for the improvement is shown in Figure 7. This graph shows it has been the combined effects of a number of different factors that have enabled the current level of system performance to be attained. System performance has been evaluated through laboratory and field measurements of respiration and heartbeat (subjects held their breath during the heartbeat measurements). Both the respiration and heartbeat of supine (lying on back) subjects currently can be detected from a range of 50 meters. However, respiration can be detected much more reliably than can heartbeat.

The most extensive field tests were conducted on the roof of the building housing our laboratory. Dimensions of this roof permitted a maximum test range of 50 meters and tests were performed over ranges of 30, 40, and 50 meters. An effective total radiated power level of only 0.05 milliwatts was used for the tests performed from 30 meters while 0.31 milliwatts was used for the 40 and 50 meter tests. The prototype system was mounted on top of a surveyor's tripod during the rooftop tests. This placed the system antenna approximately five feet higher than the test subjects, who were lying on the roof. Examples of results from the rooftop tests are discussed in the following paragraphs.

An example of respiration-related motion detected from 30 meters is shown in Figure 8. Both sine and cosine quadrature channels are shown ("Ch.1" can be considered as the sine channel and "Ch.2" can be considered as the cosine channel). A number of interesting observations can be made about the data in Figure 8. One simple point is that the respiration frequency is approximately 0.3 Hz. Therefore, the 0.07-2.0 Hz filter bandwidth used in these tests appears appropriate. It can also be seen that the information on both the sine and cosine channels is relatively strong. This indicates that this particular target range was between points of minimum and maximum motion

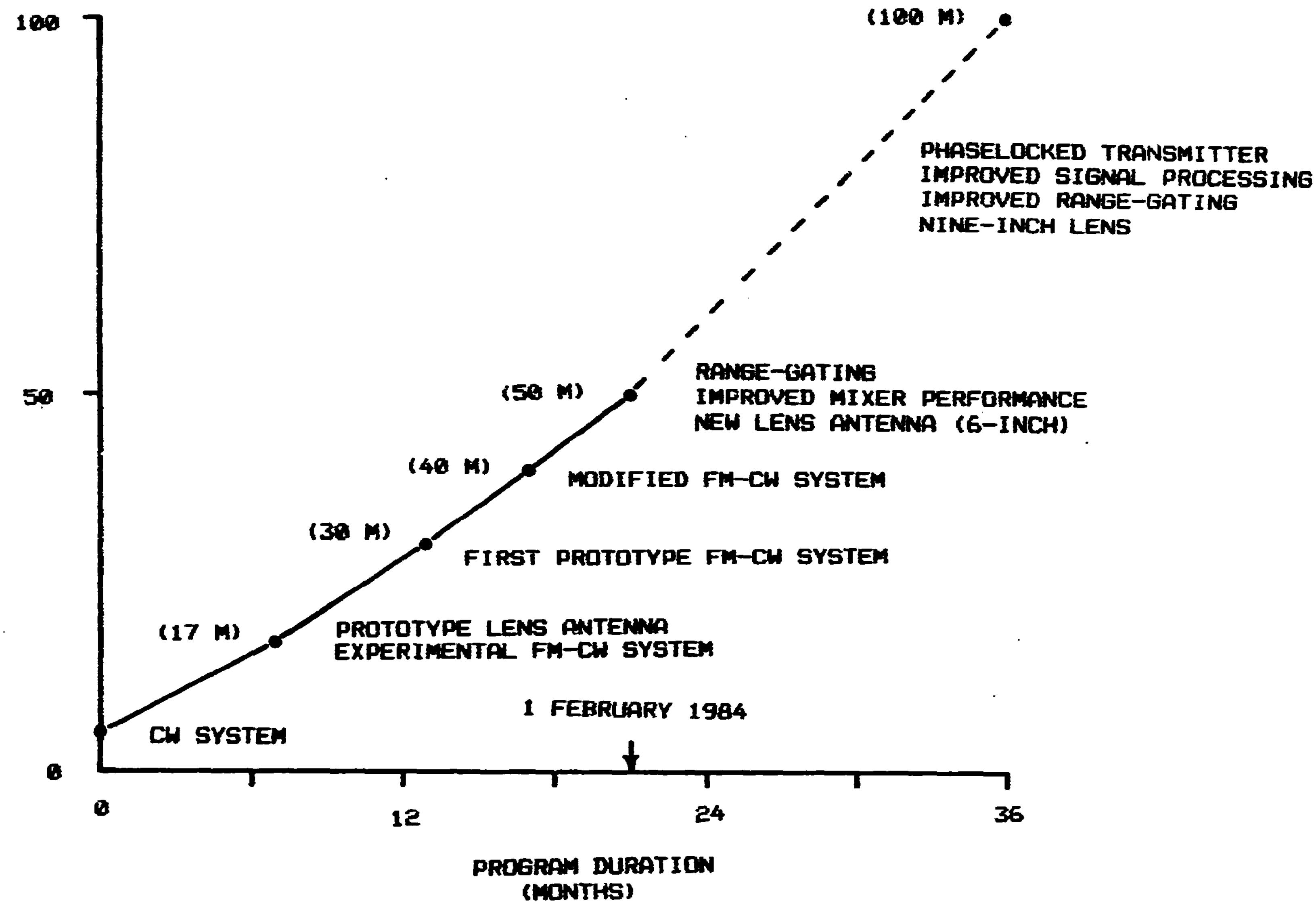
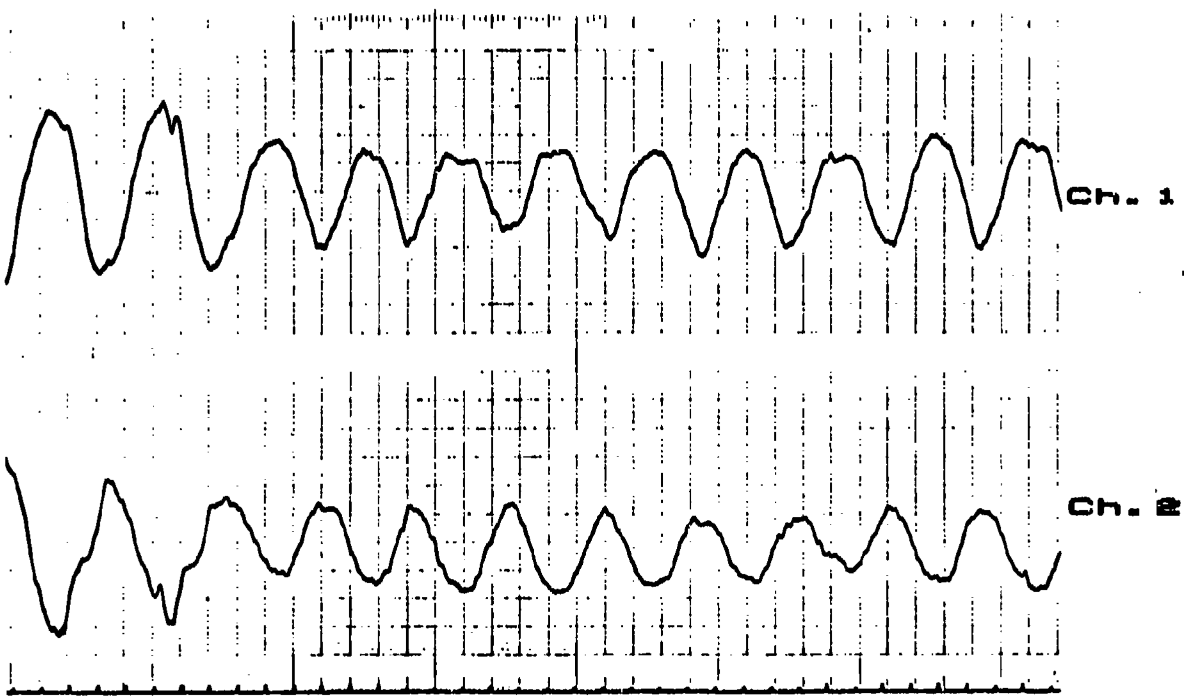


Figure 7. Graph of program progress.

CODE: 221-4 POWER: 0.05 mW

RANGE: 30 M SUBJECT: JS, SUPINE, SIDE

FREQ: 35 GHZ FILTERS (HZ): HP 0.07 LP 2.0



1 Second/Marker

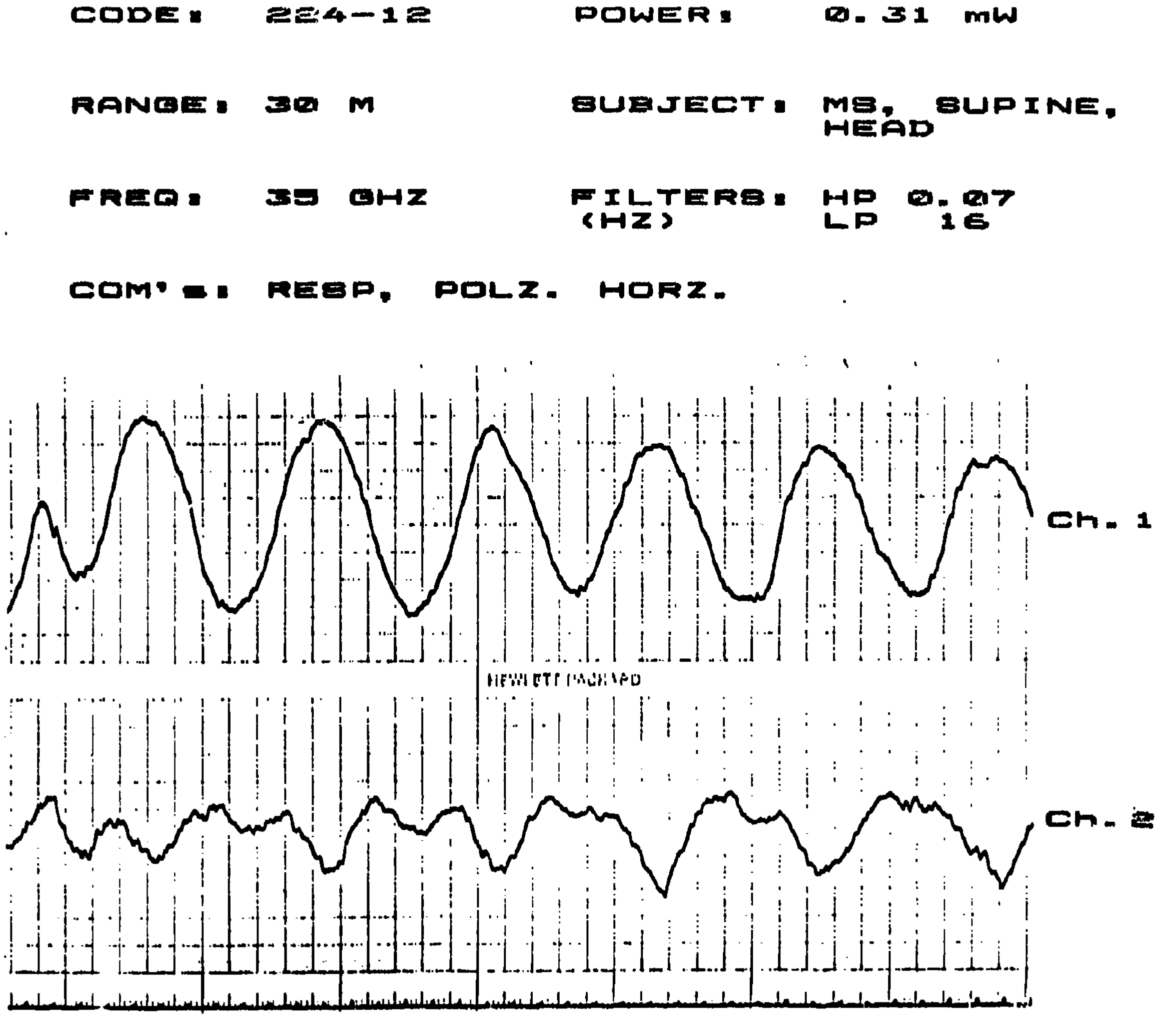
Figure 8. Respiration detected from 30 meters for subject positioned with left side toward antenna.

sensitivity for both the sine and cosine channels. In addition to being relatively strong, neither the sine or cosine channel information appears to be distorted. This indicates the respiration-related motion seen by the EM-based lifeform monitor was less than one-eighth wavelength or approximately one millimeter.

The data in Figure 8 were taken with the subject lying perpendicular to the antenna beam (subject side toward antenna). In general, this was the body orientation where respiration was most reliably detected. However, respiration also could be reliably detected for other body orientations. Respiration-related motion detected from 30 meters for a subject lying perpendicular to the antenna beam with his head toward the antenna is shown in Figure 9. In this case, it can be seen that the Ch.1 information is extremely strong and undistorted. Conversely, the Ch.2 information appears to be serverely distorted. In fact, the respiration rate on Ch.2 actually appears to be doubled during the first few respiration cycles shown. As noted previously, this type of distortion of large motions is a key problem of single channel detection systems.

Respiration-related motion detected from 30 meters for a subject lying perpendicular to the antenna beam with his feet toward the antenna is shown in Figure 10. In this case, the respiration signal is clearly evident on Ch.1. However, the detected motion appears weaker than that detected in the previous measurements. Further examination of Figure 10 shows that respiration is not present on Ch.2. This indicates the target range was at a point of minimum motion sensitivity for Ch.2. This demonstrates why the performance of systems using single channel detection can be unreliable when the target motion is small.

An example of cardiac-related motion detected from a range of 30 meters is shown in Figure 11. It can be seen from the data in this figure that heartbeat is not detected as strongly as respiration; however, heartbeat can clearly be detected. This is apparent if the data in Figure 11 are compared to the baseline data shown in Figure 12. Although the heartbeat data in Figure 11 are relatively weak, they do have a very distinct and repeatable pattern. As noted previously, these characteristics should aid in detecting heartbeat once a suitable signal processor is implemented.



1 Second/Marker

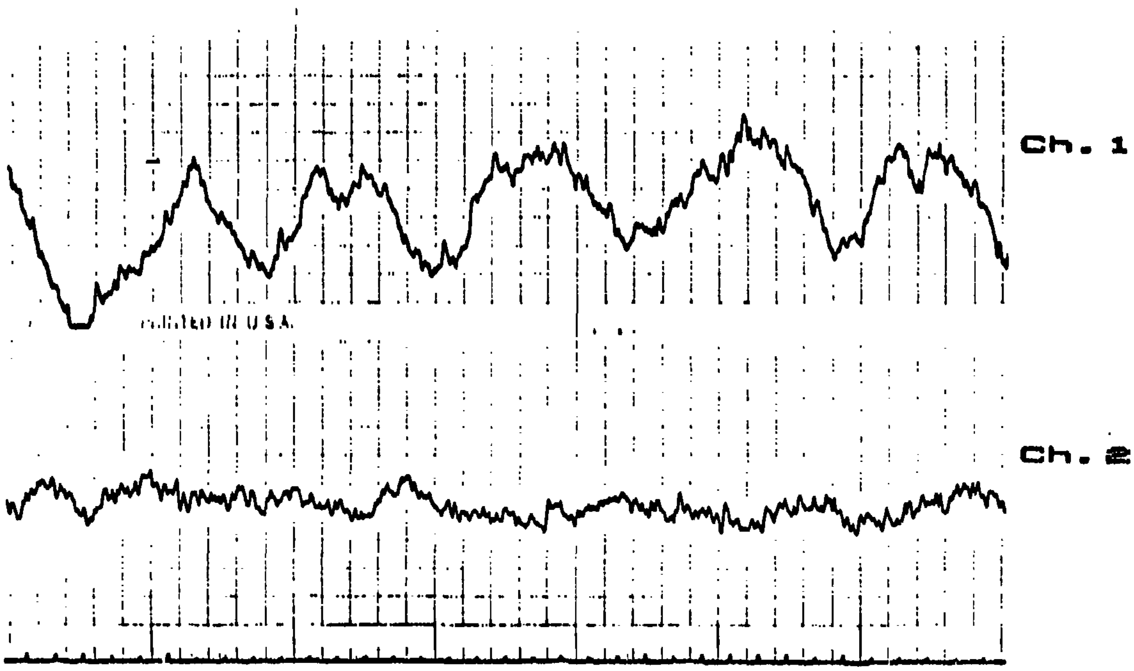
Figure 9. Respiration detected from 30 meters for subject positioned with head toward antenna.

CODE: 224-12 POWER: 0.31 mW

RANGE: 30 M SUBJECT: MS, SUPINE, FEET

FREQ: 35 GHZ FILTERS: (HZ) HP 0.07 LP 16

COM'S: RESP, POLZ. HORZ.



1 Second/Marker

Figure 10. Respiration detected from 30 meters for subject positioned with feet toward antenna.

CODE: 221-5 POWER: 0.05 mW

RANGE: 30 M SUBJECT: JS, SUPINE, SIDE

FREQ: 35 GHZ FILTERS: (HZ) HP 0.07 LP 2.0

COM'S: HB

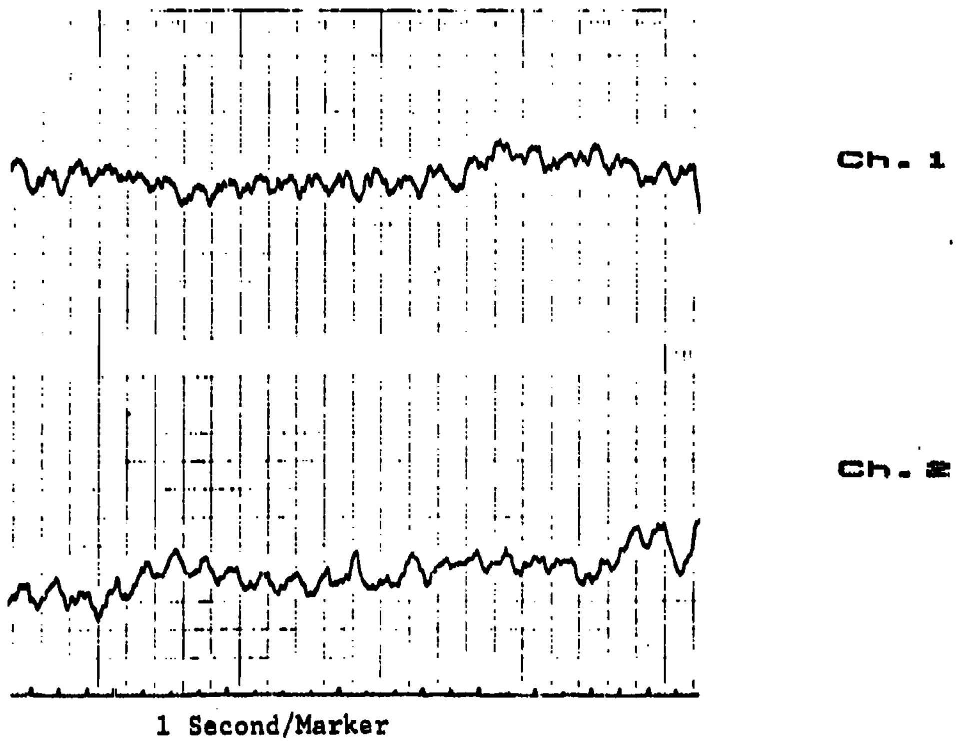


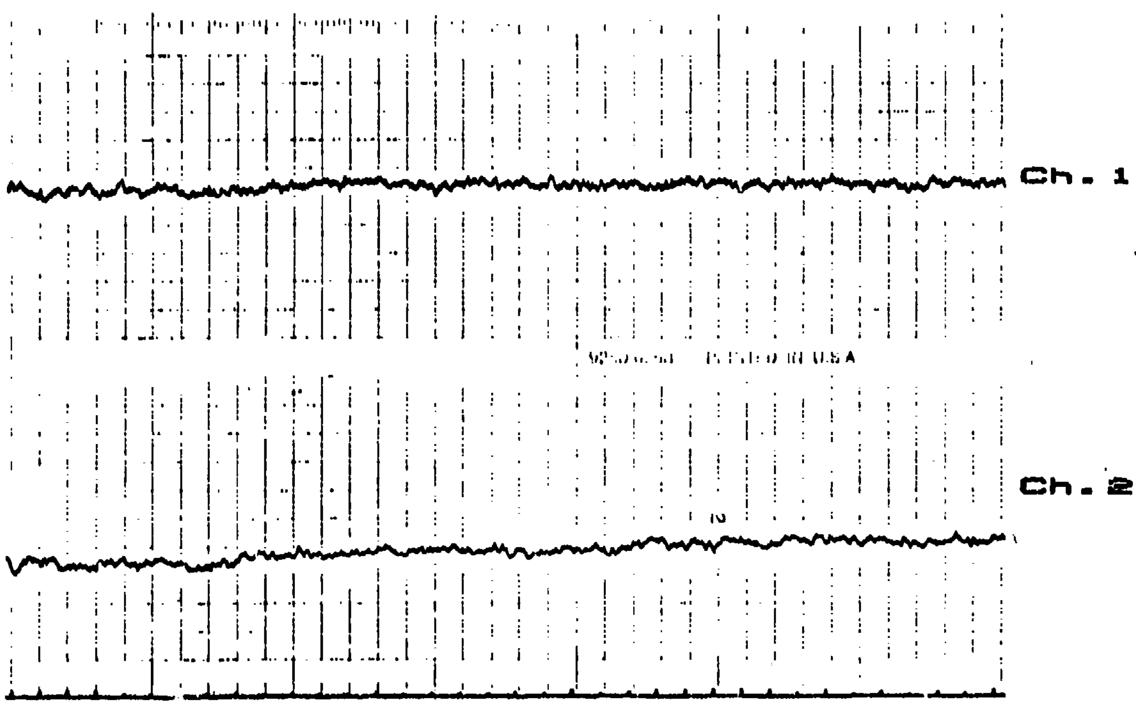
Figure 11. Heartbeat detected from 30 meters using narrow-band filters (subject holding breath).

CODE: 221-5 POWER: 0.05 mW

RANGE: 30 M SUBJECT: JS, SUPINE, SIDE

FREQ: 35 GHZ FILTERS (HZ): HP 0.07 LP 2.0

COM'S: BASELINE



1 Second/Marker

Figure 12. Baselines for heartbeat data shown in Figure 11.

An example of respiration-related motion detected from a range of 40 meters is presented in Figure 13. Respiration can clearly be detected on Ch.2 in this figure but cannot be seen on Ch.1. The absence of a respiration signal on Ch.1 again demonstrates the potential range-dependent motion sensitivity problem of single channel systems. A second example of respiration-related motion detected from 40 meters is presented in Figure 14. In this case, the respiration signal can be clearly seen on both Ch.1 and Ch.2 It is interesting to observe that the respiration frequency is approximately 0.21 Hz in Figure 13 and approximately 0.31 Hz in Figure 14. This is a relatively large difference considering the two sets of measurements were taken only minutes apart using the same test subject. If this type of variation occurs in normal subjects, it appears the final signal processor will have to be capable of handling an extremely wide range of respiration rates.

An example of cardiac-related motion detected from 40 meters is shown in Figure 15 where the heartbeat signal is very clear on Ch.2. It may also be present on Ch.1, but this is difficult to judge because noise is also present. The noise observed on Ch.1 appears to have been subject-related because it is not present in the baseline data shown in Figure 16 which was taken with the subject out of the main antenna beam. Since the wind was very strong during these measurements (estimated wind speeds of 10-20 MPH), it is suspected the observed noise was due to the subject's clothing blowing in the wind. If clothing motion was the problem, the observed noise may be considered to be a localized clutter effect. If so, it appears (at least in this case) that the use of quadrature channels may actually aid in clutter rejection.

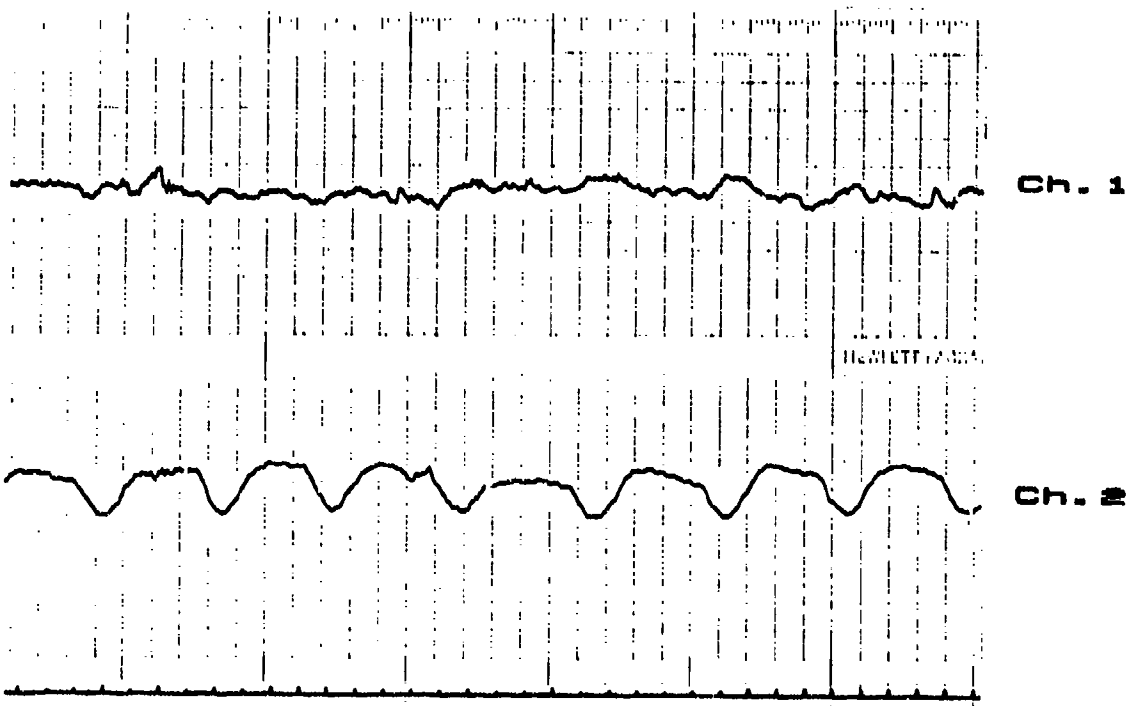
The frequency of the heartbeat signal in Ch.2 of Figure 15 is approximately 1.06 Hz. To insure that any existing high frequency components were not being suppressed, these data were taken using a relatively wide filter bandwidth of 0.07-16 Hz instead of the 0.07-2.0 Hz bandwidth used to obtain the heartbeat data in Figure 11. However, comparison of Figures 11 and 15 reveal that the heartbeat signature obtained with the wider bandwidth is not appreciably different from that previously obtained with the narrower band-filters. Therefore, it appears the upper cutoff frequency of the heartbeat filter only needs to be 2-3 times higher than the highest heartbeat frequency of interest. For example, if the highest heartbeat rate of interest

CODE: 224-4 POWER: Ø.31 mW

RANGE: 40 M SUBJECT: JS, SUPINE, SIDE

FREQ: 35 GHZ FILTERS: (HZ) HP Ø.07 LP 16

COM'S: RESP.



1 Second/Marker

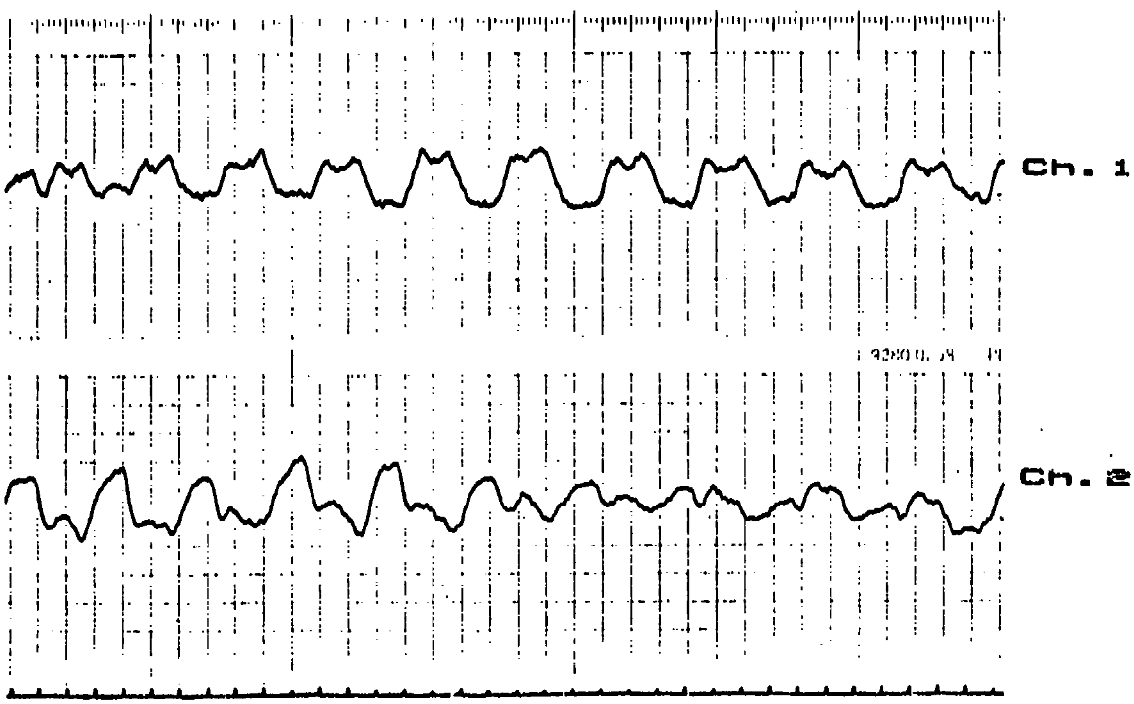
Figure 13. Respiration detected from 40 meters. No signal on Ch. 1 because of range-dependent motion sensitivity problem.

CODE: 224-3 POWER: 0.31 mW

RANGE: 40 M SUBJECT: JS, SUPINE, SIDE

FREQ: 35 GHZ FILTERS: HP 0.07
(HZ) LP 16

COM'S: RESP.



1 Second/Marker

Figure 14. Respiration detected from 40 meters. Respiration signal present on both Ch. 1 and Ch. 2.

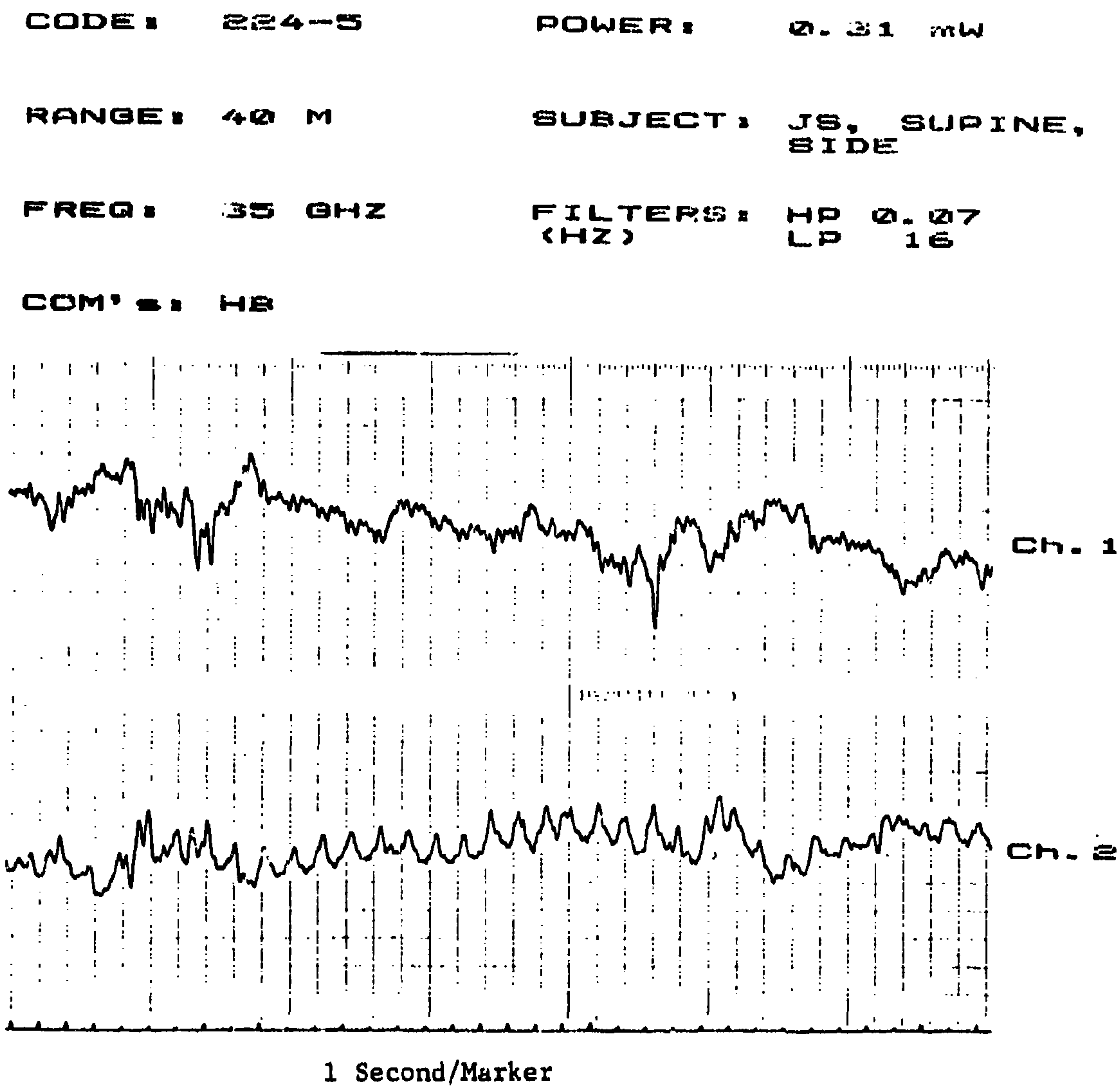


Figure 15. Heartbeat detected from 40 meters using wide-band filters (subject holding breath).

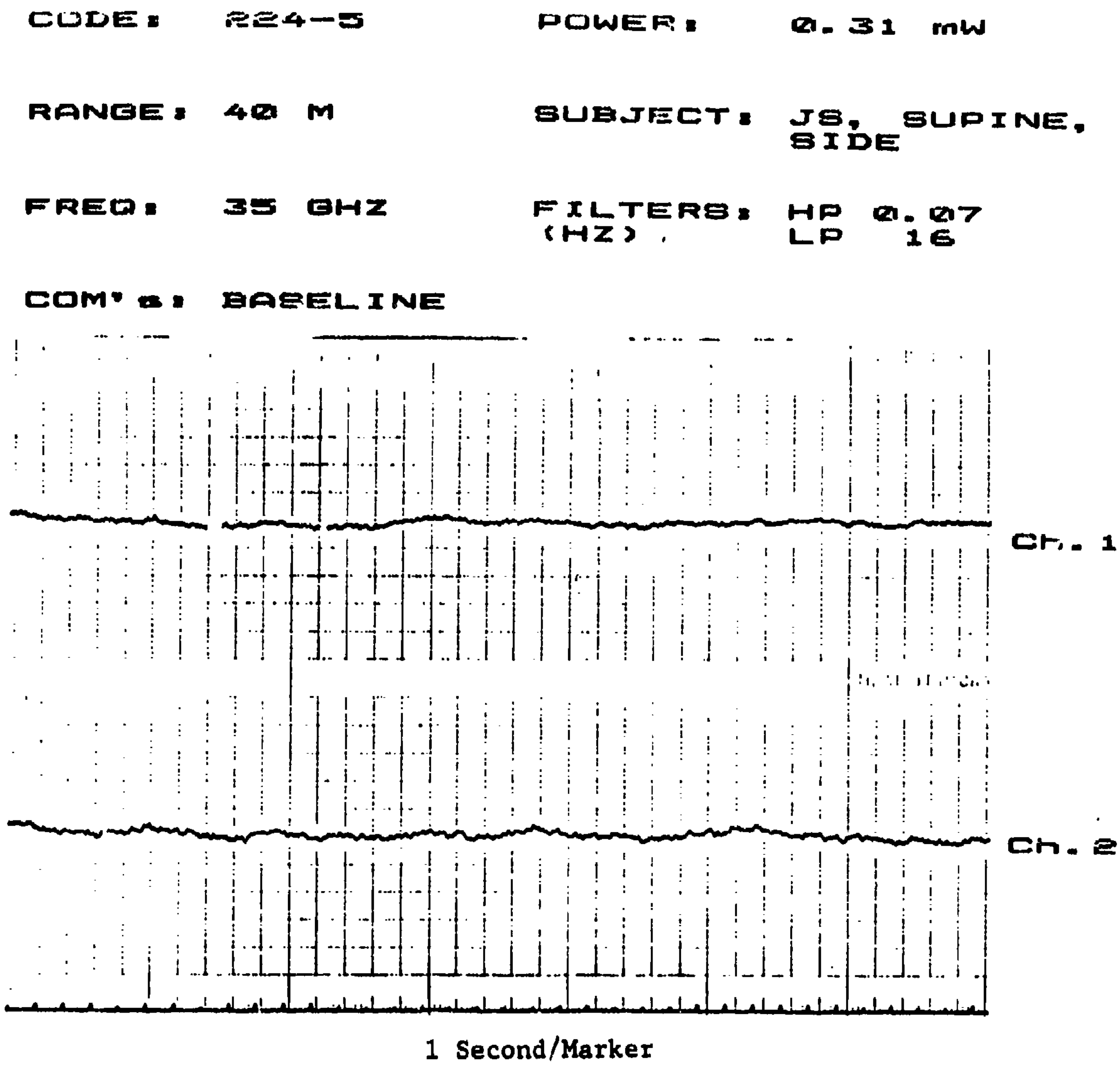


Figure 16. Baselines for heartbeat data shown in Figure 15.

was 180 beats/minute (or 3 Hz), a filter cutoff frequency in the range of 6-9 Hz would be adequate (although a higher cutoff frequency will probably be employed once a more sophisticated signal processing system is implemented).

A second set of heartbeat data taken from 40 meters is shown in Figure 17. By comparing the data in this figure to the baseline data in Figure 18, it can be seen that a heartbeat signal is present on both Ch.1 and Ch.2 with the stronger signal appearing on Ch.2. The data in Figure 17 were measured using a filter bandwidth of 1.0-16 Hz. Changing the filter's high-pass cutoff to 1.0 Hz from the previous value of 0.07 Hz noticably altered the shape of the detected heartbeat signature. Since the heartbeat frequency in this case is 1.07 Hz, it appears the high-pass nature of the 1.0 Hz filter produced some signal differentiation. This differentiation enhanced the high-frequency components of the heartbeat signal and resulted in the "spikier" signature seen in Figure 17. This type of effect eventually may prove beneficial for detection of the weaker heartbeat signal.

An example of respiration-related motion detected from 50 meters is shown in Figure 19. It should be noted that the 1.0 Hz high-pass cutoff frequency normally used in heartbeat tests was inadvertently used in these measurements. Since the repetition frequency of the observed respiration signal is only 0.25 Hz, the data in Figure 19 were being attenuated. However, a strong respiration signal can still be detected on both Ch.1 and Ch.2. The fact that the respiration signal can be detected through the 1.0 Hz filter indicates it should be feasible to apply heavy filtering to the respiration channels. This may prove helpful in reducing some of the effects of undesired noise and clutter. It also indicates that it will be extremely difficult to use conventional filtering to remove respiration signals present in the heartbeat channels.

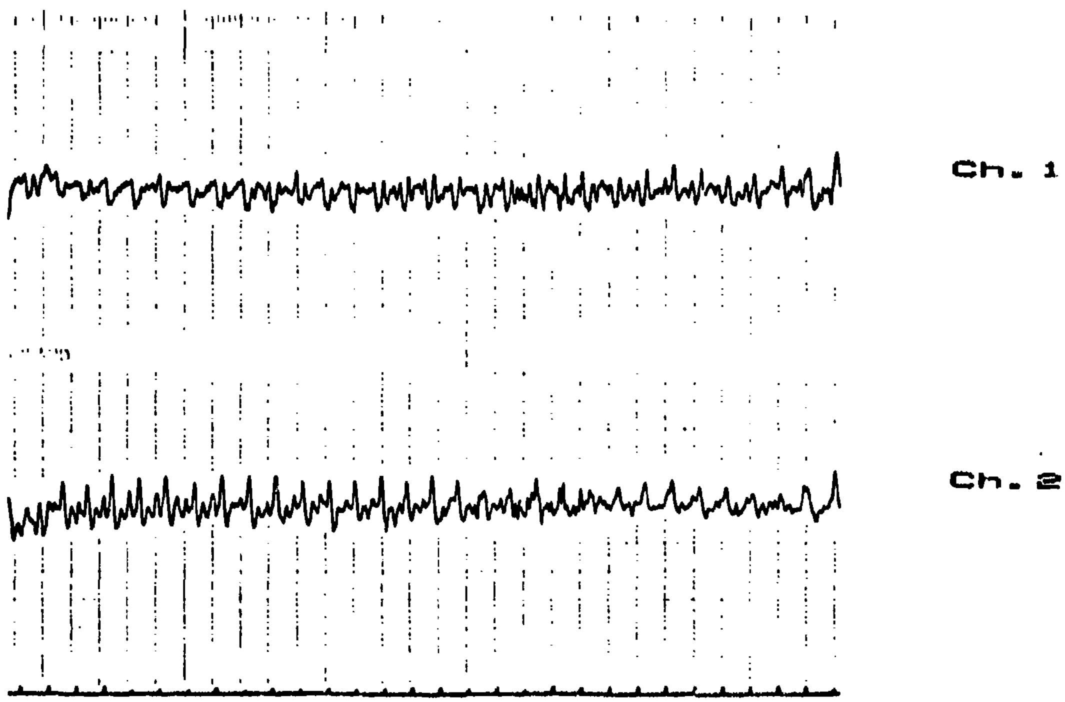
A second example of respiration-related motion detected from 50 meters is shown in Figure 20. Note that a new test subject was used for this test. The respiration signal in this case is evident only in Ch.2. The fact that the respiration signal cannot be seen on Ch.1 indicates that only a small amount of respiration-related body motion was being detected. It is not clear whether this indicates that system sensitivity is subject dependent or whether the new test subject was simply breathing more shallowly. In addition, it is possible the slower respiration frequency (approximately 0.19 Hz) could have caused the signals to be more heavily attenuated by the 1.0 Hz filter which was still in place.

CODE: 224-7 POWER: 0.31 mW

RANGE: 40 M SUBJECT: JG, SUPINE, SIDE

FREQ: 35 GHZ FILTERS: (HZ) HP 1.0 LP 16

COM'S: HB



1 Second/Marker

Figure 17. Heartbeat detected from 40 meters using 1 Hz high-pass filter (subject holding breath).

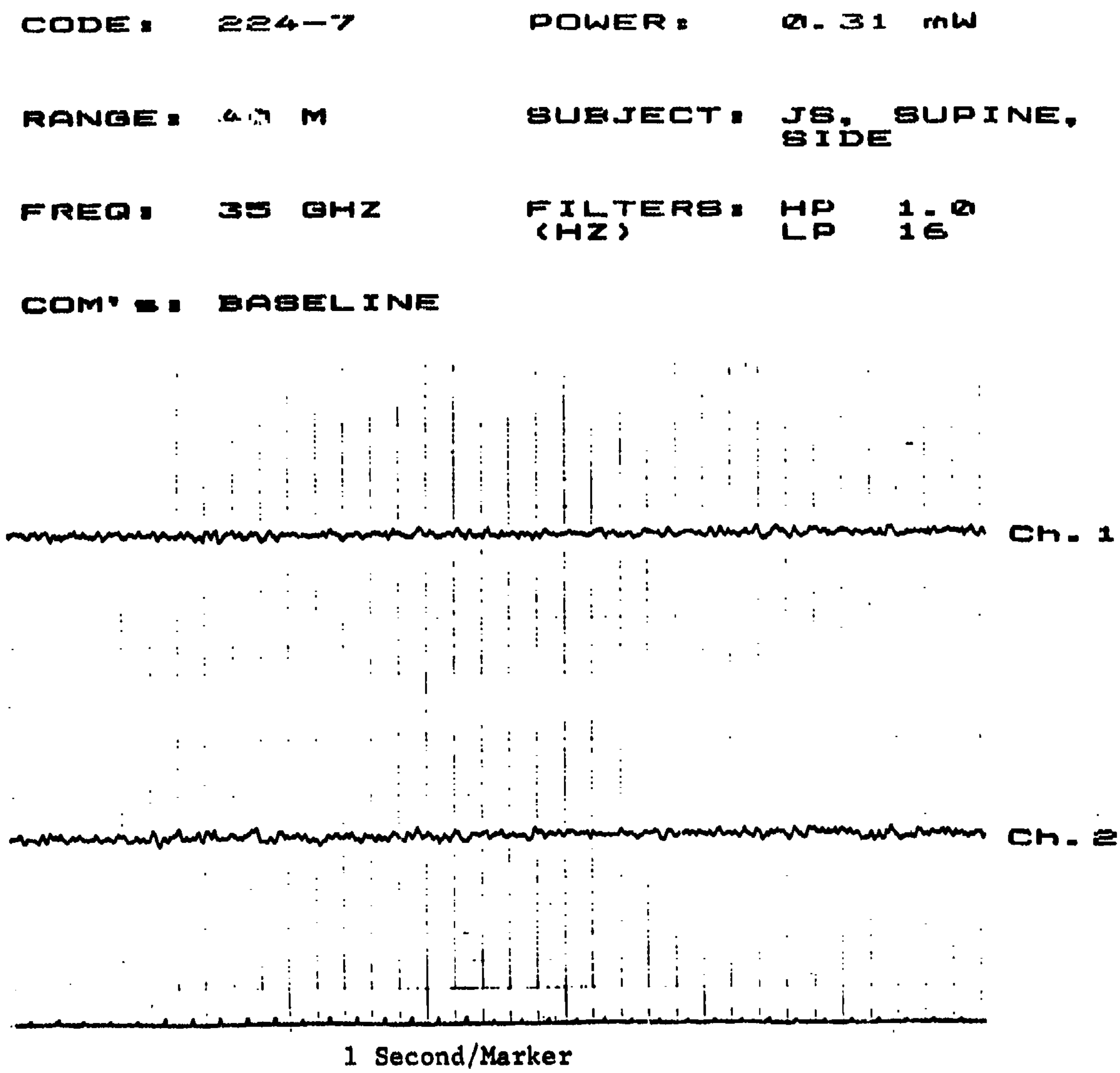


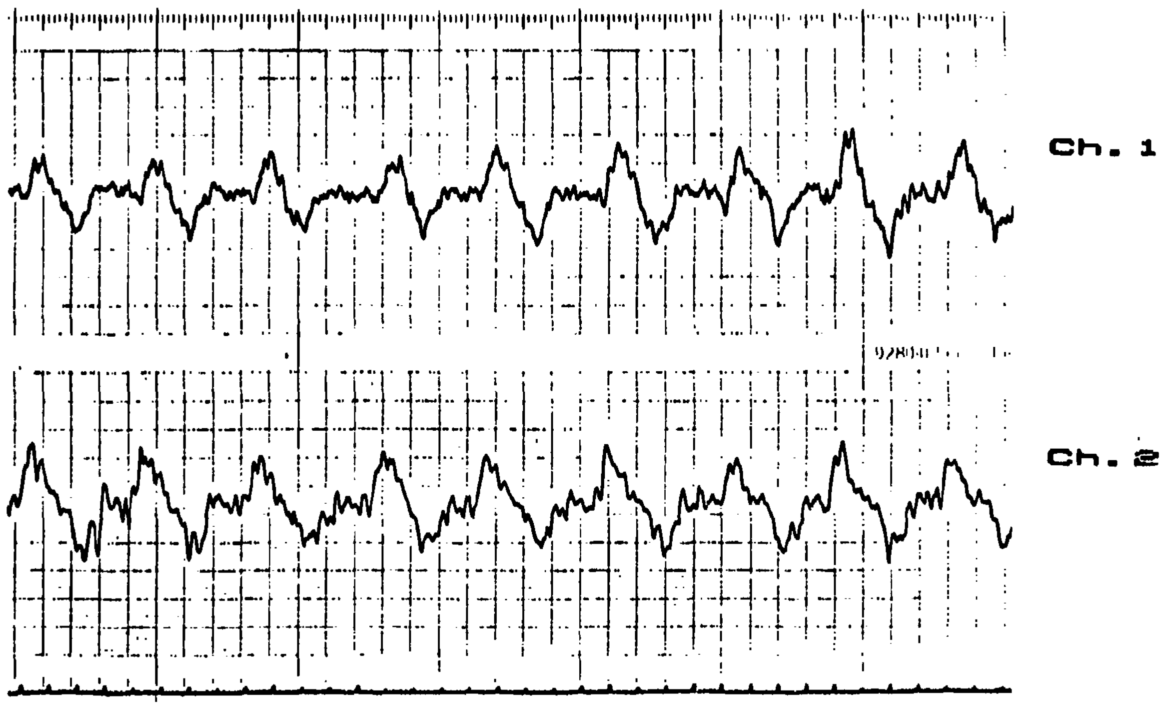
Figure 18. Baselines for heartbeat data shown in Figure 17.

CODE: 224-8 POWER: 0.31 mW

RANGE: 50 M SUBJECT: JS, SUPINE, SIDE

FREQ: 35 GHZ FILTERS: (HZ) HP 1.0 LP 16

COM'S: RESP, POLZ. HORZ.



1 Second/Marker

Figure 19. Respiration detected from 50 meters using 1 Hz high-pass filters. Respiration signals present on both Ch. 1 and Ch. 2.

CODE: 224-9 POWER: 0.31 mW

RANGE: 50 M SUBJECT: SS, SUPINE, SIDE

FREQ: 35 GHZ FILTERS: (HZ) HP 1.0 LP 16

COM'S: RESP, POLZ. HORZ.

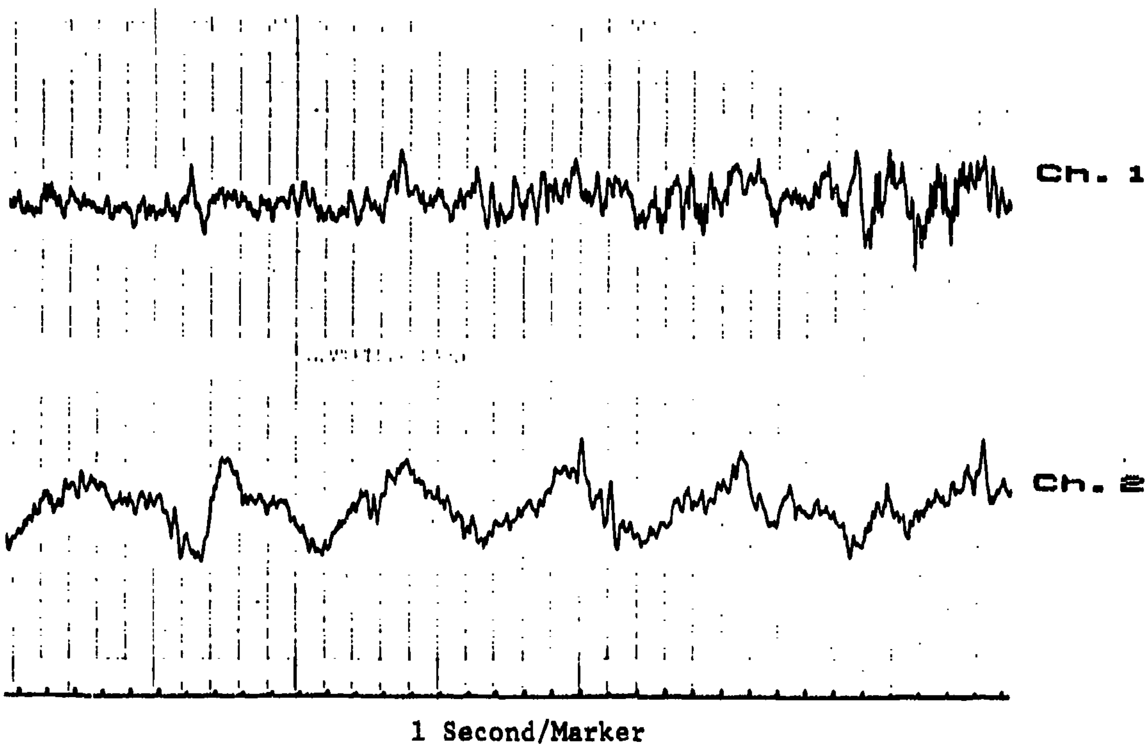


Figure 20. Respiration detected from 50 meters using 1 Hz high-pass filters. Respiration signal present on Ch. 2.

In the final series of rooftop tests, measurements were performed to determine if the prototype system was capable of detecting cardiac-related motion from 50 meters. It was generally difficult to reliably detect heartbeat from this range. Results from a successful set of measurements are presented in Figure 21. The corresponding baseline data are presented in Figure 22 (both the chart speed and recorder vertical sensitivity have been increased in these figures). Examination of Figure 21 shows that a heartbeat signal is present on Ch.1 while only noise appears to be present on Ch.2. The heartbeat signal on Ch.1 is partially masked by the presence of a large noise component. However, with the enhancement produced by the differentiating action of the 1.0 Hz high-pass filter, distinct signal peaks can be observed for each of the seven heartbeats that appear in these data. These signal peaks should be easily detectable with the signal processing system that will be developed during the third program year.

The rooftop measurements were impacted by the effects of various noise sources. The effects of these noise sources were evaluated by comparing the outputs of the prototype system when it was aimed at the empty rooftop to its output when it was aimed at the open sky. When aimed at the sky, an extremely small return signal should be received and the output of the prototype system should approximately equal the internal system noise. When aimed at the roof, the output of the prototype system should indicate the combined effects of internal system noise, external noise (building vibrations, ventilator fans), and any existing transmitter phase noise.

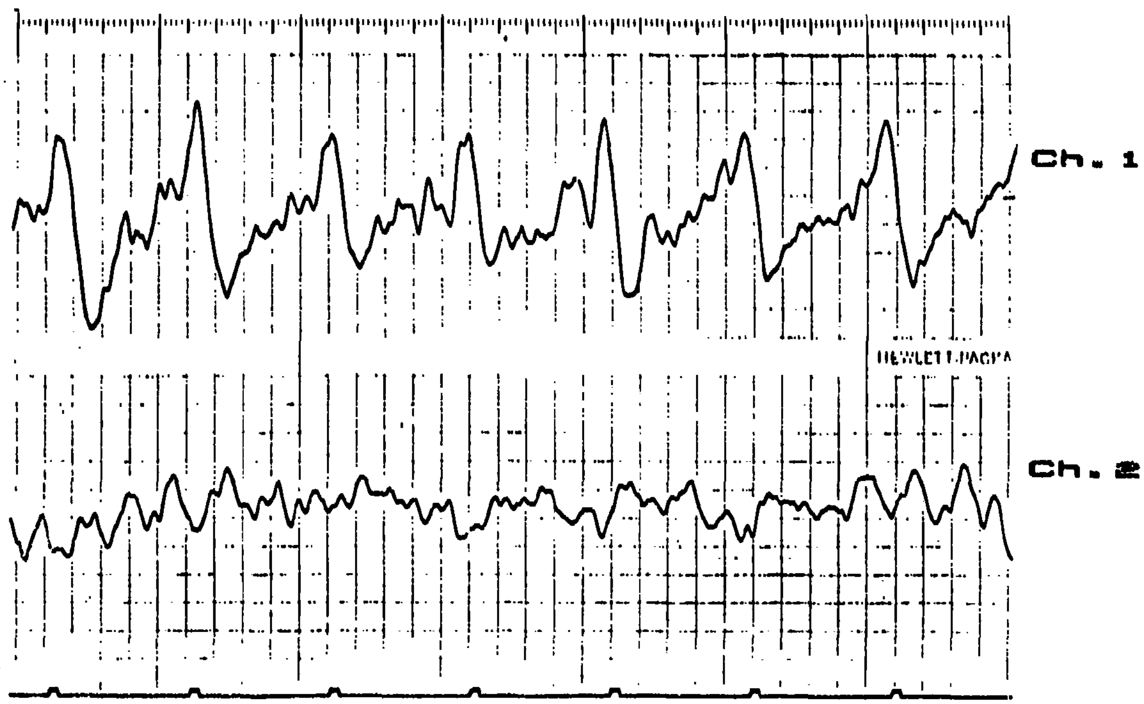
A peak-to-peak noise voltage of approximately 10 millivolts was observed when the prototype system was aimed at the sky. A peak-to-peak noise voltage of approximately 60 millivolts was observed when the protype system was aimed at the empty rooftop. Thus, noise effects present on the roof degraded system performance by approximately 16 dB from that which would be obtained in an ideal anechoic chamber where performance would be limited by the internal system noise. It was previously noted that flicker noise reduction resulting from the FM-CW scheme being used in the prototype system improved internal system noise by up to 30 dB. It is important to note that without this improvement, the performance of the prototype system in the rooftop tests would have been internal-noise limited instead of external-noise limited.

CODE: 224-8 POWER: 0.31 mW

RANGE: 50 M SUBJECT: JS, SUPINE, SIDE

FREQ: 35 GHZ FILTERS: HP 1.0
(HZ) LP 16

COM'S: HB, POLZ. HORZ.



1 Second/Marker

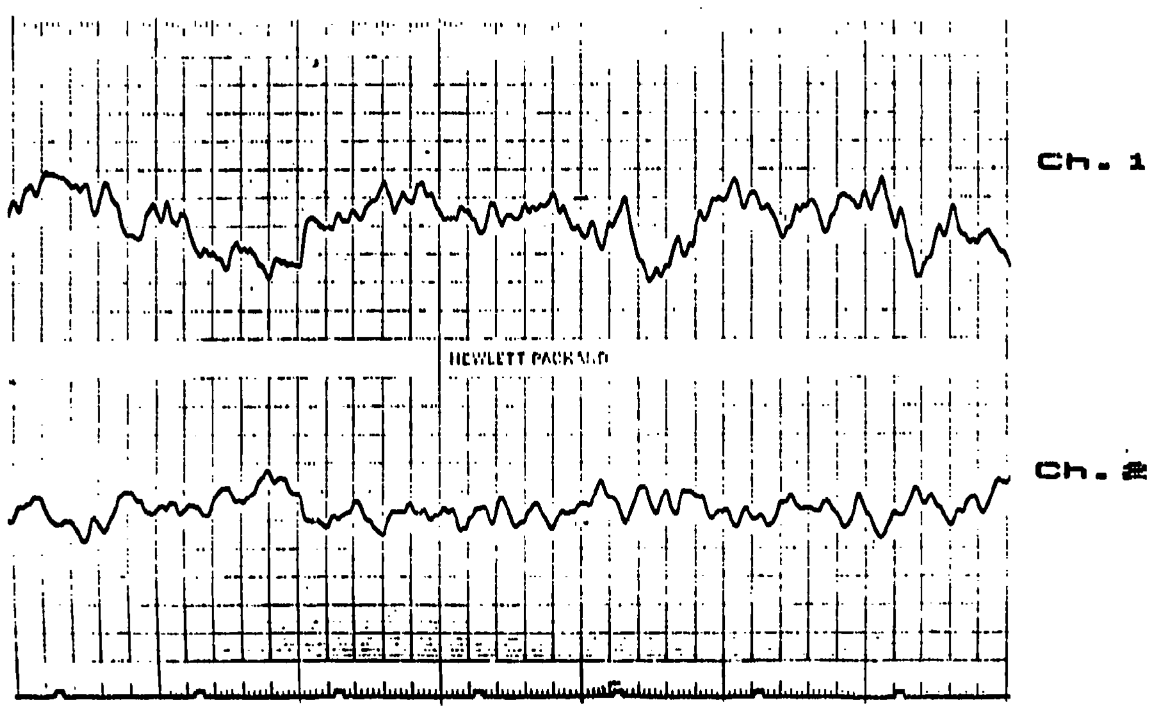
Figure 21. Heartbeat detected from 50 meters using 1 Hz high-pass filter. (subject holding breath).

CODE: 224-8　　POWER: 0.31 mW

RANGE: 50 M　　SUBJECT: JB, SUPINE, SIDE

FREQ: 35 GHZ　　FILTERS: HP 1.0
(HZ)　　LP 16

COM'S: BASELINE, POLZ. HORZ.



1 Second/Marker

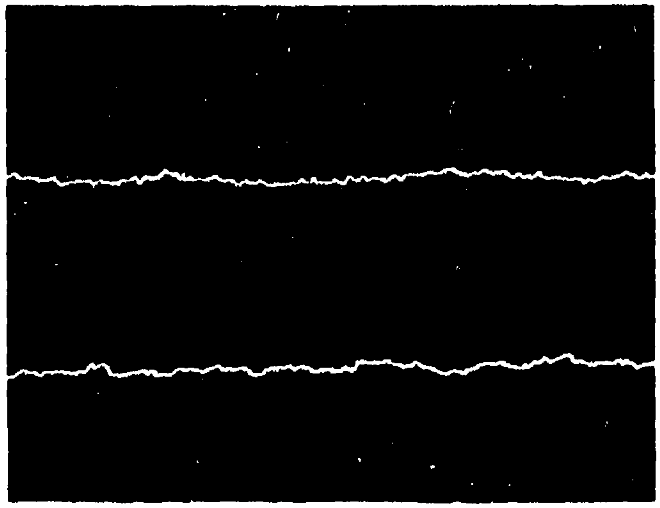
Figure 22. Baselines for heartbeat data shown in Figure 21.

This could have degraded system performance by up to 14 dB (i.e., 30 dB minus 16 dB) which would have reduced the ranges achieved in the rooftop tests by more than one-half.

Although there were not any trees, grass, or other natural clutter-producing objects present, it appears the noise observed during the rooftop tests was similar to the type of noise that would occur on a relatively open field covered with short grass. This opinion is based on noise measurements conducted on an open field adjacent to the building housing our laboratory. Measurements were made with the prototype system aimed at the open sky and at the grass-covered ground. The peak-to-peak noise voltage for the sky measurements was again approximately 10 millivolts. This indicated the internal system noise performance was the same as that for the rooftop measurements. The peak-to-peak noise voltage for the ground-grass measurements was approximately 70 millivolts which was slightly higher than the 60 millivolts observed in the rooftop tests. A comparison of the ground-grass noise measurements to the rooftop noise measurements is presented in Figure 23. Based on these results, it appears the system performance on the grass-covered field was only 1.4 dB worse than that on the rooftop.

While the prototype system was setup on the grassy field, an effort was made to measure respiration-related motion from a range of approximately 40 meters. This effort was limited in extent because of poor weather conditions and interference from vehicular and pedestrian traffic. Successful results from two of these measurements are presented in Figure 24. The top photograph in this figure shows results when the subject was "deep-breathing". The respiration signal can be seen on both Ch.1 and Ch.2 in this photograph. Comparison shows that the respiration signals in this photograph are very similar to those previously shown in Figure 14. The bottom photograph in Figure 24 shows "normal breathing" results. The respiration signal can again be seen on both Ch.1 and Ch.2. The signal on Ch.2 is very characteristic of the breathing pattern typically seen for this test subject. This pattern is one involving quick inhalation and exhalation with a short pause following exhalation. The signal on Ch.1 in the bottom photograph appears to be masked by noise or clutter. In actual fact, the observed effects are more likely due to distortion produced by the well-discussed range-dependent motion sensitivity problem.

a.

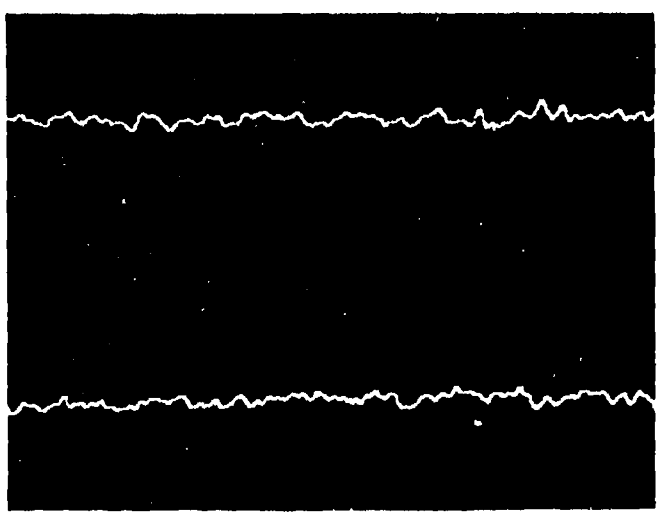


Ch. 1

200 mV/cm

Ch. 2

b.



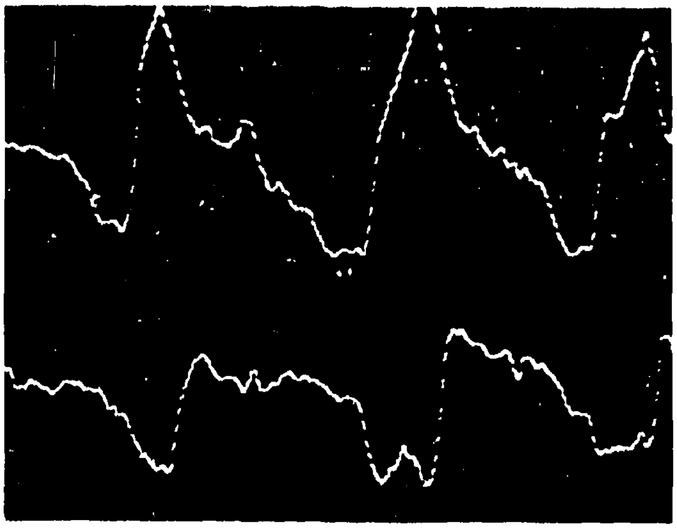
Ch. 1

200 mV/cm

Ch. 2

Figure 23. Noise measurements made (a) on rooftop and (b) on grass-covered field.

a.

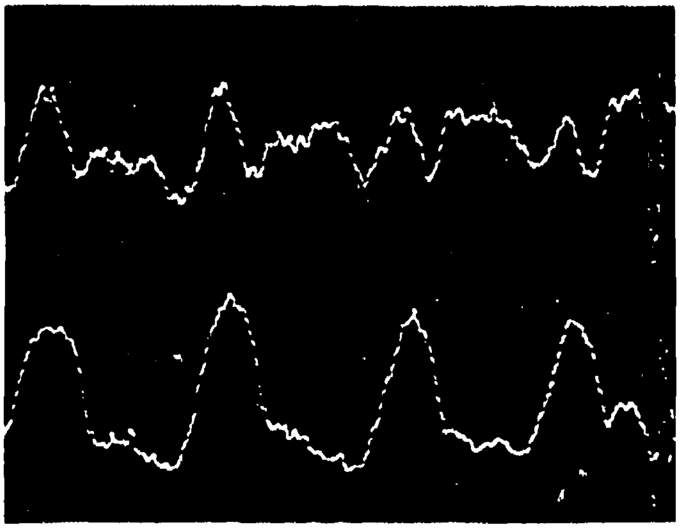


Ch. 1

200 mV/cm

Ch. 2

b.



Ch. 1

200 mV/cm

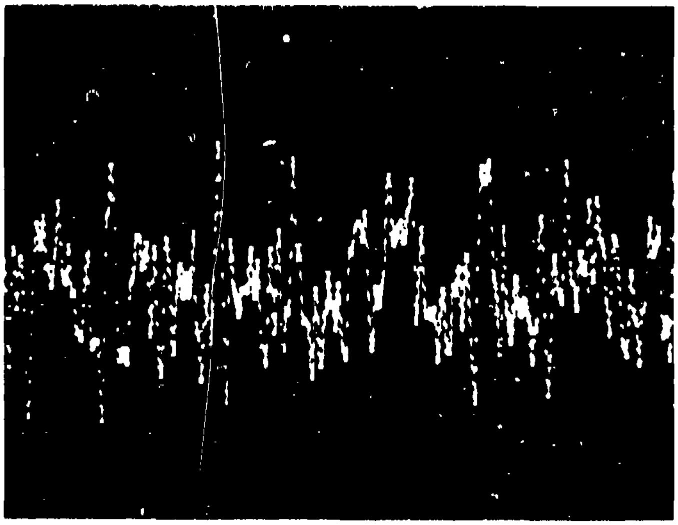
Ch. 2

Figure 24. Respiration detected for subject lying on grassy-field, (a) deep-breathing, (b) normal breathing.

In a final test performed while the prototype system was setup on the grassy field, the effectiveness of the system's range-gating capabilities was evaluated by testing its ability to reject clutter produced by a large tree located approximately 30 meters away. In these tests, the prototype system was first operated in an unmodulated mode in order to simulate the operation of a plain CW system. A photograph showing the pronounced effects of the tree clutter for the unmodulated case is shown in Figure 25a. The prototype system was then modulated with a range-setting of 30 meters (corresponding to the range of the tree) and a range resolution of $\pm$ 3.8 meters. As expected, the tree clutter for this case was similar to that for the unmodulated case as demonstrated by the photograph in Figure 25b.

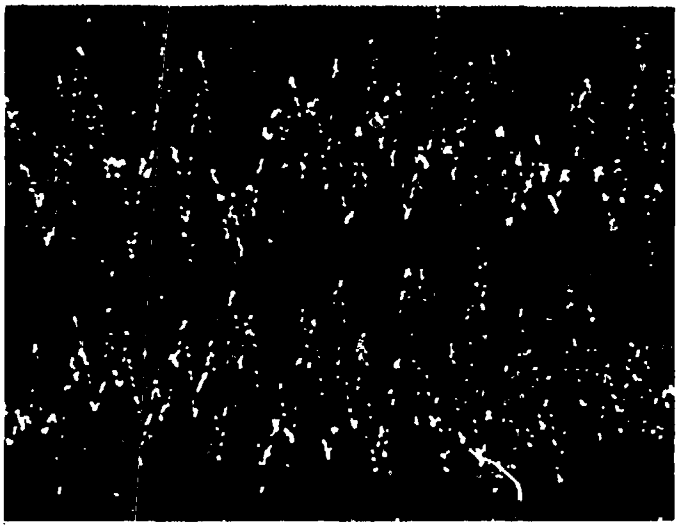
The range-setting on the prototype system was then changed to 40 meters. Since the tree was still at 30 meters, the effects of the tree clutter should have been reduced. An appreciable reduction of the tree clutter was indeed observed. When the range-setting was increased to 50 meters, the clutter reduction was even more pronounced. Results for these last two tests are shown in Figure 26. These results clearly demonstrate the manner in which the range-gating capabilities of the prototype system can be used to significantly reduce range degrading clutter effects.

a.



2 mV/cm

b.



Ch. 1

200 mV/cm

Ch. 2

Figure 25. Detected clutter from tree located at a range of 30 meters, (a) output of CW system, (b) output of FM-CW system tuned to 30 meters. (Note that the different sensitivities for the CW and FM-CW cases were due to the different amplifier gains used for these two cages.)

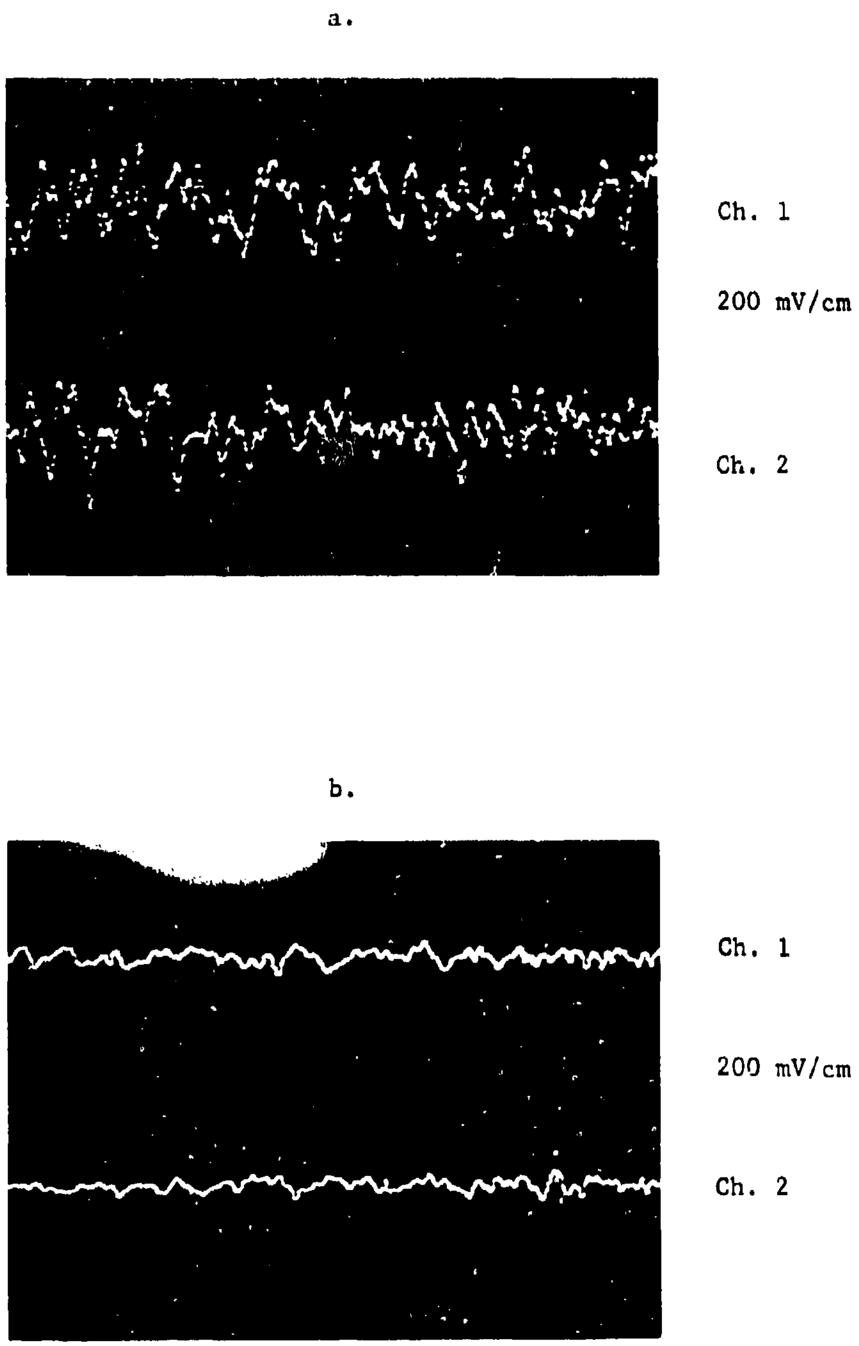


Figure 26. Detected clutter from tree located at a range of 30 meters, (a) output of FM-CW system tuned to 40 meters, (b) output of FM-CW system tuned to 50 meters.

G. Conclusions

The goal of efforts during the first 21 program months has been to (1) identify key problem areas, (2) develop effective solutions for the identified problem areas, and (3) implement an experimental system capable of demonstrating the feasibility of the EM-based lifeform monitor concept. Test results presented in the preceding discussion of experimental data clearly indicate that this goal has been accomplished.

The current prototype system has been used to detect both respiration and heartbeat from a range of 50 meters. In general, the detected respiration signals have been very strong and it appears the existing system is probably capable of reliably detecting respiration from ranges exceeding 50 meters. The detected heartbeat signals have been comparatively weak. Heartbeat has been detected from 50 meters as previously stated; however, 30 meters more accurately represents the range from which heartbeat currently can be detected with reasonable consistency.

The goal of efforts during the remainder of this program year and the requested third program year will be to (1) achieve longer detection ranges and (2) improve the consistency with which respiration and heartbeat can be detected. To achieve this goal, it will be necessary to direct future program efforts toward achieving several key objectives. One objective will be to refine the motion-sensing capabilities of the current prototype system. It appears this will mainly involve eliminating the effects of any existing transmitter phase noise and improving the methods being used to reject clutter.

A second key objective will be to design and implement a suitable computer-based signal processing system. It is anticipated adaptive algorithms will be employed in this system. The relative slowness of the respiration signals detected in previous field tests (typically 0.2-0.3 Hz) may make respiration a poor candidate for computer-based processing unless prolonged sampling and processing periods are acceptable. However, this is not a critical concern at this time. The detected respiration signals have been extremely strong and it does not appear that they will require significant levels of enhancement.

It is anticipated that computer-based signal processing will have a more significant impact on the ability to detect cardiac-related motion. The faster rates (typically 1.0-1.3 Hz) of the heartbeat signal will make it possible to acquire a large number of samples within a reasonable sampling period. It also appears the heartbeat signature is more distinct and consistent than that of respiration. This may make it possible to use various types of pattern recognition techniques to detect the presence of weak heartbeat signals.

A third key objective will be to better define the mechanisms through which respiration- and cardiac-related motions are being detected. A better understanding of these mechanisms should greatly aid in achieving more reliable and consistent system performance. This will require extensive analysis of data taken under a variety of test conditions so effects of factors such as body position, antenna aim, signal filtering, and clutter can be determined.

It should be possible to accomplish a large portion of these objectives during the remainder of this year and the requested third program year. Plans for these program periods are discussed in more detail in the next section of this report.

SECTION III

PROGRAM PLANS

A. Summary

As originally proposed, this research program was to be a three year effort to design, build, and test an EM-based lifeform monitor capable of detecting respiration in battlefield casualties from ranges extending to 30 meters. The required research and development was to be conducted in five phases as outlined in the following schedule:

Phase 1 - Preliminary analysis and design	(months 0-9)
Phase 2 - Prototype development and testing	(months 6-18)
Phase 3 - Advanced analysis and design	(months 12-18)
Phase 4 - System development	(months 12-24)
Phase 5 - System evaluation and modification	(months 18-36)

Information presented in the first Annual Technical Report indicated this schedule was strictly maintained during the first program year [1]. However, in March 1983, the Program Monitor informally requested that the scope of this program be expanded. One request was that the lifeform monitor be developed to include provisions for monitoring heartbeat in addition to respiration. It was also requested that the system's range capabilities be extended from 30 meters to a minimum of 100 meters. The combined effects of more than tripling the original range objective and also detecting heartbeat (detected cardiac-related signals are typically five to ten times smaller than detected respiratory-related signals) significantly raised the performance requirements for the monitor.

The additional technical effort needed to achieve this higher level of system performance has made it necessary to modify the original program schedule. The required schedule changes primarily will involve Phases 3, 4, and 5. Phase 3 (advanced analysis and design) was originally scheduled to be completed by the end of the month 18 (31 October 1983). However, because of the additional analysis and design efforts needed to adequately treat the expanded program objectives, Phase 3 efforts are still in progress. Based on current results, these efforts will likely continue until the end of the current program year (30 April 1984).

Phase 4 efforts (system development), scheduled to be completed by the end of month 24 (30 April 1984), will now be extended into the third program year. It appears it will be possible to complete these efforts by the end of month 33 (31 January 1985); however, this assumes it will not be necessary to make any major, unplanned system modifications to meet the expanded program objectives. For example, if it became necessary to increase the operating frequency of the current monitor in order to reduce the antenna size or to enhance motion sensitivity, the delay in obtaining new millimeter-wave components could make it necessary to extend Phase 4 efforts by an additional six months.

Phase 5 (system evaluation and modification) was scheduled to be conducted during months 18-36 of this program. Because of the delayed completion of Phase 4, it will not be possible to initiate Phase 5 efforts before the beginning of month 28 (1 August 1984). Since it is estimated that up to 18 months will be needed to complete Phase 5 efforts, it is possible that a fourth program year will be required to complete development of a prototype EM-based lifeform monitor capable of fully satisfying the expanded program objectives.

B. Plans for Remainder of Second Program Year

Technical efforts during the remaining portion of this second program year will focus on completion of Phase 3 studies. The objectives of these studies will be to evaluate the effectiveness of the numerous features that have been incorporated into the current version of the EM-based lifeform monitor and to develop new or improved techniques where needed to solve any remaining problems. Items to be studied during this advanced analysis and design phase include (1) methods for further reducing clutter effects (2) transmitter phase noise effects and techniques for phaselocking solid-state Gunn oscillators, (3) computer-based signal processing techniques, (4) range-gating techniques, (5) methods for reducing the size and improving the performance of dielectric lens antennas, and (6) the practicality of higher operating frequencies (possibly 94 GHz). Results from the Phase 3 studies will then be used to determine the specific system development tasks and system evaluation studies to be conducted during the third program year.

C. Plans for Third Program Year

1. Phase 4 - System Development

During the first half of the third program year, Phase 4 studies (system development) will be performed. The purpose of these studies will be to incorporate into the prototype lifeform monitor any new or improved techniques identified during the advanced analysis and design studies comprising Phase 3. At this time, it appears that Phase 4 studies will be concentrated in the following three key areas: (1) computer-based signal processing and detection, (2) clutter reduction techniques, and (3) transmitter phaselocking techniques.

a. Computer-based Signal Processing and Detection

As the range of the lifeform monitor is extended, its performance will become increasingly degraded by the effects of noise and clutter. The capabilities of the analog filters currently being used for signal processing are limited by the fact that spectral components of the noise and clutter overlap those of the desired respiration- related and cardiac-related signals. Thus, important efforts during the third program year will be the development and use of more powerful signal processing and detection tools. Currently, a design is being developed for a microprocessor-based signal processing system that will be built during the Phase 4 efforts.

Although spectral components of the desired respiration- and cardiac-related signals, and those of the undesired noise may overlap, there are differences in these signals which should aid in their discrimination provided an appropriate algorithm is used [9, 10, 11]. For example, the desired signals are likely to be more periodic in nature than is noise. Therefore, algorithms sensitive to periodicity may prove useful. In addition, there may exist specific respiration and heartbeat signatures which could aid in discriminating between the desired information and noise. A potential problem with using factors such as periodicity or distinct signatures to separate signals and noise is that the vital signs of trauma victims may exhibit a great deal of variability in both rate and signature. In addition, clutter characteristics may vary widely with terrain and environment. Thus, the detection algorithm used on this program must be carefully designed to be able to function reliably over a reasonable range of signal and noise conditions.

A number of detection and pattern recognition approaches are being considered for use on this program. One promising approach is adaptive processing. Since adaptive processors are capable of constantly adjusting to the prevailing signal and noise environment (essentially learning from previous results), they appear to be particularly well-suited for this application [12, 13]. Adaptive processing algorithms can be complex requiring operations such as covariance matrix estimation and inversion. However, because of the relatively low sampling rates (less than 100 samples/second) that would be required for this particular application, the necessary operations could be easily implemented using an inexpensive microprocessor-based processor such as the unit to be developed as part of the Phase 4 program efforts.

b. Clutter Reduction Techniques

Clutter (or external noise) has proven to be one of the most significant range-limiting problems encountered during preliminary field testing of the lifeform monitor. The effects of clutter currently are being minimized by reducing the volume of space (or cell size) interrogated by the lifeform monitor. Cell size reduction is being achieved by using a combination of a highly directive antenna and range-gating. Although these clutter rejection approaches have been effective, high antenna directivity requires the use of larger antennas while range-gating places certain bandwidth requirements on the scheme used to modulate the transmitter.

During Phase 3, efforts will be made to determine if alternative methods such as polarimetric techniques or improved signal detection schemes can be effective in reducing clutter [14, 15]. If these alternative techniques appear promising, they will be further investigated during Phase 4. It should be noted that the use of any alternative clutter rejection techniques may significantly increase the complexity of the lifeform monitor. However, the increased system complexity may be acceptable if it permits the antenna size or range-gating requirements to be relaxed.

c. Transmitter Phase Noise

Transmitter phase noise (or FM noise) is another factor that could significantly degrade the performance of the lifeform monitor at longer ranges. FM noise has not proven to be a major problem at shorter ranges (less than 30 meters) because of the homodyne demodulation scheme being utilized in the prototype system. With homodyne demodulation, correlation between the reference signal (i.e., the local oscillator) and returns from short-range targets provides automatic cancelling of a large part of the FM noise. However, at longer ranges (perhaps 100 meters, depending on the transmitter's characteristics), FM noise could become a serious range-limiting problem.

Measurements are currently being performed to determine the range at which FM noise will begin significantly degrading the performance of the lifeform monitor. If results of these measurements indicate that FM noise is a problem at ranges below 300 meters, a suitable phaselock network will be built as part of the Phase 4 efforts. A number of complications will arise if it becomes necessary to phaselock the 35-GHz oscillator being used in the prototype system. For example, the reference source required for phaselocking could substantially increase the amount of power consumed by the prototype system. In addition, a relatively innovative phaselock design will have to be used because of the need to simultaneously frequency modulate the oscillator. Currently, several previously developed phaselock designs are being re-evaluated to determine the method best-suited for use on this program.

2. Phase 5 - System Evaluation and Modification

Phase 5 studies will be initiated during the latter part of the third program year. The purpose of these studies will be to thoroughly evaluate the performance of the prototype monitor and to make final system modifications. The system evaluation studies will consist of extensive testing under both laboratory and field conditions. Laboratory testing will be conducted primarily to check out the internal performance of the prototype system's receiver and to obtain a preliminary evaluation of the effectiveness of the computer-based signal processing system that is to be developed. The signal processing system will be evaluated using measured data that has been stored on an FM tape recorder. This will permit the different signal processing algorithms to be evaluated using identical sets of raw data. The data used for these evaluations will be collected under a wide range of conditions so the signal processing system's ability to discriminate against various types of noise contamination can be thoroughly evaluated.

An important objective of the Phase 5 studies will be to establish a better understanding of factors associated with the mechanisms by which respiration- and cardiac-related motions are being detected. For example, it would be extremely useful to know the affective radar cross section and the magnitude of the relative body motions associated with the detected respiration- and cardiac-signals. This type of information would make it possible to accurately predict the detection range that should be possible for a given set of operating conditions (i.e., receiver noise figure, operating frequency, antenna gain, clutter, etc.). By correlating this information with data taken using conventional measurement techniques, it also may prove possible to relate the signatures of signals detected with the lifeform monitor to various physiological conditions. This could aid the effectiveness of the signal processing algorthms that are to be implemented and may also permit the detected signals to be used for diagnostic purposes.

It would also be desirable to determine the specific locations on the body from which respiration- and cardiac-related motions can be detected. This knowledge could be a key to understanding how the reliability of the lifeform monitor can be affected by various conditions. For example, this knowledge may be beneficial in determining how factors such as frequency, polarization, antenna aim, and incidence angle can be adjusted to eliminate performance inconsistencies due to conditions such as body size, body type, or body position.

As the system evaluation studies are performed, various needed system improvements will become evident. Needed improvements that are within the scope of the proposed level of effort will be implemented as part of the Phase 5 efforts. Modifications that exceed the proposed scope will be documented and included as part of a proposed follow-on effort.

SECTION IV

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