Unobtrusive Suicide Warning System

Final Technical Report

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Sponsor:
National Institute of Justice
Program Manager: Frances Scott, Ph.D.
Sensors and Surveillance Portfolio Manager

Performer:
General Electric Global Research
Principal Investigator: Jeffrey M. Ashe
GE Team: Ghulam Baloch, Meena Ganesh, Catherine Graichen
UTRC Team: Nicholas Soldner, Vijay Lakamraju, Joe Zacchio, Mark Vogel

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Executive Summary

The rate of in-custody suicide is currently lower than that of the general public largely due to comprehensive screening, assessment, treatment and surveillance programs for at-risk subjects. Despite the low rate of occurrence, inmate suicide remains a problem for correctional institutions both as a fundamental tragedy with the loss of life as well as the failure of the system to protect those in custody. Even rare suicide incidents can still place large burdens on the institution that tarnish the reputation of law enforcement, increase the costs of litigation, and drive expanded operational needs for continuous inmate monitoring.

In completing Phases I, II and III (Awards 2007-DE-BX-K176 and 2011-IJ-CX-K003) of this program, we have developed a prototype demonstration system that can measure an inmate's heart rate, breathing rate and general body motion without being attached to the inmate (i.e. from a non-contact distance). The system is based upon measuring a ballistogram which is comprised of subtle motions appearing on the surface of the body due to the motion of internal components such as the heart and lungs. The system is based on a modifying version of a commercialized Range Controlled Radar (RCR) that was originally designed as a motion detector for home security systems. The detection of the ballistogram required RCR hardware modifications for increased physiological sensitivity and the development of new signal processing algorithms to detect and classify features.

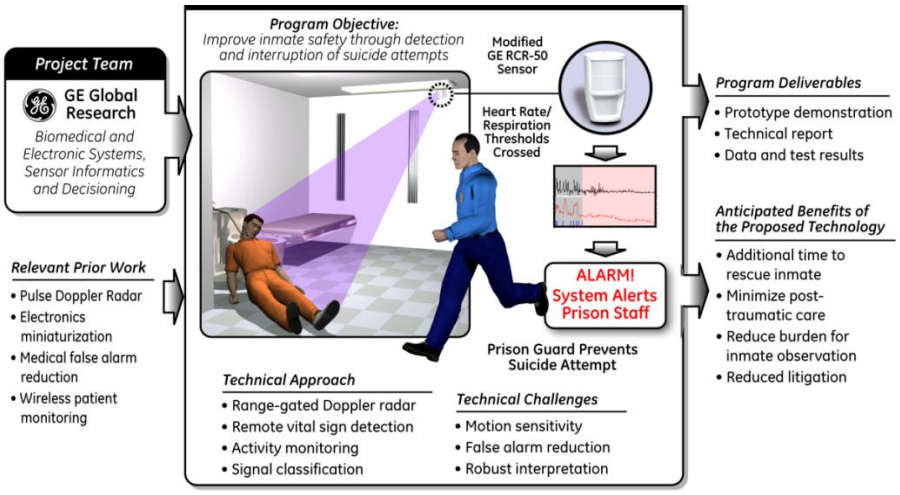

Figure 1 – Program Summary

Although there are many possible methods of suicide, this program focused on asphyxia (typically by hanging or by ligature around the neck) since it is a predominant method experienced in-custody. The prototype demonstration system was designed to detect and classify levels of motion and activity (including large motions, relative inactivity or stillness, and noise from an empty or lifeless room) and subsequently estimate heart rate and breathing rate when needed during times of key interest. These parameters feed into a classification system that alerts corrections officers of a suspicious event in progress to trigger a rapid intervention. It is expected the alerting algorithm could be readily modified to detect other methods of suicide (such as exsanguination) based on recognizing different patterns which would rely on the same motion, activity and heartbeat/breathing parameters. Although the system is capable of generating alerts, it will likely be most useful

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as an adjunct situational awareness tool to help corrections officers implement their ongoing at-risk treatment and continuous surveillance programs.

The Phase I efforts focused on hardware modifications and the development of software algorithms to establish the baseline capability of the system. The Phase II efforts focused on the goal of bringing the prototype system to a field demonstration in an actual prison environment and continuing the algorithm development to increase sensitivity and specificity in order to increase detections and reduce false alarms. The Phase III efforts focused on hardening and integrating the system for long-term testing in an operational setting. This involved pre-production engineering and implementation of the hardware and algorithms developed in prior program phases in addition to making the system tamper-proof and suicide-proof for deployment in an operational setting. The changes included modifying the RCR to match the earlier prototype system, identifying a data acquisition mechanism that could be packaged with the RCR, supplying a long-term power source and installing into a prison-rated fixture. New software to collect the RCR signals and perform the state and alarm analyses was implemented on a central computer.

Multiple in-room units were built that connect by Power-over-Ethernet to the central computer since power is required and wireless communication was unreliable through the Western Correctional Institution (WCI) cell walls. The fundamental component of the system, the RCR sensor, is available at retail for approximately $50. The computer, router and prison-rated housing are also commonly available within prison facilities. Cost-effective adoption of the system will depend heavily on assessment of the infrastructure installation costs which may vary considerably across federal, state and local facilities of varying construction.

Radio frequency exposure safety was re-examined in the Phase III configuration. The RCR50, as configured for retail, complies with Part 15 of the FCC rules. Since Part 15 predominantly addresses interference and compatibility with other equipment, an additional analysis was conducted to compare the energy exposure of the modified unit to that of FCC bulletin OET65 for the maximum permissible exposure in an uncontrolled setting (meaning the user could be exposed continuously without awareness or ability to change their exposure). For a subject directly touching the antenna, the modified unit is 1/25 of the limit. The exposure quickly drops to smaller than 1/1000 of the limit at a distance of 40 cm from the antenna. These margins are acceptable for in-cell installation. However, further analysis is required to compare to regulations for use with pregnant women or developing fetuses.

A long-term system test was originally envisioned at WCI. However, departmental approvals were not obtained from the state research committee for studying inmates. A prior study was conducted at WCI by obtaining informed consent from corrections officers who followed scripted activities while being monitored by the prototype system. Although the proposed long-term study was modified to request informed consent from the participating inmates, the state board determined the inmates housed in the WCI facility were already at-risk and the study may worsen their conditions. Due to the delays created seeking this approval, long-term inmate monitoring data was not obtained but additional in-house testing was performed to demonstrate the readiness of the hardened system and to assess the capability and accuracy of the algorithms. At the completion of this program, there remains a strong need to perform long-term testing in real-world environments to optimize the configurations, settings and features of the system to quantitatively confirm the benefits to both inmates and correction officers.

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1.0 Motivation

Despite many improvements, inmate suicide remains a longstanding problem for correctional institutions. Suicide rates have been observed as high as 47 per 100,000 inmates in local jails and 15 per 100,000 inmates in prisons. Apart from the fundamental tragedy in loss of life, suicide incidents contribute to the morbid atmosphere of jail, tarnish the reputation of law enforcement, place an undue burden on institutions to continuously monitor inmates, and increase cost of litigation associated with wrongful death.

Hanging is the principal method of suicide in prisons. In most cases, death is not immediate and strong physiological responses that result from asphyxia become apparent prior to actual end of life. Asphyxia symptoms include: spontaneous gasping, struggling associated with the mental anguish of oxygen starvation (dyspnea), and sudden changes to or an absence of heartbeat and breathing. If properly monitored and interpreted, these motions can be used to determine whether or not asphyxiation is in progress.

Extracting motion-based parameters of breathing and heart rate, and interpreting types of activities, are key factors in determining when an inmate's life is in immediate jeopardy that requires rapid intervention.

The reports for the earlier phases of this project included a literature review related to this topic.

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2.0 Approach

GE Global Research has developed an unobtrusive, Doppler radar-based sensor system that will indicate a suicide attempt in-progress by observing and interpreting motion related to heartbeat, breathing, and limb movement. This non-contact monitoring device can detect, interpret, and relay information about strong and sudden changes in physiology associated with asphyxia through self-strangulation or hanging, without corrections officers having to directly observe a prisoner. This system will give prisons and jails an effective method to monitor at-risk individuals without resorting to expensive or tedious surveillance solutions such as 1-to-1 observation, suicide patrols, or closed circuit video.

The GE system development has involved:

(1) Redesigning the elements of a commercially available, low-cost motion sensor to enable increased sensitivity to body motion.

(2) Developing signal classification software to detect abnormalities of physiological parameters consistent with a surrogate for suicide attempt.

(3) Integrating the motion sensor and algorithms into a working virtual prototype for laboratory demonstration and testing.

The demonstration system has been evaluated by capturing limb motion, breathing and heartbeat from approximately 20 volunteer human subjects in a mock cell environment and 10 corrections staff in an actual cell environment. These individuals included males and females of varying ages, heights, and weights, in various body positions, and simulating asphyxia by withholding breath. All human studies are conducted under the approval of an accredited Independent Review Board (IRB).

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3.0 Program Goals and Objectives

The goal of this multi-phase program was to develop a remote sensing system that can capture vital signs related to the physiology of an individual and provide an assessment of those signs. Several technical objectives were met during the research program:

In Phase I (see Appendix A – Phase I Final Technical Report),

- A commercially available radar-based motion sensor, the Range Controlled Radar (RCR), was modified to enhance its sensitivity to detect fine movements, such as pulsations on the surface of a person's body.
- Software was developed that can interpret and classify the information provided by the RCR sensors.
- The suicide warning system was evaluated and tested using volunteer subjects in a mock laboratory jail cell setting. A total of 20 subjects, both males and females of varying ages, heights, and weights performed testing to assess sensitivity to respiration, breathing, and general motion.
- Quantitative objectives of the program were met to measure heartbeat and breathing rates to within 20% rate accuracy and to establish the baseline sensitivity and specificity of the demonstration system.

In Phase II (see Appendix B – Phase II Final Technical Report),

- The practical feasibility of non-intrusive sensing of physiological variables (respiration, heart rate, motion) under representative jail cell conditions was demonstrated at Western Correctional Institution.
- The performance of the system to process the sensor signals using human activity monitoring methods was verified to achieve a level of accuracy consistent with the requirements for suicide intervention commensurate with the goals of 95% sensitivity, 80% specificity, and not more than 20% rate estimation error.
- The hardware and software elements were integrated into a unified prototype system for testing, evaluation, and demonstration.

In Phase III,

- The RCR was modified to match the original GE prototype used in Phase I & II.
- A hardened system was constructed that met prison's requirements for tamper-proof and suicide-proof packaging.
- A software system to collect data through the new hardware data acquisition system was implemented and demonstrated.
- Sample data was collected to review the signal characteristics and assess algorithm's accuracy with the updated hardware and packaging, particularly related to state estimation for motion, quiet and concern.
- The hardware and software elements were integrated into a unified prototype system for testing, evaluation, and demonstration.

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4.0 Research Design, Schedule, and Resources

Phase III of this program involved five main tasks over an approximately 18-month period. The program status vs. the work breakdown structure (WBS) as used to guide the program developments is provided in Table 1. Task 3 could not be completed because IRB approval from the State of Maryland was denied. Also, due to the denial, Task 4 could not be completed as originally proposed and was subsequently modified to encompass in-house testing. All other proposed activities on this Phase of the program have been completed and are described in detail in this report.

Project financial performance will be submitted separately through the SF-425 forms in the GMS online system. Project financial expenditures are commensurate with the technical progress on the program.

Table 1 – Project Schedule and Status of Each Element of the Work Breakdown Structure

Task #	Task Description	Status
1.0	**Design and development of the system architecture**	**Complete**
1.1	Design of the antenna, transmitter and receiver architecture	Complete
1.2	Design of digitization and signal processing architecture	Complete
1.3	Design of power distribution and data communication	Complete
1.4	Design of the user interface	Complete
2.0	**Implement the system components**	**Complete**
2.1	Implement of hardened in-room units	Complete
2.2	Implement embedded processing nominal DSP platform	Complete
2.3	Packaging per prison specifications	Complete
2.4	Implementation of infrastructure	Wireless not used, Power complete
2.5	Implementation of user interface	Complete
3.0	**Install the system and obtain regulatory approvals**	**Unable to complete, Denied approval**
3.1	Install system at WCI	Not done
3.2	Obtain regulatory approvals	IRB denied
4.0	**Operate and monitor the deployed system**	**Limited**
4.1	Monitor system performance	Limited
5.0	**Collect feedback and generate the final report dataset**	**Complete**
5.1	Create final report	Complete

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5.0 Technical Activities and Results

Task 1—Design and development of the system architecture

This task focused on the design of the hardware and the software required for long-term data collection in a prison setting. The focus of the design revolves around modifications to the RCR50, a radar based motion sensor sold by Interlogix, a United Technologies Corporation (UTC) business unit. The description of the hardware is included in the United Technologies Research Center (UTRC) report included in Appendix D1 - RCR Modification and Testing at UTRC. In addition the design address the software for the data acquisition device and for the PC software to receive and analyze the signals from the RCR50

Task 1.1—Design of the antenna, transmitter and receiver architecture

See Appendix D1 - RCR Modification and Testing at UTRC.

Task 1.2—Design of digitization and signal processing architecture

See Appendix D1 - RCR Modification and Testing at UTRC.

During the design of the digitization and signal processing architecture, the number of significant bits representing the radar signals was set at 10 bits. In the earlier phases of this effort, data collected via the Biopac and Agilent devices collected and transmitted the signals as real values. The original data was received as 14-bit analog signals. The data collected from the WCI study in Phase II was decimated to 10 bits and reanalyzed to confirm that the state estimation accuracy would not be significantly impacted by this change in the granularity of the data. Minimal degradation was observed from the decimation in the GE Study dataset and no degradation was observed in the WCI study data set. Figure 2 and Figure 3 show the original accuracy results from the GE Study data and WCI study data respectively. Figure 4 and Figure 5 show the accuracy results from decimating the data to 10 bits. Further analysis of the data decimated to 6 bits is shown Figure 6 and Figure 7. Interestingly, the overall accuracy improves, however it is worth observing that the improvement is in the motion state detection and there is minor degradation of quiet and concern detections. Thus 10-bit signal was determined to be acceptable change for data acquisition.

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ORIGINAL	14bits	Pad segment data					
Overall	2406 matches / 3600 (66.83%)						
No Unk	2406 matches / 2905 (82.82%)						
	Unknown	Motion	Still	Concern	Row Total	Sensitivity	% Samples
Unknown	0	217	357	121	695	0%	19%
Motion	0	1177	249	10	1436	82%	40%
Still	0	45	715	138	898	80%	25%
Concern	0	0	57	514	571	90%	16%
Column Total	0	1439	1378	783	3600		
	Specificity	96%	70%	78%			

Figure 2 – Original state estimation accuracy from GE Study data

ORIGINAL	14bits	Pad segment data					
Overall	1374 matches / 1800 (76.33%)						
No Unk	1374 matches / 1596 (86.09%)						
	Unknown	Motion	Still	Concern	Row Total	Sensitivity	% Samples
Unknown	0	0	149	55	204	0%	11%
Motion	0	601	92	5	698	86%	39%
Still	0	2	459	109	570	81%	32%
Concern	0	0	14	314	328	96%	18%
Column Total	0	603	714	483	1800		
	Specificity	100%	81%	73%			

Figure 3 – Original state estimation accuracy from WCI study data

10bits		Pad segment data					
Overall	2403 matches / 3600 (66.75%)						
No Unk	2403 matches / 2905 (82.71%)						
`	Unknown	Motion	Still	Concern	Row Total	Sensitivity	% Samples
Unknown	0	217	357	121	695	0%	19%
Motion	0	1176	250	10	1436	82%	40%
Still	0	46	714	138	898	80%	25%
Concern	0	0	58	513	571	90%	16%
Column Total	0	1439	1379	782	3600		
	Specificity	96%	70%	78%			

Figure 4 – GE Study data decimated to 10 bit signals

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10bits		Pad segment data					
Overall	1374 matches / 1800 (76.33%)						
No Unk	1374 matches / 1596 (86.09%)						
	Unknown	Motion	Still	Concern	Row Total	Sensitivity	% Samples
Unknown	0	0	149	55	204	0%	11%
Motion	0	601	92	5	698	86%	39%
Still	0	2	459	109	570	81%	32%
Concern	0	0	14	314	328	96%	18%
Column Total	0	603	714	483	1800		
	Specificity	100%	81%	73%			

Figure 5 – WCI Study data decimated to 10 bit signals

6bits		Pad segment data					
Overall	2432 matches / 3600 (67.55%)						
No Unk	2432 matches / 2905 (83.71%)						
	Unknown	Motion	Still	Concern	Row Total	Sensitivity	% Samples
Unknown	0	251	324	120	695	0%	19%
Motion	0	1216	213	7	1436	85%	40%
Still	0	58	705	135	898	79%	25%
Concern	0	4	56	511	571	89%	16%
Column Total	0	1529	1298	773	3600		
	Specificity	95%	72%	78%			

Figure 6 – GE Study data decimated to 6 bit signals

6bits		Pad segment data					
Overall	1392 matches / 1800 (77.33%)						
No Unk	1392 matches / 1596 (87.21%)						
	Unknown	Motion	Still	Concern	Row Total	Sensitivity	% Samples
Unknown	0	0	149	55	204	0%	11%
Motion	0	618	75	5	698	89%	39%
Still	0	2	463	105	570	81%	32%
Concern	0	3	14	311	328	95%	18%
Column Total	0	623	701	476	1800		
	Specificity	99%	84%	74%			

Figure 7 – WCI Study data decimated to 6 bit signals

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Task 1.3—Design of power distribution and data communication

See Appendix D1 - RCR Modification and Testing at UTRC.

Task 1.4—Design of the user interface

The software system is composed of the firmware on the Arduino device and a PC application to communicate with the Arduino device and analyze the radar signals to determine the observation state and decide whether an alarm to the monitor is necessary. Figure 8 provides a conceptual view of the key components: the RCR units enclosed in an appropriate fixture with an Arduino board for data communication via Ethernet, a switch or router and a PC running the monitoring software.

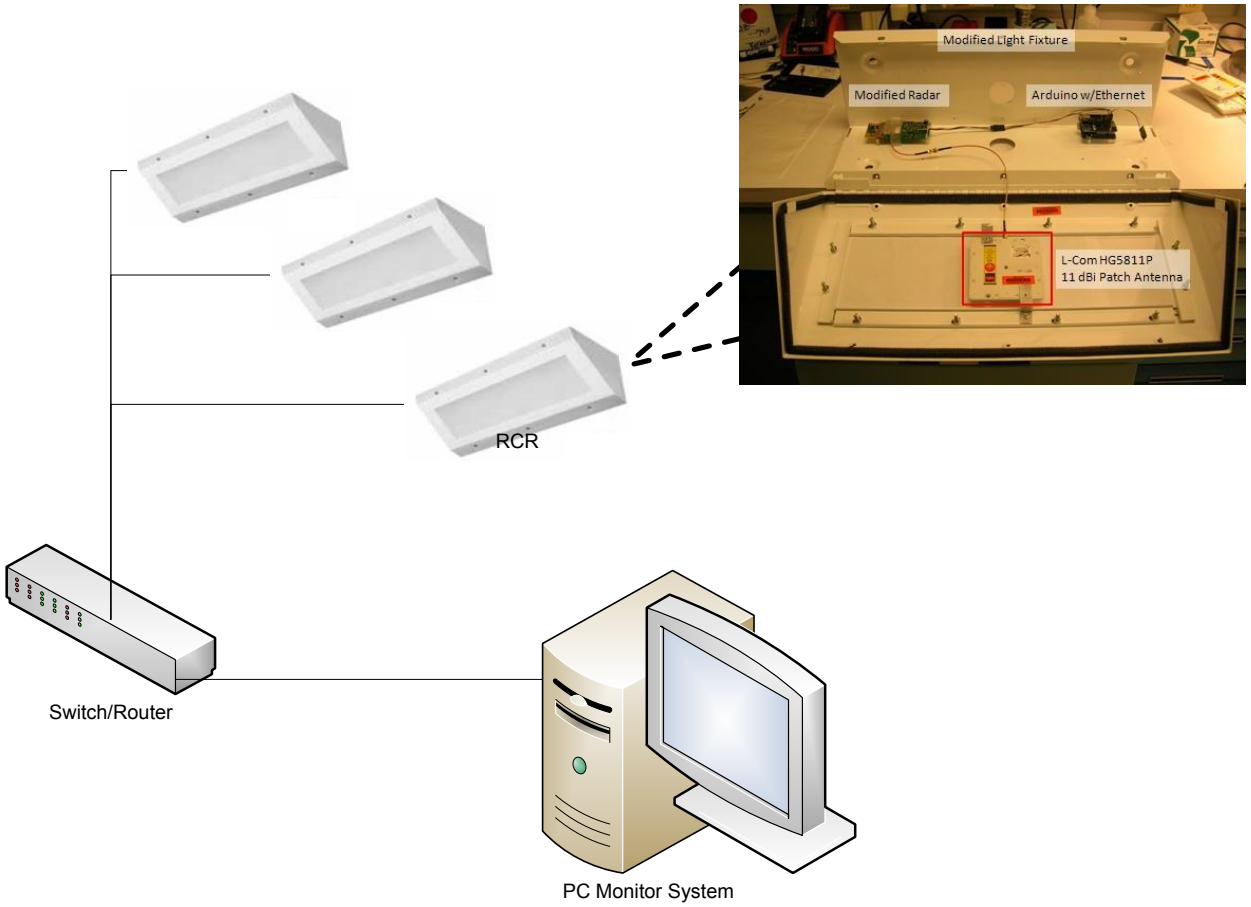

Figure 8 – System Components

The Arduino software is implemented by writing a "sketch" with the Arduino software. The software language is C-like in nature. When completed it is downloaded to the Arduino board. The essence of any sketch is a ***setup*** method that is executed when the board is powered on or the software is reloaded and a ***loop*** method that is processed repeatedly. For this application, the startup section identifies the MAC address, the IP address and various

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configuration values such as the amount of data that will be transmitted during each request. The loop method captures the signals from the analog I/O pins (which are the low and high gain channels from the radar device) and stores them in a buffer and includes the delay to get the desired sample rate. The loop method also listens for a request from the PC. If a request is detected, the current buffer of data is sent to the PC as an xml packet within an html document. A sample snippet of the content is shown in Figure 9.The signal values are transmitted as the analog integer value between 0 and 1023 (2^{10}-1).

The firmware for the Arduino device uses two buffers, one that is actively collecting data and one that has data ready to transmit. When the buffer being populated is filled, then the firmware code switches buffers and starts filling the second buffer. This allows a full packet of a predetermined size to be transmitted when requests are made. Additional information such as a packet number and the current index of the elements being populated in the storage buffer are also transmitted. Provided the radar has been powered on longer than the packet size prior to the first request, the buffer of data sent will be populated with real signals.

```
<!DOCTYPE HTML>
<html>
<?xml version="1.0" encoding="utf-8" ?>
<RCR_Data URL="192.168.1.112" Packet="240331" Buffer="0"
WorkingBuffer="1" WorkingSample="72" Time="914694727">
<data ch0="497" ch1="557"/>
<data ch0="497" ch1="560"/>
<data ch0="496" ch1="556"/>
  . . .
<data ch0="494" ch1="466"/>
<data ch0="496" ch1="465"/>
</RCR_Data>
</html>
```

Figure 9 – Sample snippet of Arduino data packet

The PC software design includes a user interface for configuration of the data collection. When monitoring is started, a new thread is created for the connection. This thread is a continuous data acquisition loop that requests data from the Arduino device. After receiving the data, it processes the data to estimate the state of the observed area and determine if alarming is appropriate. Figure 10 is a class diagram of the PC software. The ConnectionForm is the form class to create a connection to an Arduino device. A connection object will be instantiated for each new connection using the HTTPRequest object. The DAQ_Arduino object is created with the connection to process and store the data received including converting from the raw signal to the 0 - 5 volt range expected. In addition to the C# code described, the analytics algorithm will be implemented with Matlab™ and integrated with C# through a DLL. The analytics logic and software is described in reports from the earlier project phases, see Appendix A – Phase I Final Technical Report and Appendix B – Phase II Final Technical Report.

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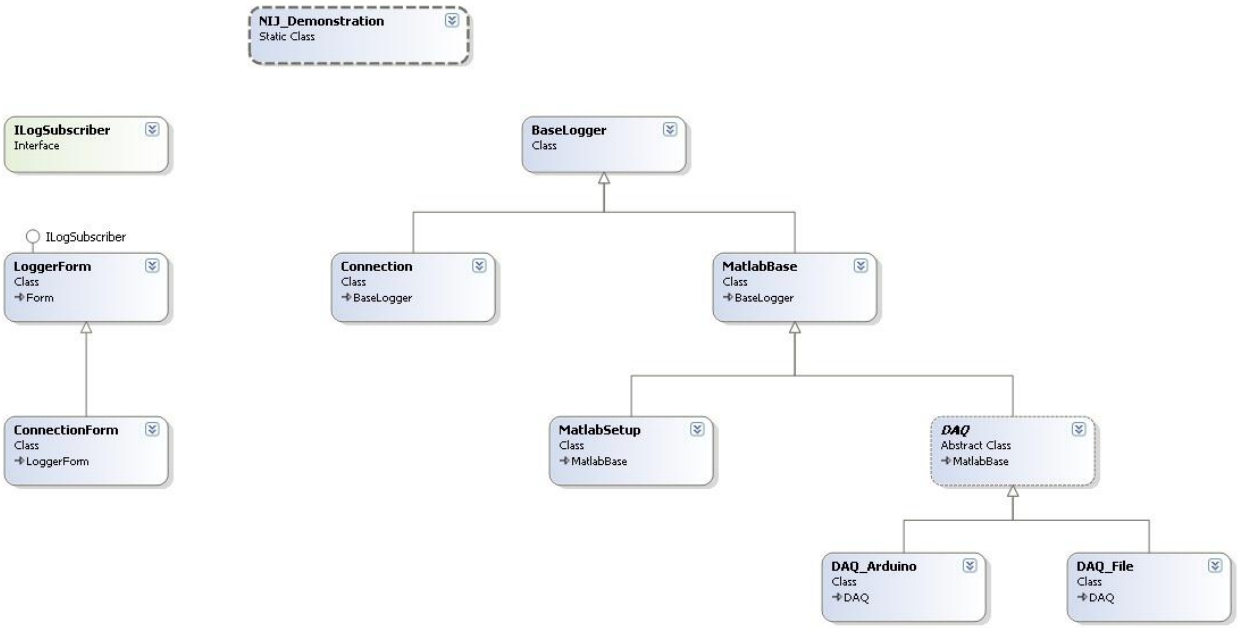

Figure 10 – PC Software Class Diagram

For this demonstration, a simple data storage model is used. Packet data will be written to a file with the associated analytics for each sample measurement. This storage model is not the most efficient in terms of physical storage, but simplifies the complexity for post-processing and debugging. The file format is a simple ASCII-based comma-separated format. To keep the file sizes manageable, the system writes data in a file for approximately one day, then closes that file and creates a new one. Filenames embed the date and time to make finding specific date/time ranges feasible. Binary formats and database storage options may be more appropriate in a product. This would make it easier to retrieve data for selected periods of time. It is expected that historical results will need to be saved for auditing and analysis purposes, but the volume of historical data that must be preserved has not been discussed. It may not be necessary to keep data longer than a day or week provided an extract or other mechanism could be defined (e.g. a "black box" model) to save data that is required for a specific investigation.

In addition to processing data from the Arduino connection, the PC code has been designed with some debugging features. Specifically, the software will have the capability to read historical data files and process them again. This can be used to test modifications to the analytics and determine if improvements in accuracy can be achieved.

When the PC code receives data from the Arduino connection it uses the packet number to determine if the packet received is new or a duplicate of the previous packet. If a duplicate packet is received, then the PC code waits a short period and then requests a new packet. The packet number can also be used to determine if packets were skipped. If the duplicate packet rate is too high, then the delay between requests for packets should be increased. If the lost packet rate is high, the delay between requests for packets should be reduced. Note that since the PC can recover from duplicates, but cannot recover lost data, the balance between the duplicate and lost rate should favor receiving duplicates rather than lost

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packets. However, too many duplicate packets will increase the communication demand on the PC and may limit the number of devices that can be supported simultaneously.

Task 2—Implement System Components

United Technologies prepared a prototype RCR device to validate the hardware modifications. They constructed 3 units in the prison-compatible lighting fixture that contained the RCR, a data acquisition board, and antenna. The units can be powered by connecting the data acquisition board with an Ethernet cable using the Power over Ethernet protocol.

GE Global Research created demonstration software to collect the data in real-time from the data acquisition unit, perform the state analysis and alarm logic. The system runs on a PC that is connected through a switch to one or more RCR units.

Task 2.1—Implementation of the hardened in-room units

See Appendix D1 - RCR Modification and Testing at UTRC.

Task 2.2—Implement embedded processing on nominal DSP platform

See Appendix D1 - RCR Modification and Testing at UTRC.

Task 2.3—Packaging per prison specifications

See Appendix D1 - RCR Modification and Testing at UTRC.

Task 2.4—Implementation of infrastructure

Wireless communication was ruled out during the design phase of the project. The power requirements for the radar and data acquisition unit are supplied using Power over Ethernet protocol. For more details see Appendix D1 - RCR Modification and Testing at UTRC.

All the devices on the LAN (RCR and PC) must use the same subnet or the PC will not be able to communicate with the RCR devices.

Task 2.5—Implementation of user interface

The user interface portion of the demonstration software was implemented in C#. The analytics including state estimation and alarm logic were implemented in Matlab™ and compiled into a DLL that was integrated with the C# user interface system. The Arduino device acts as a web server and is assigned an IP address within the code pushed onto the Arduino board. Communication from the PC to the Arduino data acquisition unit was through HTTP requests. The C# user interface establishes a connection using the pre-defined IP

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address.

The bulk of the Matlab™ analytic software was reused from the results of the early award phases. Modifications focused mostly on creating an interface for the C# program to use and a simple implementation of the alarm logic. The original work leverages Simulink™ and StateFlow™ in Matlab™. Although there are code generation features from those tools, a faster route to implementation in a stand-alone executable lay in implementing the logic in Matlab functions since the current alarm algorithm is not particularly complex logically.

The Arduino implementation was modified from the original software provided by UTRC. The new implementation is derived from the Arduino web server example. As described in the design, data buffers are used to store the signal values before transmitting them to the PC. To communicate efficiently and allow time to perform the analytics on the PC, packets are required for the communication. The size of the packets is also limited by the maximum size of the data buffers that can be downloaded to the Arduino board. Currently, packets of 3 seconds of data can be created, stored and communicated.

To minimize repeated packets, the PC code must include a delay before requesting a new packet of data. The delay should be equal to the packet size minus the execution time of the packet analysis. Currently, a constant that is approximately equal to the expected execution is used, but more sophisticated strategies can be used to enhance the reliability of the data acquisition. With the current simplistic approach, an occasional packet of information is lost.

The user interface stores the signal data, state evaluation and alarm value and count in a text file and displays some diagnostics information on the screen as shown in Figure 11. The connection name will be shown on the list of connections currently configured. It is also the base name of the file containing the output. The IP address and port will be pre-defined by the configuration of the Arduino board. The Test button can be used to confirm that the PC can communicate with the Arduino board. Save is used to save the connection, but the other options also typically perform that task. The Start Monitoring starts the data collection process and Stop Monitoring gracefully ends the process and closes the data collection file.

The status of all connections is shown on a list as shown in Figure 12. The intent of this screen is to provide a status of all connected monitoring sessions. The list requires an update with the alarm value. Currently it is only showing whether communication is occurring with the unit.

Further enhancements to pull up plots (such as those that are currently obtained as a post-processing step from collected data as shown in Figure 13) could be created. A final product would reduce or eliminate most of the screen diagnostic logging and replace it by one or more of the following: an alarm indicator (red, yellow, and green), a plot of signals, or a plot of state.

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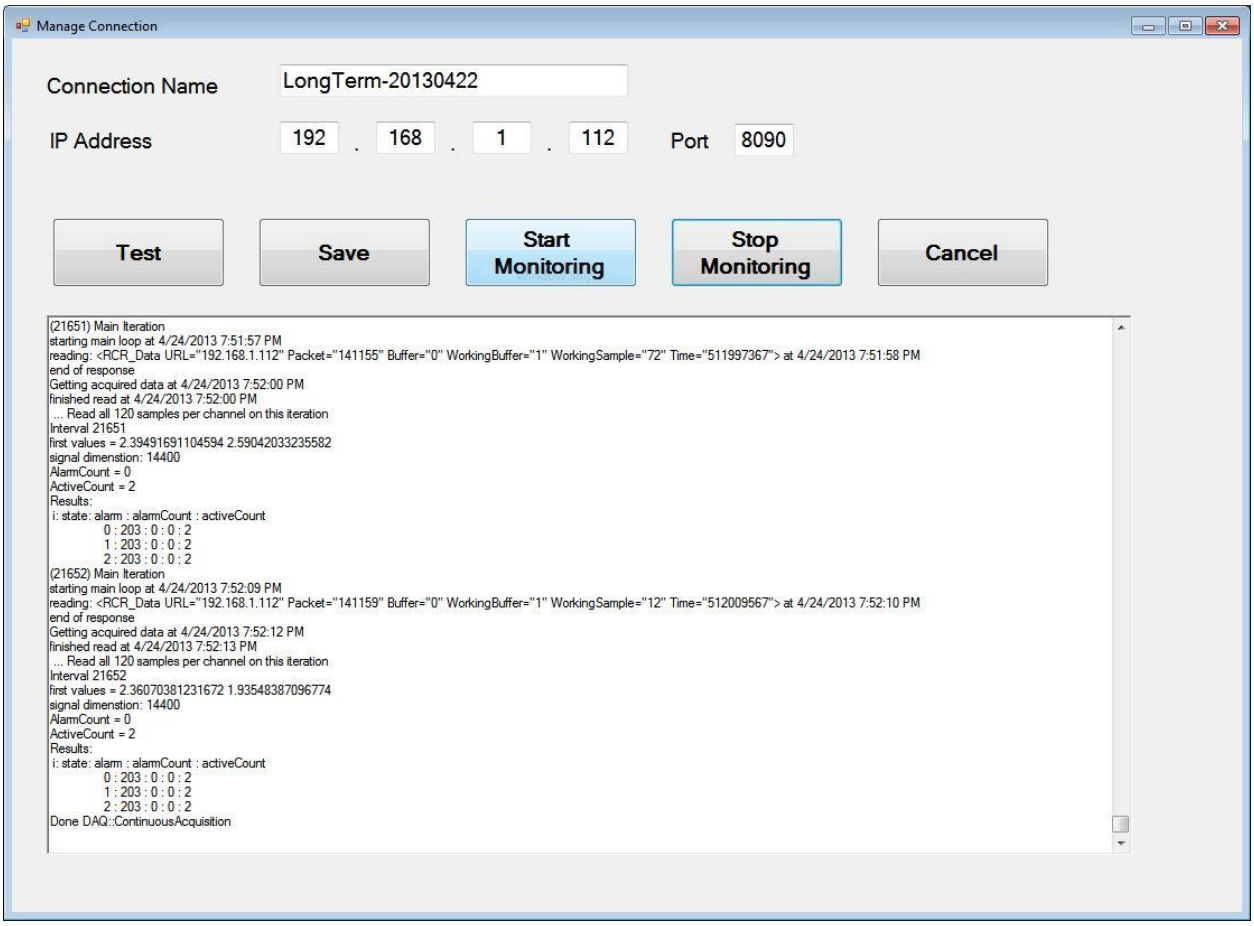

Figure 11 – Current display while capturing data

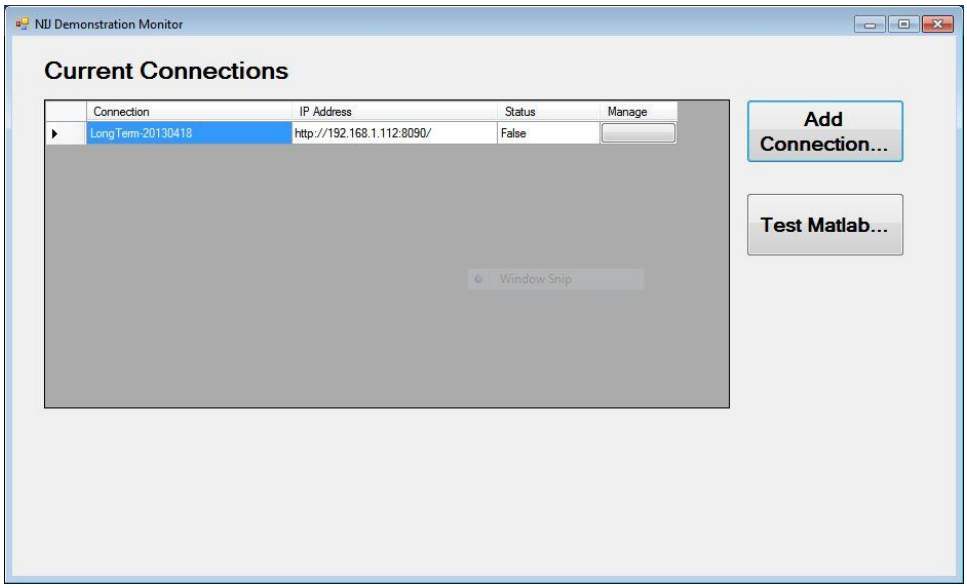

Figure 12 – Status Screen

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Task 3—Install System and Obtain Regulatory Approvals

The original goal of this task was to collect data for extended periods to better assess the ability of the analytic algorithms to identify periods of concern and identify the false alarm rate. This would help validate whether the system would be suitable for use in a prison environment to assist with monitoring for suicide prevention. Unfortunately, the IRB approvals from the State of Maryland's Corrections Research Review board did not give their approval for an experimental setup at WCI.

Task 3.1—Install system at WCI

This task was not performed because the IRB was not approved.

Task 3.2—IRB submission and management

GE and UTRC visited WCI early in phase III to discuss the type of study and support required for installation and conducting the tests. WCI was very receptive to supporting the tests and advised GE to prepare an update to the Memorandum of Understanding (MoU) used in the prior phase testing. During the MoU preparation efforts, it was discovered that the Maryland Department of Public Safety and Correctional Service (DPSCS) Departmental Research Committee (DRC) would need to approve the study. GE contacted the DRC and worked closely with them to incorporate their concerns for observing inmates into the study protocol (see Appendix C1 – WCI Inmate Study Protocol) and the study consent (see Appendix C2 – WCI Inmate Study Consent). After several in-depth discussions with the DRC the IRB study was submitted to GE's IRB and Maryland's DRC (see Appendix C3 – WCI Inmate Study MD DPSCS DRC Application). GE's IRB provided a list of requested modifications which were able to be addressed with minor changes to the IRB (see Appendix C4 – WCI Inmate Study IRB Feedback). However, after an extended review period, the Maryland DRC denied the request to perform the study at WCI's Special Observation Housing unit with prison inmates (see Appendix C5 – WCI Inmate Study MD DPSCS DRC Rejection). In the denial, Maryland's DRC provided no guidance on possible modifications to address their concerns. Due to the time and expense extended in the DRC and IRB application process, it was decided to complete the final demonstration testing in-house at GE.

Task 4—Operate and Monitor the Deployed System

The system can be easily tested. First, locate the Arduino units in the location to be monitored. Then, connect the Arduino units to a switch (or router) that provides Power over Ethernet (PoE) capabilities. The Ethernet cables to the Arduino units should be plugged into the PoE ports. The PC computer to monitor the units is also connected to the same switch in a non-PoE port. The connections between devices should resemble the connection shown in Figure 8. Power the switch. To confirm that power is working, the Arduino board and Ethernet shield have small lights, although under normal operation it would not be possible to view those. The RCR units will need a warm-up period (~5 minutes) before they start

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working correctly. During this period, any signals captured will report 5 Volts for both the high and low gain channels. The software program on the monitoring PC can be started at any time, to check the signals. A connection is added with the desired IP address. A name for the connection is used to create the data file. The software also needs a ramp-up period to collect sufficient historical data in order to perform the wavelet analysis. Currently, a period of 180 seconds (3 minutes) is required. For accurate state estimation, the monitoring warm-up should start after the RCR units have reached operating conditions.

Limited testing of the system was performed in an office environment. Due to the delays in the program as a result of trying to obtain permission to operate at WCI, the amount of time that data was collected was limited to several days. Review of the data collected shows the signals have distinct signatures when the space is empty (concern) and when activity is present (motion). Quiet periods are observed when working at the computer as shown in Figure 13.

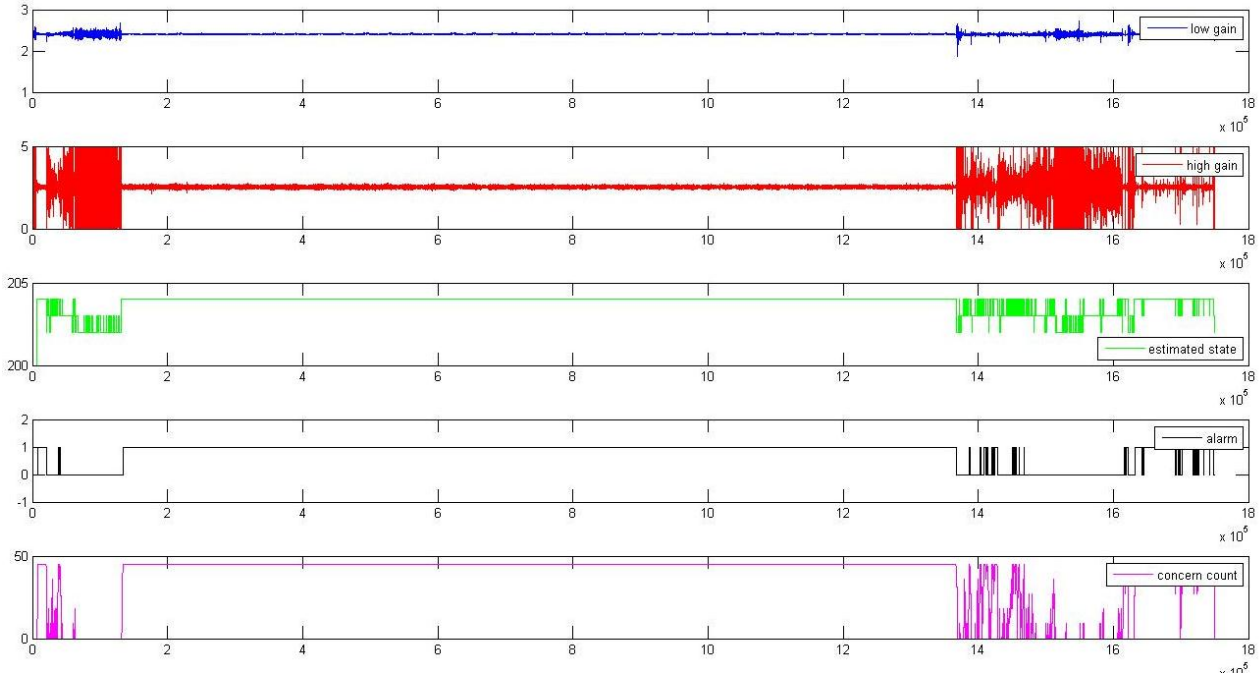

Figure 13 – Sample data results and possible graphical design

Task 4.1—Monitor system performance

Testing of the new units showed that we generally detected motion as expected, but that the algorithm was not accurately separating quiet and concern states. Since we expected that some retuning might be required in the new hardware configuration, we first explored adjusting a few of the algorithm parameters. However, the changes did not make much improvement and often did not make any changes at all. After a few unsuccessful retuning attempts, we reviewed the characteristics of the features used in the algorithm, especially since this was the first time we were collecting data with the new UTRC-constructed units. In particular, the wavelet features which are critical for separating quiet (by detecting

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respiration) and concern were examined. Figure 14 shows a comparison of features for quiet and concern from the high gain and low gain channels from the original GE Study datasets. Figure 15 shows a similar comparison from some initial data collected from a new device in the enclosure. From a visual inspection, it appears that it would be very difficult to tune an algorithm that would separate the data into two classes.

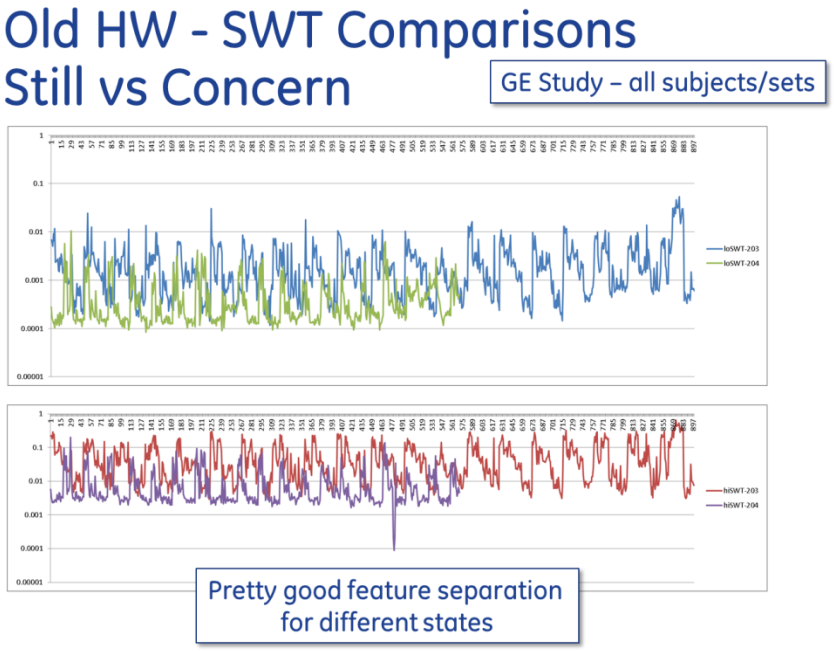

Figure 14 – Comparison of wavelet features for quiet and concern states from GE Study data sets

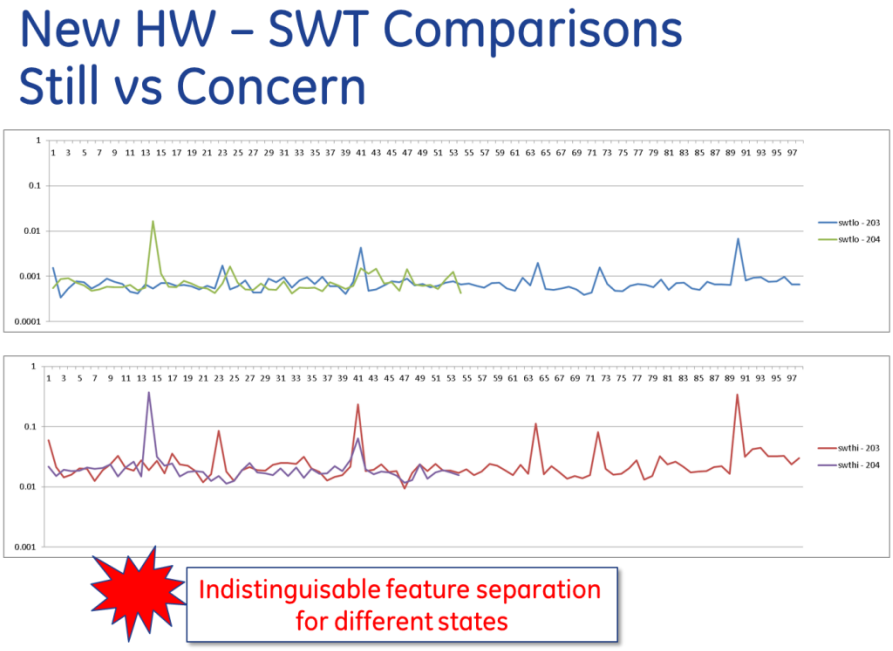

Figure 15 – Comparison of wavelet features for quiet and concern states from UTRC device

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After this observation, an analysis of the specifications of the new hardware (electronics) was performed and several iterations of hardware adjustments and sample data collection were performed to identify the causes of the differences between the UTRC-built devices and the original GE-built devices. This process identified unexpected differences between units and differences from the original GE-built units. Several iterations of reviewing the electronic configuration, gain, filters, etc. were performed, especially on the UTRC-built unit. The steps to refine the electronic configuration are included in Appendix D2 - RCR Validation and Testing at GEGRC. It was observed that the high gain channel of the UTRC-built units has less low frequency response than the original GE-built units used at WCI. In conducting a deeper analysis, it was concluded that although UTRC did build the units to the GE specification, the GE specifications did not match the original GE-built unit used at WCI. After careful analysis and one-to-one comparison, a final modification was made to the UTRC-built units. The long-term data collected uses the final modification of the UTRC-built unit. These specifications include narrowing the band pass characteristics of the baseband receiver to cover frequencies of 0.1 to 1.7 Hz (3dB), providing an increased baseband gain of 78dB, and increasing the capacitance of AC coupling circuit between the low gain and high gain stages.

Even after adjusting the UTRC-built unit, we observed that the analytical results did not appear to have the same accuracy determining states as we had achieved in the original studies. Figure 16 is a sample of the same results shown in Figure 13 prior to retuning. Generally, it appeared that the system detected large motion easily. The majority of the data should result in a concern state and an associated alarm. This represents nighttime in the office environment when no one was present. This chart shows a lot of misclassification of concern (when the room was empty) and quiet. A key element of that classification is derived from the support vector values, including the support vector, the alpha values and the bias. A subset of known concern and quiet states were extracted and used to retrain the support vector parameters. The new support vector appears to have high accuracy for the concern state – particularly overnight when the office is empty as shown in Figure 13. It may still be over-assigning concern, but we see that there is regular assignment to quiet as well.

Interactive observation of the state classification also noted that the radar may not be capturing breathing when it is pointed primarily at the side of an individual. This difficulty had also been observed during some of the WCI data collection where particular individuals were difficult to detect based on their position during the experiment. A system with 2 or 3 radars that are orthogonal directions may be required to achieve the accuracy needed to keep false alarming under a reasonable operational threshold.

Interactive observation of the state classification also noted that there may be a lag for the state estimator to change states. This particular observation has not been truly quantified. However, some reruns of study data as a concatenated set also observed some changes in the classifications compared with the initial batch classifications. When the run-time algorithm was initially constructed and implemented, only the last few state values were validated because the state estimation requires a period of historical data. This adjustment in the algorithm is different than the batch analysis which used the same period of data for all the assessments.

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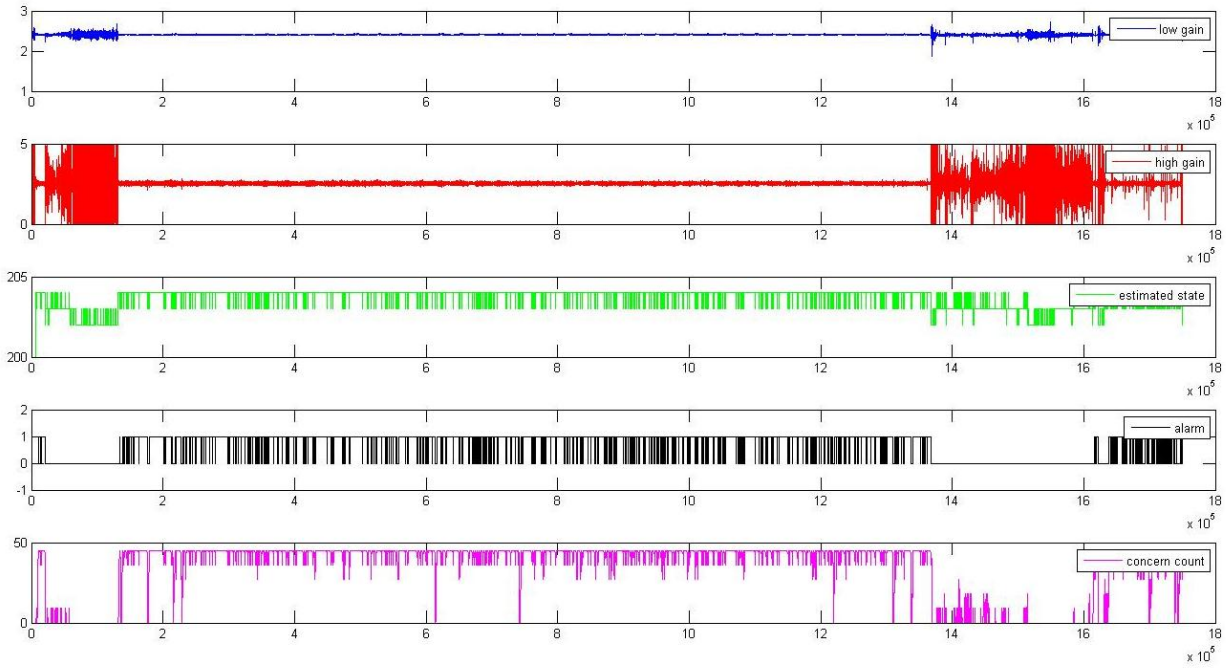

Figure 16 – Sample data prior to retuning support vector

The system ran successfully collecting data for several days at a time. One day of data as written to a simple ASCII text file required a file of approximately 50MB. With this simple data collection scheme, adequate disk storage is required for the system based on the number of days of data that will be collected and the number of units that will be monitored.

The data collection also determined that the communication delay in the main loop may need tuning on different computers. This is a result of the time processing the analytics requires. Capturing the packet number from the Arduino device is critical to accurately setting this value. Ultimately, the system could adapt the timing delay based on its performance. For instance it could automatically shorten the delay if packets are lost.

A brief test was run where data was collected from two separate units. Both units successfully wrote data to the data collection files. They both reported diagnostic information to the log window. One improvement would be to log to a separate window for each unit.

Task 5—Generate Final Report and Dataset

This report, with the inclusion of the Phase I and Phase II Final Reports (Appendices A and B), comprises the final report. In addition to the in-house and WCI data collected in prior phases, new data was collected during Phase III in an office environment over the course of several days. Since it is difficult to obtain a continuous independent reference of the activity in the office, only a limited annotation of the data is available. Night-time is easily observed in the signals and should be classified as concern. During the day, the office is typically occupied

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by one individual working on a computer. Motion is usually detected when entering or leaving the office. Occasionally, motion is also observed when the individual moves around or has a colleague visiting. During the computer work, usually quiet state would be expected, perhaps with occasional motion. For some testing, occasionally the individual will hold breath and view the state estimation interactively. For other testing, over an extended period of time, it was not possible to get detailed annotation of the behavior that is being observed.

Task 5.1—Generate Final Report and Dataset

Several days of data have been collected from an office environment. The data sets do not identify if packets were duplicated or dropped. Later data collection was improved to eliminate duplicate data packets. Some of the initial analysis was performed using the packet size of 3 seconds as the state estimation frame size. This frame size is too small to accurately capture respiration. Later data sets were collected where the software collected multiple packets to form a more suitable frame of data for analysis. The data is in a format such that all data sets could be reanalyzed offline with different frame lengths and updated analytic parameters (support vectors).

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6.0 Next Steps and Future Program Phases

This phase of the program made significant improvements in developing a deployable system for a prison environment, including a physical configuration that is safe and secure for installation in a prison cell that requires only Ethernet cabling for both data transmission and power and a software system that can collection and analyze data. The system can easily be demonstrated by placing the radar in a safe, secure location within a room and attaching to the switch and router.

There are many further possible improvements to the software to provide ease of use features related to data storage, visualization, and tuning configuration. The analytic evaluation of states and derivation of an alarm level correlates well with the visual interpretation of the signals. However, to avoid unacceptably high levels of false alarms, the alarm logic and tuning parameters may also require some further refinements. More sophisticated alarm logic beyond simple counting may be required. The delay introduced by a possible lag in state changes also warrants further investigation so that appropriate specifications on the speed of alarm notification can be determined.

Follow-on efforts to commercialize the system are being sought for corporate investment.

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Appendix A – Phase I Final Technical Report

Unobtrusive Suicide Warning System

Final Report

Award Number: 2007-DE-BX-K176

Sponsor:
National Institute of Justice
Program Manager: Frances Scott, Ph.D.
Sensors and Surveillance Portfolio Manager

Performer:
General Electric Global Research
Principal Investigator: Jeffrey M. Ashe
GE Team: Meena Ganesh, Lijie Yu, Ken Welles, Bill Platt, Joy Chen

March 31, 2009

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Executive Summary

Despite many improvements, inmate suicide remains a longstanding problem for correctional institutions. In addition to the fundamental tragedy of loss of life, suicide incidents place huge burdens on the institution that contributes to the tarnishing of the reputation of law enforcement, increasing the costs of litigation, and driving new needs to continuously monitor inmates.

In completing Phase I of this program, GE has developed a prototype demonstration system that can measure an inmate's heart rate, breathing and general body motions without being attached to the inmate. The system is based upon measuring a ballistogram using a modified version of GE Security's Range Controlled Radar (RCR) that was originally designed as a motion detector for home security systems. The detection of the ballistogram (subtle motions on the surface of the body due to the motion of internal components such as the heart and lungs) required modifications to the RCR hardware for increased physiological sensitivity and the development of new signal processing algorithms to detect and classify features.

Since asphyxia (typically by hanging or by ligature around the neck) is the predominant form of suicide experienced in these settings, the GE prototype demonstration system was designed to detect and classify levels of motion and activity (including large motions, relative inactivity or stillness, and noise from an empty or lifeless room) and subsequently estimate heart rate and breathing when needed during times of key interest. These parameters feed

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into a classification system that will alarm corrections officers of a suspicious event in progress to trigger a rapid intervention.

The GE prototype demonstration system was tested in a mock setting using volunteers under an Independent Review Board (IRB) approved study. In total, 20 subjects participated in the study to perform various activities while being measured by the GE prototype system in addition to a medical monitor. For safety of the volunteers, breath holding was used as a practical surrogate for asphyxia. This surrogate provides adequate opportunity to assess the capability to extract key physiological features for interpretation and alarming functions.

The newly developed algorithms include Principal Component Analysis (PCA) for determining types of motion activities and Fourier spectral analysis for heart rate and breathing rate estimation. GE's Phase I results produced a sensitivity of 83% and a specificity of 45% for distinguishing an empty room from an occupied room. For rate detection, GE's spectral analysis techniques produced an average heart rate error of 9.9 % and an average breathing rate error of 18.5 % averaged over all subjects during all periods of relative stillness. These results meet our goal of 20 % rate estimation accuracy in order to detect trends and warn of distress.

All planned activities on the $450K, 18-month, Phase I program have been completed. The technical objectives have included:

- The modification a commercially available radar-based motion sensor, the Range Controlled Radar (RCR), to enhance its sensitivity to detect fine movements, such as pulsations on the surface of a person's body. These activities have included modification of the pulse generating circuits, modification of the output analog signal conditioning circuits, and the development of new, steerable antenna technologies.

- The development of software that can interpret and classify the information provided by the RCR sensors. These activities included the development of physiological rate estimation techniques (heart rate and breathing) as well as the development of statistical motion classification algorithms to determine when a room is occupied, but "still enough" to reliably extract physiological signals.

- The integration of the hardware and software elements into a unified prototype system for testing, evaluation, and demonstration. This involved the collection of data from 20 volunteer subjects and the testing of volumetric coverage of the system in a mock cell setting.

Requirements for this program have been gathered from potential corrections end users. A close collaboration was created with the Massachusetts Department of Corrections (MADOC) through Dr. Alex Fox, Director of Security Technology. With this collaboration, the GE team was able to discuss features (and practical concerns) with corrections officers, healthcare staff, legal staff, and operations staff as well as visit real-life prison settings (MCI-Cedar Junction). This relationship should serve as a role model of how corporations should work together with the user community early in the research and development phases.

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Extremely valuable in itself, the data collected through the human subjects study is rich in features and information. Twenty subjects performed a range of physical activities within in mock prison cell setting in our GE laboratory. Each subject completed a series of ten 3-minute activities while simultaneously measuring radar, ECG (heart rate gold standard), Spirometer (breathing rate gold standard), and video (for archival reference). The activities included both motion and still periods while standing, seated, and supine (laying down) including breath holding as a surrogate for asphyxia. The data set has been de-identified to ensure privacy and has been annotated to classify heartbeats, breathing cycles, and types of motion for continuing algorithm developments.

While the first pass baseline performance has been impressive, there is much work to do. In particular, the confusion between the state of an empty room and an occupied room with very little motion can be improved with more advanced signal processing algorithm development. Based upon voice-of-the-customer input collected in phase I, a meaningful goal for continuation phases of this program aim to achieve a high sensitivity (>95%) for early detection and adequate specificity (>20%) to reduce nuisance alarms. A second goal for continuation phases is to produce a system that is mechanically hardened to survive being mounted within a prison cell. While the hardening goal may sound trivial, equipment (even simple things like light fixtures) must be specially engineering to provide function while holding up to abuse and not being exploited as a weapon. In addition, prisoners are not generally cooperative test subjects and algorithms, including adaptive algorithms, will need to be continually updated as prisoner behaviors emerge to spoof or abuse the system.

A staged development plan is recommended to bring the Phase I results to a fielded product. This involves the development of more advanced algorithms, expanding the statistical significance of the data set by collecting from more volunteers (goal of up to 100), developing mitigation techniques for spoofing, and hardening the system and developing a user-interface for corrections deployment.

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1.0 Motivation

Despite many improvements, inmate suicide remains a longstanding problem for correctional institutions. Suicide rates have been observed as high as 47 per 100,000 inmates in local jails and 15 per 100,000 inmates in prisons. Apart from the fundamental tragedy in loss of life, suicide incidents contribute to the morbid atmosphere of jail, tarnish the reputation of law enforcement, place an undue burden on institutions to continuously monitor inmates, and increase cost of litigation associated with wrongful death.

Hanging is the principal method of suicide in prisons. In most cases, death is not immediate and strong physiological responses that result from asphyxia become apparent prior to actual end of life. Asphyxia symptoms include: spontaneous gasping, struggling associated with the mental anguish of oxygen starvation (dyspnea), and sudden changes to or an absence of heartbeat and breathing. If properly monitored and interpreted, these motions can be used to determine whether or not asphyxial trauma is in progress.

Extracting motion-based parameters of breathing and heart rate, and interpreting types of activities, are key factors in determining when an inmate's life is in immediate jeopardy that requires rapid intervention.

2.0 Approach

GE Global Research has developed an unobtrusive, Doppler radar-based sensor system that will indicate a suicide attempt in-progress by observing and interpreting motion related to heartbeat, breathing, and limb movement. This non-contact monitoring device can detect, interpret, and relay information about strong and sudden changes in physiology associated with asphyxia through self-strangulation or hanging, without guards having to directly observe a prisoner. This system will give prisons and jails an effective method to monitor at-risk individuals without resorting to expensive surveillance solutions such as 1-to-1 observation, suicide patrols, or closed circuit video.

The GE system development has involved:

(1) Redesigning the elements of a commercially available, low-cost motion sensor to enable increased sensitivity to body motion.

(2) Modifying GE's signal classification software to detect abnormalities of physiological parameters consistent with a surrogate for suicide attempt.

(3) Integrating the two radar and algorithms into a working virtual prototype for laboratory demonstration and testing.

The demonstration system has been evaluated by capturing limb motion, breathing and heartbeat from approximately 20 volunteer human subjects in a mock cell environment.

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These individuals included males and females of varying ages, heights, and weights, in various body positions, and simulating asphyxia by withholding breath. All human studies are conducted under the approval of an accredited Independent Review Board (IRB).

3.0 Program Goals and Objectives

The goal of this program was to develop a remote sensing system that can capture vital signs related to the physiology of an individual and provide an assessment of those signs.

Three technical objectives were met during the research program.:

- The first technical objective was to modify a commercially available radar-based motion sensor, the Range Controlled Radar (RCR), to enhance its sensitivity to detect fine movements, such as pulsations on the surface of a person's body.

- The second technical objective was to develop software that can interpret and classify the information provided by the RCR sensors.

- The third technical objective was to integrate both the hardware and software elements into a unified prototype system for testing, evaluation, and demonstration.

The third objective also included evaluation and testing of the suicide warning system using volunteer subjects in a mock laboratory jail cell setting. A total of 20 subjects, both males and females of varying ages, heights, and weights performed testing to assess sensitivity to respiration, breathing, and general motion. Quantitative objectives of the program were to measure heartbeat and breathing rates to within 20% rate accuracy and to establish the baseline sensitivity and specificity of the demonstration system.

4.0 Literature Review

Prison and jail suicide rates have declined over the past 30 years due to better practices in prevention and quality-of-care for at-risk prisoners. [1,2] Screening inmates for placement into safe cell units, improved training to recognize suicidal behavior, on-site facilities to treat the mentally ill, and the use of suicide patrols for direct intervention all contribute to the declining in-custody suicide rates. [3]

However, the prison environment and statistics from prior studies demonstrate a continued need for the development of unobtrusive methods to detect suicide attempts. [4,5] Approximately 80 percent of all suicides involve hanging and many involve the victim still in contact with the floor during the act. [6] The ligature used to constrict blood flow can be one of many items commonly available to the inmate including belts, bed sheets, shoelaces, and any other item that can support a weight as little as 2 kg. [5] Ligature points used to support a body, such as hooks, bed frames, doors, or shower fittings, are typically accessible. Due to the accessibility to commonly-issued clothing and structures, it is not possible to completely

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remove the threat of suicide in a correctional setting without completely dehumanizing the quality of life for inmates or violating the basic human rights of the prisoner.
Standoff methods to remotely observe individuals have continually progressed due to advances in miniaturized electronics, wireless communications, and low-cost manufacturing techniques. [7-9] Radar is used for unobtrusive monitoring since it is noninvasive, can operate in a diverse environment, and can capture subtle motions of the body. These body motions include mechanical contractions of the heart and motion of the chest wall through clothing and building materials. [10-12] These methods principally work by evaluating the spectral content and round-trip time of electromagnetic echoes reflected from the target, which in this case is the chest. Because of these properties, radar has been used to find survivors in earthquake rubble, to detect combatants behind obstacles, and to locate targets behind foliage. Radar systems developed to monitor humans have shown promise but have not yet solved the size, cost, and usability issues of a jail environment. Privacy and human rights issues limit the effectiveness of readily identifiable, but intrusive video surveillance methods. Acoustic methods, although useful for respiration monitoring, but may not be able to detect the activity of an internal organ, such as the heart. [13]

Although there is little work concerning the use of monitoring technology in a prison setting relevant to suicide intervention [14], there is considerable prior work in the area of civilian health and activity monitoring to deal with the problem of rising health care costs. [15,16] Many programs have focused on monitoring in the home for disease management [17-20] and others examined patient monitoring in hospitals for false alarm reduction and more efficient workflow. The feasibility of using unobtrusive monitoring signals to infer certain forms of human behavior (such as locomotion, sleep, and other activities of daily living) has been established, which may be extended to evaluate behavior in a jail or prison setting.

5.0 Research Design, Schedule, and Resources

The program involved three tasks over an approximately 18-month period. The research design methodology addresses the key technical risk areas:

(1) To establish practical feasibility of non-intrusive sensing of physiological variables (respiration, heart rate, motion) under mock jail cell conditions.

and

(2) To verify that the sensor signals can be processed using human activity monitoring methods to achieve a level of accuracy consistent with suicide prevention.

The hardware and software subsystems were assembled into a prototype demonstration for preliminary verification tests using human subjects. The human subject tests were intended to demonstrate the baseline capability of the proposed system to achieve the performance objectives of the preliminary design, to provide enough calibrated data for basic system tuning verification, and to provide demonstration and confirmation of system operation at a level suitable for progression in technology readiness level during the next program phase.

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The program status vs. the work breakdown structure (WBS) as used to guide the program developments is provided in Table 1. All proposed activities on this phase of the program have been completed and are described in this report.

Table 1 – Project Schedule and Status of Each Element of the Work Breakdown Structure

Task #	Task Description	Status
1.0	**Doppler Radar Hardware Modification**	
1.1	System Architecture	Complete
1.2	Pulse Design	Complete
1.3	Antenna Design	Complete
1.4	Signal Conditioning	Complete
1.5	Lab System Integration	Complete
2.0	**Human Activity Monitoring**	
2.1	Monitoring Algorithm	Complete
2.2	Statistical Tuning	Complete
3.0	**Demonstration System Integration and Test**	
3.1	Hardware Performance Evaluation	Complete
3.2	Software Performance Evaluation	Complete
3.3	Testing in Mock Cell	Complete
3.4	Final Demo and Report	Complete

Project financial performance will be submitted separately through the SF-425 forms in the GMS online system. Project financial expenditures are commensurate with the technical progress on the program. Project resources have been allocated to roughly 39% for the hardware developments, 47% for the algorithm development and data analysis, and 13% for the human subjects studies and performance verification tests.

6.0 Technical Activities and Results

Task-1 Doppler Radar Hardware Modification

The objective of Task 1 was to modify a radar-based motion sensor (RCR) to be highly sensitive to the fine pulsatile motions of the chest associated with breathing and heartbeat.

Task-1.1 System Requirements and Architecture

The initial stages of the project involved defining the system and architecture necessary for successfully developing a radar-based cardiorespiratory sensing system. More generally, this task was segmented into gathering inputs from potential corrections end users, transferring these needs and objectives into defined design guidelines of the USW, and finally synthesizing the architecture through prototypes and testing.

Customer Input – Requirements, and Environment

Defining the requirements of the USW system was conducted in collaboration with project team members and in consultation with the Massachusetts Department of Corrections

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(MADOC). A meeting was held at the MCI-Cedar Junction facility at Walpole, MA to discuss the operational environment of an in-cell vital signs monitor. The objectives of this meeting were to:

- Hear first-hand accounts from senior corrections officials of the operational, functional, and environmental requirements for such an electronic warning system to be deployed in a corrections environment.
- Visually inspect the prison facilities to understand how the radar should be installed in a prison cell.
- Tour the Bridgewater Correctional Complex to evaluate the area in which an in-cell field-test of the system may take place.

Requirements were elicited from corrections administrators as listed in Table 2.

Table 2 - List of requirements based on observation at MIC-Cedar Junction corrections facility

Requirement	Rationale	Impact
Wired infrastructure (no wireless communication)	No need for battery servicing. Improved hardening.	Removes design constraint for low-power operation
Amenable to device hardening, preferable slab shaped device	Prisoners prone to destroying and weaponizing salvaged parts	No complex geometry for final shape, simpler design for packaging and installation
Extremely low cost	Assume that device will be destroyed	Device may be replaced several times a year if routinely destroyed
Water resistant	Food and wet paper commonly used by inmates	Corrosion resistant materials and water-resistant packaging
Safety from microwave exposure	Mitigate safety concerns from corrections officers and prisoners	Limit power output below FCC levels
Low false alarm rate	Provide accurate analysis, to earn trust of administrators	Method to accurately present conditions and provide meaningful escalation level
Simple user interface	Minimize training time and to prevent information overload	Visual cue to accurately present conditions
Operate in 7'x10'x10' cell	Typical size of prisoner housing	Reduces need for extended range and hardware requirements
Operate in relative humidity of 10% to 90%	Operation of device in warm, humid, seasonal climates	Ensure electronic devices operate within desired range
Operate in temperature range between 20 to 40C	Operation of device throughout year in either semi-arid or continental climate	Ensure electronic devices operate within desired range
Minimum detectable target velocity at 1 mm/sec	Estimated slowest velocity of chest wall during breathing	Sensitivity to low frequency motion
Minumum target size at 2 square foot	Estimated profile of thorax at oblique angle	Cross section of target as observed through antenna
Room volume coverage up to 7 ft. minimum from floor level. Entire 7' x 10' area of floor must be covered	Reports of inmates crawling to elevated position from room floor at room corner	Reduces volumetric coverage required for adequate sensing
Preferred size: Compatible w/ hardened lighting fixtures at approx. 12" x 12", or electrical box at 3" x 3"	Reduce packaging to proven designs and standard dimensions used by corrections	Constrains printed circuit board size and placement of components.
Voltage input: +5 or +12V DC, compatible with corrections institutions	Utilize standard voltage w/ corrections practice	Eliminates need to modify power electronics
Onboard processing of data at sensor	Eliminate transmission of prisoner information over network	Places computational burden of information processing at RCR sensor

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Subsequently, an on-site review was conducted with Dr. Alex Fox, Director of Security Technology for the Massachusetts Department of Corrections. Dr. Fox has served as a liaison for GE with the corrections community and has brought considerable user insight for how the system needs to operate and identifying other unique challenges (spoofing, tampering, etc.) exist in prison settings. This relationship should serve as a role model of how corporations should work together with the user community early in the research and development phases. During Dr. Fox's visit, we reviewed all program aspects as well as visited the mock setting in the GE Lab and reviewed our data collection progress.

We also conducted an on-site review with Dr. Frances Scott, Sensors and Surveillance Portfolio Manager for the National Institute of Justice. During this official, annual program review, we provided a deep-dive review of each technical area of the program in addition to reviewing contractual and reporting requirements. This was an extremely useful review for the GE team to get direct feedback on their progress and results. The timing of this review was also fortunate to follow the completion of the IRB data collection study such that the demonstration system data could be observed first-hand. The preliminary results indicate significant first-pass performance but also highlight the need for future program phases to confirm the statistical performance of the system before deploying a commercial product.

Functional Partitioning

The RCR electronics architecture was dissected and functionally partitioned to determine technical or functional gaps in the design, and to develop a course of action that could remedy these unmet needs. A simplified block diagram is shown in Figure 1 with relationship to the proposed hardware modification task.

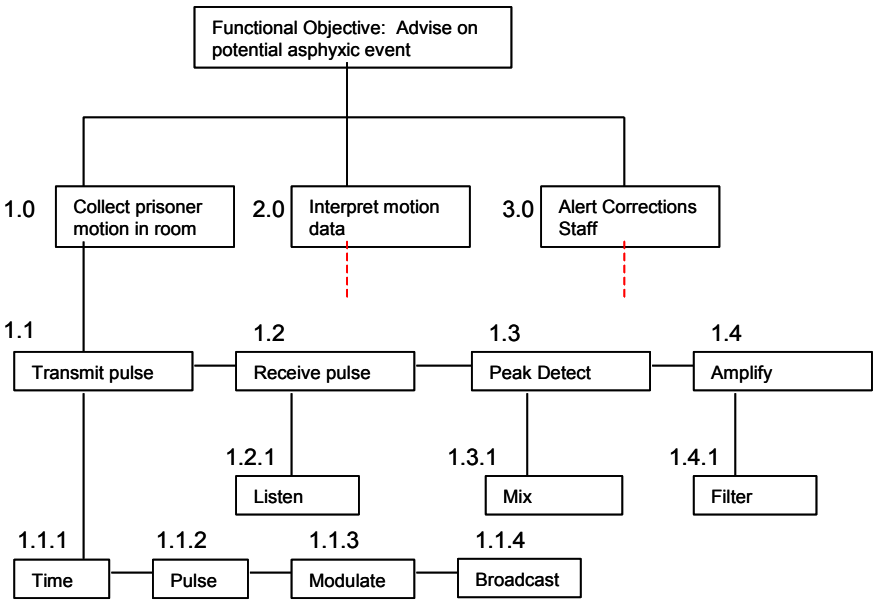

Figure 1 – Functional partitioning of motion sensor of USW subsystem.
Each required task is compartmentalized and resolved to the smallest function to evolve a quantifiable performance spec. The proposed effort is a modification of prior work in the RCR such that many requirements will not deviate significantly from a hardware perspective.

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Task-1.2 Pulse Design

Modifying the pulse firing sequence and microcontroller involved changing the stock RCR unit to be more responsive to targets within the 15 ft. limit. To perform this task, onboard timing and pulse shaping elements on the RCR unit were disabled, and subsequently connectorized to an arbitrary waveform generator to assess the effects pulse shape and duration as seen at the antenna output.

The round-trip time at the maximum range of 15 ft requires a minimum pulse width of 30 ns to allow for intermodulation at the receiver. A time delay from the pulse delivery to the actual excitation of the antenna requires an additional 20 ns. Thus, a minimum pulse length for reception should be at approximately 50 ns. Assuming a 50% duty cycle square wave, a maximum repetition rate should be no more than 10 MHz. Note that at pulse widths greater than 50 ns, the transmitted pulse will intermodulate with the receive signal at the peak detector, and range functionality is lost. This is acceptable since the USW system will be used to evaluate the motion of people that are assumed to be located in the cell.

For the experimental study, the RCR internal pulse circuit was removed and a pulse train was provided directly from a waveform generator. Since the subject is at close range (typically <10 feet from the radar antenna) the 2-pulse range-gate circuit from the commercial RCR is not necessary and the pulse width of a single pulse can be lengthened to increase the signal-to-noise ratio. We have chosen a 5 MHz square wave with a 50% duty cycle, which produces roughly a 100 ns pulse, every 200 ns. In this mode, the radar operates more like a conventional Continuous-Wave (CW) Doppler radar. A sample trace of the radar output is given in Figure 2. From a piece-wise integration of the waveform envelope, the power of 8 dBm is confirmed.

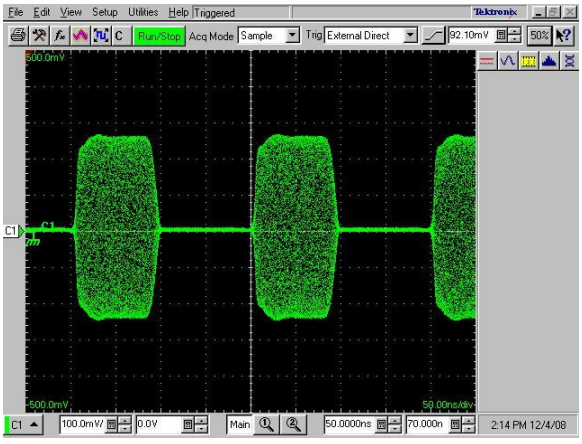

Figure 2 – RF Output Waveform of Experimental Modified RCR

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Task-1.3 Antenna Design

Dielectric Lens (Rotman-Turner) Approach

In evaluating the most cost effective approach in implementing a phased array, the dielectric lens was ranked as one of the most feasible options due to its relative simplicity, size, and backward compatibility to the existing RCR system. The rationale for such an approach is to provide adequate coverage for the entire cell volume to mitigate the risk if placement of a fixed antenna does not provide adequate coverage. The dielectric lens, or more specifically the Rotman-Turner lens, is a double-sided copper clad board of dielectric material which has one side etched to yield the characteristic pattern as shown in Figure 3. The circular shape of its center region serves as a true time delay path for allowing for phase shifting across antenna elements due to the changes in electrical lengths between feed ports at the left edge and antenna element ports at the right edge. The primary advantage of this approach is the relative simplicity of phasing across multiple elements without the use of very expensive phase shifting components. The primary drawback is the design effort required to develop a properly shaped lens and the discrete number of beams that can be generated based on the number of feed ports.

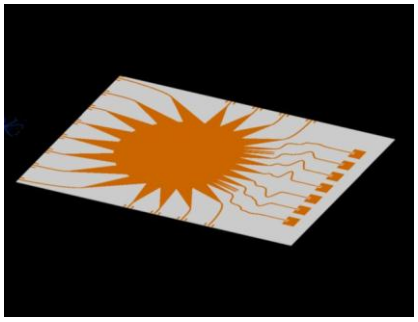

Figure 3 – Physical Design of the Rotman-Turner lens

Phase delaying and beam steering accomplished through electrical length of board alone. A switch to control the input port is only active element needed to control the device.

The plan in the USW project was to evaluate whether or not a steerable approach can provide equivalent gain compared to fixed antennas and to permit wider coverage in the event of radar shadows that can preclude motion measurement. To investigate this limitation further, a seven-element system as shown in Figure 3 was designed (Rotman Lens Designer, Remcom, State College, PA) for evaluation and use in our RCR prototype. The seven-element design was selected because this was maximum number of elements that could fit within the 12" x 12" constraint without incurring significant penalties in the performance figures of merit, such as VSWR, and port coupling.

The array factor of the design is shown in Figure 4. Assuming placement near the ceiling will obviate the need for range information, the +/- 50 degree coverage at the –3 dB point (half power beam width) should be sufficient for interrogating the lower 2/3 room volume.

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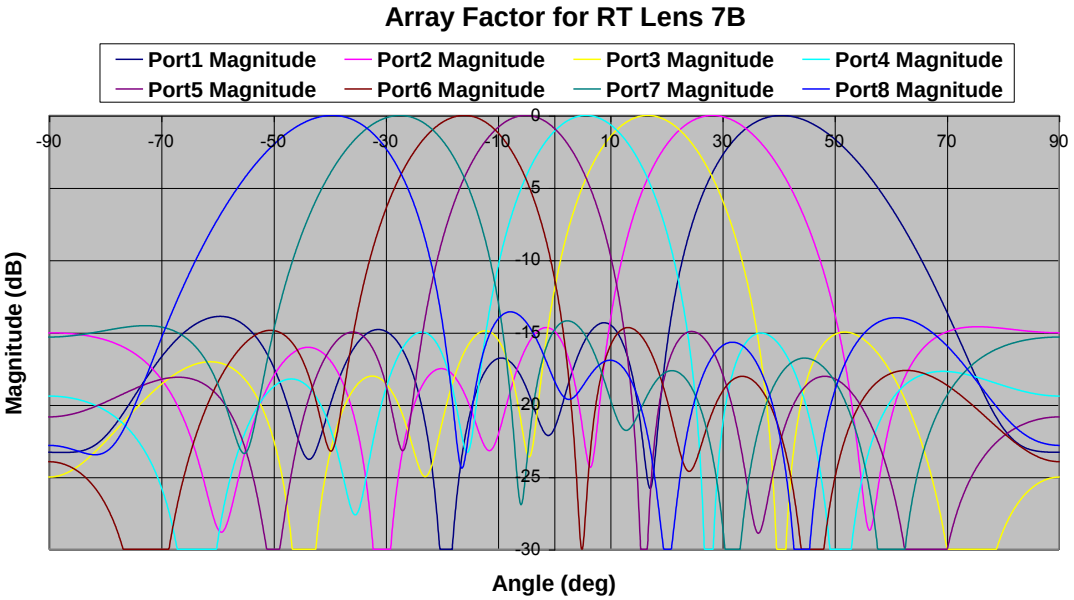

Figure 4 – Predicted Pattern of the Rotman-Turner lens.

Phase delaying and beam steering accomplished through electrical length of board alone. A switch to control the input port is only active element needed to control the device.

Testing of the Rotman-Turner dielectric lens was completed in a field-range to verify the beam steering capability of the low-cost antenna design. Subsequent antenna measurements were completed at Electro-Metrics, Inc (Johnstown, NY) using a Diamond Engineering antenna measurement system. Pictures of the equipment setup and field-range are given in Figure 5 and the corresponding experimental measured patterns are shown in Figure 6 for each of the 8 beam ports.

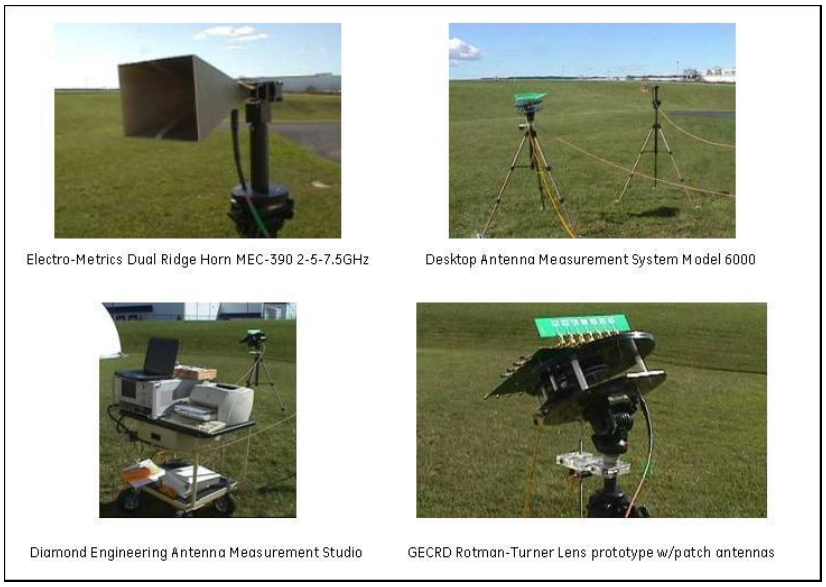

Figure 5 – Rotman Antenna Testing at Electro-Metrics, Inc.

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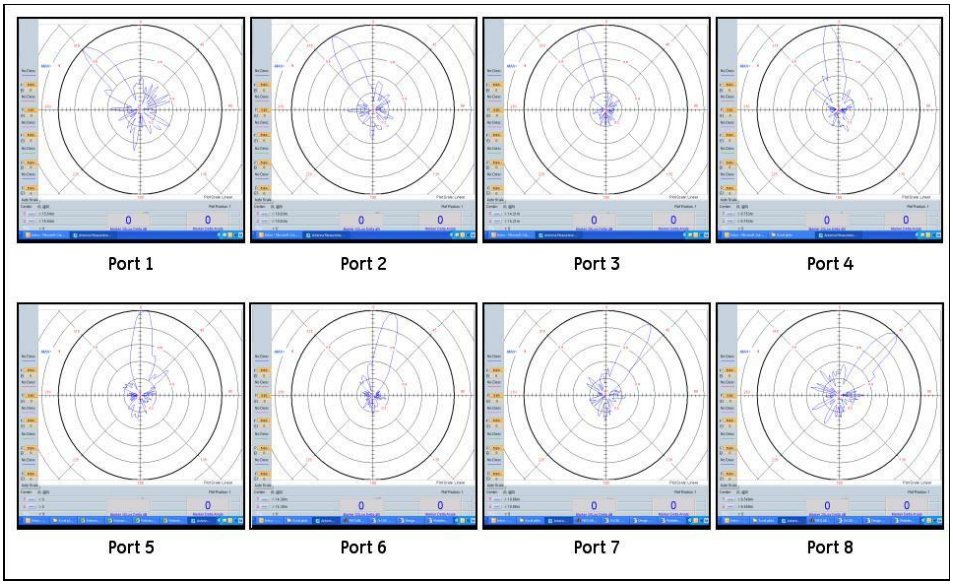

Figure 6 – Rotman Antenna Experimental Measured Patterns at 0 deg Elevation

The Rotman lens preformed as predicted by the design software. The general shapes of the beams are consistent with the expectations when using a simple set of patch antenna radiating elements. More importantly, the beam steering directions are consistent with the intentions of producing 8 beams uniformly spaced roughly between +/- 40 degrees in Azimuth. The actual beam shape is not critical for this application as long as the beams are steered different enough so that a subject that might be weak in one beam will appear stronger in another. Further analysis of the lens antenna performance is described in the section "Bridgewater Testing".

Task 1.4 – Signal Conditioning

The stock filter characteristics in an unmodified RCR unit are between 1 Hz and 47 Hz with a uniform gain of 60 dB across this frequency range. Notch filtering was used to remove noise at 60 Hz and 120 Hz. Although physiological signals are perceptible at close range in the stock configuration, a large degree of high frequency noise was also passed through, resulting in an inability to visibly perceive the heartbeat signal beyond 4 ft with occasional dropouts of the signal. To improve the signal quality, surface mount capacitors in the band pass op-amp circuits were replaced with higher capacitor components to change the frequency range to 0.1 Hz to 15 Hz, which is more suited to physiological ranges of interest.

Task 1.5 – System Integration

The system modifications were performed and assembled in the lab as a bench top prototype. The bench top prototype was used to perform several tasks including measurement and testing for safety, collection of the training data from human subjects, and collection of the demonstration/validation data from human subjects. Electromagnetic safety is discussed here and data collection is discussed in subsequent report sections.

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Electromagnetic Safety

As with any experimental setup, safety is of the utmost importance. With a Human subjects experiment, all anticipated aspects of safety must be fully understood. Since our device under test is a modified version of a commercial product, we must ensure the modifications do not present additional danger to the test subjects or to the personnel in the nearby vicinity. Since this device emits radiofrequency electromagnetic waves, we need to consider the filed exposure according to FCC guidelines under Bulletin OET-65.

Under the OET-65 guidelines, there are two types of exposures at the 5.8 GHz frequency:

- *Controlled Exposure* – The subject is aware of the radiation and can control his/her exposure level by shielding or avoiding the field. For our application this is limited to 5 mW/cm2 over a 6-minute interval. This means you could be exposed to less than 5 mW/cm2 indefinitely or the equivalent averaged over time (for example if exposed to 10 mW/cm2 the subject could be present for up to 3 minutes of each 6 minute period).
- *Uncontrolled Exposure* – The subject is either unaware of the radiation or cannot control his/her exposure. This requirement is more stringent and for our case is limited to 1 mW/cm2 over a 30-minute interval.

The exposure calculations for the experimental setup as used in the IRB study (including the 17 dBi antenna) are given in Figure 7. For reference, the calculated, and measured, output power of the modified RCR radar is 8 dBm (or equivalently 6.3 mW) such that at 15 cm away the experiment exposure is 1/10 of the uncontrolled limit, at 50 cm the exposure is 1/100 of the uncontrolled limit, and at 160 cm the exposure is 1/1000 of the uncontrolled limit.

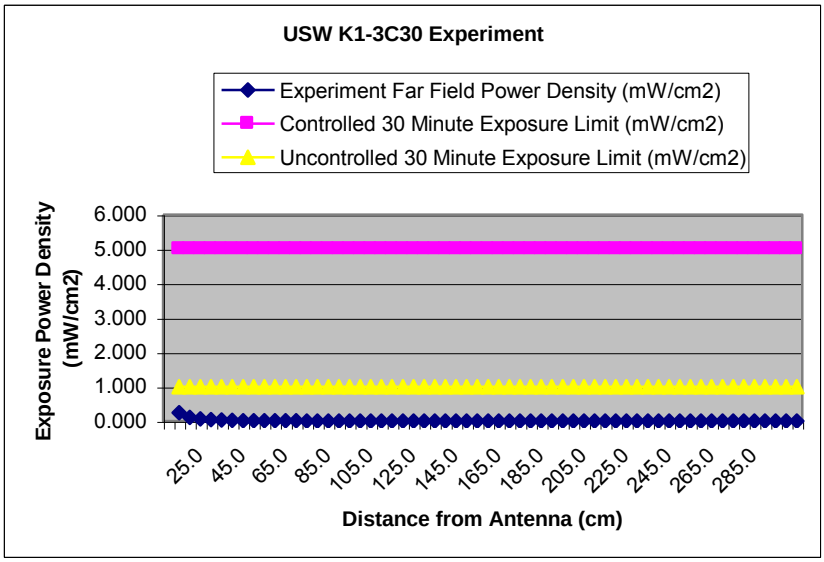

Figure 7 – Experimental Exposure is Greatly Below the FCC OET-65 Exposure Limits

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Task-2.0 Human Activity Monitoring

The second objective is to develop software algorithms that can reliably extract heart rate, breathing, general motion, and provide subsequent interpretation of the information.

IRB Data Collection Study

Since the study involved Human Subjects, the study protocol needed to be approved by a medical IRB. In this study, GE Global Research contracted with IRC Inc. (www.irb-irc.com). The application and approval process is comprehensive and considers many factors including ethics, safety, confidentiality, volunteer recruitment, and data integrity. GE prepared and provided the following materials for the IRB review (copies of which are retained in the Principal Investigators files at GE Global Research):

- Principal Investigator Application
- Conflict of Interest Disclosure
- Investigative Device (Radar) Description
- Employee Subject Fairness Procedures
- Study Protocol
- Informed Consent Form
- Volunteer Recruiting Ads
- Privacy Certification
- Human Subjects Assurance

In addition, at the conclusion of the study collection period, a final study summary was supplied to IRC Inc. Included in this summary was the description of one adverse or unanticipated event from the GE conducted study. This event was deemed "not serious" but was "unanticipated and probably related" to the study. Nonetheless, the event was documented and reported promptly to the IRB. The event is described as follows:

> "Subject #10 experienced a bloody nose while wearing the facemask for IRB 07189. Subject #10 refused any medical attention and stated that they often get bloody noses with the change of seasons and dry conditions. We halted the experiment at that time. We determined the incident, based upon the subject's history, was minor. Subject #10 returned to the study on 11/19/2008 and suggested we conduct the experiment again without the facemask but by using a breathing tube. The subject completed the data collection without incident."

No other unanticipated events occurred and the study was completed on schedule.

Study Protocol

The study was designed to give a good cross section of participants (male, female, age, weight, height, etc.) with a good cross section of activities and viewing angles (moving, still, standing, seated, supine, front, back, side, etc.). Each volunteer subject was asked to conduct 10 sets of activities, each of 3 minutes in duration. The data collection was administered by

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the Principal Investigator with a scripted set of instructions given to each subject throughout each activity. These data set activities are described in Table 3.

Table 3 – Pilot Protocol Data Sets
Data Sets are Color Coded with Green=Good State, Yellow=Good but Possible Transition, Red=Alarm for Intervention
Heart Rate and Breathing Rates are Computed During "Still" States 4,6,7,9, and 10

Data Set	Description	Rationale
1	No Subject Present	Establish Radar Baseline
2	Randomly Walking Subject with Arms, Legs, and Torso Movements	Standing Dynamics, General Limb Motion, Translational Motion, Random Views & Distances
3	Standing with Arms, Legs, and Torso Movements, Change View Angles From Front to Side to Back on 60 Sec Intervals	Standing Dynamics, General Limb Motion without Translational Motion, Multiple View Angles
4	Standing as Still as Possible with Normal Breathing, Change View Angles From Front to Side to Back on 60 Sec Intervals	Standing Dynamics, Natural Body Sway, Multiple View Angles
5	Sitting in Chair with Arms, Legs, and Torso Movements, Change View Angles From Front to Side to Back 60s Intervals	Seated Dynamics, General Limb Motion without Translational Motion, Multiple View Angles
6	Sitting in Chair as Still as Possible with Normal Breathing, Change View Angles From Front to Side to Back 60s Intervals	Seated Dynamics, Stillness without Body Sway, Multiple View Angles
7	Sitting in Chair as Still as Possible with Breath Holds on 30 Sec Intervals, Change View Angles From Front to Side to Back on 60 Sec Intervals	Seated Dynamics, Breath Holding, Stillness without Body Sway, Multiple View Angles
8	Supine on Cot with Arms, Legs, and Torso Movements, Change View Angles From Front to Side to Back 60s Intervals	Supine Dynamics, General Limb Motion without Translational Motion, Multiple View Angles
9	Supine on Cot as Still as Possible with Normal Breathing, Change View Angles From Front to Side to Back 60s Intervals	Supine Dynamics, Stillness without Body Sway, Multiple View Angles
10	Supine on Cot as Still as Possible with Breath Holds on 30 Sec Intervals, Change View Angles From Front to Side to Back on 60 Sec Intervals	Supine Dynamics, Breath Holding, Stillness without Body Sway, Multiple View Angles

Laboratory Setup

A 10'x7' area was cordoned off in a laboratory at GE Global Research. The Radar was placed at one end of the mock cell on a tripod of approximately 6 feet in height. A 17-dBi antenna was connected to the radar output and angled down toward the mock cell area. Within the 10'x7' space a chair and a cot were located. Subjects were allowed to walk in an L-shaped area in front of the chair and cot for the motion sets. Subjects stood or were seated approximately 8 feet from the radar at a location roughly near the center of the cot for the other experiments. Pictures of the experimental setup are given in Figure 8.

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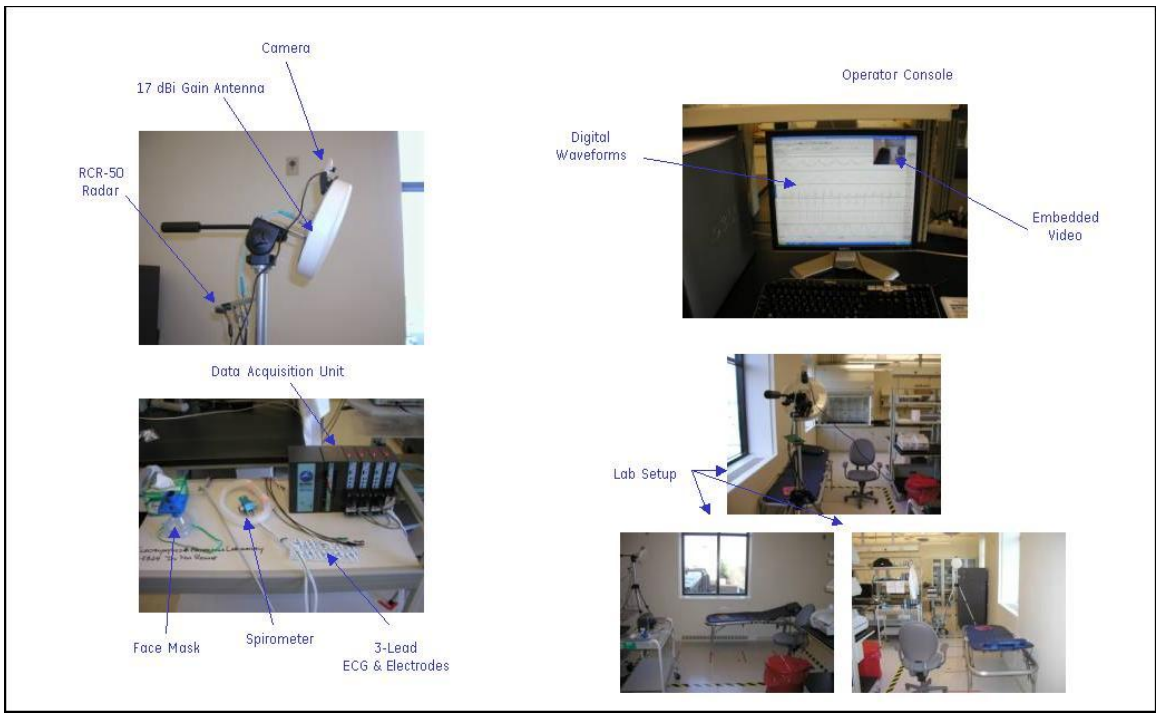

Figure 8 – Laboratory Setup for IRB Data Collection Experiments
Upper Left: RCR Radar and External 17-dBi Antenna on Tripod at end of Mock Cell
Lower Left: ECG and Spirometer Data Collection System
Upper Right: Operator Console with Radar, ECG, and Spirometer Waveforms Plus Video Capture
Lower Right: Mock Cell Layout (Multiple Views)

Data Annotation

Heartbeats and breathing cycles were annotated in the ECG and Spirometer channels, respectively, using a combination of automated and manual techniques. Traditional ECG or respiration algorithms were not well suited for the data collected due to the lack of adequate pre-filtering and post-processing capability in the general purpose data acquisition system. An automatic technique was used to detect the peaks of the QRS-complex in the ECG data (choosing the best of the 3 leads available) or the transition from inspiration to expiration (air flow reversal) in the Spirometer data. A second-pass was performed manually to review each selected point and either confirm or adjust the location based upon visual observation. Examples of the types of waveforms encountered are provided in Figure 9.

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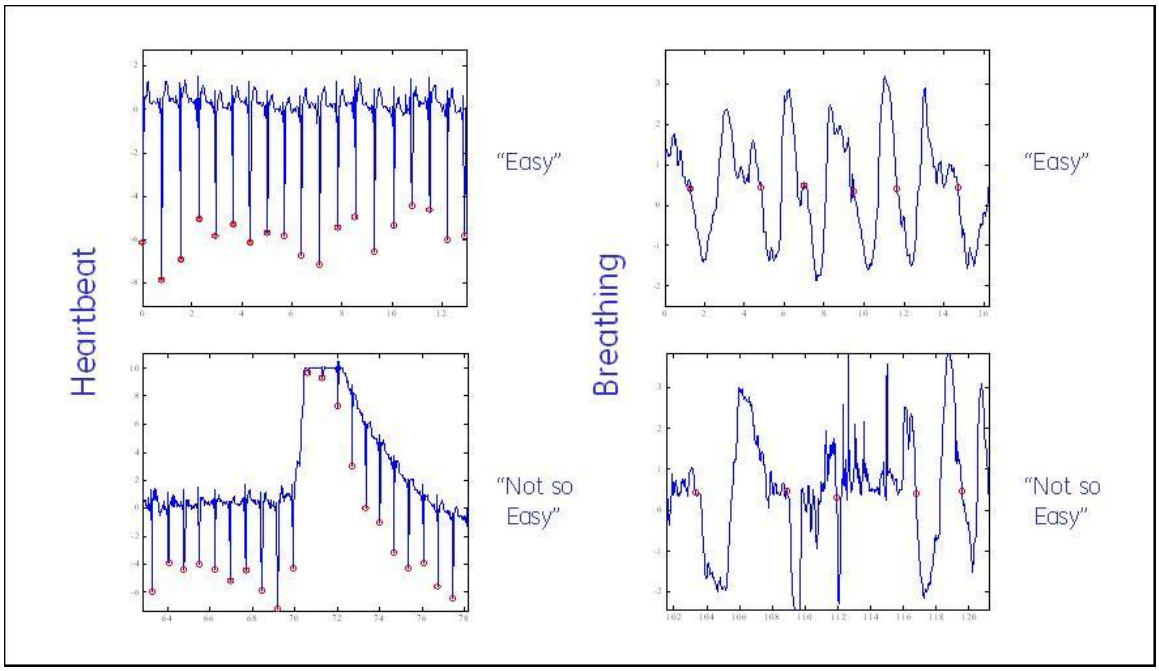

Figure 9 – Heartbeat and Breathing Annotations
"Easy" sets are free of noise and/or transients
"Not so Easy" sets require manual interpretation during noise events

Motion types were annotated in the data sets by viewing the video and noting the times of different activities (moving, still, transitioning/turning, etc.) as well as reviewing the ECG and Spirometer waveforms for unobservable traits (e.g. breath holding). The motion types were divided into 11 main categories with subsets based upon view angles for a total of 30 different possible types of motion. The states are listed in Table 4 and are depicted graphically in Figure 10 for all 10 sets of subject #1 (as an example).

Table 4 – Motion States for Annotation

State	Description	State	Description
0	Unknown (void)	**7.1**	Still Hold Seated Front
1	Empty Room	**7.2**	Still Hold Seated Side
2	Moving Walking	**7.3**	Still Hold Seated Back
3.1	Moving Standing Front	**8.1**	Moving Supine Back
3.2	Moving Standing Side	**8.2**	Moving Supine Side
3.3	Moving Standing Back	**8.3**	Moving Supine Stomach
4.1	Still Standing Front	**9.1**	Still Supine Back
4.2	Still Standing Side	**9.2**	Still Supine Side
4.3	Still Standing Back	**9.3**	Still Supine Stomach
5.1	Moving Seated Front	**10.1**	Still Hold Supine Back
5.2	Moving Seated Side	**10.2**	Still Hold Supine Side
5.3	Moving Seated Back	**10.3**	Still Hold Supine Stomach
6.1	Still Seated Front	**11.1**	Transition Standing
6.2	Still Seated Side	**11.2**	Transition Seated
6.3	Still Seated Back	**11.3**	Transition Supine

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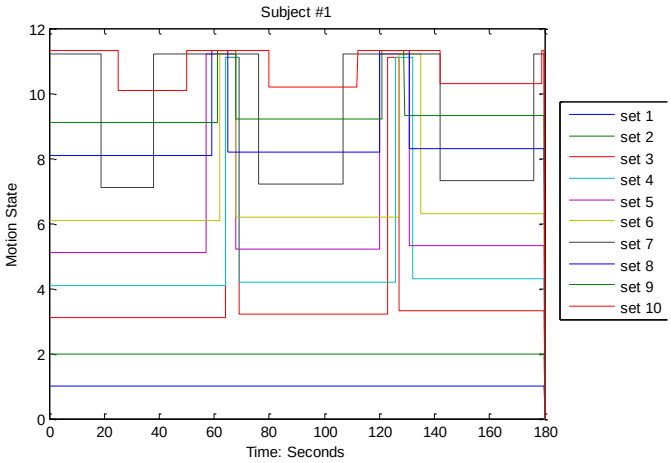

Figure 10 – Motion States For All 10 sets of Subject #1 Data
Transitions can be noted on 60 Second Intervals for Changing of View Angles

Feasibility Assessment

The modified RCR with changes to the antenna, range control, and filters, as described from Task 1, was mounted to a tripod and attached to a data acquisition unit equipped with an electrocardiogram (ECG), spirometer (airway flow sensor), and general-purpose acquisition amplifiers. The ECG waveform provides a gold standard reference for determining a mechanically observable heart rate through the RCR unit. The spirometer serves as the gold standard reference for determining a mechanically observable respiration rate through the RCR unit. Occasionally, in the absence of a spirometer measurement, the envelope information of the ECG waveform provides a pseudo-reference for the respiration waveform. Figures of the test bed and of a test subject during a test are shown in Figure 12.

In a typical test, a subject is seated in front of the RCR unit at approximately 8 to 10 ft. The RCR unit will have attached to it either a patch antenna or a backfire antenna, as these types are most easily amenable to miniaturization and hardening. The subject is further instrumented with ECG leads, and a face mask and tubing connected to a spirometer. The subject's movements are captured on low-resolution video. All RCR and physiological data is stored using a PC-based data acquisition system. The subject is prompted to perform a series of maneuvers. Some of these maneuvers include: breathing at an increased or decreased rate, varying the force of inspiration, holding breath, walking near the radar, or moving the limbs while seated.

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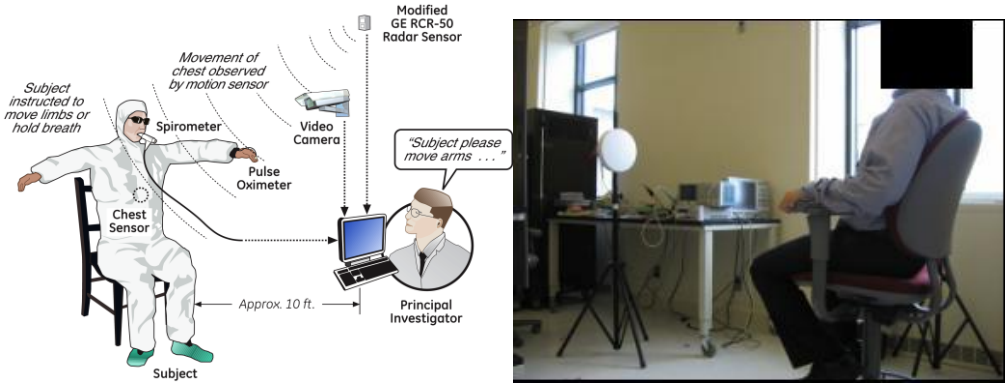

Figure 11 - PC-based data collection system for simultaneous recording of Radar and Physiological (ECG, Spirometer) signals as a subject performs a range of activities and motions in a mock scenario

The initial goal of the test bed was to provide a data set that will drive the development of feature extraction and state estimation algorithms. These data sets include a variety of motions and activities intended to mock typical behaviors as well as behaviors associated with asphyxiation and impaired breathing (e.g. holding breath). A partial description of the rationale for collecting such data sets is listed in Table 5. A library of such data sets was acquired throughout the program using several subjects under several different mock scenarios. These data sets were also used to assess and predict the statistical performance (probability of detection, probability of false alarm, etc.) of the feature extraction and state estimation algorithms.

Table 5 - Partial list of subject activities.

Performed during data collection in mock scenarios with rationale indicating which features and evaluations can be assessed or extracted from such activities.

Subject Activity	Rationale
Subject walking in front of radar	Characterize large scale motions
Subject breathing normally in chair	Determine threshold at moderate motion levels
Subject breathing intermittently	Simulation of agonal gasp or struggling
Subject is holding breath, remaining as still as possible	Evaluate sensitivity to heartbeat under best conditions
Subject stays as still as possible	Evaluate baseline noise attributable to spontaneous fidgeting
Subject laying supine on bed or cot	Evaluate sensitivity of motion at oblique observation angle
Subject not present	Evaluate spontaneous noise attributable to radar alone

The preliminary data collection events were set for 5 minutes (300 seconds) with a digitization-sampling rate of 5 kHz (default of the PC-based data acquisition system) for all radar and physiological channels. Since both the Doppler and Physiological signals are composed of low

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frequency content, the digital data was off-line anti-alias filtered and decimated to sampling rates between 40 and 200 Hz. A sample of a typical set of collected waveforms is given in Figure 12.

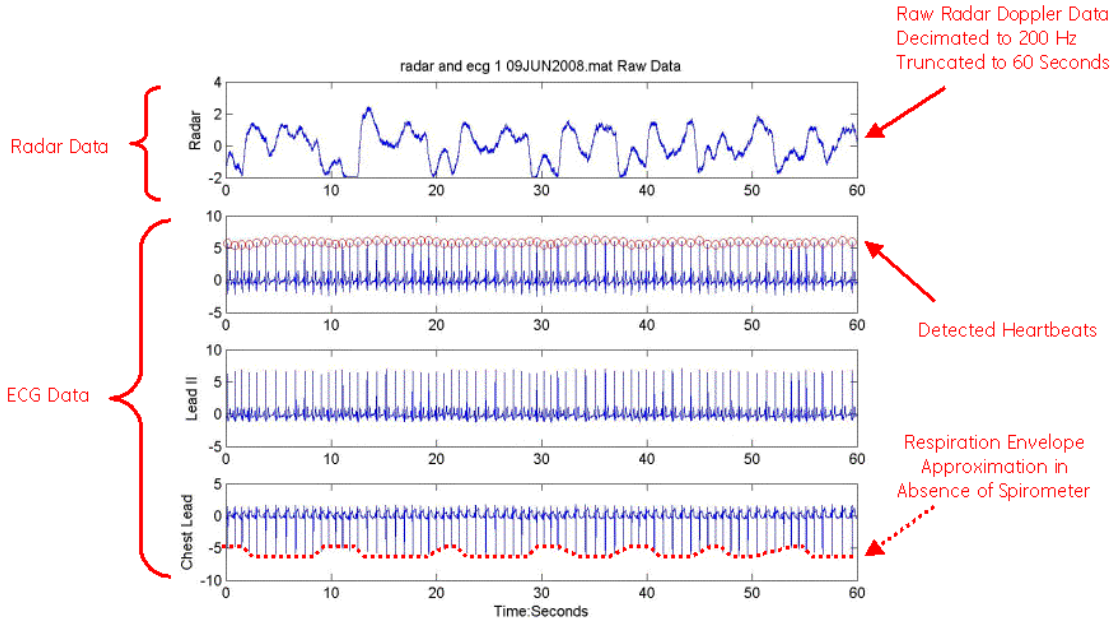

Figure 12 – Representative view of a typical data collection waveform set.

In this case, the 300 second 5 kHz raw data set of radar and ECG has been decimated to a 200 Hz sampling rate (60 seconds shown). Reference heartbeat is detected from the ECG signal. In the absence of the spirometer, the reference respiration is detected from the envelope of the ECG chest lead.

Existence of Physiologic Data in Radar Signals

Prior to developing an algorithm for feature extraction, it was necessary to establish if the measured signals contain adequate content of the desired features. An initial analysis of the collected data was performed to assess the quality of the physiologic content contained in the radar signals.

The assessment of "adequate content" can be by many means, including visual inspection. However, observation of the radar signal is difficult in that all the signals of interest (heart, breathing, and body motion) are modulated by the same Doppler effect *and* all are present simultaneously. A simple cross-correlation analysis was chosen to determine if there existed a correlated content between the observed radar waveforms and the heart rate and respiration references extracted from the ECG and spirometer. This simple cross-correlation metric not only establishes if there is a direct correlation, but the non-central peaks indicate if there is a periodic correlation as well. These periodic correlations are important in establishing the existence of signals that correlate with periodic or quasi-periodic signals such as heartbeat and respiration.

The existence of heartbeat content in the radar signals was established by cross-correlating the radar waveform with the ECG signal. In this case, one would expect a direct correlation

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(high center peak) along with a periodic correlation (recognizable sidelobe peaks) corresponding to roughly the heart rate. The cross-correlation analysis for heart rate between the radar and ECG is shown in Figure 13. In this case, the reference heart rate was computed from observing the ECG QRS complexes and is annotated on the graph to confirm the periodicity matches with the radar.

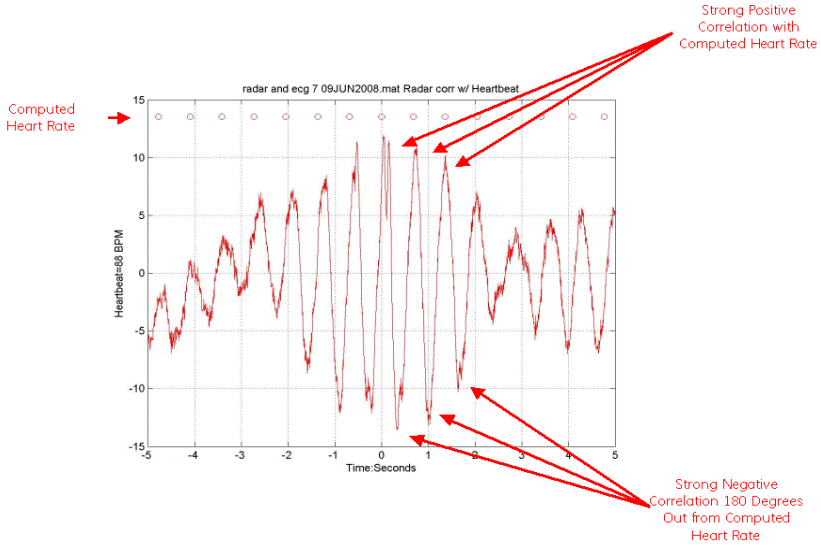

Figure 13 – Cross Correlation for Heartbeat and ECG

Cross-correlation of the radar and ECG waveforms to establish the presence of heart beat content in the RCR signals. Notice the high center peak (direct correlation) and dominant sidelobe peaks (periodic correlation) that establish heart rate content in the radar signals.

The existence of respiration content in the radar signals was established by the same method. However, in the case of the initial data collection without a functioning spirometer, the radar signal was cross-correlated with a pseudo-reference of the respiration signal. The pseudo-reference was determined from the negative envelope of the ECG chest lead signal as illustrated in Figure 12. A similar cross-correlation function was observed with high direct correlation and periodic components in the 6-8 breaths per minute ranges. The need for further quantification of the existence of the respiration signal is unlikely since the respiration content in the radar signal can easily be observed in the raw data also shown in Figure 12. It should however be noted that the respiration signal as appears in the radar waveform is often recorded as two peaks in the same direction as opposed to a bipolar pair of peaks that would be measured by inspiration flow in one direction and expiration flow in the opposite direction. This effect in the radar waveform is caused by the configuration of the present RCR system to detect movement rates but not movement directions. We do not believe measurements of the direction of movement will be required for our purposes.

This method of collecting the initial data sets afforded the opportunity to assess if there was a significant effect on physiological content in the radar waveforms vs. distance to the radar and/or vs. body position. Data was collected at distances of 4, 8, and 12 feet from the radar with the subject's chest facing the radar and with the subjects left shoulder facing the radar. The results shown in Figure 14 indicate the presence of correlated heart signals at all ranges and positions but also show a variation that is not directly related to range or position. This

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variability was analyzed in subsequent data collection activities and was determined to be the result of poor stability in the pulsing circuit. A modification was performed to adjust the waveform generator output range to correct the problem. Similar analysis was performed and similar conclusions were reached for respiration content in the radar waveform.

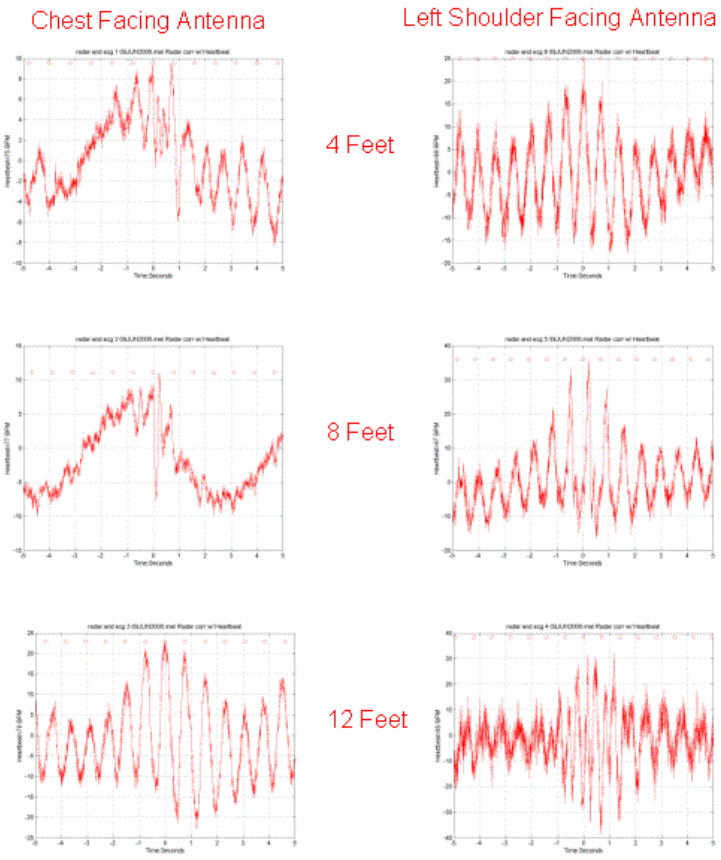

Figure 14 - Cross-correlation of the radar and ECG waveforms to establish the presence of heart beat content at 4, 8, and 12 feet ranges with the subject's chest or left shoulder facing the radar

Overall, this effort established the existence of physiological content as measured by the radar and confirmed that the radar and data collection system was adequate for subsequent algorithm development.

Preliminary Feature Extraction Algorithms

Development of an algorithm to determine whether or not a prisoner requires immediate care is conceptually a signal classification / pattern recognition problem that may be partitioned into a bimodal outcome of "situation normal" and "requires attention" or perhaps more commonly viewed as a "red light" / "green light" decisioning and alerting system. This concept of computationally recognizing a pattern and providing an alarm can be further subdivided into three automated general processes:

1) Extract features from the incoming raw motion data

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2) Cluster the features of the raw signal into a set of pre-defined characteristics or figures of merit
3) Compare the characteristics to a template or knowledge base and classify the state as red or green

In any signal classifier designed to advise of asphyxial arrest, physiologic rate information must be obtained to determine the time at the onset of interrupted breathing. Although this information will not be previewed by corrections staff, the attributes and the presence/absence of heart and respiration rate information are used to determine signal quality, life-sustaining rhythm,s and the morphological consistency that may merit an alarm.

Estimation of physiologic rates has been well studied since the inception of the electrocardiograph (ECG). However, there is a large complexity mismatch in the application of such specialized estimation techniques to radar-based measurements of human motion. This mismatch arises from the relatively simple shape of the radar-produced ballistogram as compared to the more complex features of a diagnostic ECG waveform as shown in Figure 15. As such, application of existing ECG analysis algorithms, such as the GE Healthcare EK-PRO™ automated ECG interpretation algorithm, is not suited for radar-based estimation of respiration and heart rate. Simpler estimation techniques that are less complex but still effective and robust need to be explored.

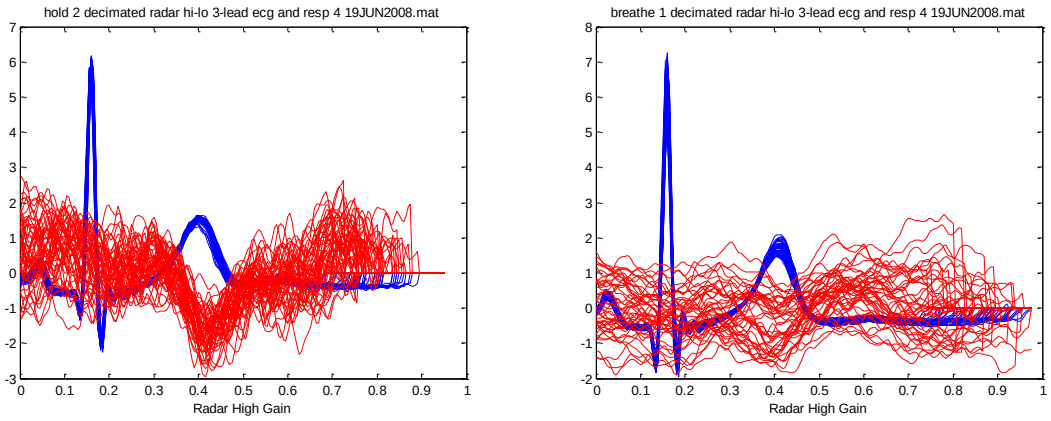

Figure 15 - Overlay of heartbeats measured by ECG and radar "ballistogram".

Notice the stark differences in waveform morphologies preclude the use of existing ECG techniques and prompt for the use of low-complexity estimators. left: while holding breath; right: while breathing normally

There are many techniques for directly or indirectly obtaining a ballistogram such as invasive arterial pressure measurements, chest volume measurements, optical plethysmography measurements, mechanical strain and displacement measurements, as well as Doppler and ultra-wideband radar techniques. Algorithms for rate detection using these measurement techniques have been explored and assessed for their applicability to radar waveform feature extraction.

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Task-2.1 Monitoring Algorithm

Algorithm Objectives

The object of the algorithm development is to design a robust data analysis process to extract statistical and physiological features from radar signal, and apply those features for subject state estimation to provide early warning for inmate suicidal attempt. This report section summarizes the data analysis algorithms and derived results from lab testing data.

The algorithm models extracted heart rate and respiration rate from the raw radar data and compared it to manually annotated heart and respiration rates to gage the accuracy of rate prediction. The algorithm models also predicted the state from the radar data and compared it to the actual state, and truth tables were generated to gage the accuracy of predicting the state.

Using the estimated physiological data and motion state, an alarming strategy will be described that is used to alert the corrections officer about abnormally detected.

Physiological Feature Extraction Algorithms

Two of the critical physiologic indicators for an asphyxiation suicide subjects are respiration and heart rate change from normal level. In this section, we will describe the approach we developed for respiration and heart rate estimation.

A three-step process is used to derive respiration and heart rate. First, radar data is passed through a series of band filters to separate signals into targeted frequency band. Then a short-term FFT and peak search algorithm is used to produce rate estimates for each data frame. Finally, a smoothing filter is applied to the rate over time to produce the final estimates. Details for each step are described in the following.

Band Filtering

Three band filters are designed to separate radar signal into difference different frequency band for further rate estimation. Typical respiration rate is between 0.2hz to 0.8hz, heart rate is between 1.5hz and 2.5hz, and motion frequency rate is above 4hz. The configuration of the three Butterworth filters is shown in Table 6, and an example spectral plot for the band-filtered data is shown in Figure 16, where red signal is for respiration band, magenta for heart, green for motion, the blue is for the original unfiltered signal.

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Table 6 – Band Filter Configuration

Signal Band	Type of Filter	Passband Corner Freq (Hz)	Stopband Corner Freq (Hz)	Max Passband Attenuation (dB)	Stopband Attenuation (dB)
Respiration	Lowpass	0.7	1	0.1	6
Heart	Bandpass	[1 2]	[0.5 2.5]	0.1	6
Motion	Bandpass	[4 10]	[3 11]	0.1	6

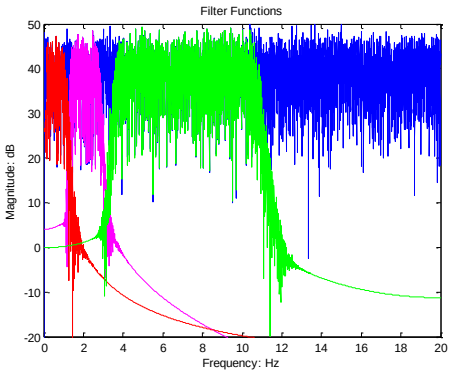

Figure 16 – Band Filtering of Radar Signal

Short Term FFT

Only respiration and heart data band is processed in this step for rate estimation. A sliding window is applied on each filtered data series to create overlapped data frames, and FFT is performed on each data frame for frequency estimation. Both the size and shift of the sliding window is independently configured for each data band. Since the respiration data has lower frequency band than heart data, a larger window is used. Configuration for the sliding windows for each data set is shown in the first 3 columns in Table 7. In the current experiment, data sampling frequency is 40hz, so the corresponding data length for respiration and heart frame is 1024 and 256 data items, respectively.

For each data frame, data normalization is first performed to remove DC content from signal, then spectral analysis is performed using standard FFT procedure. A peak searching process will search for the highest magnitude peak within the designed frequency range (refer to columns 4 and 5 in Table 7), and the peak frequency becomes the estimated rate. Note that only a small number of frequency bins is within the search band, thus for better computation efficiency in the final product implementation, instead of a full-fledged FFT, only those FFT coefficients of the included bins need to be calculated.

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Table 7 – Data Sliding Window

Signal Band	Window Size	Window Shift	Low Frequency (Hz)	High Frequency (Hz)
Respiration	25.6 seconds	3 seconds	0.08 (4.8 BPM)	0.4 (24 BPM)
Heart	6.4 seconds	3 seconds	0.45 (27 BPM)	3.2 (192 BPM)

Smoothing

To better reflect the trend of estimated rate over time and reduce noise, a 10-point moving average filter is applied on the obtained rate. For the 20 subject experiments performed in this study, the same smoothing filter is also applied to the manually annotated respiration and heart rate derived from spirometer signal and ECG signal, respectively, and the smoothed trend of rate prediction are compared against the smoothed annotated rated for validation and verification.

Physiological Algorithm Verification

To verify the correctness of the rate estimation algorithm, the process steps described above are first applied on the electronic signals of spirometer and ECG machines. The rational behind this is that signals from these specialized machines shall contain the same frequency information related to breathing and heart beat rate as captured by the radar signal, so the same algorithm should apply. In the same time, these signals may lack of any noise caused by radar itself or other unanticipated environmental factors therefore will be a cleaner and more reliable data source verify the effectiveness of the algorithm itself.

Two examples are shown below for the verification results. Figure 17 shows the estimated and annotated rate correlation for a seated still subject. In Figure 17, the left panel plot shows the respiration rate correlation, and the right for heart rate correlation. In each plot, the magenta square trend is the smoothed annotated rate, and the green plus trend is the estimated rate with spirometer signal for breathing, and ECG signal for heart rate. Excellent correlation is found for both respiration and heart rate estimation.

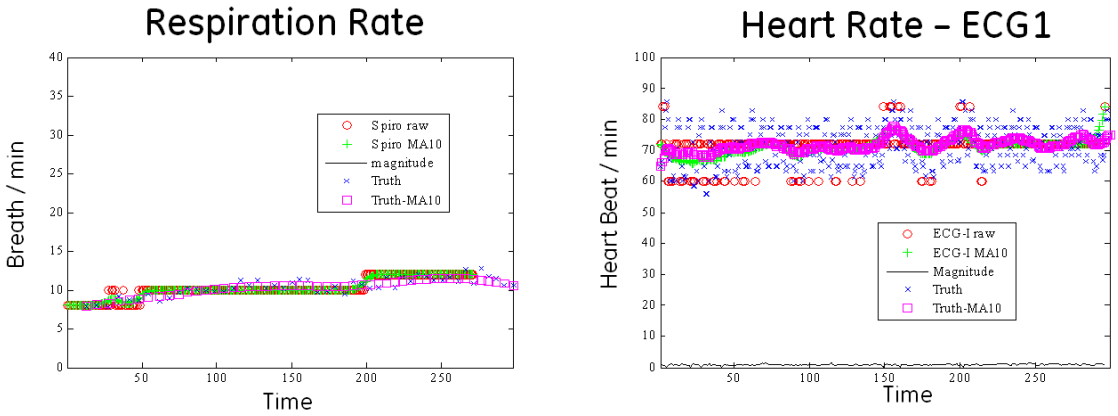

Figure 17 – Rate Algorithm Verification at Seated Still State

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Another verification result is given in Figure 18 for a subject within multiple states (using the same symbol notion as in Figure 17). Multiple-state data includes a transition period that may be more challenging for accurate estimation. Also, within the motion state there is more signal in both the high frequency and low frequency bands that poses more difficulty for band filtering and rate estimation. Again, excellent correlation is seen for the heart rate estimation, while there is difference in respiration due to signal delay and state transition, the main trend of the estimated respiration rate correlates with the annotated trend.

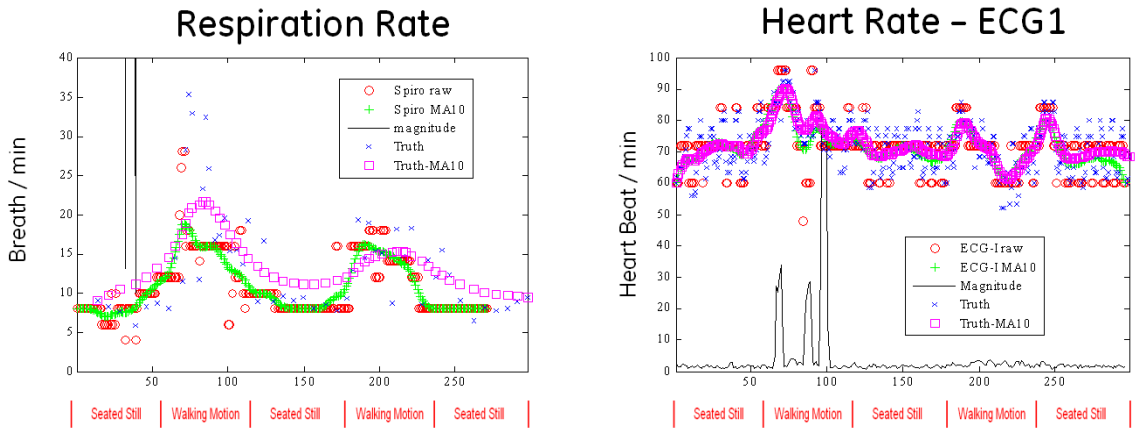

Figure 18 – Rate Algorithm Verification for a Subject in Multiple States

Radar Result Validation

The algorithms for respiration and heart rate estimation are applied on each of the 20 test subjects at various motion states. For each data set, two channels of radar signals are used, one with low gain and another high gain. The high gain radar has higher sensitivity, but may contain saturated signal.

Figure 19 shows one example of the rate estimation result using radar data as compared to manual annotated rate for a seated still subject with normal breath. The top plots are the respiration rate trend calculated using low gain and high gain radar, respectively, and the bottom two plots are heart rate trends. Again, the green plus symbol representing the smoothed radar estimate is compared with the magenta square trend representing the smoothed annotated rate. Good correlation is for all breath and heart rate estimation.

A quantitative result validation metrics is also adopted based on root mean square error (RMS). In particular, a unitless RMS ratio is used, i.e.:

$$RMS\_ratio = SQRT\ [\ MEAN\ (\ (\ (Y_i - X_i)/Y_i\ )^2\ )\ ]$$

Where Y_i is the actual rate at each data frame, and X_i is the predicted rate for the same frame, and then the square root of the data set average is obtained as the RMS_ratio for the entire data set.

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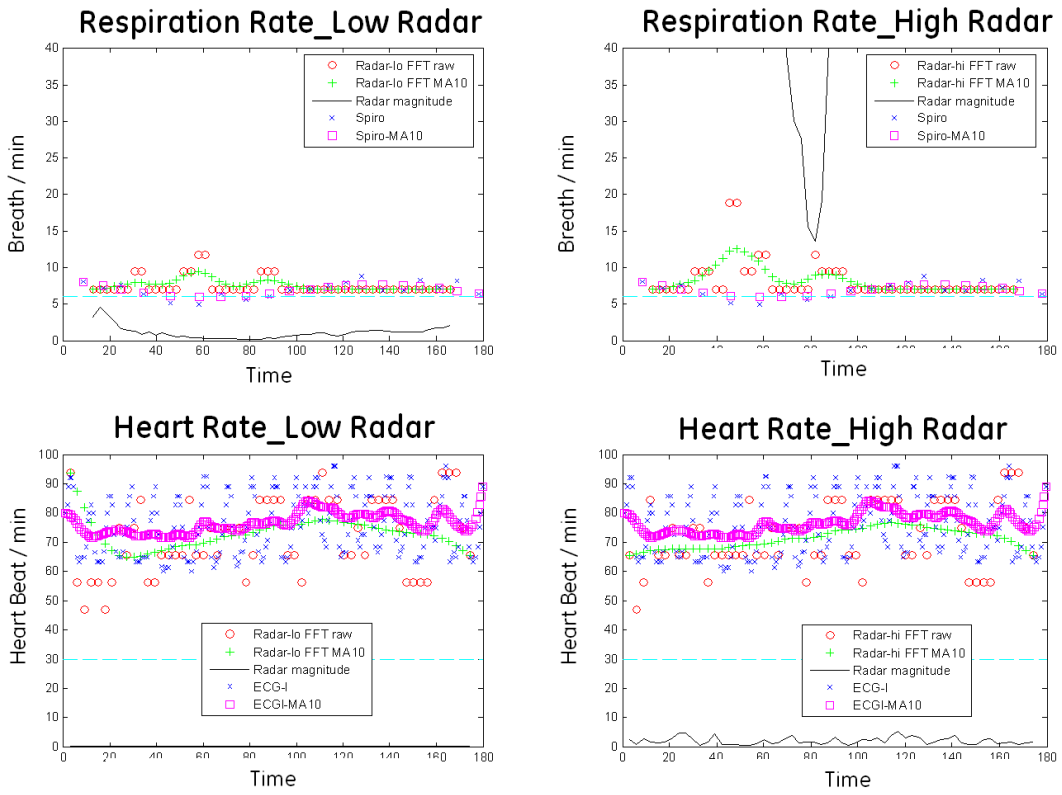

Figure 19 - Radar Rate Estimation - Seated Still

Referring to the ten data set types listed in Table 3, three different groups of states are identified:

- Noise state- state 1
- Motion state – states 2, 3, 4, 5, and 8
- Still state – state 4, 6, 7, 9, and 10.

It has been determined that only the respiration and heart rate of the still states will be used in alerting, whereas for the noise state and motion state, only state detection is necessary. This is because extreme large motion or extreme lack of motion themselves signify either the subject is active or in distress condition. The algorithm for state identification will be described later in this report, therefore only RMS_ratio of the still states are estimated here.

Table 8 lists the average RMS_ratio results. Each row is for an individual subject, and the average for all 20 subjects are listed at the bottom row. Each of the data columns is the RMS_ratio result for the corresponding rate item averaged by the data sets included in those motion states. During the still states, the heart rate prediction is consistently within the 20% error rate specification, whereas the respiration rate prediction meets the 20% on average but has several outliers that exceed the specification.

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Table 8 - Average RMS Error Rate for Different Motion States

	All States		Motion States		Hold Breath States		Still States	
SUBJECTNUMBER	HR	RR	HR	RR	HR	RR	HR	RR
1	12%	18%	9%	23%	5%	N/A	7%	10%
2	13%	30%	16%	33%	9%	N/A	12%	29%
3	7%	25%	8%	27%	4%	N/A	7%	22%
4	11%	27%	12%	30%	6%	N/A	11%	21%
5	9%	27%	10%	27%	13%	N/A	7%	17%
6	9%	21%	9%	24%	7%	N/A	10%	18%
7	10%	28%	12%	36%	11%	N/A	7%	21%
8	9%	25%	9%	29%	6%	N/A	7%	21%
9	15%	32%	15%	42%	10%	N/A	15%	19%
10	13%	32%	14%	39%	10%	N/A	13%	22%
11	9%	21%	10%	24%	4%	N/A	9%	14%
12	9%	20%	10%	19%	10%	N/A	8%	17%
13	11%	20%	12%	24%	7%	N/A	11%	13%
14	10%	24%	11%	27%	9%	N/A	10%	18%
15	10%	27%	11%	28%	7%	N/A	10%	24%
16	12%	24%	12%	26%	6%	N/A	14%	21%
17	14%	22%	15%	26%	16%	N/A	12%	15%
18	10%	22%	11%	31%	6%	N/A	9%	11%
19	11%	21%	12%	21%	8%	N/A	12%	19%
20	8%	19%	7%	19%	9%	N/A	7%	18%
Average	**10.58%**	**24.28%**	**11.23%**	**27.72%**	**8.23%**	**N/A**	**9.93%**	**18.48%**

Task-2.3 Statistical Tuning

Note: We have included the Motion State Classification Algorithms in the same section as the "Statistical Tuning" efforts due to the statistical nature of the classification techniques.

Another strong indicator for an asphyxiation suicide subject is motion, or rather lack of motion. Motion estimation algorithms are presented in this section for state classification. We discuss the algorithms in four parts:

- Data flow diagram
- Principal component analysis on the features of the radar signal
- Clustering analysis of the feature data
- State Estimation results to gage the sensitivity/specificity are discussed as truth tables

Data Flow Diagram

Figure 20 shows data flow from radar data to decision report at a context level. The features are kept in a database and the columns of the database as described in Appendix A2 – Features Database.

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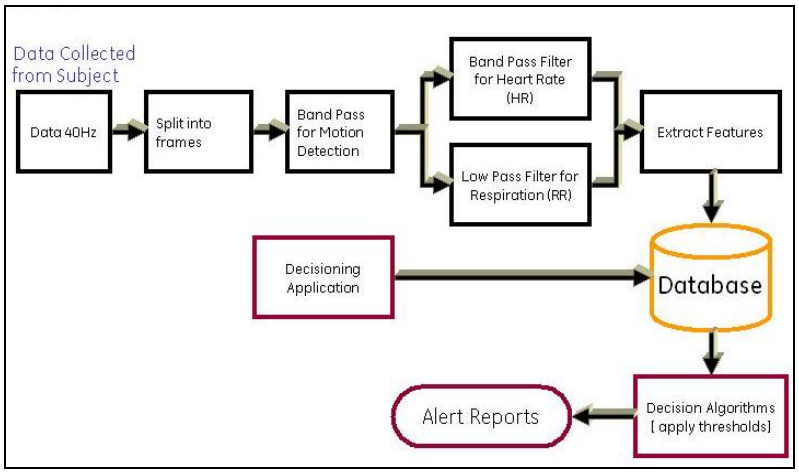

Figure 20: Context Level data Flow Diagram

Each subject data was for 30 minutes. We have 1080 frames of data for each subject. We keep a frame of data for the high gain and low gain channel of radar data. Each frame was for 10 seconds of duration. Each 10-second of data generates 3 frames – one saving all motion features, one for heart rate features and one for respiration rate.

For training purposes we used the data from first 10 subjects. We then studied the principal components in the feature data for four categories of states:

- Noise
- Motion
- Hold Breath
- Still

Principal Component Analysis (PCA)

Principal component analysis (PCA) was done on the training data. Figure 21-Figure 24 shows correlation maps from the PCA. It shows a projection of the initial features in the factor space. If two features are far from the center, and if they are close to each other they are significantly positively correlated. For example the HR/RR rate and the top four FFT frequencies in all the figures are significantly positively correlated. If they are orthogonal they are not correlated. If they are on opposite sides then they are significantly negatively correlated. Principal component analysis was performed to avoid using only correlated features in the decision algorithm and to reduce the dimensionality. Doing the PCA also helps to get an overview of which features are important vs. which convey the same information. With a better overview of the features we are able to set the number of clusters. For the baseline algorithm development, we set the number of clusters to 4.

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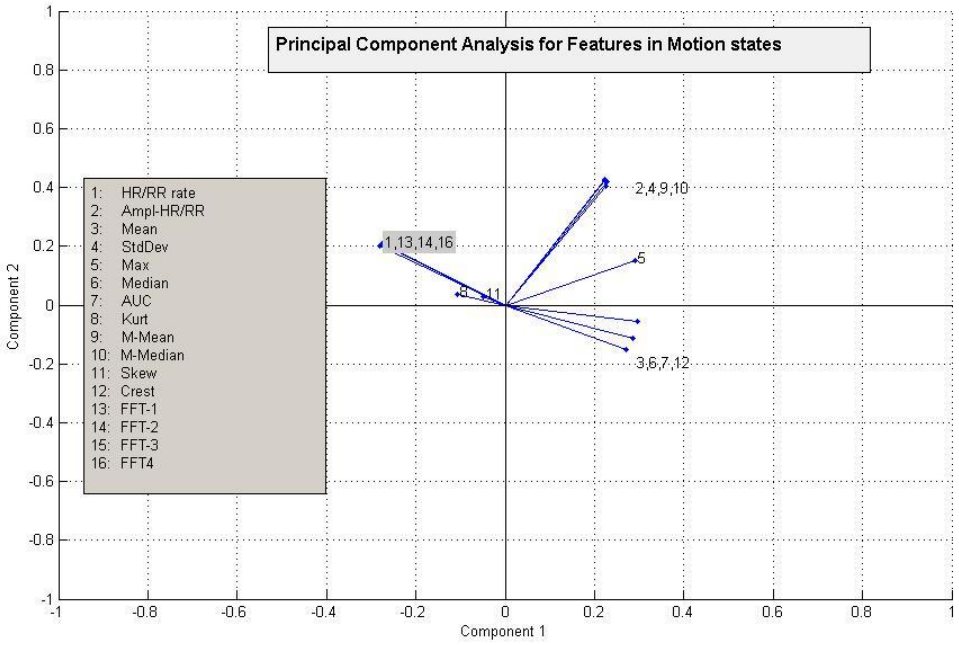

Figure 21: PCA for Motion States

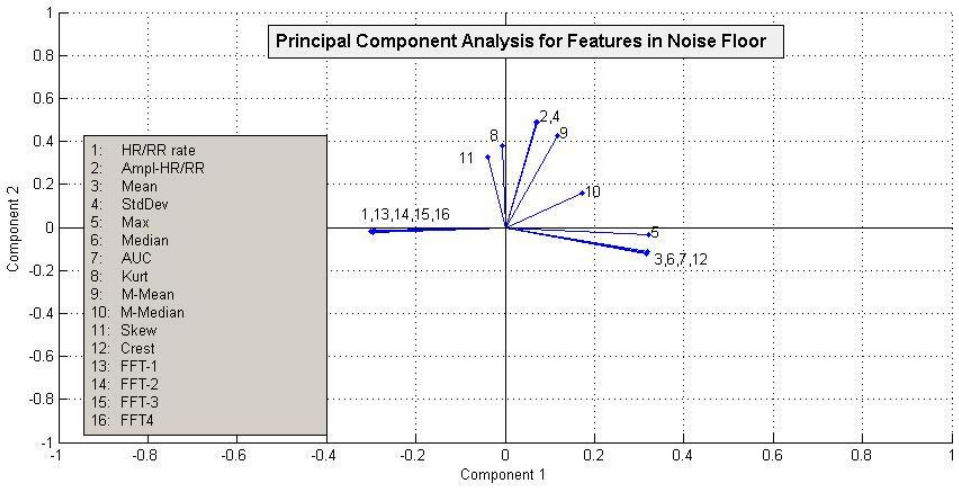

Figure 22: PCA for Noise States

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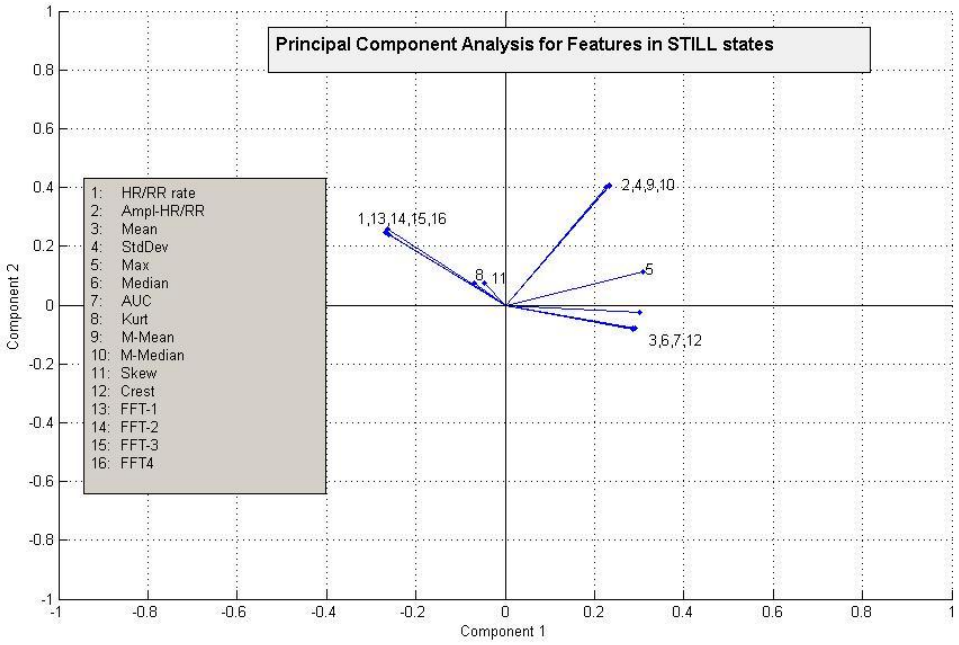

Figure 23: PCA for STILL states

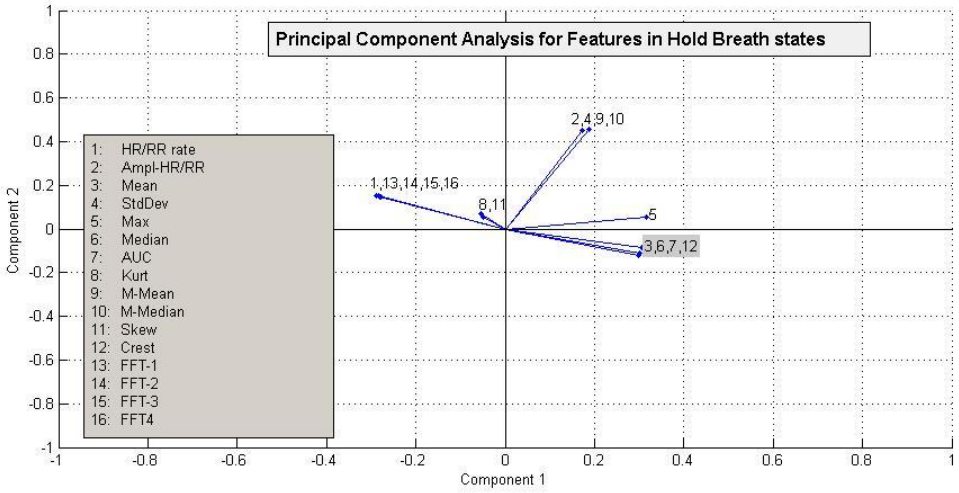

Figure 24: PCA for Hold Breath States

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Clustering

We performed two types of clustering, EM Clustering and K-Means clustering. The results shown below are from K-means clustering. EM clustering did not perform as well and could be further analyzed in future phases. The thresholds for the algorithms were based on these results. The data shown is for dominant clusters.

Noise	
	Cluster 0
PREDRRHR	0.02
MEAN	2.75
STDD	0.01
MAX	2.77
MEDIAN	2.75
AUC	27.44
MADMEAN	0.01
CREST	2.75
FREQ1	0.00
FREQ2	0.08
FREQ3	0.16
FREQ4	0.23

HoldBreath	
	Cluster 1
PREDRRHR	2.98
MEAN	0.00
STDD	0.05
MAX	0.19
MEDIAN	0.00
MADMEAN	0.03
MADMED	0.02
CREST	0.05
FREQ1	3.00
FREQ2	3.04
FREQ3	3.11
FREQ4	3.14

Motion	
	Cluster 1
PREDRRHR	0.77
STDD	0.15
MADMEAN	0.09
MADMED	0.05
FREQ1	4.31
FREQ2	4.39
FREQ3	4.44
FREQ4	4.51

Still	
	Cluster 0
PREDRRHR	2.24
STDD	0.10
MADMEAN	0.08
MADMED	0.06
FREQ1	2.20
FREQ2	2.20
FREQ3	2.24
FREQ4	2.29

Figure 25: K-Means clustering results

After deriving the thresholds, we generated the "Predicted State" for heart rate and respiration rate in each frame as described below.

State Estimation Results

For 20 subjects we have a total of 21,600 frames, out of which 14,400 are for heart rate and respiration. From the 14,400 frames we have 1,128 frames that were transition states or unknown. Example of a transition state is when subject is transitioning from moving to still. So we have 13,272 states (14,400 – 1,128) for which we have generated truth tables.

Note: inside the table we show the actual number of frames, but we have also calculated the sensitivity and specificity for each truth table.

The following abbreviated terms appear in the truth tables:

- TP – True Positive, TN – True Negative
- FP – False Positive, FN – False Negative
- Sensitivity = TP / (TP+ FN)
- Specificity =TN / (TN + FP)

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These tables form our baseline for further improvements to the algorithms by refining our thresholds and using the temporal aspects of the statistical estimates.

Truth Table for Noise State

In this view, Noise corresponds to an empty room and Non-Noise corresponds to an occupied room. For frames classified as noise, no estimates of heartrate and breathing rate will be performed. For frames classified as occupied, further motion analysis will be performed before physiological rate estimation will be performed (e.g. physiological rate estimates will not be performed when high motion is detected). We have baseline Sensitivity = 83%, Specificity = 45%.

Total Frames Classified = 13272	Noise State	
	Algorithms Classified Frame as Noise	Algorithms Did NOT Classify Frame as Noise
Manually Classified as Noise (1368)	1139 (TP)	229 (FN)
Manually Classified as Non-Noise (11904)	6583 (FP)	5321 (TN)

Figure 26: Truth Table for Noise State

Truth Table for Motion State

In this view, Motion corresponds to a subject present and intentionally moving and Non-Motion is the combined sum of empty room and subjects intentionally remaining still. For states classified as motion, no physiological rate estimates will be performed. For states classified as Non-Motion *and* Non-Noise, corresponding heartrate and breathing rate estimates will be computed. We have baseline Sensitivity = 72%, Specificity = 31%.

Total Frames Classified = 13272	Motion State	
	Algorithms Classified Frame as Motion	Algorithms Did NOT Classify Frame as Motion
Manually Classified as Motion (5744)	4121 (TP)	1623 (FN)
Manually Classified as Non-Motion (7528)	5189 (FP)	2339 (TN)

Figure 27:Truth Table for Motion State

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Truth Table for Hold Breath State

In this view, Hold Breath corresponds to a subject trying to hold breath. We have the least amount of data in this state because it was not easy for subjects to hold breath for a long time. We can improve the sensitivity in this if we have more data and train the algorithms better. We have a baseline Sensitivity = 6%, Specificity = 56%

Total Frames Classified = 13272	Hold Breath State	
	Algorithms Classified Frame as Hold Breath	Algorithms Did NOT Classify Frame as Hold Breath
Manually Classified as Hold Breath (1844)	114 (TP)	1730 (FN)
Manually Classified as Non-Hold Breath (11428)	5082 (FP)	6346 (TN)

Figure 28: Truth Table for Hold Breath State

Truth Table for Still State

In this view, Still State corresponds to a subject trying to stay as still as possible. Again, this state sensitivity can be improved with more data. We have a baseline Sensitivity = 25%, Specificity = 60%

Total Frames Classified = 13272	STILL State	
	Algorithms Classified Frame as STILL	Algorithms Did NOT Classify Frame as STILL
Manually Classified as STILL (4316)	1086 (TP)	3230 (FN)
Manually Classified as Non- STILL (8956)	3582 (FP)	5374 (TN)

Figure 29: Truth Table for Still State

Confusion matrix for all states

A confusion matrix is shown below for all states. This table shows us the errors in assigning the wrong state. Each column of the table represents the instances in a predicted state, while each row total represents the instances in an actual state. In the example confusion matrix below, of the 1,368 actual Noise states, the algorithm predicted that 1,139 as Noise, 5 as Motion, 98 as Hold breath and 126 as Still. We can see from the table that the algorithm

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can predict Noise state well. But for Hold Breath and Still state the algorithms could benefit from additional tuning.

					Row Total
	Noise	Motion	Hold Breath	Still	
Noise	1139	5	98	126	1368
Motion	151	4121	116	1356	5744
Hold Breath	726	458	114	546	1844
Still	945	2021	264	1086	4316
Column Total	2961	6605	592	3114	13272

Figure 30: Confusion Matrix for all 4 states

Task-3.0 Demonstration System Integration and Test

The third objective is to integrate both the hardware and software elements into a unified prototype system that permits real-time acquisition and analysis in a portable setting.

Task-3.1 Hardware Performance Evaluation

"Bridgewater" Prison Cell Survey

As part of the collaboration with the Dr. Fox and the Massachusetts department of Corrections, an opportunity emerged to test our radar coverage in an actual prison cell. Due to IRB restrictions, we were not able to test on Human Subjects outside of the GE lab but could evaluate the radar signal coverage within a cell volume. This testing would identify if there were blind spots where a prisoner might not be in the view of the system within a cell.

Given the shear number of measurements to make to ensure volumetric coverage of the cell, an automated system was developed for the testing. Unfortunately, some delays resulting from equipment interface issues as well as other commitments of the prison staff precluded us from testing at the abandoned Bridgewater, MA prison site. Instead, we conducted our experiments in an unused office at GE Global Research as our "Bridgewater" surrogate site.

The automation of the data collection system was driven by the time required to perform each measurement and the potential for errors when performing a repetitive manual measurement routine. One thousand measurement points are required for a 10'x10'x10' volume sampled at 1' centers. At 60 seconds per measurement, this would take 16 hours. Our computerized implementation (as shown in Figure 31) reduces the time by a factor of 20 and provides the capability to test several radar antennas at once. Overall, the automated test takes about 2 hours.

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The system makes measurements across a 150 MHz bandwidth centered at the 5.8 GHz center of the RCR. Post-processing reduces the data to average values within a +/-5 MHz band corresponding to our prototype operational mode using a 5 MHz pulse sequence. Representative raw and the post-processed signals are shown in Figure 32. The results show the radar bandwidth will make it unlikely for the entire signal to fall in a deep null and that minimum average signal power increases by about 20 dB from the raw measurements.

Our "Bridgewater" office was divided into 1'x1' squares across the floors and the tops of desks, shelves and bookcases. The simulated RCR antenna's (17 dB High Gain Antenna from our lab test, an RCR dipole, and the Rotman antenna were placed in a corner of the room near the ceiling. The vertical array of receiving antennas were placed at each of the 1'x1' intersections, measurements were taken, and the vertical array was moved to the next site. The vertical array was modified to fit under/over the furniture when the 1'x1' intersection happened to be located there. Pictures of the setup are included in Figure 33.

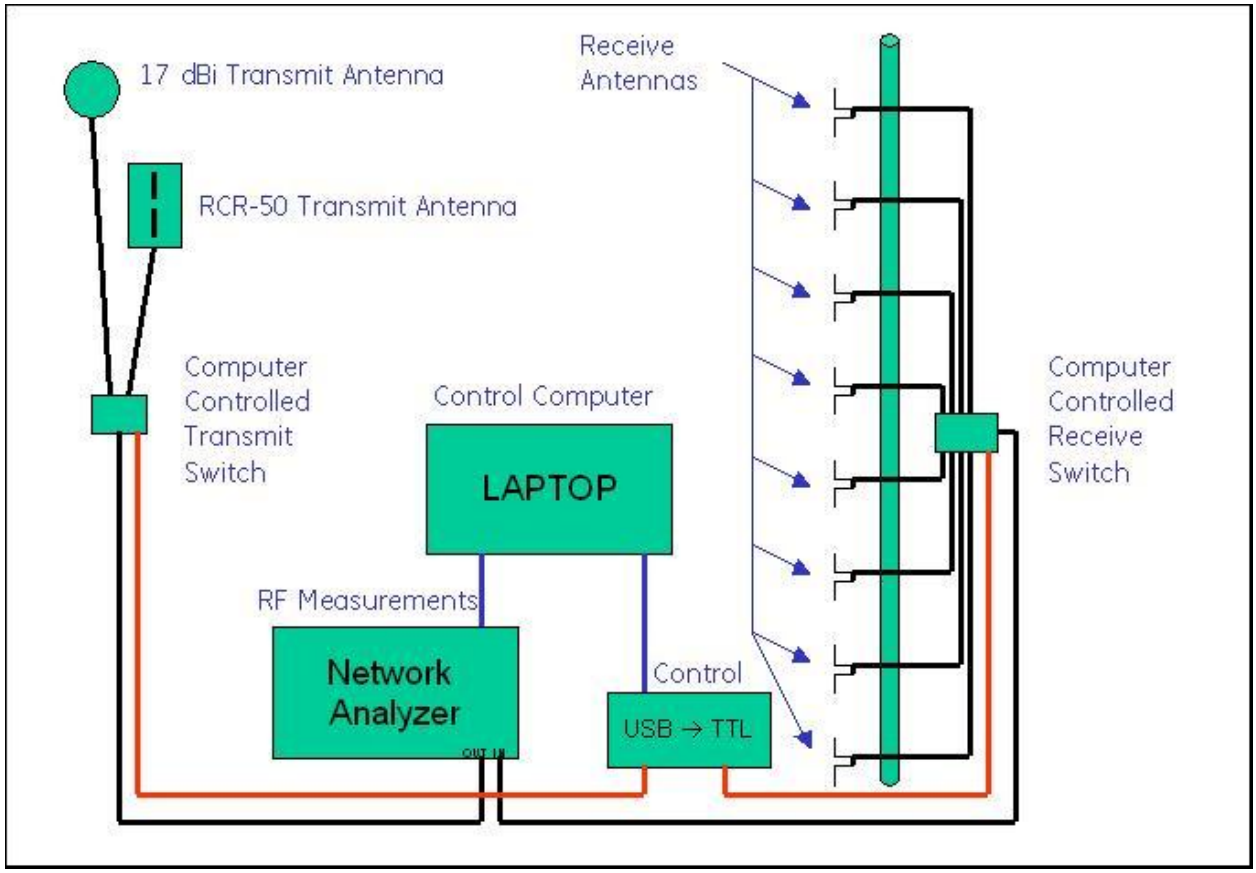

Figure 31 – Automated Cell Coverage Measurement System

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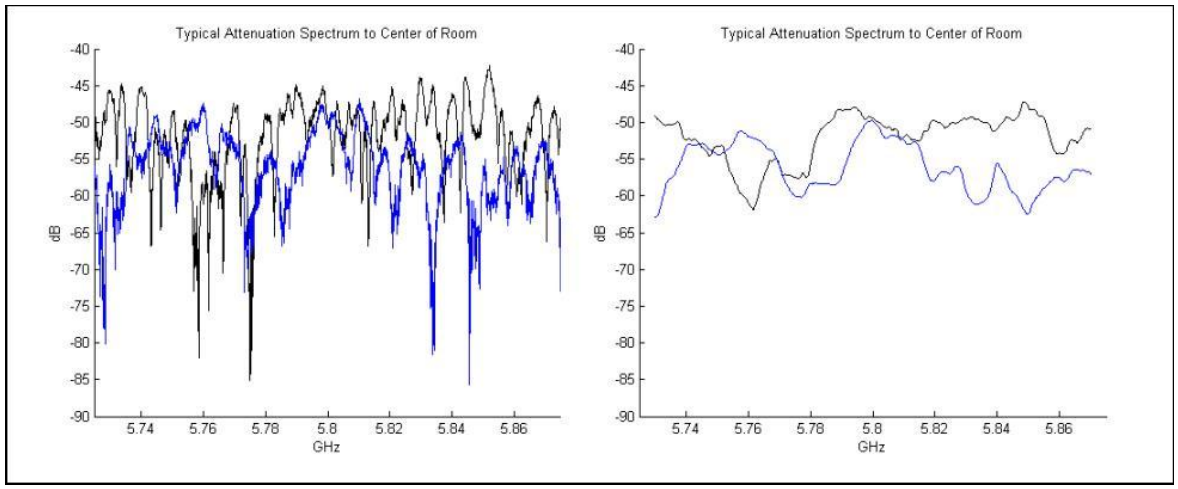

Figure 32 – Representative Raw and Post Processed Coverage Measurements

Figure 33 – Office and Measurement Antenna Setup

The resulting signal strengths in planes parallel to the floor are depicted graphically in Figure 34 for the 17 dBi antenna. Areas of blue/green indicate weak signal strength and areas of red indicate high signal strength. The highly directive antenna is not optimal to provide uniform volumetric coverage of the cell area. Also, quite obvious from the plots, locating the antenna above the desk (in this case the bed simulates a bunk) is not effective at providing coverage under the desk. For reference, the antenna is located in the lower right corner of each plot corresponding to the North East corner of the room. **Note: the desk height is just over 2 feet. The plots at 1 and 2 feet are recorded under the desk and the plots at 3-8 feet are recorded above the desk.**

The 17 dBi antenna was repositioned to the North West corner of the room to determine if coverage under the desk could be improved. The corresponding results are shown in Figure 35 and indicate changes in the penetration of the signal under the bed (at the 1 ft and 2 ft levels). The North West location provides slightly more coverage opposite the antenna but both views have blind spots. A more optimal placement would likely be the South West corner that was unavailable for testing at this time.

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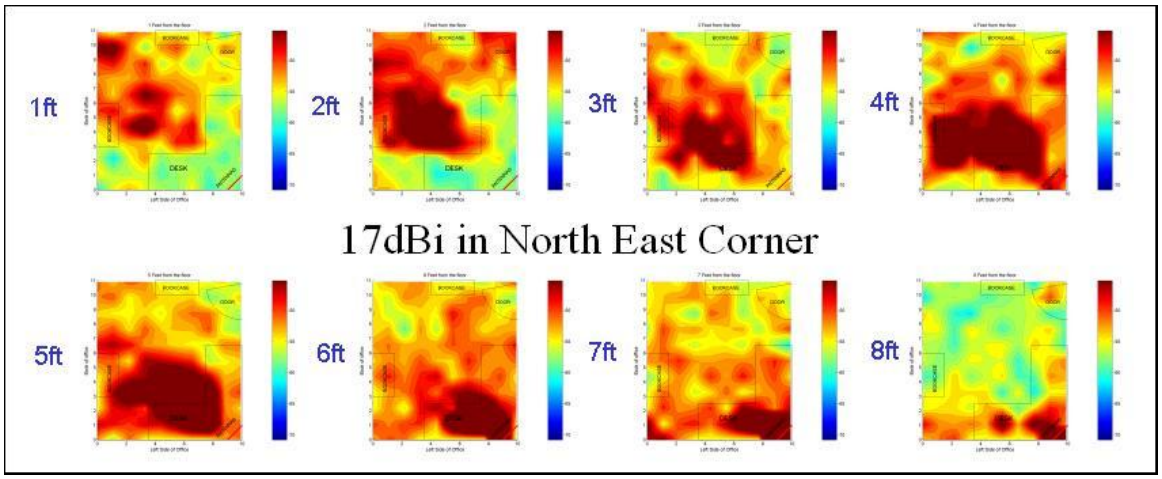

Figure 34 – Planar View of RF Signal Coverage within a 10'x10'x10' "Cell" using a 17 dBi Antenna, NE

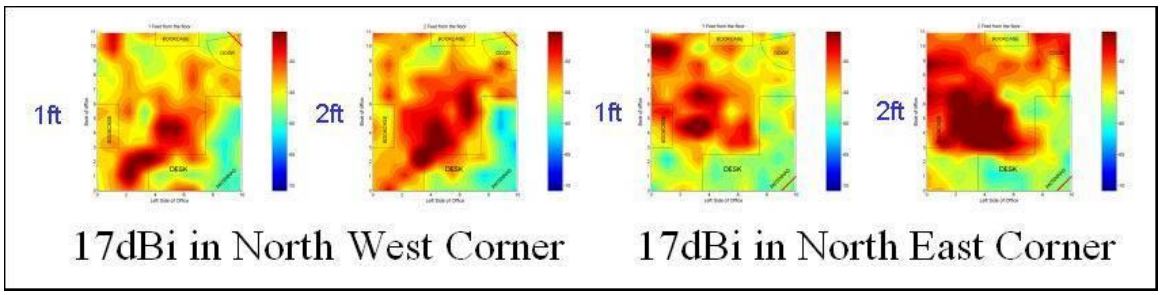

Figure 35 – Planar View of RF Signal Coverage within a 10'x10'x10' "Cell" using a 17 dBi Antenna, NW & NE

Similar signals were obtained from the standard RCR dipole structure as observed in Figure 36-Figure 37. In this case, the coverage of the room is much more uniform due to the broad beam width of the antenna. This is not surprising since the RCR antenna is designed to flood the room for security system motion detection. The peak gain is less that the 17 dBi antenna, but this is more than made up for in general coverage.

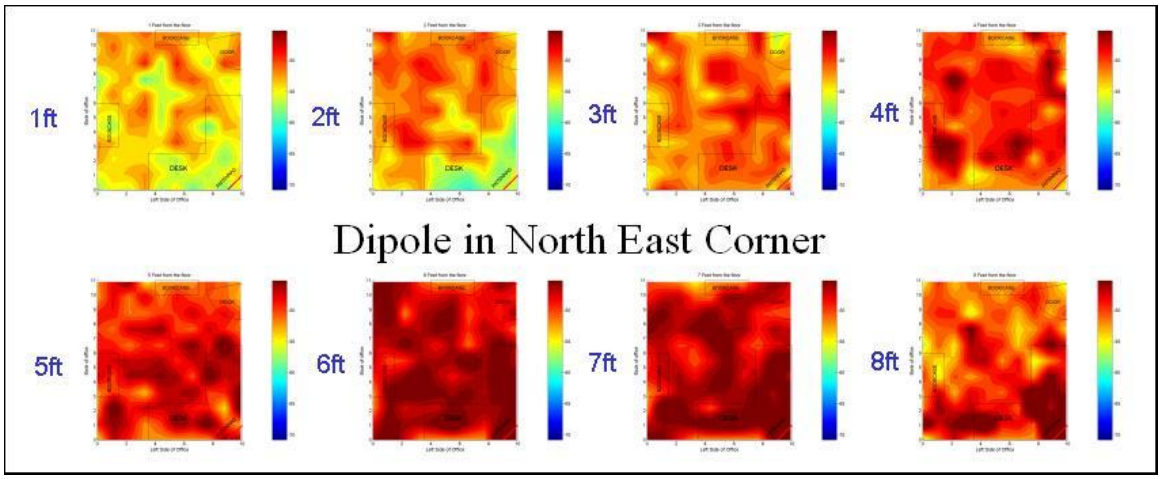

Figure 36 – Planar View of RF Signal Coverage within a 10'x10'x10' "Cell" using a RCR Dipole, NE

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Not surprisingly, the coverage under the desk is still of concern. It is interesting to note the coverage under the desk is slightly better in the North East corner that may be a result of reflection from the far wall or floor. Again placement in the South West corner would seem to be optimal but was unavailable for testing.

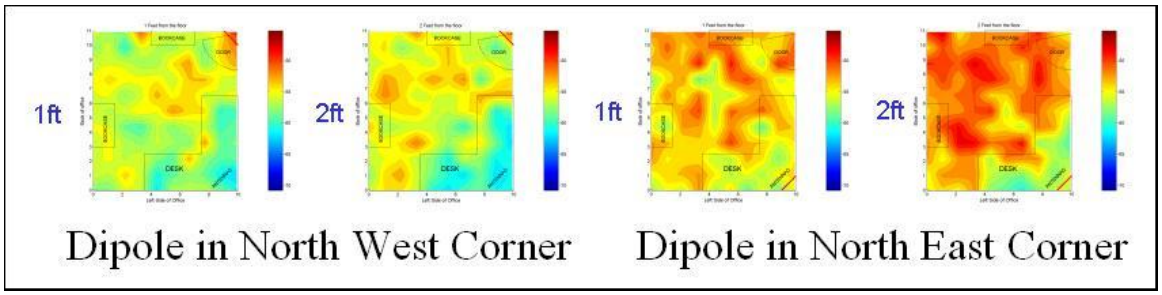

Figure 37 – Planar View of RF Signal Coverage within a 10'x10'x10' "Cell" using a RCR Dipole, NW & NE

The Rotman testing confirmed the basic beam steering capabilities as observed in the antenna test range at Electrometrics, but suffered from overall low signal strength. This could be a result of the many interconnect cables required to switch and connect each Rotman beam port to the network analyzer. In practice, the beam ports of the Rotman would be connected directly to the RCR to avoid these losses. Had the 17 dBi or the RCR dipole performed poorly, we would have investigated the Rotman further. However, for flooding the room with signal, the RCR dipole (with proper placement) seems to be adequate.

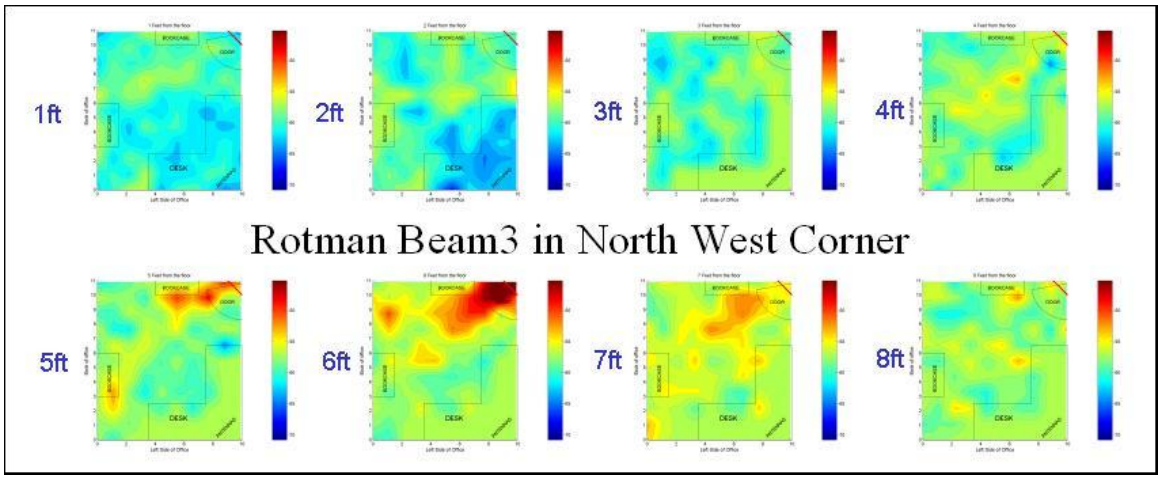

Figure 38 – Planar View of RF Signal Coverage within a 10'x10'x10' "Cell" using a Rotman Antenna, NW, Beam 3

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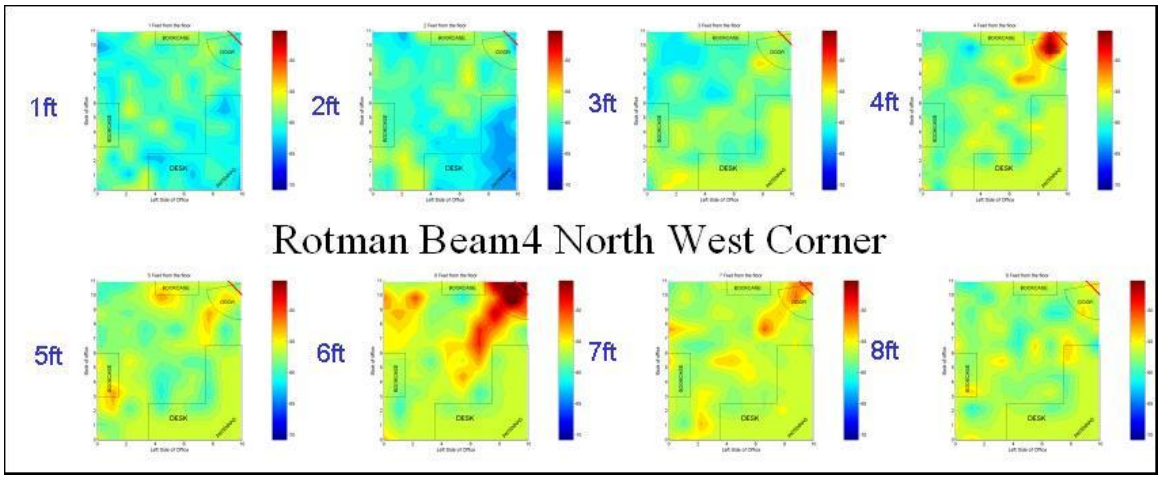

Figure 39 – Planar View of RF Signal Coverage within a 10'x10'x10' "Cell" using a Rotman Antenna, NW, Beam 4

Task-3.2 Software Performance Evaluation

Software performance evaluation is fully described in Task-2. Data collection activities from the human subjects study has been conducted in a manner such that several sets of data are used for training and algorithm development and the remaining sets are used for performance evaluation and analysis.

Task-3.3 Testing in Mock Cell

Testing in a mock cell is also fully described in Task-2. Data collection activities from the human subjects study has been conducted in a manner such that several sets of data are used for training and algorithm development and the remaining sets are used for performance evaluation and analysis.

Task-3.4 Final Demo and Report

For this phase, the final deliverable is a report on the performance of the laboratory prototype system. The demonstration prototype is the combination of the laboratory data acquisition system coupled to the software algorithms and analysis. Our measure of performance is how well the system can effectively classify types of motion states and how well (when still enough) the system can estimate heart rate and breathing rate.

In future research and development phases, the system may be reduced to a field-deployable unit that can capture data over a long period of time and provide real-time guidance to the staff as the statistical performance continues to improve. This approach has a few unique challenges that must be addressed:

- Ultimately, the success of the overall system will rely on the incorporation of features based upon the feedback of the user community. Collaborations such as the GE-Massachusetts Department of Corrections relationship will be essential for such efforts.

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- Prisoners are in general not cooperative test subjects. As such, gold standard data such as the ECG and Spirometer will not be available in the field and operational feedback (most likely based on reasons for false alarms) will drive system modifications.
- Prisoners are also a vulnerable population in the eyes of the IRB. As such, experiments using prisoners will have critical elements in terms of ethics, safety and privacy.

These issues are not insurmountable and can be addressed during phase II of the proposed program.

7.0 Next Steps and Future Program Phases

Phase IA : Exploit existing rich 20-subject dataset (GE Research)

Exploration of alternate/additional classification approaches and techniques
Incorporation of physics and physiology-based knowledge to aid classification decisions
Optimization of classification and detection algorithms and decision thresholds
Development of temporal processing and alarming algorithms
Generation of receiver operative curves (ROC) based-upon analysis of the existing dataset
Conduct VOC reviews and present interim results to corrections community
Conduct tollgate review with stakeholders for proceeding to Phase II
6-9 months duration

Phase II: Optimize and refine system operation (GE Research)

Increase confidence in sensitivity and specificity
Extend data collection library on volunteers in mock settings (up to 100 subjects)
Develop mitigation techniques for spoofing
Conduct design reviews with corrections community - Ongoing Collaboration with MA-DOC
Conduct tollgate review with stakeholders for proceeding to Phase III
9-12 months duration

Phase III: Design hardened "commercial" system (GE Security - Weert)

Harden system for deployment in actual prison setting
Develop corrections user interface
Conduct field trial in prison setting - Ongoing Collaboration with MA-DOC
6-9 months duration

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Appendix A2 – Features Database

Database table "NIJ_Features", where the signal data features are stored.

NIJ_Features	
FileName	Name of file where raw data is stored
StatePreDefined	Annotated state
SubjectNumber	A number assigned to subject to keep anonymity
FrameN	Frame number - Data is split in several frames
FrameSize	The size of the frame - We tried two sizes 400 and 800
Channel	We have two channels - Low Gain Channel and High Gain Channel
SampFreqHz	Sampling Frequency - This was 40Hz
FilterN	Filter Number - 1: Motion, 2:HR 3:RR
ActualRRHR	The annotated rate for HR or RR
PredRRHR	The predicted rate for HR or RR
PredRRHRAmp	The amplitude of the RR or HR signal
ActualState	Annotated state for the frame
PredState	Predicted state forhe frame
NoiseInd	Indicator suggesting it is noise
MotionInd	Indicator suggestion it is motion
Mean	Mean value of the signal in the frame
StdD	Standard Deviation of the signal in the frame
Max	Maximum value of the signal in the frame
Median	Median value of the signal in the frame
AUC	Area of the signal in the frame
Kurt	Kurtosis value of the signal in the frame
MadMean	Mean absolute deviation value of the signal in the frame
MadMed	Median absolute deviation value of the signal in the frame
Skew	Skew value of the signal in the frame
Crest	Crest value of the signal in the frame
Freq1	Topmost Frequency in the FFT bins
Freq2	Second Highest Frequency in the FFT bins
Freq3	Third Highest Frequency in the FFT bins
Freq4	Fourth Highest Frequency in the FFT bins
Freq5	Fifth Highest Frequency in the FFT bins
Freq6	Sixth Highest Frequency in the FFT bins
Freq7	Seventh Highest Frequency in the FFT bins
Freq8	Eighth Highest Frequency in the FFT bins
Freq9	Ninth Highest Frequency in the FFT bins
Freq10	Tenth Highest Frequency in the FFT bins
FileNum	Gives us the temporal position of the signal. Varied from 1-10
AlgVersion	Number to track which algorithm gives best results
RMSError	Root Mean Square error between actual and predicted rates
UPDATE_TIME	Time when the record was created in the database

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Appendix B – Phase II Final Technical Report

Unobtrusive Suicide Warning System

Final Technical Report

Award Number: 2007-DE-BX-K176

Sponsor:
National Institute of Justice
Program Manager: Frances Scott, Ph.D.
Sensors and Surveillance Portfolio Manager

Performer:
General Electric Global Research
Principal Investigator: Jeffrey M. Ashe
GE Team: Meena Ganesh, Lijie Yu, Catherine Graichen,
Ken Welles, Bill Platt, Joy Chen,

October 31, 2011

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Executive Summary

Despite many improvements, inmate suicide remains a longstanding problem for correctional institutions. In addition to the fundamental tragedy of loss of life, suicide incidents place huge burdens on the institution that contributes to the tarnishing of the reputation of law enforcement, increasing the costs of litigation, and driving new needs to continuously monitor inmates.

In completing Phase I and Phase II of this multi-phase program, GE has developed a prototype demonstration system that can measure an inmate's heart rate, breathing and general body motions without being attached to the inmate. The system is based upon measuring a ballistogram using a modified version of a commercialized Range Controlled Radar (RCR) that was originally designed as a motion detector for home security systems. The detection of the ballistogram (subtle motions on the surface of the body due to the motion of internal components such as the heart and lungs) required modifications to the RCR hardware for increased physiological sensitivity and the development of new signal processing algorithms to detect and classify features.

The technical effort on Phase I of the program was substantially completed in March 2009. The Phase I efforts focused on hardware modifications and the development of software algorithms to establish the baseline capability of the system. A Phase II continuation program (depicted in Figure 1) was awarded in October 2009 with the goal of bringing the prototype system to a field demonstration in an actual prison environment and continuing the algorithm development to increase sensitivity (increase detection) and to increase specificity (reduce false alarms). Technical work on the Phase II program was substantially completed by December 2010.

Since asphyxia (typically by hanging or by ligature around the neck) is the predominant form of suicide experienced in these settings, the GE prototype demonstration system was designed to detect and classify levels of motion and activity (including large motions, relative inactivity or stillness, and noise from an empty or lifeless room) and subsequently estimate heart rate and breathing when needed during times of key interest. These parameters feed into a classification system that will alarm corrections officers of a suspicious event in progress to trigger a rapid intervention.

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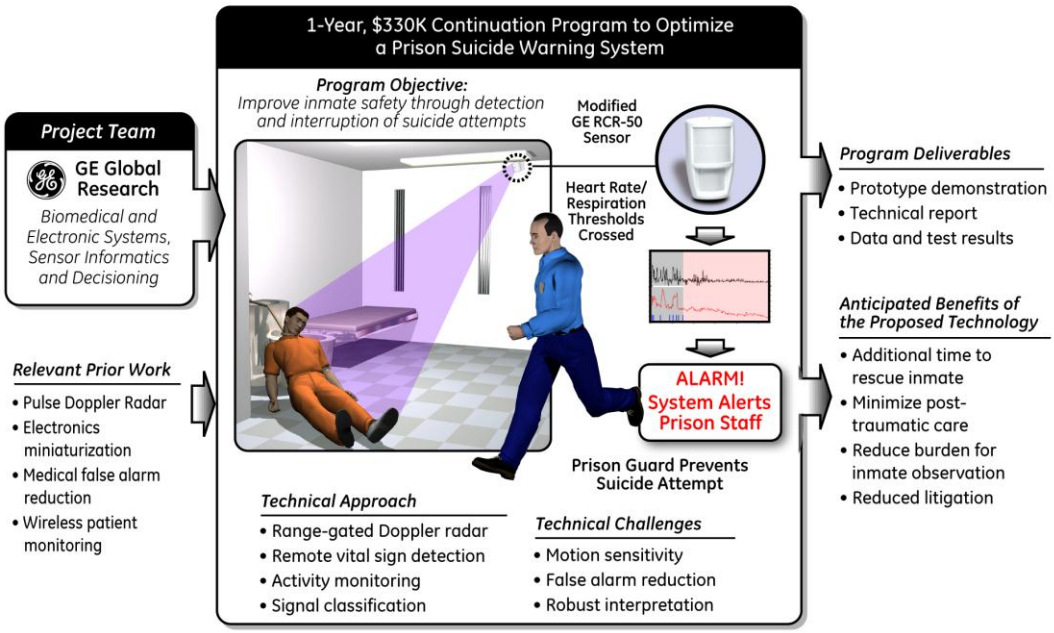

Figure 1 – Phase II Program Summary

Baseline activity state performance results from Phase I using a dataset collected from 20 volunteer subjects under IRB at GE Research produced a sensitivity of 83% and a specificity of 45% for distinguishing an empty room from an occupied room. GE's spectral analysis techniques rate estimation techniques produced an average heart rate error of 9.9 % and an average breathing rate error of 18.5 % during all periods of relative stillness – exceeding the goal of not more than 20 % rate estimation error in order to detect trends and warn of distress for the intended application.

The Phase II continuation program has produced several key improvements over Phase I and is maturing the technology for a long term field trial in the final Phase III effort. In completing Phase II, GE has produced the following results:

- State estimation algorithms have been improved by inclusion of the continuous wavelet transform (CWT) and stationary wavelet transform (SWT) to the previous principal component analysis technique. The CWT has shown considerable advantage in improving the estimation of "Hold Breath" states where only heartbeat is observable. The SWT has shown considerable advantage in estimating the "Still" state where breathing and heartbeat are the only movements. A hierarchical classification scheme has been implemented and results with the 20-subject GE dataset have achieved sensitivities of 82%, 80%, and 90% with specificities of 97%, 85%, and 94% for "motion", "still" and "concern" states, respectively with an overall diagnostic accuracy of 83%.

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- Rate algorithms have been improved by computing metrics of signal quality that also serve as additional features for classification. Specifically, a metric of Signal-to-Noise Ratio (SNR) was developed for rate estimation. The algorithm has shown improvements in HR accuracy achieving 7% rate accuracy for still, breath holding settings (goal of <20%) while retaining about 70% of the estimates. Improvements over all sets, including motion, achieved 15% rate accuracy while retaining about 50% of all estimates.

- Alarming algorithms have been developed to alert when the system stays in a "concern" state for a specified period of time either by motion classification or by exceeding heart rate and/or breathing rate limits. In the 20-subject GE dataset, all alarm targets have been detected with a false alarm rate less than 6%.

- Field data has been collected at the Western Correctional Institution of the Maryland Department of Corrections. Ten volunteer corrections staff participated as test subjects to capture signals mimicking inmate behavior in a real cell environment. The WCI data was processed using the algorithms and classification thresholds from the GE-study dataset without adjustment or modification. Results with the 10-subject WCI dataset have produced:

    - State classification sensitivities of 86%, 81%, and 96% with specificities of 100%, 90%, and 91% for "motion", "still" and "concern" states, respectively with an overall diagnostic accuracy of 86%.
    - Rate estimation accuracies 5% to 10% better than the 20% goal during periods of relative stillness.
    - Alarming and alerting performance with no missed events while achieving a false alarm rate less than 5%.

- A near-real time implementation of the system has been prototyped. Real-time analysis of the existing datasets has produced identical results to the offline processing developed during Phase I and Phase II.

Building upon the success of the first two Phases, a final Phase is proposed to design a "hardened" system for long-term deployment in an operational setting. Such a development would involve pre-production engineering and implementation of the hardware and algorithms developed in prior program phases in addition to making the system tamper-proof and suicide-proof for deployment in an operational setting. Additionally, the development of a first generation user interface would address green/yellow/red status for corrections officer feedback and optimization. Such a system would be deployed to monitor prisoners in a controlled setting, such as the SOH at WCI, for a period of several months. In successfully completing Phase III, follow-on efforts to commercialize the system will be sought for corporate investment.

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1.0 Motivation

Despite many improvements, inmate suicide remains a longstanding problem for correctional institutions. Suicide rates have been observed as high as 47 per 100,000 inmates in local jails and 15 per 100,000 inmates in prisons. Apart from the fundamental tragedy in loss of life, suicide incidents contribute to the morbid atmosphere of jail, tarnish the reputation of law enforcement, place an undue burden on institutions to continuously monitor inmates, and increase cost of litigation associated with wrongful death.

Hanging is the principal method of suicide in prisons. In most cases, death is not immediate and strong physiological responses that result from asphyxia become apparent prior to actual end of life. Asphyxia symptoms include: spontaneous gasping, struggling associated with the mental anguish of oxygen starvation (dyspnea), and sudden changes to or an absence of heartbeat and breathing. If properly monitored and interpreted, these motions can be used to determine whether or not asphyxial trauma is in progress.

Extracting motion-based parameters of breathing and heart rate, and interpreting types of activities, are key factors in determining when an inmate's life is in immediate jeopardy that requires rapid intervention.

2.0 Approach

GE Global Research has developed an unobtrusive, Doppler radar-based sensor system that will indicate a suicide attempt in-progress by observing and interpreting motion related to heartbeat, breathing, and limb movement. This non-contact monitoring device can detect, interpret, and relay information about strong and sudden changes in physiology associated with asphyxia through self-strangulation or hanging, without corrections officers having to directly observe a prisoner. This system will give prisons and jails an effective method to monitor at-risk individuals without resorting to expensive or tedious surveillance solutions such as 1-to-1 observation, suicide patrols, or closed circuit video.

The GE system development has involved:

(1) Redesigning the elements of a commercially available, low-cost motion sensor to enable increased sensitivity to body motion.

(2) Developing signal classification software to detect abnormalities of physiological parameters consistent with a surrogate for suicide attempt.

(3) Integrating the motion sensor and algorithms into a working virtual prototype for laboratory demonstration and testing.

The demonstration system has been evaluated by capturing limb motion, breathing and heartbeat from approximately 20 volunteer human subjects in a mock cell environment and

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10 corrections staff in an actual cell environment. These individuals included males and females of varying ages, heights, and weights, in various body positions, and simulating asphyxia by withholding breath. All human studies are conducted under the approval of an accredited Independent Review Board (IRB).

3.0 Program Goals and Objectives

The goal of this multi-phase program was to develop a remote sensing system that can capture vital signs related to the physiology of an individual and provide an assessment of those signs. Several technical objectives were met during the research program:

In Phase I,

- A commercially available radar-based motion sensor, the Range Controlled Radar (RCR), was modified to enhance its sensitivity to detect fine movements, such as pulsations on the surface of a person's body.

- Software was developed that can interpret and classify the information provided by the RCR sensors.

- The suicide warning system was evaluated and tested using volunteer subjects in a mock laboratory jail cell setting. A total of 20 subjects, both males and females of varying ages, heights, and weights performed testing to assess sensitivity to respiration, breathing, and general motion.

- Quantitative objectives of the program were met to measure heartbeat and breathing rates to within 20% rate accuracy and to establish the baseline sensitivity and specificity of the demonstration system.

In Phase II,

- The practical feasibility of non-intrusive sensing of physiological variables (respiration, heart rate, motion) under representative jail cell conditions was demonstrated at Western Correctional Institution.

- The performance of the system to process the sensor signals using human activity monitoring methods was verified to achieve a level of accuracy consistent with the requirements for suicide intervention commensurate with the goals of 95% sensitivity, 80% specificity, and not more than 20% rate estimation error.

- The hardware and software elements were integrated into a unified prototype system for testing, evaluation, and demonstration.

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4.0 Literature Review

Prison Suicide

Prison and jail suicide rates have declined over the past 30 years due to better practices in prevention and quality-of-care for at-risk prisoners. [1,2] Screening inmates for placement into safe cell units, improved training to recognize suicidal behavior, on-site facilities to treat the mentally ill, and the use of suicide patrols for direct intervention all contribute to the declining in-custody suicide rates. [3]

However, the prison environment and statistics from prior studies demonstrate a continued need for the development of unobtrusive methods to detect suicide attempts. [4,5] Approximately 80 percent of all suicides involve hanging and many involve the victim still in contact with the floor during the act. [6] The ligature used to constrict blood flow can be one of many items commonly available to the inmate including belts, bed sheets, shoelaces, and any other item that can support a weight as little as 2 kg. [6] Ligature points used to support a body, such as hooks, bed frames, doors, or shower fittings, are typically accessible. Due to the accessibility to commonly-issued clothing and structures, it is not possible to completely remove the threat of suicide in a correctional setting without completely dehumanizing the quality of life for inmates or violating the basic human rights of the prisoner.

Standoff methods to remotely observe individuals have continually progressed due to advances in miniaturized electronics, wireless communications, and low-cost manufacturing techniques. [7-9] Radar is used for unobtrusive monitoring since it is noninvasive, can operate in a diverse environment, and can capture subtle motions of the body. These body motions include mechanical contractions of the heart and motion of the chest wall through clothing and building materials. [10-12] These methods principally work by evaluating the spectral content and round-trip time of electromagnetic echoes reflected from the target, which in this case is the chest. Because of these properties, radar has been used to find survivors in earthquake rubble, to detect combatants behind obstacles, and to locate targets behind foliage. Radar systems developed to monitor humans have shown promise but have not yet solved the size, cost, and usability issues of a jail environment. Privacy and human rights issues limit the effectiveness of readily identifiable, but intrusive video surveillance methods. Acoustic methods, although useful for respiration monitoring, but may not be able to detect the activity of an internal organ, such as the heart. [13]

Although there is little work concerning the use of monitoring technology in a prison setting relevant to suicide intervention [14], there is considerable prior work in the area of civilian health and activity monitoring to deal with the problem of rising health care costs. [15,16] Many programs have focused on monitoring in the home for disease management [17-20] and others examined patient monitoring in hospitals for false alarm reduction and more efficient workflow. The feasibility of using unobtrusive monitoring signals to infer certain forms of human behavior (such as locomotion, sleep, and other activities of daily living) has been established, which may be extended to evaluate behavior in a jail or prison setting.

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Sleep Apnea

Sleep apnea where individuals stop breathing for some period during their sleep represented a significant potential cause of false alarms. To understand the factors defining sleep apnea, some key facts were retrieved. [21-24] An "apnea" can last from a minimum of 10 seconds to minutes. Individuals are diagnosed with sleep apnea if five or more apnea events occur within an hour. It may be a necessary requirement for an alarming product to provide a sensitivity control to reduce sensitivity for individuals that appear or are known to have sleep apnea to reduce false alarms. However, reduced the sensitivity would result in an increased delay before alarming for a true event.

Asphyxiation

In our original proposal, we postulated that "The proposed system will be able to identify a potentially life-threatening asphyxia event by characterizing motion stemming from the heart, lung, and limbs, leading to an increase in the amount of time available to intervene in a suicide attempt. System benefits include enabling corrections officers to more effectively monitor at-risk prisoners. Financial benefits include reduced care associated with permanent traumatic injury from failed suicide attempts and liability associated with wrongful death."

In the context of this research program, our focus has been on detecting asphyxia events, where the airway and/or blood supply has been blocked due to ligature around the neck with the spine remaining intact. In most cases, death is not immediate and strong physiological responses that result from asphyxia become apparent prior to actual end of life. These asphyxia symptoms include: spontaneous gasping, struggling associated with the mental anguish of oxygen starvation (dyspnea), and sudden changes to or absence of heartbeat and breath. At the time of the original proposal, the timeline of asphyxia events was postulated as shown in Figure 2. With proper detection and interpretation, these motions can be used to monitor an inmate to determine whether or not an asphyxia-related trauma is in progress. As such, motion-based parameters of activity, breathing and heart rate become important to determine whether an inmate's life is in immediate jeopardy and requires a rapid intervention.

The effectiveness such increased "situational awareness" is dependent on both the system technical capability and the observable physiological changes associated with asphyxia events. The system technical capability has been reported consistently throughout the research program, however the physiological changes assessment has not been refined since the original proposal. It was advisable to revisit the available literature during this program period to confirm or modify the timeline of events associated with asphyxia.

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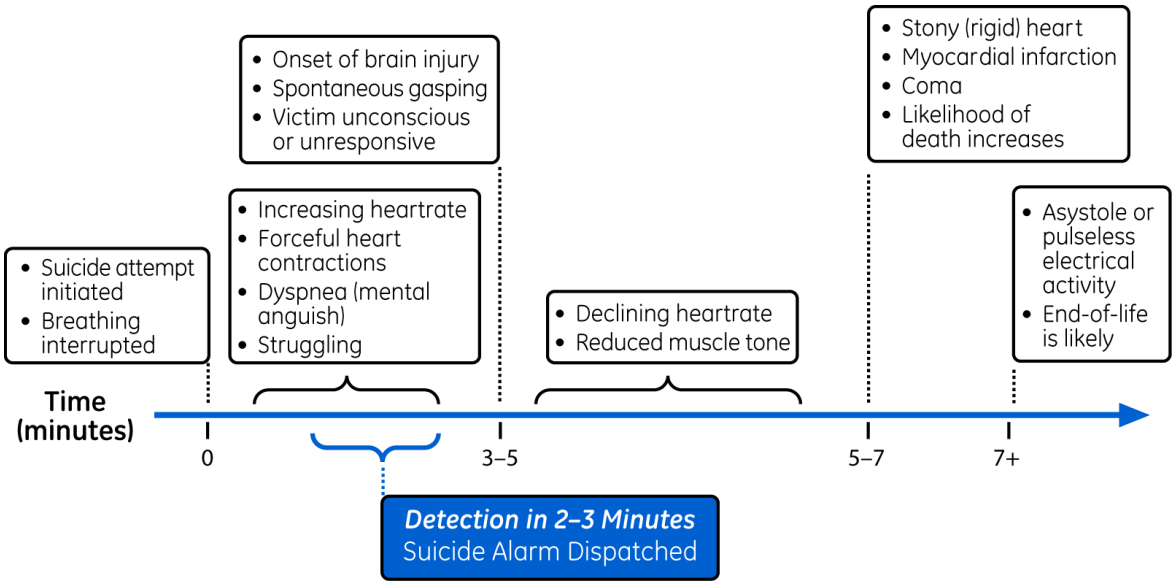

Figure 2 – Timeline associated with a suicide attempt by asphyxiation and time to alert (as presented in original proposal)

Historically, knowledge of physiological changes during asphyxiation was obtained from the 18th and 19th century during which hanging was prevalent as a form of execution. However, execution-style hangings typically involve the fracture of the spine, resulting in a different set of physiological changes than those from strangulation. Fortunately, there is a growing body of video evidence of suicide by strangulation available to the law enforcement community. This video evidence is typically self-recorded from either planned suicides or from accidents during autoerotic activities. The most comprehensive analysis of these recordings has been performed by Dr. Anny Sauvageau from the Office of the Chief Medical Examiner in Alberta, Canada.

In Dr. Sauvageau's work [25], the symptoms of asphyxia are categorized as:

- Loss of consciousness
- Convulsions, tonic-clonic type
- Complex patterns of decerebrate rigidity and decorticate rigidity (stage 1 and stage 2)
- Deep respiratory attempts
- Loss of muscle tone
- Cessation of movement

Of particular interest are the chronological patterns of these symptoms and the variability of the starting and ending points in time. Although a data set of 8 is quite small to observe the statistical variation of biological information, this is the best dataset available to guide our research program at this time. The earliest start and latest end of each symptom period from among the eight subjects studied by Sauvageau are provided in Figure 3.

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Despite the recent documented evidence of rather complex patterns of motions associated with the body automatically trying to compensate for the lack of oxygen, all primary muscle movements, including convulsions, decerebrate and decorticate rigidity, and deep respiratory attempts are practically non-existent after 2 minutes. Sporadic muscle movements may occur infrequently after 2 minutes. This more detailed timeline supports our initial assumption that we could detect symptoms of suicide within 2-3 minutes after insult by assessing the subtle, pulsatile motions of the body, produced by the heart, lungs, and diaphragm when being driven by the autonomic nervous system after an asphyxia event. Our currently developed logic approach operates on the detection of irregularities in these observations (or on the complete absence of these observations) while "riding through" sporadic motion events by the use of an up-down counter in the alarm logic.

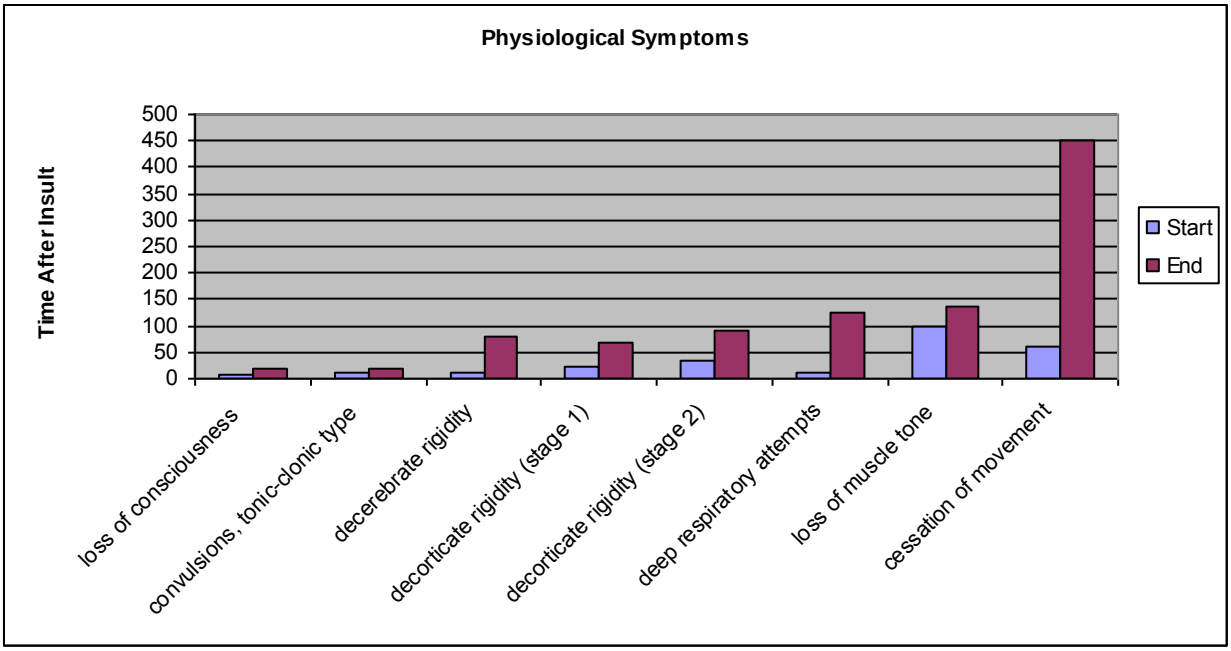

Figure 3 – Physiological symptoms associated with a suicide attempt by asphyxiation and the time of onset and cessation of each symptomatic period among eight subjects (as adapted from Sauvageau, et.al. 2010 [25])

5.0 Research Design, Schedule, and Resources

The main tasks of Phase I of this program are completed and fully described in Appendix A – Phase I Final Technical Report.

Phase II of this program involved three main tasks over an approximately 15-month period. The program status vs. the work breakdown structure (WBS) as used to guide the program developments is provided in Table 1. All proposed activities on this Phase of the program have been completed and are described in detail in this report

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Project financial performance will be submitted separately through the SF-425 forms in the GMS online system. Project financial expenditures are commensurate with the technical progress on the program.

Table 1 – Project Schedule and Status of Each Element of the Work Breakdown Structure

Task #	Task Description	Status
1.0	**Algorithm Development for Increased Sensitivity and Specificity and Accurate Rate Estimation**	**Complete**
1.1	Exploration of alternate/additional classification approaches and techniques using existing data set	Not Required
1.2	Incorporation of derived features (physics and physiology-based knowledge) to aid classification decisions using existing dataset	Complete
1.3	Optimization of classification and detection algorithms and decision thresholds using existing dataset	Complete
1.4	Development of temporal processing and alarming algorithms using existing dataset	Complete
1.5	Application of algorithms to the field-collected dataset to analyze and quantify predictive performance.	Complete
2.0	**Field Data Collection in Representative Prison Environment**	**Complete**
2.1	System characterization for coverage, leakage, and crosstalk	Complete
2.2	Data collection in a representative prison environment from 20 subjects (Data set)	Complete, Designed for 10 subjects
3.0	**Program Management**	Complete
3.1	Conduct voice of user reviews with the corrections community	Complete
3.2	IRB submission and management	Complete
3.3	Audit for compliance purposes	Complete
3.4	Tollgate review and final report submission	Complete

6.0 Technical Activities and Results

Task 1—Algorithm Development for Increased Sensitivity and Specificity and Accurate Rate Estimation

This task focused on improvement of the Phase I analytical algorithms using the existing dataset from 20 GE volunteers under informed consent and applying the improved algorithms to a new dataset collected from 10 subjects at the WCI prison. The goals of this Phase are to explore additional features and classification schemes to reach a goal of 95% sensitivity, 80% specificity, and not more than 20% rate estimation error.

Data Annotation

Some of the limitations of the Phase I performance results were based on imperfections in the annotation of the 20 subject GE data collection. The previous analysis of HR and RR accuracy was based upon detailed measurements of "relatively still" data sets. The ECG and

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Spirometer references in all states, including motion and transition, were annotated to indicate each heartbeat and breath. The process uses an automated first pass followed by a manual confirmation/correction (meaning every heartbeat and every breath needs to be observed by a person).

The Phase II annotation efforts were expanded to include all datasets. Predominantly, the changes were made within Motion and transition states with minor corrections identified in "relatively still" data sets.

The modifications consisted of:

- Deleting a breath or heartbeat
- Removing a peak that was erroneously identified by the previous analysis
- Adding a breath or heartbeat
- Adding a peak that was erroneously missed by the previous analysis
- Adjusting the position of a recognized breath or heartbeat
- Aligning a peak based on visual observation

There were 20 subjects enrolled in study with 10 data sets per subjects. Each data set is 180 seconds creating 36,000 seconds of data (600 minutes or 10 hours).
Of the180 total heartbeat files, 85 files had some heartbeat annotation changes.
41,320 total original heartbeats; 41,563 total updated heartbeats; 2,619 heartbeats modified
Of the 180 total breath files, 98 files had some respiration annotation changes.
6,855 total original breaths; 6,980 total updated breaths; 417 breaths modified

Table 2 – Changes to annotation in motion states of 20-subject GE dataset

State	Heartbeat Changes	Breath Changes
Unknown	3	0
Empty	0	0
Moving	2047	186
Still	34	3
Still Hold	45	18
Transition	490	210
Total Changes	**2619**	**417**

Data Segmentation

Just as we revisited the heart rate and breathing gold-standard annotations produced from the electrocardiogram and spirometer sensors to provide a more accurate reference for determining heart rate and breathing accuracy during periods of motion, we also reviewed our gold-standard annotation of the type of motion or activity that was taking place. This annotation is produced from the scripted activities performed by volunteers in the "GE Research Study" as well as by observation of the recorded video taken during the original data collection experiments.

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In conjunction with generating the alarming algorithm, it was decided to simplify our classification of states to ones that more closely matched the red/yellow/green approach. Following this logic, the motion/activity states have been reclassified as the following:

Prior state	->	New state	Comments
Motion	->	Motion	Major movements, Cannot reliably estimate heart rate and/or breathing Things are generally ok
Transition	->	Motion	Major movements, typically between two "Still" states Cannot reliably estimate heart rate and/or breathing Things are generally ok
Still	->	Still	No major movements, Can reliably observe heart rate and/or breathing Assessment is made on rates and patterns
Hold Breath	->	Concern	No major movements, Can reliably observe heart rate, cannot observe breathing Alarm if state persists
Empty	->	Concern	No major movements, Cannot observe heart rate and breathing Alarm if state persists
Unknown	->	Unknown	Not able to be annotated from observation or video Treated as don't care states in analysis

Under this reclassification, perhaps the most important change is the grouping of Hold Breath and Empty classifications into a common "Concern" state. Both of these previous states should trigger an alarm if they persist. The lack of observable breathing or the complete lack of observable vital signs is highly correlated to the progression of asphyxia symptoms. However, they could also reflect other important, but not alarming, conditions such as sleep apnea. Setting the appropriate time for persistence prior to alarm will be important to differentiate these conditions.

In changing the classification scheme, it was also observed that for training and performance analysis using existing "GE Research Study" data, there exist numerous frames of data that contain data from two different states. This obviously makes for a difficult time in determining the ground truth state. Previously, we annotated a frame of data based upon whichever state had the majority of the samples in the frame. However, realizing there is a natural hierarchy of states, many states that were predominantly "Still" but had a portion of a large motion state such as "Motion" or "Transition" are typically dominated by the large motion state as you go through the classification logic. To compound this problem, as the

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frame size changes (let's say from 10 seconds for heart rate estimation to 30 seconds for breathing estimation), the boundaries of the frames change in relation to the recorded data.

To overcome the multiple states within a frame problem, we determined that for training and performance there are two possible approaches employed in our analysis:

- Exclude all frames that contain more than one annotated state (i.e. make them "Unknown" states
- Classify all frames that contain any "Motion" or "Transition" annotations as "Motion", even if the motion is a small minority compared to another annotated state

Nomenclature

We will try to carefully describe what frame size, what truth classification approach, and the total number of available frames for consideration for each subsequent analysis. Due to the parallel development efforts for the rate estimation, state estimation, and alarming algorithms, this is sometimes confusing. This confusion will be alleviated with the real-time code that will have a single, consensus set of rules for framing and annotation. Also, as a refresher, the following sections describe key elements and definitions of signals and terms used to describe the system.

Radar Output - The radar operates on the Doppler principle and produces output signals with frequency content relative to the velocity of moving objects within the field of view of the antenna. There are two radar output signals:

- *Low Gain Channel* – This channel the output of the first amplification stage in the radar receive chain. The signal is from 0 to 5 volts, quantized to 16-bits and sampled at 40 Hz. The amplification stage limits the analog bandwidth from roughly 0.1 to 10 Hz. This channel is used primarily for estimating motion and respiration rate that tend to be larger signals than heartbeat. Large motion events may saturate the channel. Heartbeat signals may be corrupted by quantization noise.

- *High Gain Channel* - This channel the output of the second amplification stage in the radar receive chain. This channel is predominantly an amplified version of the first channel with similar characteristics (0 to 5 volts, quantized to 16-bits and sampled at 40 Hz). The amplification stages limit the analog bandwidth from roughly 0.1 to 10 Hz. This channel is used primarily for estimating respiration rate and heartbeat that tend to be smaller signals than motion. Large motion and respiration events will saturate the channel. Heartbeat signals will be larger than quantization noise.

Band Filtering - There are 3 band filters in use in the digital processing. Both of the radar output signals are passed through each of the three band filters independently to generate a total of 6 signals available to the rate estimation and state classification routines. (Note: It is possible to include the raw radar output signals without band limiting for a total of 8 signals). The band filters consist of the following:

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- *Low Band Filter* – The low band filter is a bandpass FIR filter with an approximate pass band from 0.2 Hz to 0.7 Hz. The filter output is primarily used by the respiration rate estimation routines and additionally used for state classification of motion and non-motion states.

- *Mid Band Filter* - The mid band filter is a bandpass FIR filter with an approximate pass band from 1.0 to 2.0 Hz. The filter output is primarily used by the heart rate estimation routines and additionally used for state classification of motion and non-motion states.

- *High Band Filter* – The high band filter is a bandpass FIR filter with an approximate pass band from 4.0 Hz to 10.0 Hz. The filter output is primarily used for state classification of motion states.

Task 1.1—Exploration of alternate/additional classification approaches and techniques using existing dataset

The improvement discovered in Task 1.2 through the new derived features and the fusion techniques were adequate so that additional classification approaches were not required.

Task 1.2—Incorporation of derived features (physics and physiology-based knowledge) to aid classification decisions using existing dataset

State Estimation Derived Features

State algorithms have been developed to improve sensitivity and specificity by investigating the application of the continuous wavelet transform (CWT) and stationary wavelet transform (SWT) to the previously collected data sets. The CWT has shown considerable advantage in improving the estimation of "Hold Breath" states where only heartbeat is observable. The SWT has shown considerable advantage in estimating the "Still" state where breathing and heartbeat are the only movements. Both states are now observable with sensitivity in excess of 85% (whereas the previous algorithm achieved less than 25% for these difficult cases).

As we wanted to leverage the temporal aspects of the radar signal, we researched several types of wavelet transforms that would be most effective for our goals. All wavelet transforms have the key advantage over the FFT in temporal resolution and we found the *continuous wavelet transform* and the *stationary wavelet transform (*which is a slightly modified version of the discrete wavelet transform) to be most suited for our goals.

Continuous wavelet transform (CWT) for Hold Breath state prediction

In signal processing, determining the frequency content of a signal by FFT helps one understand the characteristics of a signal. In Phase I we have extracted the FFT and used them in our algorithms for heart/respiration rates and also for state determination. However, obtaining the frequency content alone is not sufficient for analyzing the radar signals when

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person is still or holding breath. The FFT loses the time information after transforming time-based signal to frequency-based signal.

The use of CWT and SWT have enhanced the Phase I algorithms, especially for *hold breath* and *still* states because the wavelet function are localized in space and can detect time dependent (temporal) features better than frequency dependent features used for determining heart rate/respiration rate.

We started with *Continuous Wavelet transforms (CWT) for hold breath states. The* CWT is highly recommended when we have to synthesize local variations such as transients or abrupt changes. Hold breath is a very abrupt change and we found the CWT very effective in computing the abrupt change. In our algorithms we compute the CWT-coefficients. Mathematically, Equation 1 shows the definition of CWT as the sum over all time of the signal multiplied by the scaled, shifted versions of the wavelet function ψ

$$CWT(scale, position) = \int_{-\infty}^{\infty} f(t)\psi(scale, translation, t)dt$$

Equation 1 - CWT formula

The CWT-coefficients are calculated at 4 scales for a 3-minute signal. Note that we have 10 signals of 3-minute duration for each subject. Further we keep the sum of coefficient of the 4 scales. Since our models are built on the 10-second frames, we keep track of the CWT coefficients in each frame. We also calculate the slope of the coefficient between adjacent frames. Note that the data used for the CWT coefficients is the radar data from which we calculate respiration rate. Figure 4 "A" shows how we train our models using the existing data from the first three subjects and how we build the support vectors. Figure 4 "B" shows how we use the support vectors to predict the hold breath state.

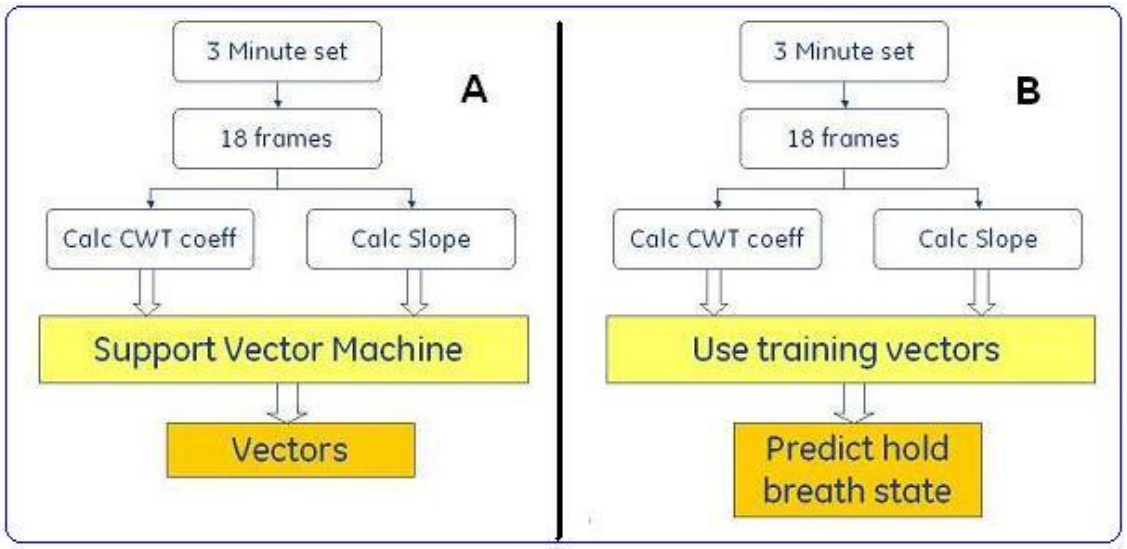

Figure 4 - Process Flow - training and predicting for CWT

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We used Support Vector Machines (SVM) for classification. SVM's are machine-learning (supervised learning) methods used for classification. In our methodology we take our feature vector, consisting of the CWT coefficient and CWT slope, to construct a separating hyperplane that maximizes the margin between the hold breath state and the non- hold breath states. In Figure 5, we show the hyperplane and the classification accuracy of 88%.

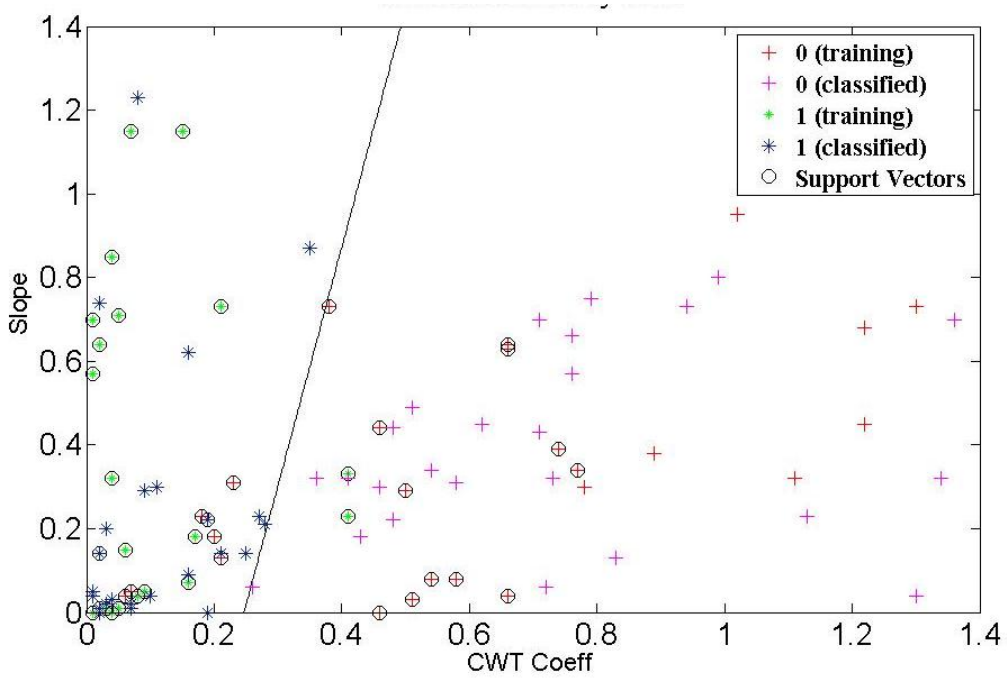

Figure 5 - SVM classification for CWT

Stationary wavelet transform (SWT) for Still state prediction

The classical DWT suffers a drawback since it is not a time- invariant transform. This means that the DWT of a translated version of a signal X is not, in general, the translated version of the DWT of X. Basically, there is a loss in translation. So to restore the translation invariance some different DWT is averaged and is called ϵ-decimated DWT, to define the stationary wavelet transform (SWT). This property is useful for several applications such as detecting breakdown points and in our case detection of breakdown during a *still* state.

The basic idea in SWT is very simple. At every level appropriate high pass and low pass filters are applied to the data to produce two sequences at the next level (See Figure 6) The SWT is identical to the DWT in terms of the decomposition structure except that no down sampling is involved and therefore the algorithm takes more time. This gives us a set of detail coefficients (Cd1, Cd2, ...) and a set of approximate coefficients (Ca1, Ca2, ...), where the subscripts 1,2, are the levels.

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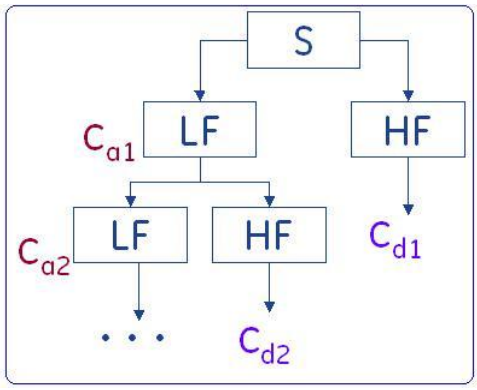

Figure 6 - SWT levels with coefficients

The SWT-coefficients are calculated at 3 levels for a 3-minute signal. Note that we have 10 signals of 3-minute duration for each subject. Further we save the approx coefficient at level 1 (Ca1) and the sum of three detail coefficients at 3 levels (Cd1+Cd2+Cd3). Since our models are built on the 10-second frames, we keep track of the SWT coefficients in each frame. Note that the data used for the CWT coefficients is the radar data from which we calculate heart rate. Figure 7 "A" shows how we train our models using the existing data from the first three subjects and how we build the thresholds from the classification tool. We used the classification and regression trees tool (also known as CART) to classify and derive thresholds. We input the CWT coefficient and the SWT coefficients to train the CART tool. In Figure 8 we show the tree generated by the CART tool. We observed that we had two sets of thresholds – one for radar data obtained from the high gain channel and one for radar data from low gain channels. For our algorithm model for predicting we used both sets of thresholds depending on the radar data. Figure 7 "B" shows how we use the CART thresholds to predict the still state.

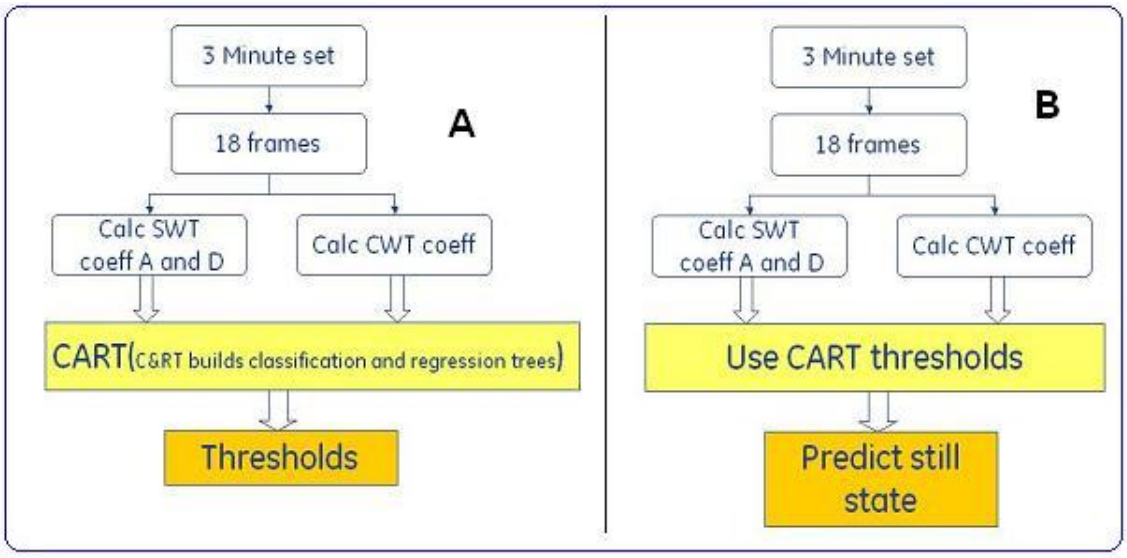

Figure 7 - Process Flow - training and predicting for SWT

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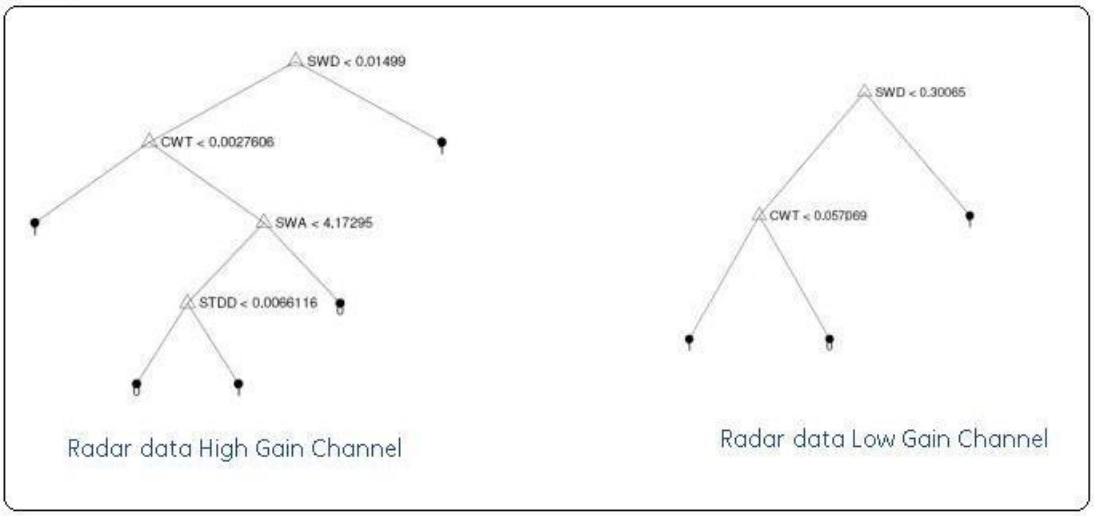

Figure 8 - CART tree for SWT

Rate Estimation Derived Features

Rate algorithms were developed to improve estimation accuracy by computing metrics of signal quality that also serve as additional features for classification. Specifically, a metric of Signal-to-Noise Ratio (SNR) was developed for heart rate (HR) and respiration rate (RR). The algorithm has shown improvements in HR accuracy achieving 7% rate accuracy for still, breath holding settings (goal of <20%) while retaining about 70% of the estimates. Improvements over all sets, including motion, achieved 15% rate accuracy while retaining about 50% of all estimates. While similar improvements are anticipated for RR accuracy, the methodology for HR has not successfully been applied to RR to-date.

The method to compute SNR is described as follows:

1. Take FFT Spectra of signal in a frame
2. Find frequency of peak spectra as rate estimate
3. Find signal power in bins around the peak
4. Find noise power in bins away from peak
5. Compute SNR (power of signal / power of noise)
6. Compare SNR to threshold, ignore rate estimate if SNR is below the threshold

The methodology has three basic parameters:

- Number of bins *included* in the signal calculation
  - 1 bin included (S=0), 3 bins included (S=1), 5 bins included (S=2), …
- Number of bins *excluded* in noise calculation
  - 1 bin excluded (N=1), 3 bins excluded (N=2), 5 bins excluded (N=3), …
- SNR Threshold
  - In dB, typically use 3 dB

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An example FFT spectrum is shown in Figure 9 for a ten second frame in the heartbeat channel. Each FFT point is illustrated with an x. Data is sampled at 40 Hz. Data points illustrated with a red circle indicate points included in the signal calculation. Data points illustrated with a blue circle indicate points included in the noise calculation. Data points illustrated by only a blue x are ignored from all calculations. The specific example shows S=1 for three bins *included* in the signal calculation and N=3 for five bins *excluded* from the noise calculation.

The benefit of such a scheme is the error associated with estimates is smaller for high SNR. The drawback of such a scheme is the estimates are ignored for low SNR leaving gaps in the time record. Since the alarming and processing algorithm will take into account the temporal aspect of the state and rate estimates, it has the capability to "ride through" short periods of dropout. As such, we would like to keep about 75% of all estimates after the threshold comparison.

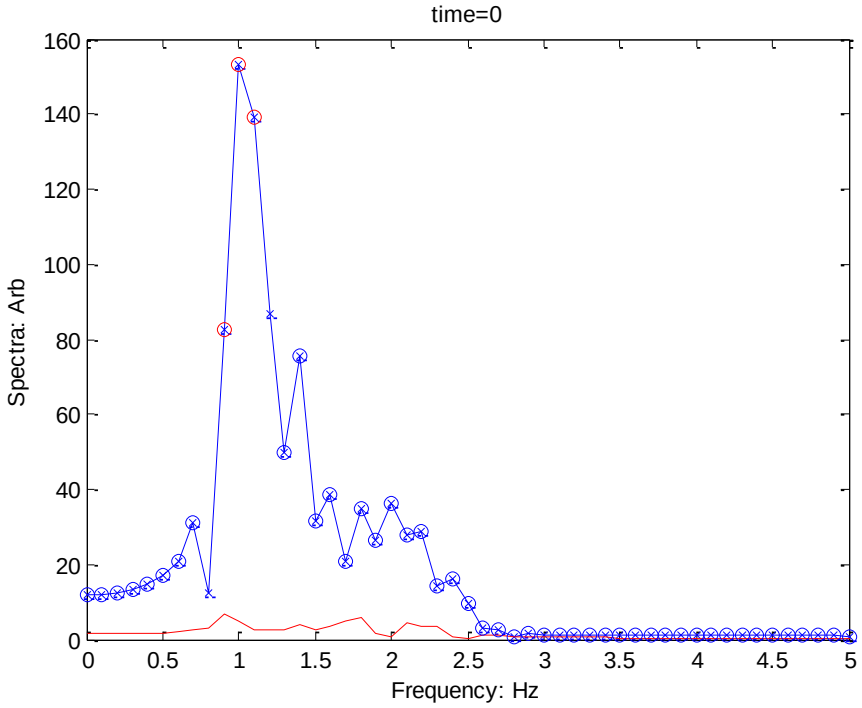

Figure 9 – Illustration of SNR methodology (S=1, N=3)

A parametric analysis was conducted exploring the effect of the number of bins included in the signal calculation vs. the number of points excluded in the noise calculation. The results are summarized in Table 3 and
Table 4. The optimal setting for heartbeat estimation is S=1, N=5 which was able to show improvements in HR accuracy achieving 7% rate accuracy for still, breath holding settings (vs. the goal of <20%) while retaining about 70% of the estimates. Improvements over all sets, including motion, achieved 15% rate accuracy while retaining about 50% of all estimates. While similar improvements are anticipated for RR accuracy, the methodology for HR has not successfully been applied to RR to-date.

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Table 3 – Parametric SNR Threshold Analysis for HR with S=0

Heartbeat, High Gain Channel, Update 1 second, Frame 10 seconds					
	Number of Segments	**Avg Rate BPM**	**RMSE BPM**	**Avg Error %**	
all sets	24510	77.55	19.95	19.59	
seated or supine still	5478	71.08	14.94	15.43	
seated or supine hold	2240	70.87	15.13	12.67	
SNR Thresholding, Signal 0 bins, Noise 3 bins					
all sets with SNR> 3	2463	73.02	13.95	11.82	10%
seated or supine still	1092	68.99	11.03	11.12	20%
seated or supine hold	728	73.52	6.41	3.96	33%
SNR Thresholding, Signal 0 bins, Noise 5 bins					
all sets with SNR> 3	6894	75.11	15.42	13.99	28%
seated or supine still	2664	70.70	11.65	11.81	49%
seated or supine hold	1228	72.93	7.87	5.60	55%
SNR Thresholding, Signal 0 bins, Noise 7 bins					
all sets with SNR> 3	13509	76.42	16.81	16.27	55%
seated or supine still	4087	71.14	13.46	13.89	75%
seated or supine hold	1635	72.40	10.65	8.30	73%
SNR Thresholding, Signal 0 bins, Noise 9 bins					
all sets with SNR> 3	19347	77.15	18.03	17.74	79%
seated or supine still	4912	71.21	14.32	14.85	90%
seated or supine hold	1922	71.95	12.23	10.14	86%
SNR Thresholding, Signal 0 bins, Noise 11 bins					
all sets with SNR> 3	22810	77.40	19.12	18.80	93%
seated or supine still	5317	71.10	14.70	15.20	97%
seated or supine hold	2130	71.18	13.74	11.50	95%

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Table 4 – Parametric SNR Threshold Analysis for HR with S=1

Heartbeat, High Gain Channel, Update 1 second, Frame 10 seconds					
	Number of Segments	**Avg Rate BPM**	**RMSE BPM**	**Avg Error %**	
all sets	24510	77.55	19.95	19.59	
seated or supine still	5478	71.08	14.94	15.43	
seated or supine hold	2240	70.87	15.13	12.67	
SNR Thresholding, Signal 1 bins, Noise 3 bins					
all sets with SNR> 3	4955	74.0061	15.3992	13.7421	20%
seated or supine still	1925	69.5981	11.4105	11.6722	35%
seated or supine hold	1077	72.289	6.8596	4.9025	48%
SNR Thresholding, Signal 1 bins, Noise 5 bins					
all sets with SNR> 3	11642	76.0032	16.6699	15.6793	47%
seated or supine still	3780	70.6902	12.5275	12.8579	69%
seated or supine hold	1550	72.1484	9.0685	6.9405	69%
SNR Thresholding, Signal 1 bins, Noise 7 bins					
all sets with SNR> 3	18142	76.84	17.63	17.25	74%
seated or supine still	4846	71.10	14.02	14.52	88%
seated or supine hold	1906	71.69	11.33	9.45	85%
SNR Thresholding, Signal 1 bins, Noise 9 bins					
all sets with SNR> 3	21970	77.2854	18.6792	18.4186	90%
seated or supine still	5273	71.1003	14.5384	15.0679	96%
seated or supine hold	2063	71.5615	12.7477	10.7102	92%
SNR Thresholding, Signal 1 bins, Noise 11 bins					
all sets with SNR> 3	23769	77.4838	19.4469	19.1306	97%
seated or supine still	5427	71.0924	14.7893	15.3063	99%
seated or supine hold	2179	71.1088	13.7619	11.6154	97%

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Task 1.3—Optimization of classification and detection algorithms and decision thresholds using existing dataset

The state estimation process evaluates the 6 signals described in the data segmentation section to assign a state for a given time window (e.g. 5 or 10 seconds). One of 3 states can be predicted: MOTION, STILL or CONCERN. During this program period, the state estimation algorithm was improved by fusing the information from the six signals into one estimate per time frame, padding the signal prior to wavelet analysis to eliminate edge effects, refining the parameters for individual signal estimation, and an improved interpretation of the annotations for each frame.

In the prior program period, a state estimate was predicted for each signal independently. The features to classify the signals were selected after various analyses performed in the prior program period and are discussed in more detail in the corresponding reports. To review, the algorithm to estimate the state prediction for each signal follows the logic shown in Figure 10.

The MadMed variable represents the median absolute deviation defined as *median(abs(X – median(X))* for the frame interval (e.g. 10 second interval) of the signal vector X. The variable swt represents the stationary wavelet detail coefficient for the selected frame performed on the mid-band signal . The stationary wavelet is calculated on a larger historical time window (e.g. 30 – 180 seconds). The variable y represents the support vector calculation derived from the continuous wavelet mean and slope. The continuous wavelet is calculated on a larger historical time window (e.g. 30 – 180 seconds) for the low band signal. The support vector equation is defined as:

$$y = \left(sv * \begin{bmatrix} cwtSlope \\ cwtMean \end{bmatrix} \right)^T * alpha + bias$$

Equation 2 - CWT support vector formula

The matrix *sv* and vector *alpha* are parameters retrieved from the support vector analysis. The values defined from the analysis of the study data can be found in Appendix A - Phase I Final Technical Report.

The state estimation objective requires combining the six signals into a single prediction. This program period focused on creating an accurate algorithm to fuse the initial signal predictions into a combined result for each frame interval. A hierarchy is applied to determine the fused result. The same process is applied to the three signals associated with each of the channels. There is a bit of overlap with the individual signal assignment, particularly related to the motion state as shown in the above signal predictions. The next key step is to reassign any unknown states for the mid-band and low band signals. If the mid-band signal is Unknown, then it is assigned Concern. If a low band signal is Unknown and the mid-band signal is still, then the low band signal is assigned still. If the low band signal remains as unknown and the low band signal for the other channel is still, then the

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low band signal is assigned still. If the low band signal has not been assigned at this point, then it is assigned Concern. This is equivalent to the fusing logic shown in Figure 11.

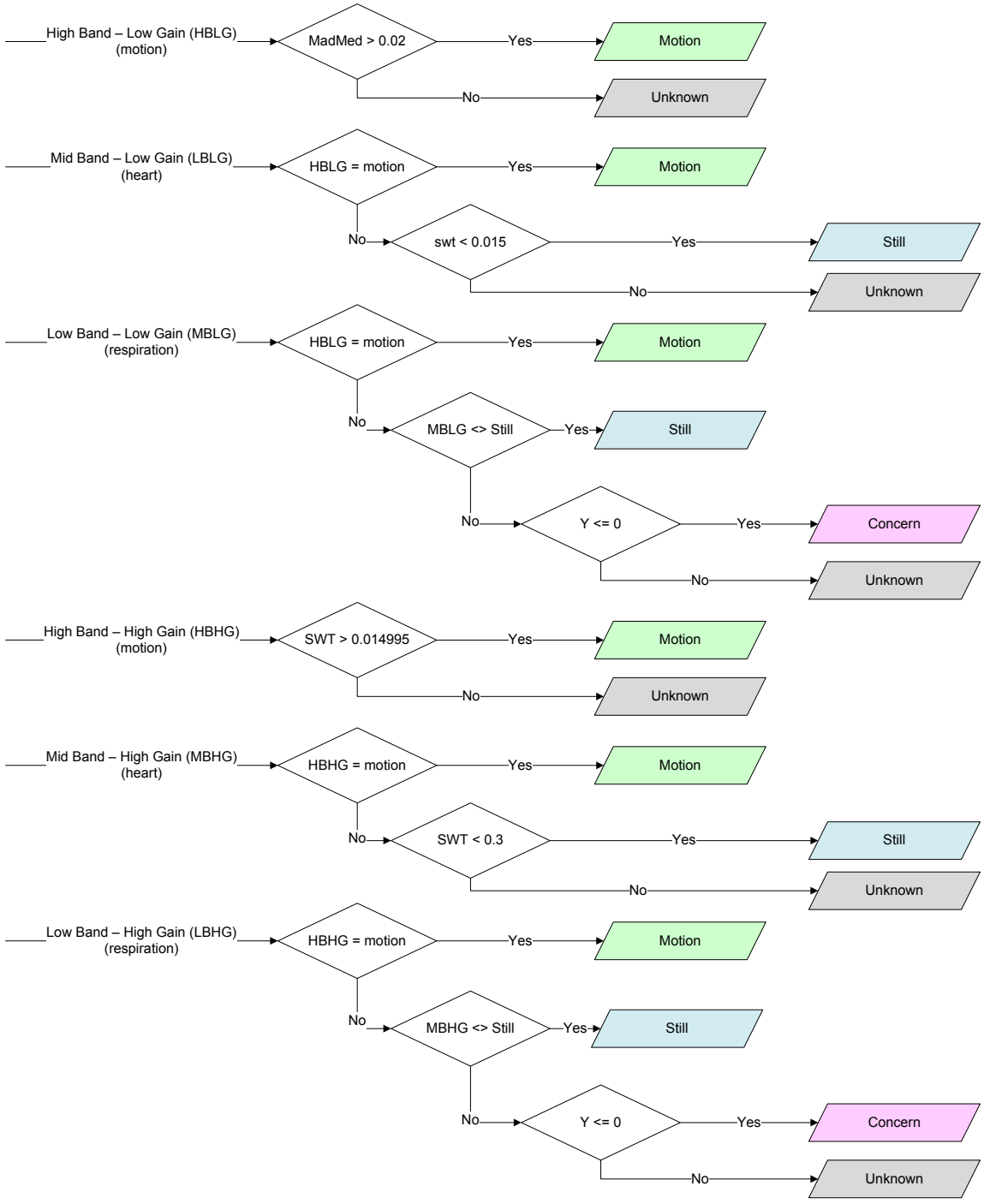

Figure 10 – A high-level logic flow for assigning a state prediction to each individual signal

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A vote among the low-band and mid-band signals is performed and the state estimate with the most votes is assigned to the overall state estimate. There can be a tie if the two channels do not result in the same logic. If that is the case, then the following hierarchy resolves the tie: motion, still, concern. That is, if motion can be detected, it is the assigned state. If not motion and still can be detected, it is the assigned state. Initially, one might think that a conservative approach is to assign concern when that appears to be detected. However, if one of the channels is capable of detecting respiration and the heart rate, then that actually means that the environment meets the still criteria. It may be that the signal is not strong enough to be detected by both channels.

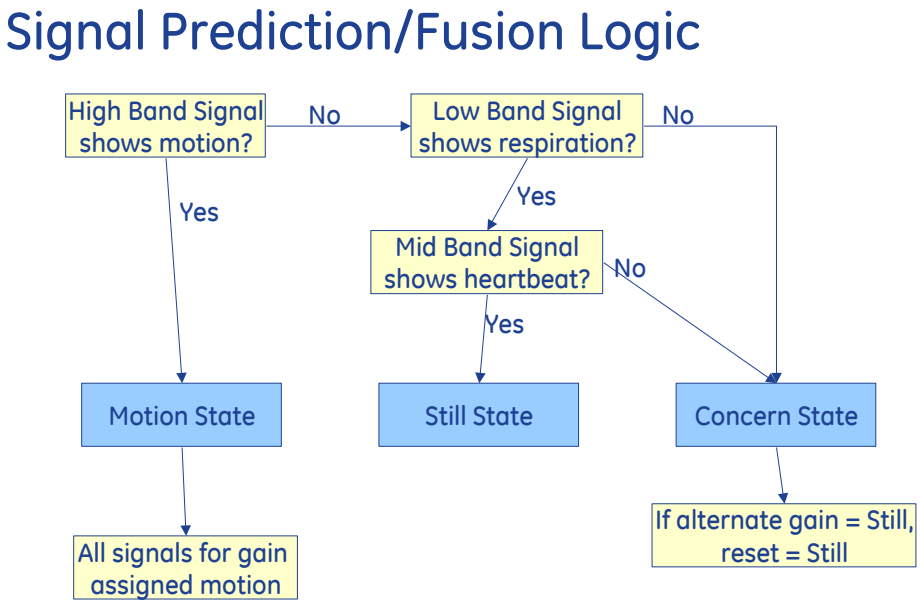

Figure 11 – A high-level logic flow for fusing the individual signals into a single state estimate

After the initial fusion implementation was created the desired sensitivity and specificity were not achieved. Investigation for sources of the misclassifications identified that the 1st and last frames of each data set file had significantly higher misclassifications. In fact, the last frame had 100% misclassification rate. This suggested a fundamental issue with the existing approach. A quick plot of some key wavelet features indicated that the calculated wavelet features were suffering from an "edge" effect of the data set as shown in Figure 12. The strong similarity in the starting and ending frame values regardless of the data set suggest that the edge of the data is influencing the value more than the measured signal. To counteract this difficulty, the incoming signal was padded by repeating the 1st and last frame of data, then performing the wavelet analysis and stripping off the added frames to reduce the features to the original signal. With this approach the wavelet parameters appear more evenly distributed over a range of values as shown in Figure 13. Similar results were observed for the other continuous wavelet feature (slope) and stationary wavelet features.

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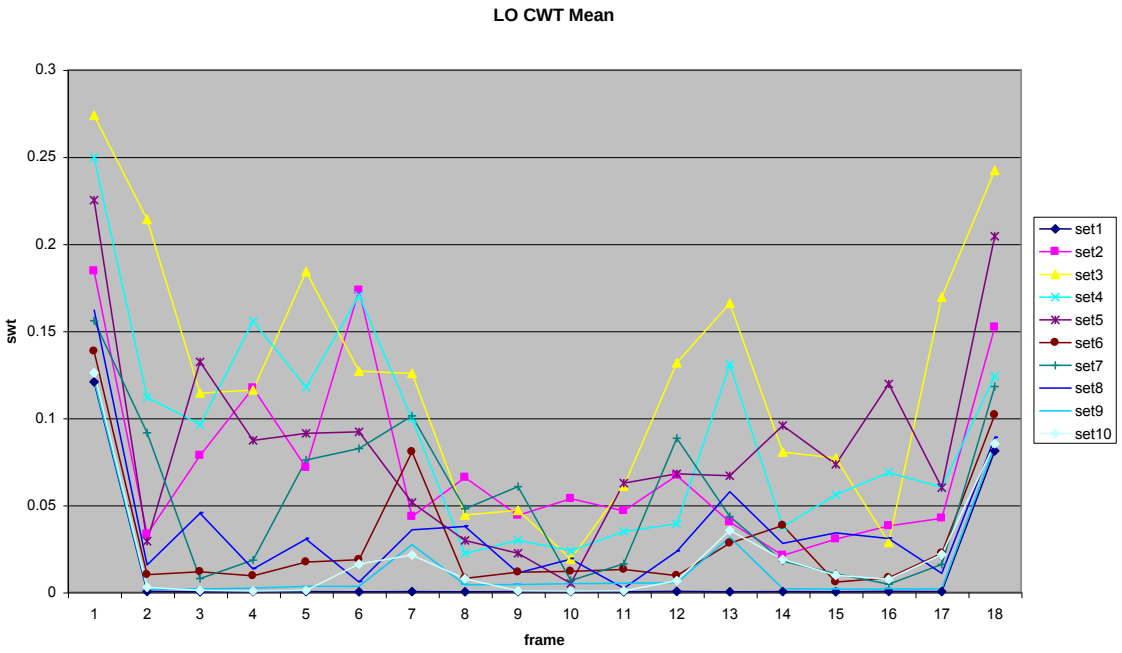

Figure 12 – Low channel continuous wavelet means for one subject over all 10 data sets

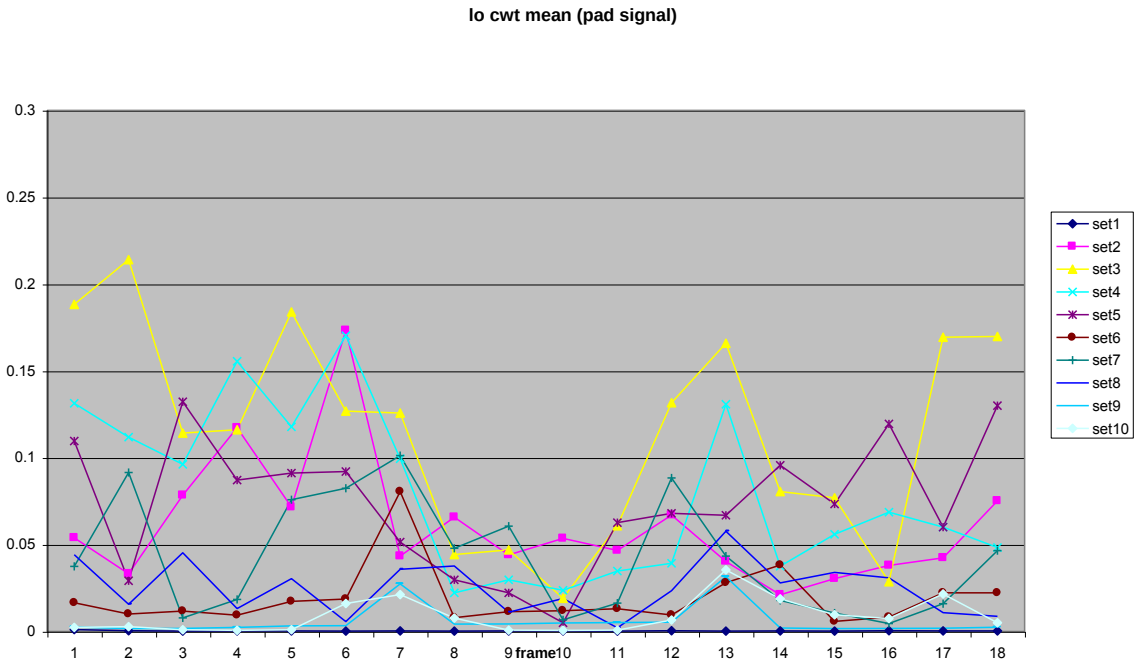

Figure 13 – Low channel continuous wavelet means for one subject over all 10 data sets after padding

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The last significant algorithm improvement is an assessment of the bias parameter when identifying the concern state with the respiration signal. In the prior program effort, the bias factor was set at –0.48. This resulted in classifying the hold breath state 86% of the time. However, this classification was never fused with the other states and in fact, this bias setting results in an over prediction of the concern state. New bias settings were assigned to improve the estimation of the concern state. For the low band channel, the new value is assigned to –0.048 and for the high band channel, the new value is –0.09. It is expected however, that collecting data in the prison facility may require further refinement of the model parameters, at which point a more rigorous approach to selecting the parameters will be performed.

As discussed earlier, the interpretation of the annotated results was reviewed in assessing the accuracy of the state estimation algorithm. The 1st key change is the redefinition of the predicted states to motion, still and concern. In particular, if the system is unable differentiate whether a heart is beating or not successfully, but is able to detect a lack of respiration, that state estimate should be considered success. The 2nd key change is aggregating the annotations for a frame period. Multiple annotations are possible and in the prior program period, generally, the majority ruled. However, since observations such as motion or even respiration and heart rate could be observed if they occur during a subset of the time covered by the frame, it is unreasonable to expect accurate results with that definition. To handle this an additional "truth" state, unknown, is defined. The state estimation algorithm never predicts unknown.

When assessing the accuracy, it is assumed that any estimate is acceptable. (This is not 100% accurate as it may only be 2 of 3 states, but for simplicity, we generally ignore the results of the unknown truth states.) Two alternatives were considered. In the first, all frames that had multiple annotations are assigned an unknown state. In the second alternative, frames that had any motion within the frame time period are assigned motion, all remaining frames are assigned unknown. With the all of the changes discussed in this section, the accuracy results for a 10 second time window are shown in Figure 14 and Figure 15. The main difference between the results is that there are fewer unknown and more motion states. Of the 168 frames that are redefined as motion, 142 are correctly classified.

The results of analyzing 3600 ten second frames from the 20-subject GE dataset, with hierarchical annotation combined with the SWT and CWT features produced sensitivities of 82%, 80%, and 90% with specificities of 97%, 85%, and 94% for motion, still and concern states, respectively. The overall diagnostic accuracy is 83%. These results are calculated from Figure 15 by excluding the unknown states.

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Overall 2264 matches / 3600 (62.88%)
No Unk 2264 matches / 2737 (82.71%)

	Unknown	Motion	Still	Concern	Row Total	Sensitivity	% of sample
Unknown	0	359	382	122	863	0%	24%
Motion	0	1035	224	9	1268	82%	35%
Still	0	45	715	138	898	80%	25%
Concern	0	0	57	514	571	90%	16%
Column Total	0	1439	1378	783	3600		

Figure 14 – Accuracy results for 100% annotation frame truth, 10 second time window

Overall 2406 matches / 3600 (66.83%)
No Unk 2406 matches / 2905 (82.82%)

	Unknown	Motion	Still	Concern	Row Total	Sensitivity	% of sample
Unknown	0	217	357	121	695	0%	19%
Motion	0	1177	249	10	1436	82%	40%
Still	0	45	715	138	898	80%	25%
Concern	0	0	57	514	571	90%	16%
Column Total	0	1439	1378	783	3600		

Figure 15 – Accuracy results for motion hierarchical annotation frame truth, 10 second time window

Since we are requiring the frame to have all the same annotation to determine its truth state, one suggestion is to reduce the size of the frame window. However, this must be compared with the minimum size required to observe the features necessary to accurately estimate the state. Figure 16 shows the accuracy results (using motion hierarchy truth definition) for 5-second frame windows. The number of sample frames doubles (3600 to 7200), but the number of unknown frames reduces to 17% (instead of 19%). However, there is a slight drop in accuracy, particularly in the ability to separate still and concern, but also to separate motion and still. At this point, keeping the time windows at 10 seconds appears to be near the optimum tradeoff between frequency of estimates and accuracy. Again, the frame window size may require adjustment after collecting data from a more realistic environment. It may also be necessary to tradeoff the frame window size with parameter settings for the alarm logic to achieve the best alarm accuracy.

Overall 4872 matches / 7200 (67.66%)
No Unk 4872 matches / 5985 (81.4%)

	Unknown	Motion	Still	Concern	Row Total	Sensitivity	% of sample
Unknown	0	405	638	172	1215	0%	17%
Motion	0	2303	513	28	2844	81%	40%
Still	0	137	1470	277	1884	78%	26%
Concern	0	1	157	1099	1257	87%	17%
Column Total	0	2846	2778	1576	7200		

Figure 16 – Accuracy results for motion hierarchical annotation frame truth, 5 second time window

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Task 1.4—Development of temporal processing and alarming algorithms using existing dataset

Alarming algorithms have been developed to determine the appropriate action based on assessment from the real time monitoring system. The determined alarm level will be used to inform correction officers of abnormal activity level of a subject. Once an alarm is triggered, a correction officer may perform a manual check up at the cell to verify the alarm situation or dismiss the alarm.

Alarm Logic

Alarm level can be designed as a continuous scale value from least concern to most critical level. In the current analysis, we use a simpler binary alarm level notation that represents alarm on and alarm off. The alarming algorithm process input data as time series. It takes into account temporal consistency of the state and physiological rate estimate. The temporal consistency check is designed as a scalar variable, referred to as alarm counter. At each assessment point of time, based on state estimate and physiological rate estimate, alarm counter is increased by ΔC^{+} if alarm condition is satisfied, or decreased by ΔC^{-} if alarm condition is not satisfied. The alarm condition is a function of state and rate estimate, which is summarized in Table 5. Then an upper bound and lower bound counter threshold, UTH, and LTH, respectively, are used to compare to the alarm counter to determine whether alarm is set on or off. The overall alarm logic is implemented using a state flow diagram as shown in Figure 17.

The upper potion state flow diagram captures the three main states and state transition logic. The middle portion controls the heart rate and respiration rate normality and validity checking. The lower portion controls the alarm counter change and decision on alarm on and off.

Table 5 - Alarm Conditions

State	Rate	Alarm Counter	Rational
Motion	N/A	Decrease	Subject motion exists
Still	Normal and valid	Decrease	Still with normal rate
Still	Abnormal or Invalid	Increase	Still with abnormal rate
Concern	N/A	Increase	Subject in concern state

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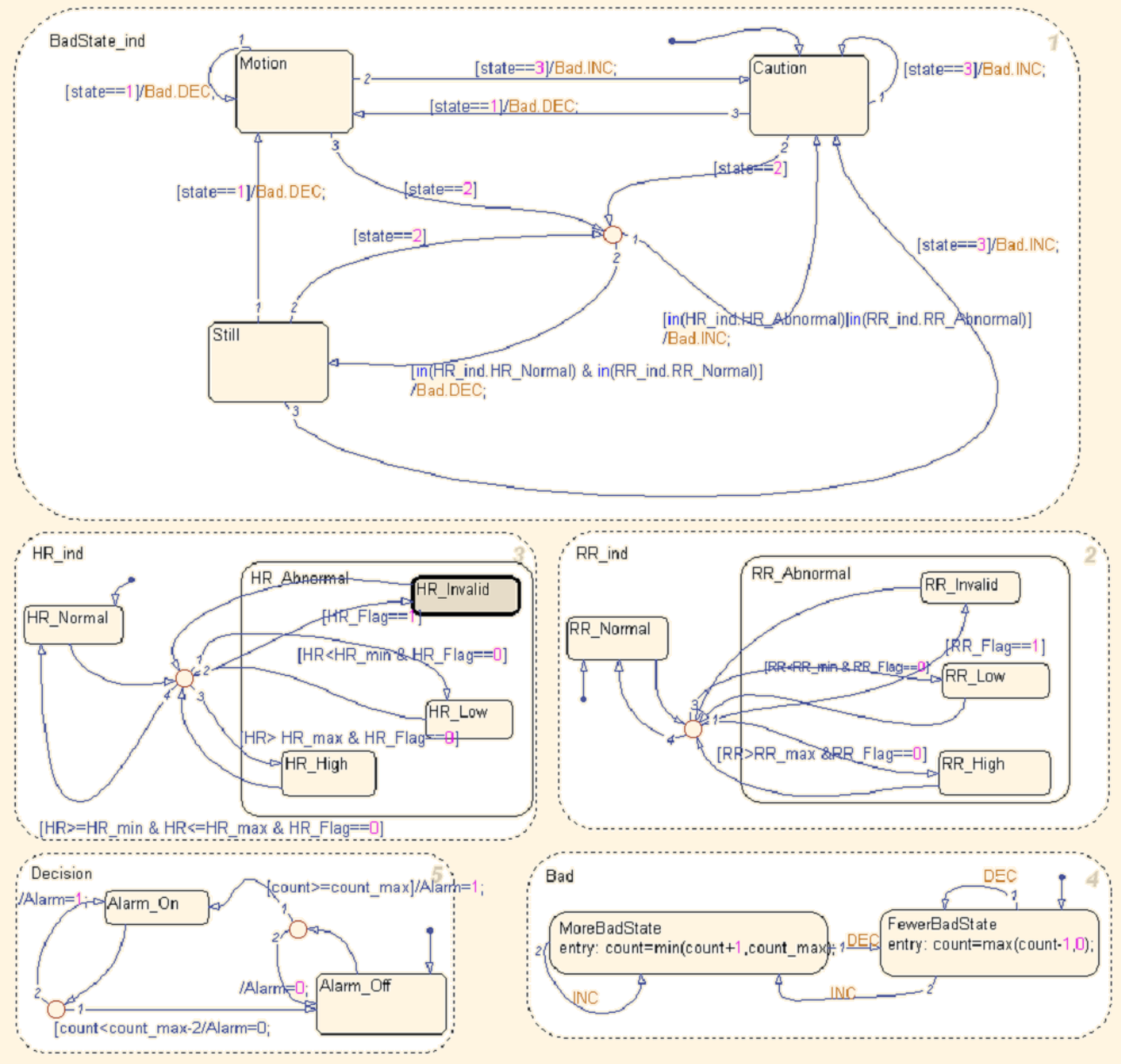

Figure 17 - Alarm Logic State Flow Diagram

In the still state, an upper and lower bound of respiration and heart rates are used to check whether rate is in normal range. In the same time, a pre-threshold and post-threshold algorithm is used to examine the validity of rate estimate. Pre-threshold is to check in-frame variance of band-filtered data, which deems a rate is invalid if the frame variance is below certain threshold. This helps to identify no-signal or low energy data frames. Post-threshold algorithm is used to assess the signal to noise ratio (SNR) after rate has been calculated for a given frame. This is done in the frequency domain, as illustrated in Figure 18.

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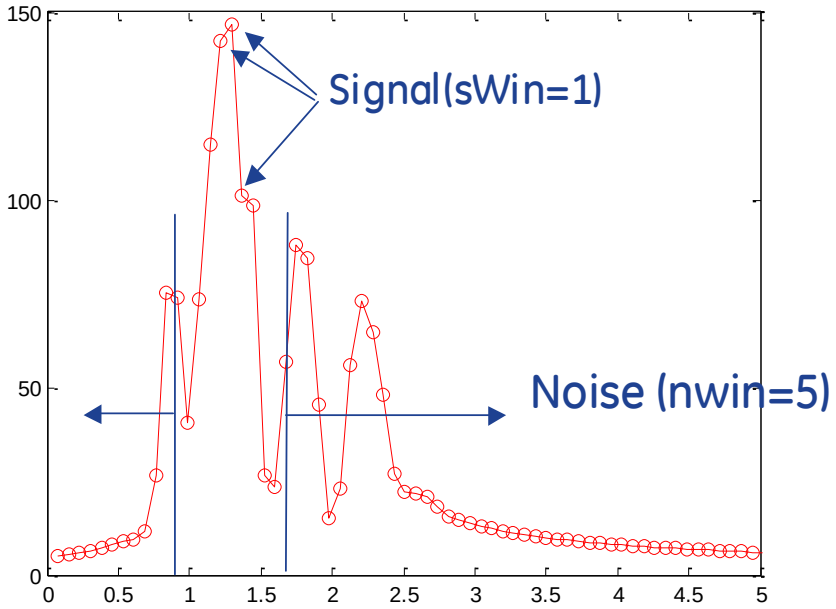

Figure 18 - SNR Calculation for Post-threshold A small window near the peak signal is selected, and power strength inside the window is calculated to represent signal strength, Pow_s

A small window near the peak signal is selected, and power strength inside the window is calculated to represent signal strength, Pow_s.

$$Pow_s = \sum x_s^2, \qquad s \in [p - sWin, p + sWin]$$

Equation 3- Signal Power Calculation for SNR

Noise strength Pow_n is calculated as total energy from the noise zone, that is nWin item away from signal peak:

$$Pow_n = \sum x_n^2, n < p - nWin \quad or \quad n > p + nWin$$

Equation 4 - Noise Power Calculation for SNR

Then signal to noise ratio (SNR) is calculated as

$$SNR = 10 * Log_{10}(\frac{Pow_s}{Pow_n})$$

Equation 5 - SNR Calculation in dB

If SNR is lower than a specified threshold, the post-threshold validity check is flagged. Either pre-threshold or post-threshold flag will set the rate validity of the corresponding data frame to be invalid.

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It is found that typically both motion state (non-concern state) and holding-breath (concern state) has lower SNR than still state. Therefore SNR cannot be directly used in the alarm state classification, rather applied to still state only, aimed at differentiating still with normal breathing/heart rate versus still but lack of rate signal.

Alerting Simulation Model

A Simulink alarm simulation model, as shown in Figure 19, is created to connect input and output variables with the alarm logic state flow block. A few different input options are added in the model, such that it can easily switch between annotated and estimated state or rate, or even constants for testing and validation purposes.

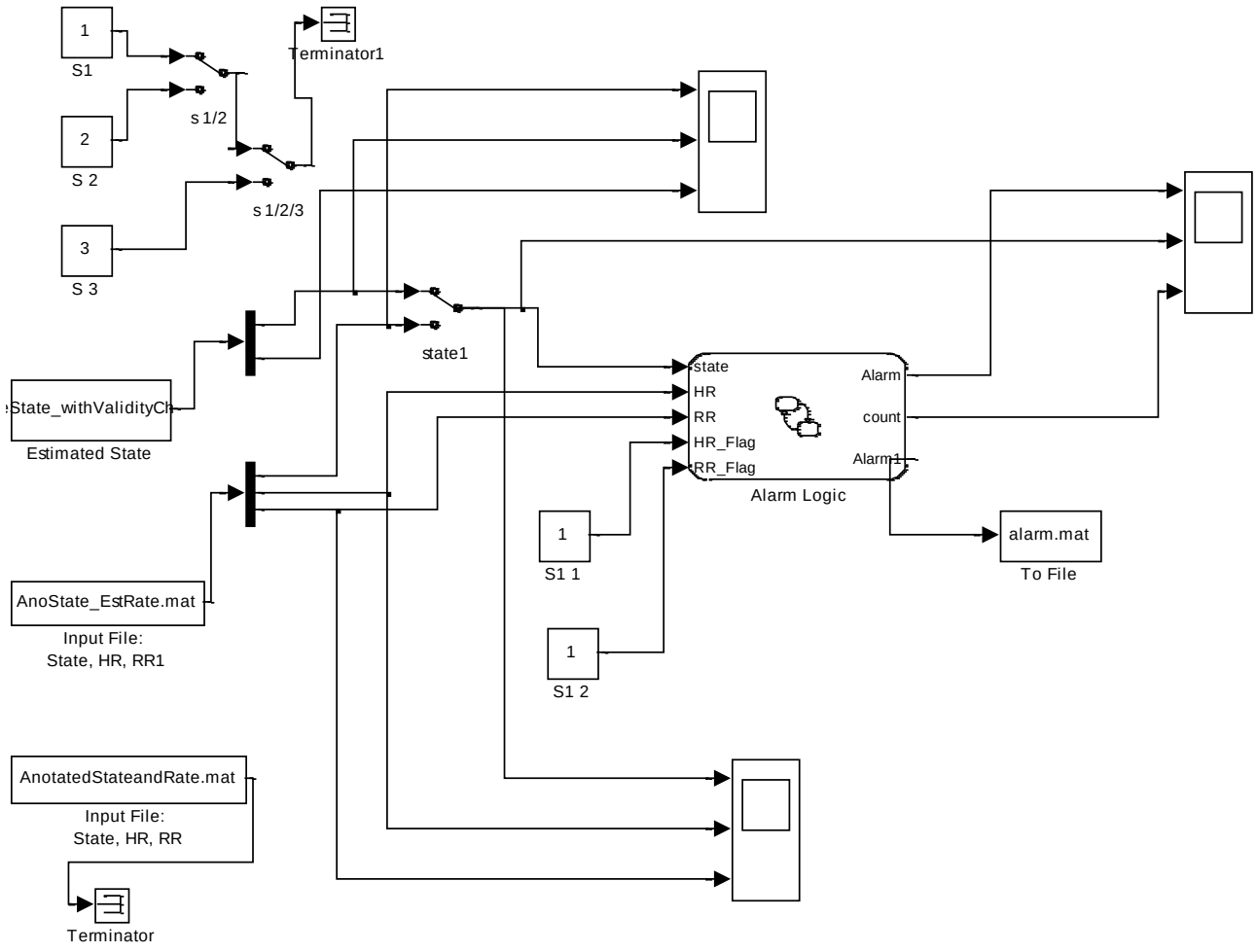

Figure 19 - Alarm Simulation Model in Simulink

At running mode, state, heart rate, and respiration rate estimates are aligned in time, and presented to the alarm logic one set at a time for alarm assessment. Output variables include alarm and alarm counter are displayed in the simulation model, and may also be stored in files for post processing.

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The 20-subject IRB data sets are used in the simulation model to evaluate the alarm logic. Rate and state estimates are pre-generated, and concatenated as time series inputs to the alarm simulation model. Since all these data sets are annotated with true state and rate information, these information is used to create true alarm target, and the alarm output from the simulation model is evaluated against the alarm target to check alarm logic correctness, and obtain alarm detection rate and false positive alarm rate.

For algorithm evaluation purpose, alarm targets are marked up in the concatenated time series. An alarm target refers to the point of time when alarm should be triggered. It is determined based on true state and time duration of a particular concern state, where the time duration by the unit of second is a control variable specified in the alarming algorithm, referred as alarmTH. For example, when a subject starts holding breath (to simulate losing-breath concern state), after alarmTH second, an alarm target is set up. The appropriate value of alarmTH should be chosen to detect abnormal situation before irreversible physical damage to the subject, in the same time, minimize false positive alarms caused by intentional or unintentional (sleep apnea, etc.) situation. Time delay from an alarm target to the next triggered alarm is used to determine event detection capability.

Table 6 listed the configuration variables specified in the current alarming algorithms. Based on this configuration, there are 17752 frames in the concatenated data set with one-second update rate, and 19 alarm targets found. All alarm targets are detected, and false positive alarm break into different annotated state is shown in
Table 7. Notice here the majority false positive alarms are recorded where the true state is concern. The reason that these alarms are classified as false positive alarm is because they are triggered earlier than the specified alarm target, so we treat this as “soft false positive”, whereas the FP rate when subject in motion and still state are both much lower.

Table 6 - Alarm Algorithm Configuration Variables

Name	Description	Current Value
Count_max	# of continuous abnormal frame before alarm (1 sec per frame)	45
Count_reset	# of normal frame to reset alarm	2
Count_step	Counter INC/DEC steps	1
Alarm_th	Time delay (sec) after continuous caution state to create annotated alarm target	50
Reset_th	Time delay (sec) after continuous non-caution state to remove annotated alarm target	5

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Table 7 - False Positive Alarm

State	FP Alarm Count	FP Alarm Rate
Motion	20	0.1%
Still	50	0.2%
Concern	1095	6.1%

Some limitations in the 20-subject IRB dataset constrain the level of model validation may be accomplished. Most notably only short period of still/holding breath state has been tested at lab setting, and in between transition states causes lower SNR with long delay. What is needed is more realistic data collection that reflects subject daily activities with realistic temporal duration and transition. Further model optimization and validation is planned for the on-site data collected from WCI.

Task 1.5— Application of algorithms to the field-collected dataset to analyze and quantify predictive performance

The state, rate and alarming algorithms have been applied to the 10-subject data collection obtained from volunteers at WCI. The data collection activities and human subjects methodology are more fully described in Task 2 of this report.

State Estimation Performance

The algorithm developed earlier was applied to the data collected from the WCI experiments. The resulting truth table is shown in Figure 20. The overall sensitivity percentages are slightly improved over the GE training data with a smaller percentage of "unknown" (mixed state frames).

Overall	**1374 matches / 1800 (76.33%)**						
No Unk	**1374 matches / 1596 (86.09%)**						
	Unknown	**Motion**	**Still**	**Concern**	Row Total	Sensitivity	**of sample**
Unknown	0	0	149	55	204	0%	11%
Motion	0	601	92	5	698	86%	39%
Still	0	2	459	109	570	81%	32%
Concern	0	0	14	314	328	96%	18%
Column Total	0	603	714	483	1800		
		100%	81%	73%			

Figure 20 – Accuracy results for WCI field study data, 10-second frames

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The reduction in unknown states can be primarily attributed to the change in the data collection that required the subject to change the viewing angle within each data set (side, front, back) since that introduced extra motions. The unknowns that are included are more of transition periods through the natural changes in state from the data collection. Some improvements in the motion prediction may be attributed to the instructions, particularly when lying down to move around, including turning over. Since turning requires significant gross motor activities, that level of activity is easily detected by the analysis of the radar signal. In the original GE training data, movement while lying down did not include turning since a particular viewing direction was required. Some of the misclassification between motion and still states can be attributed to different levels of interpretation of when to annotating motion. For instance, small movements of the hand may be so slight that the criteria required predicting motion is not satisfied. Since motion is primarily a state to determine that it is not feasible to estimate heart rate or respiration rate because of the energy in the radar signal, these misclassifications should have minimal impact on the overall alerting accuracy. When expected, the concern state is very accurately predicted. The empty room data set had 100% accurate prediction, since the prison cell prevented outside activity from being observed by the radar device. However, there were several misclassifications of still as concern states and required further detailed review.

To investigate the misclassifications of still as concern, we looked at the accuracy of the results for each subject and each data set to see if there were mitigating circumstances. We determined that data set 8, still supine had a high misclassification for several subjects. Many of these subjects were lying on their backs. The position of the radar device may have made observation of this position, particularly for subjects with shallow respiration difficult to observe. One mitigation option is to mount the radar above the subjects (e.g. from the ceiling) to more easily observed the respiration from that viewpoint. A robust product may require two radar sensors: a wall-mounted and ceiling-mounted device to reduce the “hidden” directions in a room. Similarly, one subject, (subject 8) also had high misclassification for the seated still data set (5). This subject maintained an exceptionally still position with little visible evidence of respiration. In fact, they leaned over resting their elbows on their knees. Again, a different angle for the radar may improve the detection.

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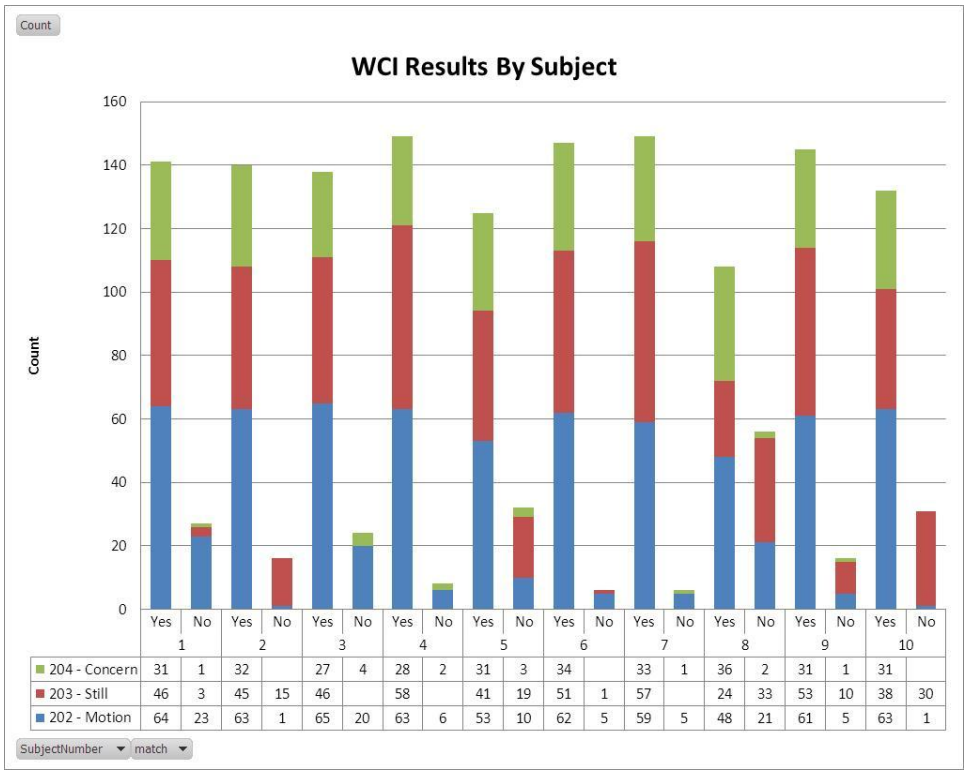
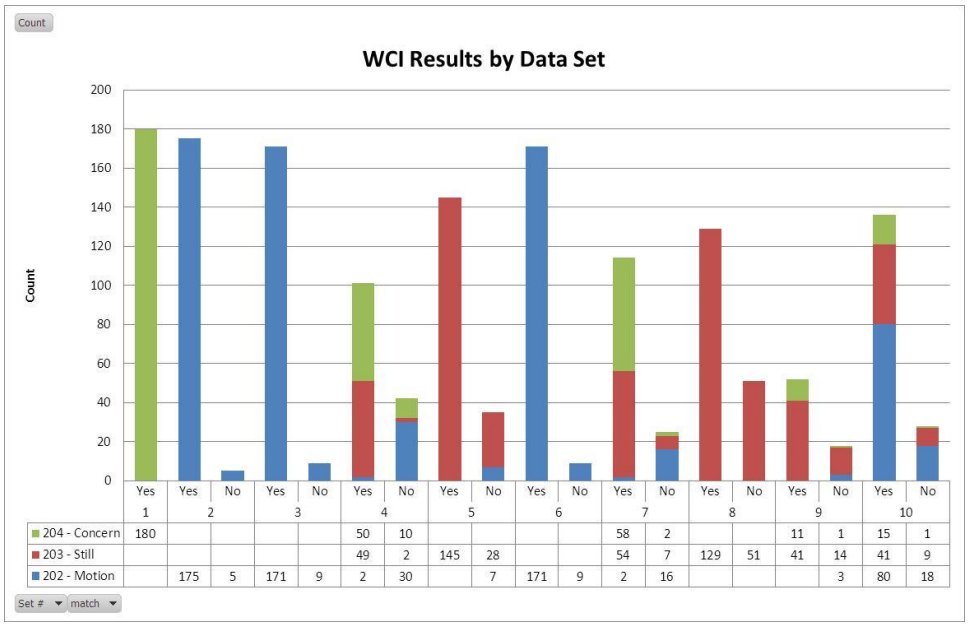


	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
	1		2		3		4		5		6		7		8		9		10	
204 - Concern	31	1	32		27	4	28	2	31	3	34		33	1	36	2	31	1	31	
203 - Still	46	3	45	15	46		58		41	19	51	1	57		24	33	53	10	38	30
202 - Motion	64	23	63	1	65	20	63	6	53	10	62	5	59	5	48	21	61	5	63	1

Figure 21 – Accuracy results for WCI field study data by subject, 10 second frames
Yes indicates correct classification, No indicates incorrect state estimation



	Yes	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
	1	2		3		4		5		6		7		8		9		10			
204 - Concern	180					50	10					58	2			11	1	15	1		
203 - Still						49	2	145	28			54	7	129	51	41	14	41	9		
202 - Motion		175	5	171	9	2	30		7	171	9	2	16				3	80	18		

Figure 22 – Accuracy results for WCI field study data by data set, 10 second frames
Yes indicates correct classification, No indicates incorrect state estimation

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Data set 9 was of particular interest since we had not collected this combination in the GE study group. This data set was intended to mimic sleep apnea, but of short durations (e.g. 10-15 seconds) instead of the longer duration used in the hold breath data sets. The accuracy of this data set was quite good, except for subjects 9 and 10. Again for these subjects, the position of the radar and the subjects lying on their backs may have made it difficult for the radar to detect the respiration behaviors.

Rate Estimation Performance

Respiration and heart beat rate estimation algorithms are applied to the collected WCI field data set, and the estimated rates for each subject and various data sets using RCR signal are compared to the annotated rates for performance evaluation. The annotated heart rate is extracted using the finger-clip heart beat sensor data, and referred as the actual heart rate. The annotated respiration rate, or actual respiration rate, is extracted using the spirometer signal.

Note that in the developed alarm algorithm, only at still states the rate estimation logic is used in assessing subject status. Therefore the rate evaluation is focused on still data sets only. The WCI field data include ten data sets obtained for each subject with different targeted testing state. The majority still segments exist in data set 5, seated still, and data set 8, supine still.

The rate estimation algorithms are applied with the same configuration as used for the lab testing data. Table 8 shows the average prediction error rate for seated still and supine still states, respectively. The error rate is obtained as the difference between the averaged radar estimates and averaged actual rate divided by the averaged actual rate. Both high gain and low gain radar signals are evaluated for their performance in the heart rate and respiration estimation, and the low gain results show somewhat lower error rate for all categories of comparison. Also, the supine still result consistently has lower error rate than the seated still prediction. Overall, the error rate results are within 10% to 15% range, well below the 20% targeted value.

Table 8 – Rate Estimation Performance for Still States

		Annotated State	
Rate Type	**Data**	**Seated Still**	**Supine Still**
HeartRate_Hi	Average of Delta	10.55	9.38
	Average of Actual Rate	71.83	70.10
	Error Rate	14.68%	13.38%
HeartRate_Low	Average of Delta	10.30	9.28
	Average of Actual Rate	71.83	70.10
	Error Rate	14.34%	13.24%
Respiration_Hi	Average of Delta	1.78	1.32
	Average of Actual Rate	12.94	12.90
	Error Rate	13.79%	10.20%
Respiration_Low	Average of Delta	1.64	1.29
	Average of Actual Rate	12.94	12.90
	Error Rate	12.65%	9.96%

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Figure 23 shows some comparison of the rate prediction result for two subjects at seated still state, where subplot (a) is for subject 6, and subplot (b) for subject 7. In each subplot, the left panel shows the result for respiration rate comparison, and the right for heart rate comparison. Within each panel, the top plot compares predicted rate using low gain (Radar-lo) and high gain (Radar-hi) channel to the annotated rate (True Rate). The bottom two plots show the traces of pre-threshold flag and post-threshold flag, respectively, where a value of 1 indicates certain threshold is exceeded. As discussed in the rate algorithm section, that the pre-threshold flag algorithm sets a lower bound for in-frame signal variation. The post-threshold algorithm calculates signal to noise ratio (SNR) in the frequency domain and raises flag for low SNR frames. All horizontal axes in the plots are time in second.

It can be found that good correlation between the estimated rates using the radar signals and the annotated rate is typically obtained for high SNR data frames, i.e., when post-threshold flag has value of zero. Somewhat better correlation is found in respiration rate estimation than the heart rate estimation. For frames with poor estimation to true rate correlation, typically post-threshold flags are raised which indicate low SNR. For most still state data, pre-threshold flag is not raised, which indicates sufficient in-frame variation due to breath or heard beat motion is captured by the radar signal.

Figure 24 shows another two sets of comparison for subject 4 and 5, except for the motion state for both subjects is supine still. Again, good correlation is obtained in all rate estimation, with somewhat better accuracy in heart rate estimation than seated still state. Also, in supine state radar signal has higher signal to noise ratio, which results in fewer post-threshold flags generated.

Figure 25 presents the rate prediction and flag results for an empty room data set. It can be seen that the pre-threshold flags are consistently raised throughout the data set, which indicate insufficient signal strength related to a person's breathing or heartbeat. Also, large amount of post-threshold flags are also raised due to low SNR. Both of these flags are incorporated in the alarm logic to help raise concern when no breathing or heart beat are detected.

As an overall summary, the previously developed rate estimation algorithm has demonstrated satisfactory performance when applied to the newly collected WCI field data set. This is achieved by applying the exact algorithm and threshold configuration as used in the lab testing data without further parameter tuning. This further validates the robustness and accuracy of rate estimation algorithm.

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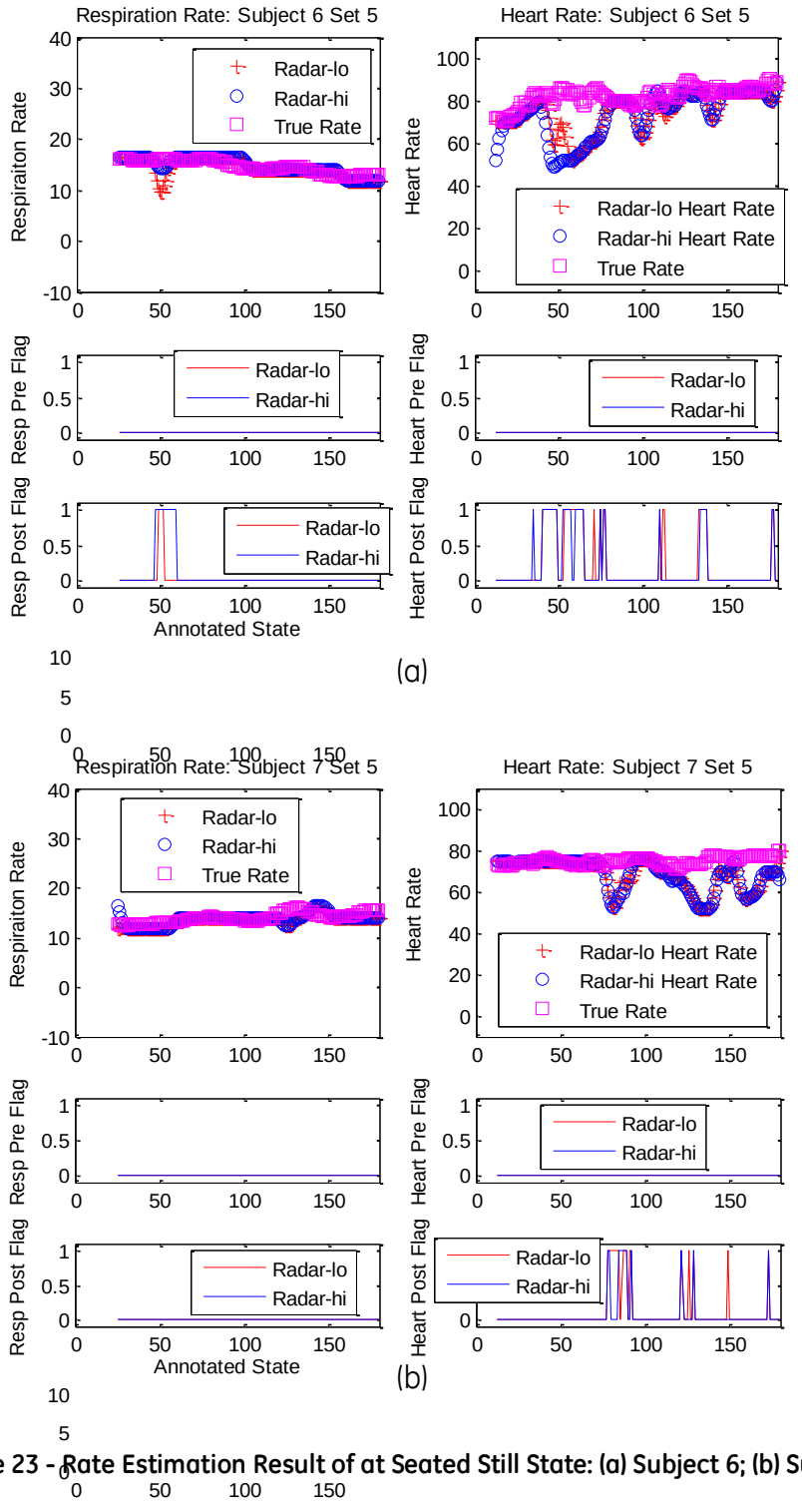

Figure 23 - Rate Estimation Result of at Seated Still State: (a) Subject 6; (b) Subject 7

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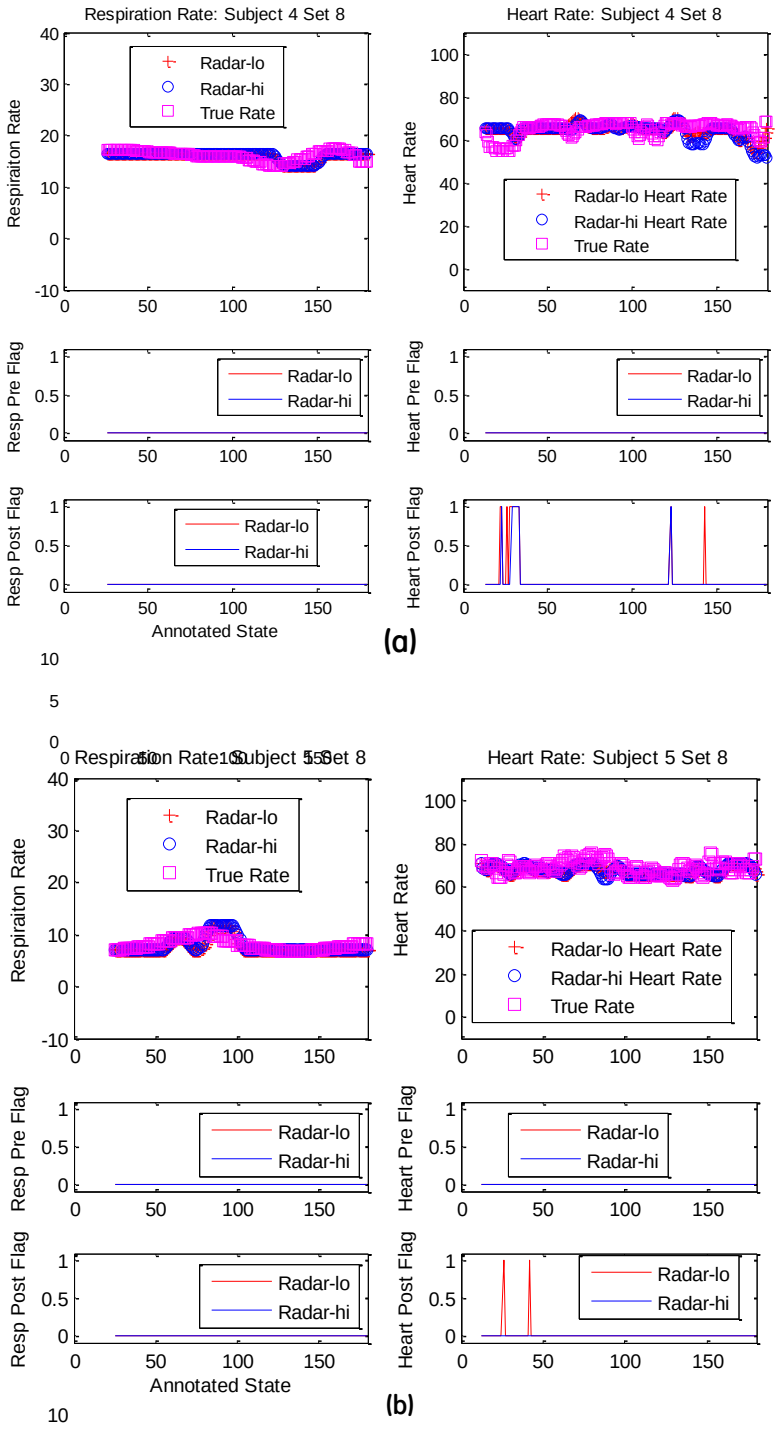

Figure 24 - Rate Estimation Result at Supine Still State: (a) Subject 4; (b) Subject 5

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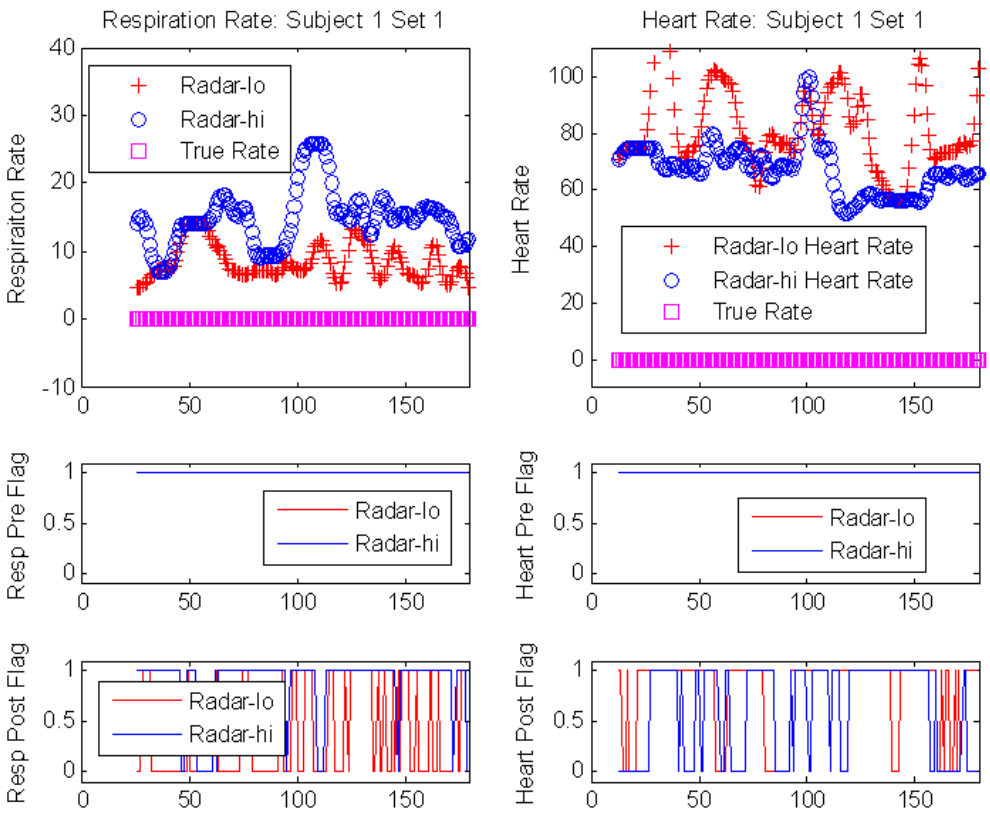

Figure 25 - Rate Estimation Result for Empty Room: Subject 1

Alerting Performance

The rate and state estimation results of all the ten subjects and ten data sets are concatenated and aligned by time to create a time series input for the alarm algorithm. One-second update interval is used for rate and state estimation, as well as alarm evaluation. The overall combined time period is 18000 second of data. However, since both respiration rate and heart rate algorithm require time delay in order to form the initial data frame, the final combined input vector length is 15500.

Using the same alarm configuration as used in GE lab testing analysis, the alarm result for the WCI field data set is shown in Figure 26. Four traces are shown in this figure, from top to bottom: the created alarm indicators, the continuous counter for abnormal state temporal consistence check, subject id, data set number. Most of the alarms are generated in data set 1, which is the empty room. From the counter plot, it shows consistent pattern of clustered peaks that correspond to the designated holding breath testing states. Table 9 provides a statistical summary of the alarm result at different annotated state. The majority alarms are triggered in the concern state. Most motion state data has alarm off. About 11% of the still states triggered false alarms, which is the main constitutor to the overall false alarm rate of 4.4% in all data frames.

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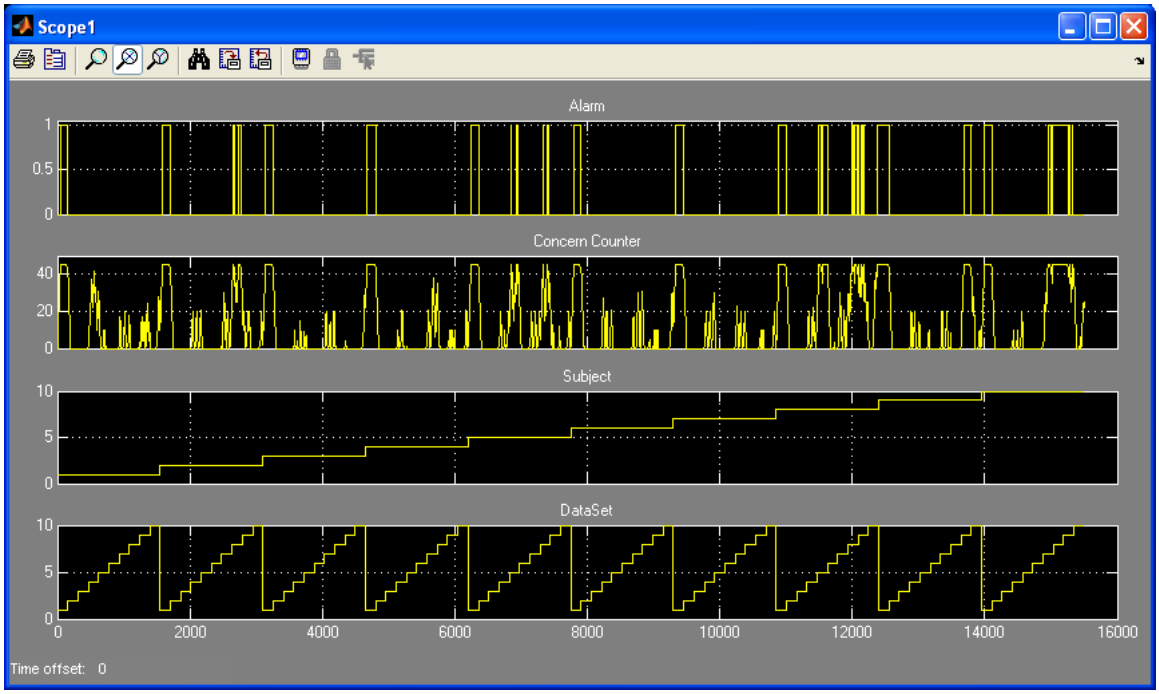

Figure 26 - Alarm Result of All Subject Concatenated Data Set

Table 9 - Alarm Distribution in Different Annotated State

	State Annotation			
Alarm	**Unknown(0)**	**Motion (1)**	**Still (2)**	**Concern (3)**
0	1653	5873	4286	1726
1	126	28	549	1259

Figure 27 further breaks down false alarm count into individual subject and data set. From subplot (a), most false alarms come from subject 8, 9, and 10, which is consistent with findings in the state estimation analysis. Similarly, from subplot (b), high false alarm volume is in data set 8, supine still, and 9, supine still with short hold breather alternation.

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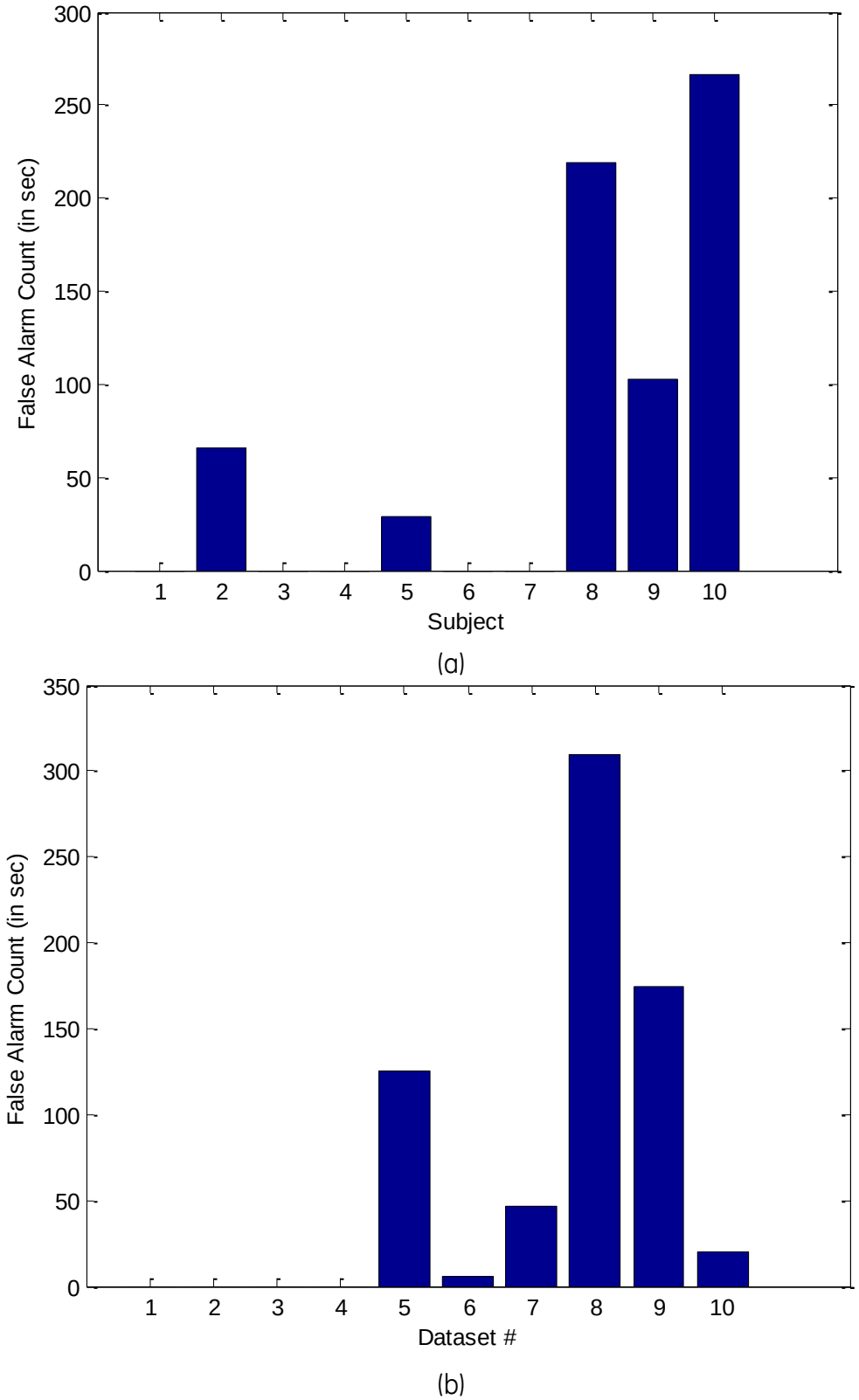

Figure 27 - False Alarm Count Statistics: (a) Group by Subject; (b) Group by Dataset File

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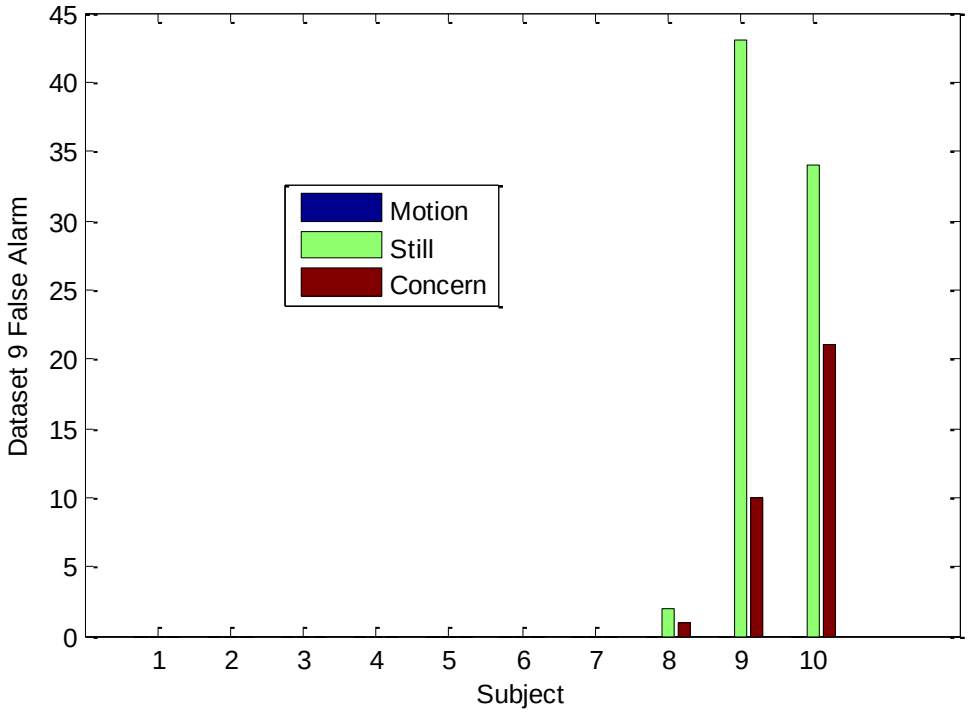

Figure 28 - Alarm Count in Alternate Hold Testing - Data Set 9

One data set of particular interest is the alternate breath hold testing, or dataset 9. In this data set, subjects hold breath for short duration – about 10 seconds, in between normal breathing rate. This is used to simulate sleep apnea scenario. The goal is to make sure the alarm algorithm is configured in such way that it would not alarm on subject with sleep apnea conditions. Figure 28 shows the alarm count in data set 9 by subject and by annotated state. Most subjects behave as expected that no alarm is triggered. Only subject 8, 9, and 10, and mostly subject 9 and 10, have alarms in this data set. Also interestingly, more alarms are created in the still state rather than in concern, or hold breath state. The uneven alarm distribution among subjects raises the question that whether behavior difference of specific subjects or testing error is the cause.

Figure 29 displays alarm details for one of the high false alarm subject: subject 8. In the top subplot, annotated alarm, with green dot symbol, is the alarm target based on the algorithm configuration, and the red-cross symbol represents triggered alarm. Also shown here are annotated versus estimated state. It can be seen that here most false alarms are generated when still state is confused with concern state. Also the second subplot shows relatively high volume of heart rate flag, which indicate poor signal to noise ratio.

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The overall performance of the alarm logic using WCI data set is consistent with the lab testing result. All target events are detected within delay threshold of 30 seconds, and false detection rate is within 5%.

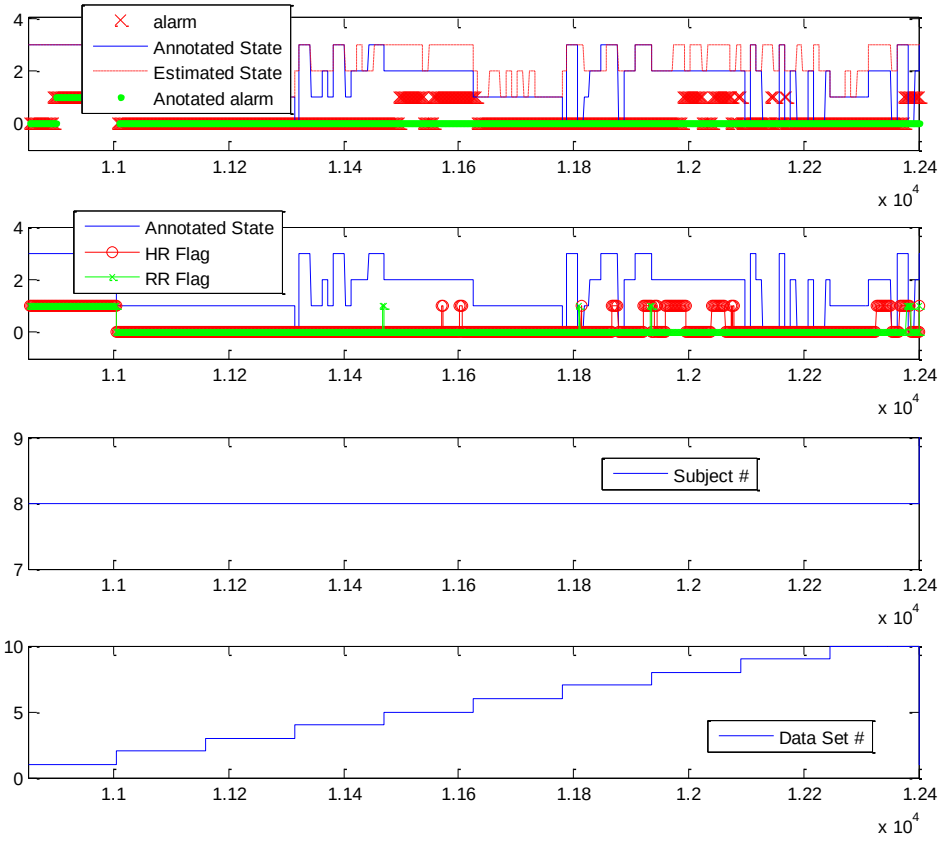

Figure 29 - Alarm Result of Subject 8

Real-time System Development

Our initial work has processed the collected data in a post-processing fashion. For demonstration purposes, a more realistic, real-time system that applies the algorithms to the data as it is collected is needed. This system illustrates that the algorithms can run in a realistic time frame and that the alerting can occur in time to provide suicide prevention and appropriate interventions.

To achieve this goal, the algorithms require reorganization to execute in a continuous manner integrated with a data acquisition (DAQ) device. The diagram in Figure 30 shows the flow of key data elements from the observed individual, through the range control radar (RCR) device. The high gain and low gain signals are captured through a data acquisition device and processed through the filtering and estimation modules. The estimates are then sent to the alarm module that continually assesses whether the alarm criteria have been

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satisfied (e.g. empty room or hold breath > x seconds). When the criteria are satisfied, an alarm indication will be shown on the monitor to complete the demonstration.

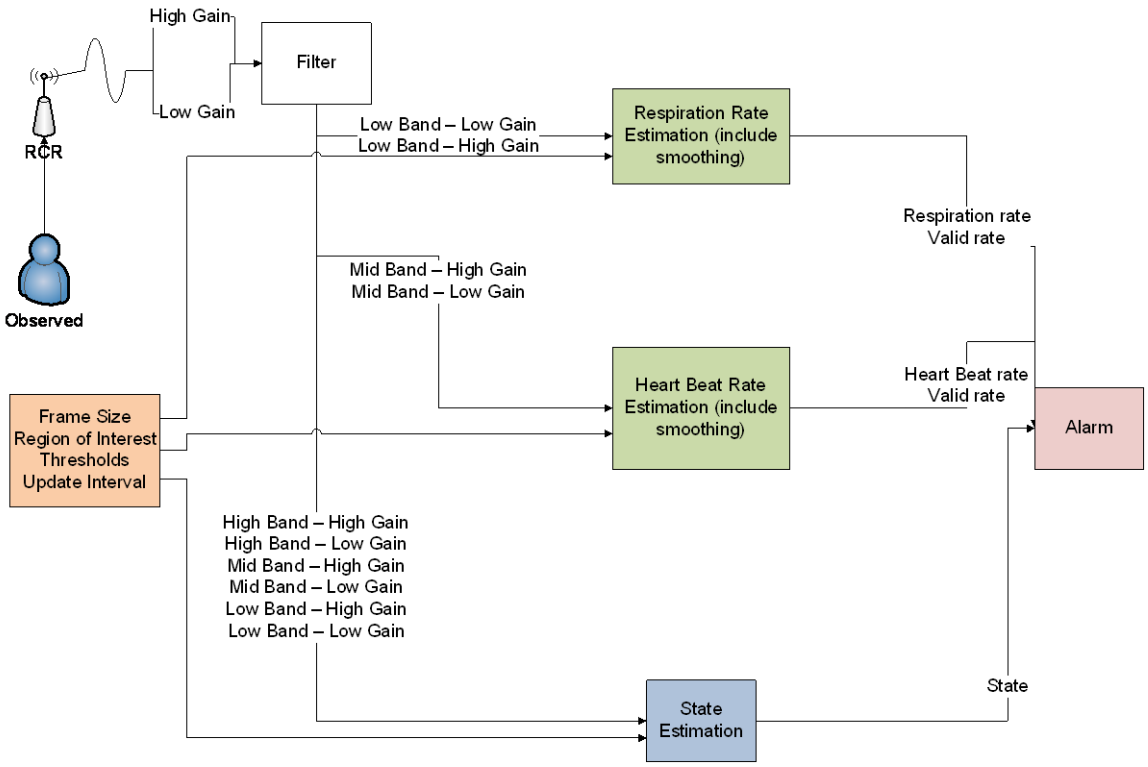

Figure 30 – High-level flow for real-time prototype

The DAQ device selected is an Agilent U2331a device that is connected to the RCR to collect the high and low gain channels. A C++ interface and Agilent libraries allow the data to be collected. The C++ interface consists of a main control loop. Each iteration of the loop collects data for a preconfigured duration. The time duration must be longer than the time required to execute all functions within the control loop (otherwise the program will fall behind and lose data). For implementation simplicity, this time period will be greater or equal to the largest frame window required by any of the underlying modules (e.g. 10 seconds required for state estimation). A ramp-up period is required to collect the minimum amount of data required for the algorithms to perform the estimations (e.g. 30-60 seconds). This provides enough historical data so that the realistic features can be determined (e.g. wavelets, FFTs).

The algorithm modules have been developed in MATLAB™ and some rely on toolboxes within MATLAB™, such as the Wavelet Toolbox. To integrate with the data acquisition control program, an overall data process function is constructed that accepts a signal array and configuration parameters for all the estimators. Each estimator is written as a similar function that accepts a signal array and configuration parameters (e.g. frame window size, etc.). The estimators will return an array of results. These functions are compiled with MATLAB's compiler into a dynamic link library (DLL).

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The alarm logic has been built in MATLAB's SIMULINK and StateCoder toolboxes. Code generation can be performed using the Real-time Workshop toolbox. This technique requires further investigation to understand how to integrate the generated code with the other modules. The alarm design may require further revisions to support integration with the prototype design.

The alarm logic is assumed to operate on the most frequent frequency (e.g. 1 second). The other estimators will report results at the same time intervals so that all the estimators and the alarm logic are synchronized. If an estimator cannot report unique values at that frequency, then the results will be repeated for the frame duration. A probable sample of estimation frequency is shown in Figure 31 where the states are estimated at 10-second intervals and respiration rate, heart rate and alarms are predicted for each second. For this scenario, each state estimate is repeated 10 times so that there is a state estimate at each second.

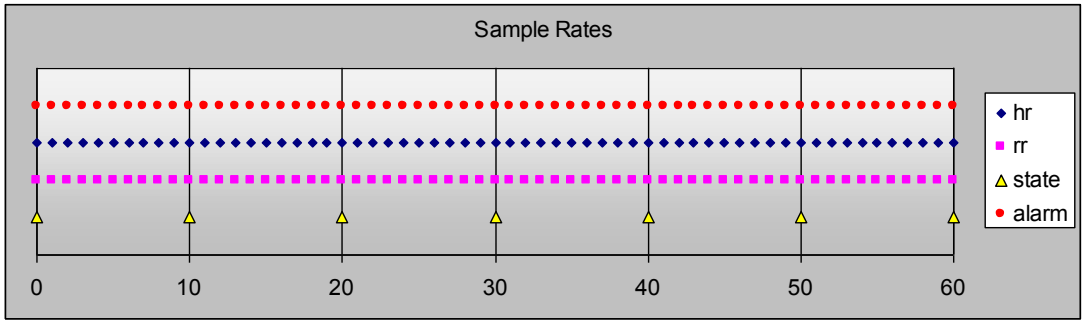

Figure 31 – Frequency estimation

The prototype implementation is currently under development. The MATLAB and C++ method descriptions developed to date are included in Appendix B2 - Real-time Method Descriptions. The data acquisition control loop has been completed and the state and rate estimator modules have been integrated with the control loop. Validation of the state estimator module has been performed. The validation consisted of running the real-time estimator code on the GE IRB datasets. Selected frames were compared with the original batch analysis results. Several different frames were compared and all matched exactly as should be expected. The rate estimation module was recently added and requires a similar validation.

The initial timing estimate for state estimation indicates that step will easily complete within the expected control loop time limit. More comprehensive timing statistics for the entire process should be acquired.

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A picture of the real-time demonstration system hardware is shown in Figure 32. The Agilent DAQ device connects to a laptop PC via a USB cable. Bench power supplies and signal generators are used for convenience. The antenna is connectorized to facilitate changing from the standard RCR dipole antenna (shown) to a directional antenna including the Rotman antenna as designed and constructed in Phase I of this program.

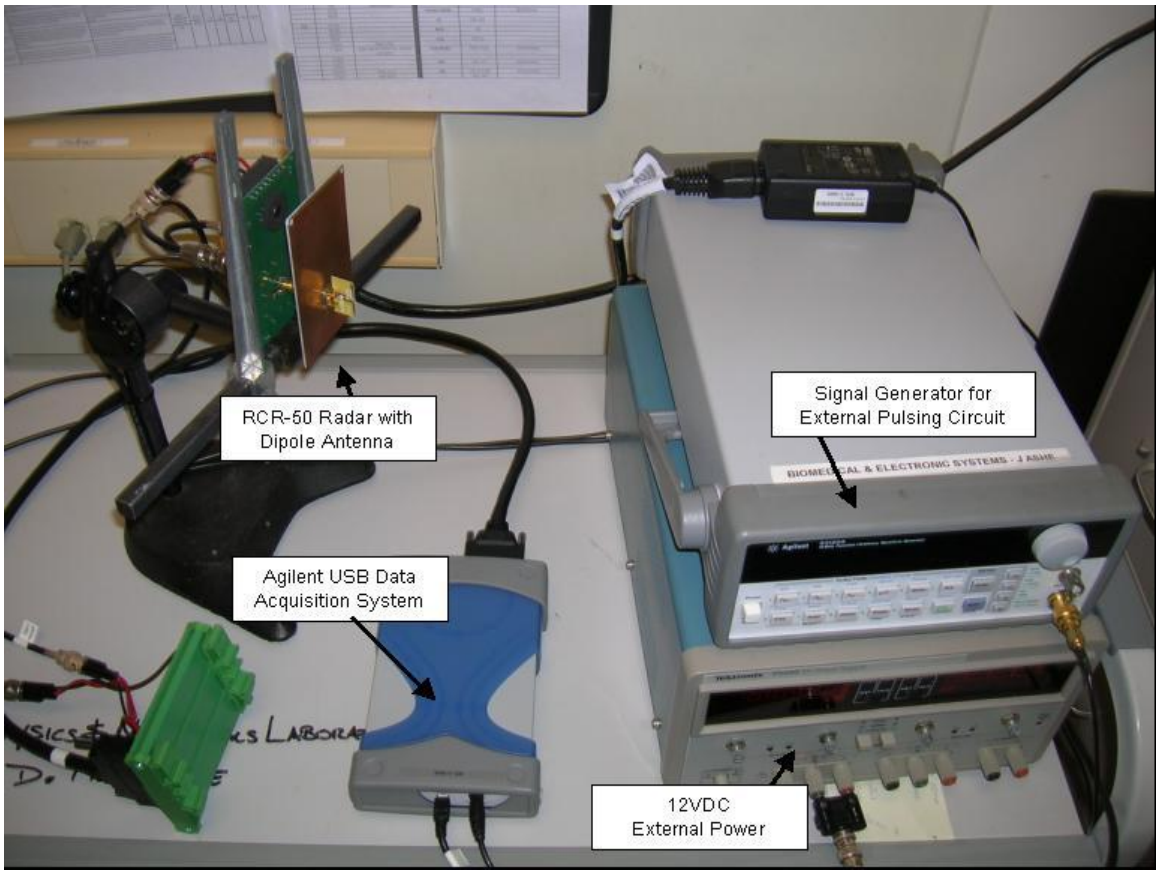

Figure 32 – Real-time system including Agilent DAQ device

Task 2—Field Data Collection in Representative Prison Environment

Field data collection has been completed with human subjects under Institutional Review Board (IRB) approval in collaboration with the Western Correctional Institution (WCI) of the Maryland Department of Corrections. Measurements have been taken within the Special Observation Housing (SOH) unit at WCI using the prototype system developed under Phase I and Phase II of this NIJ program. Through observation and analysis of the Phase II field collected data, we have confirmed:

- Acceptable coverage, leakage and cross-talk performance within the cell layout and physical construction of the representative prison environment.

- Acceptable system performance for measuring human activity through specialized anti-suicide garments (smocks and blankets) in-use in the SOH.

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- Acceptable performance for applying the state, rate, and alarming algorithms on the Phase II activity data collected from 10 volunteer staff at WCI. These results are commensurate with the predictive performance assessed from the Phase I activity data collected from 20 volunteer staff data collection at GE.

Western Correctional Institution

Under the guidance of the National Institute of Justice, the Western Correctional Institution (WCI) in Cumberland Maryland was chosen as the field site. In addition to this program, the WCI site may be used as a future test-bed for other NIJ programs. The WCI facility is designated as a maximum-security institution but houses all security levels. Presently, WCI houses over 1,600 male inmates. Prior to the field collection activities, we met with WCI officials to establish the basic study site, protocol, and agreements (see Appendix B3 - WCI Trip Report). WCI Warden, J. Philip Morgan offered the support of his staff and identified the Special Observation Housing (SOH) unit for the subsequent testing. It was agreed that corrections staff would be solicited as volunteer subjects under informed consent for the study since prisoners are a vulnerable population with special consideration under the IRB. However, testing an observational system on prisoners in a future program Phase is considered feasible but will require new agreement with GE, WCI, the NIJ and the IRB.

Figure 33 – Western Correctional Institution in the mountains and valleys of Cumberland, MD
Picture from: http://farm4.static.flickr.com/3249/3282605422_d42e886316.jpg

In addition to the IRB approval discussed in Task 3 of this report, a Memorandum of Understanding (MOU) between GE and WCI was developed and executed prior to the field data collection (see Appendix B4 – GE-WCI Memorandum of Understanding). In developing the MOU, three important issues were iterated between the parties in reaching agreement:

- *Subject Privacy* – Due to the nature of corrections staff work with prisoners, additional privacy considerations were developed to ensure staff participation in the study would be unknown to prisoners. For the study sessions, an area of the SOH would be cleared of prisoners so the staff could freely participate without inmate observation.

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- *Subject Safety* – Since the field collection activities would be conducted in an actual SOH holding cell, additional safety considerations were developed to ensure the area was clean and that the study participants could freely enter and leave the cell. To aid in cleanliness, disposable sensors and barrier materials were provided for single-subject use during the study. To aid in cell access, the SOH duty officer was tasked with unlocking and opening the cell door in the event it was accidentally closed or locked during the study.

- *Subject Compensation* – Due to staffing and budget constraints on the Maryland Department of Corrections, the study was modified to be conducted on the off-shift time of the volunteer participants. Compensation was established to cover the time and travel for each study session. Additionally, subjects are scheduled as close to possible to participate just prior to or just after their scheduled shifts.

Reaching agreement and execution of these types of administrative agreements proved to be a cumbersome process and delayed the program timeline. The NIJ program was extended without incurring additional cost due to these delays in administrative issues.

Task 2.1—System characterization for coverage, leakage, and crosstalk

WCI testing occurred in two different types of cells within the SOH. One cell was of standard construction with a small window to the outside on the far wall and a solid door with small window and access port to the interior. The other cell is used for observation with large windows facing the interior corrections officer station for continuous observation. The standard cell at WCI is depicted in Figure 34. A picture of the windowed continuous observation cell was not available at the time of writing this report.

Figure 34 – Typical SOH cell with standard construction
Left – Looking toward window to outside
Right – Looking toward interior door with window and access port

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Coverage within a mock cell was investigated thoroughly in Phase I of this program, including the design of specialized antennas (e.g. Rotmann Lens Antenna) to increase volumetric coverage within the cell and to prevent blind spots due to furniture or physical obstructions. It is anticipated that antenna location(s) could be optimized for individual cell arrangements and a system consisting of two antennas (one on the ceiling and one on the wall opposite the bed) will most likely be sufficient to ensure complete coverage. For the field-testing activity at WCI, the configuration using a fixed 17-dBi antenna on a portable tripod near the wall opposite the bed was explored (also as shown in Figure 34). Attaching an antenna to the ceiling was not feasible at this time and will be addressed in the proposed Phase III of this program.

Coverage within the cell was determined experimentally by walking or crawling around the various areas of the cell while the system operator observed the waveforms from the radar. In this configuration, signals were observable directly in front of the antenna and an area of the cell of maximum sensitivity was identified by masking tape on the floor (also as seen in Figure 34). Subjects were asked to remain mostly in this area, including standing, sitting, and laying down on the floor or the bed although excursions outside the coverage area still resulted in acceptable signals. For specialized testing, a subject crawled under the bed to confirm acceptable signals could still be obtained.

Leakage and cross-talk performance was explored within both the standard and the windowed cells (see Table 10). Within the standard cell, tests were conducted with an empty cell with the door closed as a baseline for comparison to additional tests with the door open and activity in the hall and with activity in the adjacent cell (walking around then kicking wall and door). For all leakage and cross-talk tests, no observable signals appeared in the radar output signals that correlated with the observed activities. While this confirms the applicability of the system for use in standard cells, additional testing will need to be performed when units are installed on the ceiling or walls instead of the portable tripod used for these tests.

Within the windowed cell, signals were immediately noticeable for activities conducted outside the cell near the large windows. As expected, the windows did not provide as much shielding and attenuation as the reinforced concrete walls of the standard cell. It is unlikely this system will provide acceptable performance in the windowed cell without applying special radiofrequency absorption treatments to the window itself.

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Table 10 – Coverage, Leakage and Cross-talk Tests

Subject	Set	Description
0	5	Smock covering body of subject, subject laying on back on bed
0	6	Smock completely covering subject, subject laying on side on bed
0	7	Room empty, Door open
0	8	Room empty, Door closed and locked
0	9	Room empty, Door closed and locked, activity in adjacent cell, walking, kicking wall
0	11	Subject quietly laying on side on bed
0	12	Subject quietly laying on side on bed under mattress
0	14	Subject quietly laying under metal bed
0	15	Subject quietly laying under metal bed, blanket blocking view (tent)
0	16	Subject quiet then leaving the room
0	17	Windowed cell, occupied then empty
0	18	Windowed cell, empty with activity outside the window

Additional testing was performed to determine if human activity would be shielded by the specialized anti-suicide garments (smocks and blankets as shown in Figure 35) in-use in the SOH. For these tests, a subject was observed breathing under a blanket or a smock, either with their head and hands exposed or completely covered. Under all cases, the breathing signal was immediately recognized. An additional test was conducted with the subject on the floor under the metal bed with the anti-suicide blanket blocking the view of the subject by draping the blanket over the bed frame. In this instance, no physical motion of the subject was transferred to the blanket. Distinct breathing signals were observed, again confirming the transparency of the smocks and blankets with the prototype system.

Figure 35 – Anti-suicide smocks and blankets tested for shielding effects.

Task 2.2—Data collection in a representative prison environment from 20 subjects

All human subjects testing was conducted under IRB approval. All subjects participated under informed consent. No adverse events were experienced during the testing.

Volunteer corrections staff members (officers and support personnel) were recruited for the study. The study was advertised at roll-call for a period of one week. Interested volunteers

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were asked to express their interest and 10 participants and 6 alternates were selected at random from the responses. The IRB approved up to 25 subjects. However, the study design was reduced to 10 subjects due to scheduling logistics at WCI. Nine of the 10 participants attended scheduled sessions and one alternate was enlisted for an unexpected no-show for unknown reasons. The demographics of the study population are given in Table 11.

Table 11 – Human subjects demographics
Nine participants and one alternate participated in the study

Subject	Age	Height	Weight	Gender & Ethnicity
1	40	5' 11"	233	Male, Caucasian
2	30	5' 8"	190	Female, Caucasian
3	43	6' 1.5"	245	Male, Caucasian
4	54	5' 9"	225	Male, Caucasian
5	25	5' 11"	200	Male, Caucasian
6	41	5' 9"	165	Male, Caucasian
7	24	6' 2"	200	Male, Caucasian
8	39	6' 1"	248	Male, Caucasian
9	57	5' 5"	189	Female, Caucasian
10	32	5' 5"	138	Female, Caucasian

Data was collected while the volunteer subjects performed activities within the cell. The volunteers performed routine activities that they may have observed in inmate behaviors. Volunteers sat or laid very still on the bedding or floor and held their breath for periods of time as the best, safe surrogate we currently have for asphyxia. The final test was designed to capture data from a sequence that could be played through the real-time code in an offline manner. Segments of this progression as well as the breath hold sets contain ample time in "Concern" states to trigger the alarming logic. Full details of the data collection activities are listed in Table 12.

The dataset was annotated to describe the activity or "state" as referenced in the collected video (the video is for Principal Investigator use only for privacy) and to identify each breath and heartbeat as referenced in the flow and pulse sensors, respectively. The WCI-study annotation was expediently reduced from the previous GE-study annotation in that individual positions (front, back, side, or stomach) are not recorded but could be re-annotated from the video if a need arises. All motion, still, and breath hold events are annotated for performance analysis.

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Table 12 – Human subjects data collection activities
Radar, Flow, Pulse Y/Ncolumns indicate which sensors collected data

Set	Radar	Flow	Pulse	Description
1	Y	N	N	Empty room, baseline
2	Y	N	N	Walking randomly
3	Y	N	N	Seated on bed, moving randomly, odd subjects-side, even subjects-front
4	Y	Y	Y	Seated on bed, quiet and still, holding breath for 30-second intervals, odd subjects-facing side, even subjects-facing front
5	Y	Y	Y	Seated on bed, quiet and still, breathing normal, odd subjects-facing side, even subjects-facing front
6	Y	N	N	Laying on bed, moving randomly, odd subjects-facing side, even subjects-facing back
7	Y	Y	Y	Laying on bed, quiet and still, holding breath for 30-second intervals, odd subjects-on side, even subjects-on back
8	Y	Y	Y	Laying on bed, quiet and still, breathing normal, odd subjects-on side, even subjects-on back
9	Y	Y	Y	Laying on bed, quiet and still, holding breath for multiple 10-second intervals to simulate apnea, odd subjects-on side, even subjects-on back
10	Y	Y	Y	Transition from walking/moving, seated/moving, laying/moving, laying/still, to laying/hold breath

Task 3—Program Management

The Principal Investigator has managed the program for the duration of this Phase of the program.

Task 3.1—Conduct voice of user reviews with the corrections community

Opportunities have been created by the NIJ to interact with the law enforcement and corrections communities. Foremost, the interactions with the operations and staff at WCI have provided valuable insight into prison concerns and system features. Additionally, interactions through the NIJ Sensor and Surveillance Technical Working Group have provided a broader view of technical and operational needs. Collectively, the summary of the voice-of-the-user feedback is listed below:

- System operation must be easy to use with low false alarms. Originally, it was envisioned only a red/yellow/green alert would be provided for user convenience and to avoid information overload. However, for use in a dedicated environment, such as the SOH, where the corrections staff is familiar with medical information, a waveform display may add to increased system confidence and customization. The breathing waveform is easy to comprehend and will allow an officer to interrogate an alarm or to adjust system parameters for better sensitivity and specificity. The waveform will

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not replace the alert status indicator, but perhaps could be a drill down display for those advanced users.

- Ideally a system could be integrated with the access control system that manages the cell access. However, at least some feedback suggested that in a dedicated environment such as the SOH, an independent system would be reasonable. Nonetheless, such a system requires integration with wiring to provide power and communications. If provided as an independent system, the display and physical requirements must be kept compact as different facilities may have less physical space for deployment.

- System hardening, anti-tamper and anti-suicide features must be developed for long term field testing and eventual product release. While effective for data collection, the tripod system is clearly not robust and would not survive in real use (since it was not intended for real use). The system must withstand physical abuse and not create additional opportunity for suicide ligature or weapon making. Some units, such as the WCI SOH, already contain wiring for intercom and emergency indicators that could be used to conceal the system and wiring.

- Suicide is indeed a concern among the corrections community. While much effort is aimed at risk identification and prevention, the proposed system to detect in-progress asphyxiation is useful and needed. The voice-of-the-user identified blood loss (i.e. exsanguination) as another highly likely method of suicide to be considered for this system.

Task 3.2—IRB submission and management

The IRB study was submitted and approved by Ethical and Independent Review Services, Inc. as an accredited independent review organization. The study protocol was developed and submitted (see Appendix B5 – WCI Officer Study Protocol).

In discussion with the IRB, several points were iterated to reach agreement and final approval:

- An additional risk was identified that a subject placed in a cell may feel a heightened level of discomfort. An additional screen for claustrophobia and for trust of the shift commander to open the door upon request was added to the study.

- Compensation for study volunteers was established since they participate on their own time either before or after their regular shift.

- Additional privacy authorization was developed to allow the study to be referred to as the WCI-study without compromise of individual private data.

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- Video data will never be published or shared and must remain in the sole possession of the PI for experiment annotation purposes.

- The system is intended for eventual medical use and is used as a non-invasive diagnostic device for the purposes of the study.

Task 3.3—Audit for compliance purposes

A yearly audit is performed in conjunction with other government programs at GE.

Task 3.4—Tollgate review and final report submission

A site review was held at GE Research with the NIJ program manager near the end of this Phase. The NIJ program manager also visited the WCI facility during the data collection to observe the system performance.

Project Deliverables

The deliverables of the project are the WCI demonstration, the dataset, and this final report on the performance of the algorithms. This final report will document all program activities from Phase I and Phase II.

7.0 Next Steps and Future Program Phases

Building upon the success of Phase I and Phase II, a third Phase is proposed to design a "hardened" system for long term deployment in an operational setting. Such a development would involve pre-production engineering and implementation of the hardware and algorithms developed in prior program phases in addition to making the system tamper-proof and suicide-proof for deployment in an operational setting. Additionally, the development of a first generation user interface would address green/yellow/red status for corrections officer feedback and optimization. Such a system would be deployed to monitor prisoners in a controlled setting, such as the SOH at WCI, for a period of several months. In successfully completing Phase III, follow-on efforts to commercialize the system will be sought for corporate investment.

Phase III: Design hardened "commercial" system for long-term field trial
(in collaboration with United Technologies, formerly GE Security)

- Harden system for deployment in actual prison setting
- Develop corrections user interface
- Obtain GE/NIJ/WCI/IRB approval for prisoner testing
- Conduct field trial in prison setting (WCI SOH)
- Conduct tollgate review with stakeholders for proceeding to commercialization

12-15 months duration

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Appendix B2 – Real-time Method Descriptions

MATLAB FUNCTIONS

- **processDataWrapper** – wrapper around processData – convert mwArrays to Matlab structures, view to external C++ program
    - **signal** – nsample x 2 array with high gain/low gain signals
    - **history** – tbd
    - **config** – 2 x 1: freqHz, UpdateWindow
    - **configSub** - 4 x 2: {state.thresholds, state.TimeWindow}, hr, rr, alarm
- **processData** – run state estimation, hr and rr estimation and alarm determination, report results
- **analyzeState** – state estimation
    - **signal**
    - **descr** - configuration as input, output includes intermediate calculations (e.g. wavelets)
- **estimateRate** – rate estimation applied to heart rate signal and respiration rate signal
    - **signal**
    - **descr** - configuration as input
    - **output** includes flags indicating thresholding or SNR concerns
- **checkAlarm** – placeholder method to interface to alarm evaluation
- **filterChannelSignal** – perform bandpass filtering on original channel signals to create signal for heartbeat, respiration and motion
- **basicFFT** – calculate the FFT for the signal
- **calcSwt** – calculate stationary wavelet
- **calcCwt** – calculate continuous wavelet
- **calcAreaUnderCurve** – calculate area under curve of signal
- **predictState** – determine a state estimate for a particular band signal, may be influenced by earlier calculations for same channel.
- **fusePredictions** – combine predictions associated with each band channel signal to provide overall state estimate
- **normalize** – return (data – mean(data))/sqrt((data – mean(data))**2), used for rate estimation

C++ CLASSES

- **NIJMonitorCommand** – a command-line driven main routine to run data acquisition unit.
- **DAQ** – the main class for running data acquisition unit and processing the signals

C++ CLASS DETAILS - NIJMONITORCOMMAND

- Before processing data:
    - Calls CoInitialize to setup DAQ.
    - Calls mclInitializeApplication to set up Matlab compatibility.
    - Calls processDataWrapperInitialize to set up processData library.

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- After processing data:
    - Calls CoUninitialize to release DAQ.
    - Calls processDataWrapperTerminate to terminate processData library.
    - Calls mclTerminateApplication to free Matlab resources.

C++ CLASS DETAILS - DAQ

- Constructor – DAQ(double range, int polarity, int poin) – establishes connection with DAQ
- Configure(int nChannels, int secondsInInterval, int startSeconds, char *outputFilename) – defines parameters for data expected from DAQ
- ContinuousAcquisition – continuous loop to process data acquired every "secondsInInterval", has a mechanism to allow user to stop processing gracefully (e.g. create a dummy file or other signal)
- TimedAcquisition – runs loop for specified interval of time (primarily for testing)
- ProcessData – send signals of data to Matlab processData function (via processDataWrapper)

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Appendix B3 – WCI Trip Report

1/19/2010
J.Ashe

Overview

We met with staff and toured the Western Correctional Institution (WCI) in Cumberland Maryland to assess the viability of the team and the facility to host field data collection and demonstration for the NIJ Unobtrusive Suicide Monitoring program. The SOH (Special Observation Housing) unit is a suitable location for data collection and demonstration for the GE prototype system. WCI leadership and staff agreed to support the testing of the system and will assist in the recruitment of corrections officers as the initial test subjects. The next major effort is to obtain all necessary approvals for human subjects testing coordinating between and satisfying the policies of WCI, the NIJ, and GE.

Attendees:

Warden J Phillip Morgan morganjp@dpscs.state.md.us
Dr. Margaret Reed mereed@dpscs.state.md.us
Major J Michael Stouffer JStouffer@dpscs.state.md.us
Dr. Harry Murphy HMurphy@dpscs.state.md.us
Bettie Harris Bharris2@dpscs.state.md.us (unavailable to attend)

Frances Scott Frances.Scott@usdoj.gov (unavailable to attend)
Jack Harne Jack.Harne@usdoj.gov

Jeffrey Ashe jeffrey.ashe@ge.com

Detailed Notes

We briefly discussed the problem of suicide in the prison environment. There have been significant improvements in preventing suicide in large institutions (such as WCI). Much of the issue of suicide is suspected to reside in smaller, local jail settings with newly incarcerated subjects. It is most beneficial to test the prototype system in a facility that has the infrastructure and capability to deal with suicide at this early stage of development.

Injury and death due to prison violence was discussed as a principal concern of the prison leadership and staff. The GE prototype system for suicide is not applicable to recognizing warning signs or the acts of prison violence. It is noted there are several ongoing NIJ programs (mock riot activities for example) that would be of interest to WCI.

The Special Observation Housing (SOH) portion of the medical center was deemed to be the best setting to conduct the testing of the GE prototype. This unit contains several cells for

housing at-risk inmates. There are two cells with windows for direct observation by the corrections staff and multiple "typical" cells. The typical cells are roughly 10'x10' with a full steel door. The walls are constructed of steel-reinforced, concrete-filled concrete block. There is a window and an access panel in the steel door. There is an air gap under the door such that wire and cables from the prototype system could extend to equipment placed in the hallway. There is no furniture in the windowed cells and inmates typically lay on the floor or are given a mattress pad. The typical cells contain a steel bed frame and mattress pad. Both the windowed observation cells and the typical cells are suitable for testing to confirm the effect of construction (signals from activities outside the cell) as well as conduct human subjects studies of corrections officers mimicking inmate behaviors. Dr. Reed will guide and oversee the GE efforts in the SOH.

Note: Cell motion or motion from other cells (such as an inmate repeatedly kicking a door) will be tested to see the effects in adjacent cells. Other effects, such as an officer or inmate walking down the hallway and creating vibrations that transfer to the cells will be tested.

Inmates in SOH are assigned special gowns or smocks. These "anti-suicide" garments are designed and constructed such that the material cannot be torn or utilized for constriction of the airway. Due to the nature of the garment being quilt-like and not knowing the inner materials, GE will procure some sample garments and test any impact on the prototype to detect through the garment. Dr. Reed has provided information to procure the garments.

It was suggested that prototype testing be conducted during 2nd shift where inmates are not likely to be present in the general medical center (regular doctor or optometrist appointments, etc.) unless there is a medical emergency. GE testing would be confined to a wing of the SOH in which there are no inmate occupants.

System shipment and transportation may occur prior to the GE site tests or may be brought by the GE team at the time of testing. Advanced provisions will be made to get the equipment inspected and entered into WCI by the staff to ensure site time is used efficiently.

Next Steps

The team will focus on the design and approval of the human subjects protocol. This will be coordinated between multiple entities with the main point of contact from each institution listed as: Bettie Harris, WCI; Frances Scott, NIJ; Jeff Ashe, GE.

It is desired to perform testing in 2 visits:

1. Initial data collection – record prototype outputs and post-process results back at GE. We propose to perform this activity in the last two weeks of March.
2. System Demonstration – display system operation in near real-time during the tests. We propose to perform this activity in the last two weeks of May.

The GE hardware for initial data collection (late-March) is ready. The near real-time system in development will be ready for testing in late-May.

Proposal Excerpts

Suicide Background

Prison and jail suicide rates have declined over the past 30 years due to better practices in prevention and quality-of-care for at-risk prisoners. Screening inmates for placement into safe cell units, improved training to recognize suicidal behavior, on-site facilities to treat the mentally ill, and the use of suicide patrols for direct intervention all contribute to declining suicide rates. However, suicide still exists in the prison environment and the tragedy of loss of life and resultant litigation demonstrates a continued need for the development of unobtrusive methods to detect suicide attempts in time for intervention.

Approximately 80% of all suicides involve asphyxiation and many involve the victim remaining in contact with the floor during the act. Death can also occur through drug overdose or bloodletting (exsanguination). Due to the accessibility to commonly-issued clothing and structures, it is not possible to completely remove the threat of suicide in a correctional setting without completely dehumanizing the quality of life for inmates or violating the basic human rights of the prisoner. The GE prototype system is designed to provide unobtrusive situational awareness of at-risk prisoners to alert corrections officers for further intervention.

GE Prototype and Program Description

The goals of this program are to develop a remote sensing system that can capture vital signs related to the physiology of an individual and provide an assessment of those vital signs. Remotely monitoring vital signs will provide law enforcement more time to intervene in a suicide attempt by capturing sudden physiological changes during the act. GE's Suicide Warning System will help reduce workflow issues associated with direct prisoner monitoring and potentially decrease liability associated with wrongful death.

Three technical objectives are to be met during this research program: hardware modifications; algorithm developments; and system demonstrations. Hardware modifications have been completed in phase I of this program. Additionally, the algorithm framework has been completed and the baseline system performance was established through demonstrations in a laboratory environment. The focus of the continuation program is to optimize the system sensitivity and specificity and demonstrate the refined in representative cell environment.

The hardware modification objective is to modify a commercially available radar-based motion sensor, the Range Controlled Radar-50 (RCR), to enhance its sensitivity to detect fine movements, such as pulsations on a person's skin. The RCR is a wall-mounted sensor suite (manufactured by GE) that contains an infrared sensor (PIR) and microwave Doppler radar to detect the presence of individuals within a defined area. The sensitivity of the RCR sensor will be significantly enhanced during this program to capture and discern general limb motion, respiratory motion, and breathing motion. The modified device will also be modified to

provide greater accuracy in positioning, tracking of position, and software processing to interpret motion in the cell.

The algorithm development objective of this program is to develop software that can interpret the information provided by the RCR sensors. GE markets several patient monitoring systems designed for large-scale, centralized observation of vital signs (e.g., in hospital environments). These systems contain software algorithms to track, interpret, and provide an alarm if vital signs, such as ECG or plethysmograph, are unsustainable. More importantly, these algorithms are also designed to minimize false-alarm rates, which are inherently present due to the similarity of both non-critical and life-threatening information presented to the monitoring device. During this program, these existing decision support and alarming algorithms will be developed and modified to be more suitable for the prison or jail environment with motion information as the primary health parameters to be evaluated.

The system demonstration objective is to integrate both the hardware and software elements into a unified prototype system for testing, evaluation, and demonstration. Integration will involve combining hardware and software subsystems to ensure each operates correctly with each other, and that their individual components perform as intended. This objective also includes evaluation and testing of the suicide warning system. The prototype will be evaluated in a representative jail setting using subjects, both male and female and of varying ages, heights, and weights. Testing will be performed to assess sensitivity to respiration, breathing, and general motion. This objective will also include identifying and remedying potential failure modes, and evaluating the robustness of decision support algorithms when identifying asphyxia and reducing false alarms.

Appendix B4 – GE-WCI Memorandum of Understanding

MEMORANDUM OF UNDERSTANDING

BETWEEN

MARYLAND DEPARTMENT OF PUBLIC SAFETY AND CORRECTIONAL SERVICES, WESTERN CORRECTIONAL INSTITUTION

AND

GENERAL ELECTRIC GLOBAL RESEARCH

Standoff Cardiorespiratory Monitoring

TABLE OF CONTENTS

This Memorandum of Understanding ("MoU"), dated _____, _____, sets forth the terms of an agreement between MARYLAND DEPARTMENT OF PUBLIC SAFETY AND CORRECTIONAL SERVICES, WESTERN CORRECTIONAL INSTITUTION ("Agency"), a law enforcement agency located in CUMBERLAND, MARYLAND and GENERAL ELECTRIC GLOBAL RESEARCH, an operating component of General Electric Co., ("Grantee") located in NISKAYUNA, NEW YORK.

1. Project Description

1.1 Background

Agency is interested in providing a correctional institute venue to support research activities of the National Institute of Justice.

1.2 Purpose

To evaluate Standoff Cardiorespiratory Monitoring technology in an operational law enforcement environment.

1.3 Scope

Agency will conduct research activities in accordance with National Institute of Justice award #2007-DE-BX-K176 ("NIJ Grant") using Standoff Cardiorespiratory Monitoring technology as a means to provide situational awareness of inmate activities. Specifically, Agency will conduct a study of Standoff Cardiorespiratory Monitoring technologies at the Western Correctional Institution (WCI) as set forth in the Research Protocol appended as Exhibit A. Only data pertinent to the completion of the research will be collected. Any data collected that includes individual identifiers will be handled in accordance with the attached protocol. Grantee, will observe and evaluate this research and will provide Technical Report documenting the results thereof as set forth in the NIJ Grant.

1.4 Term

This MoU is effective upon the day and date last signed and executed by the duly authorized representatives of the Parties and shall remain in full force and effect for 6 months ("Initial Term"). The MoU, upon mutual acceptance by the Parties, may be extended beyond the Initial Term.

1.5 General Tasks

Agency will:

- Solicit volunteer participants for the research study provided by the NIJ grant;
- Provide Grantee personnel access to the designated areas of the Facility to conduct the research protocols and collect associated data as set forth in Exhibit A; and
- Not incur any software or equipment costs

Grantee will:

- Oversee the research protocols for the Agency in the capacity of a beneficiary;
- Provide a Final Technical Report documenting the research performed as set forth in the NIJ grant;

1.6 Statement of Work

The Parties shall be responsible for the specific tasks described in the Research Protocol (Exhibit A) and shall use reasonable efforts to perform their respective tasks under the research program substantially in accordance with the terms and conditions of this MoU.

Nothing in the MoU shall be construed to limit the freedom of Grantee and/or other entities participating in the research program whether participants in this MoU or not, from engaging in similar research or inquiries made independently under other grants, contracts or agreements with other Parties.

Each Party represents and warrants that, to the best of its knowledge, (a) it is the sole owner of its supplied information, and (b) nothing contained in the supplied information, nor the exercise of the rights granted to the other parties, infringes upon the proprietary rights of any third party.

1.7 Key Personnel

The Principal and Technical Contacts for this MoU are provided below. Changes in the Principal or Technical Contacts must be approved in writing jointly by the Principal Agency Contact, on behalf of Agency, and by the Principal Grantee Contact, on behalf of Grantee**,** or their respective designees.

For Agency:

Principal Contact

Name: J. Philip Morgan
Title: Warden, Western Correctional Institution
Address: 13800 McMullen Hwy SW, Cumberland MD 21502
Telephone:
Fax:
Email: morganjp@dpscs.state.md.us

Technical Contact

Name: Margaret E. Reed
Title: Chief Psychologist, Western Correctional Institution
Address: 13800 McMullen Hwy SW, Cumberland MD 21502
Telephone: 301-729-7168
Fax: 301-729-7190
Email: mereed@dpscs.state.md.us

For Grantee

Principal Contact

Name: Donald S. Ingraham
Title: General Counsel (acting), GE Global Research
Address: One Research Circle, Niskayuna, NY 12309
Telephone: (518) 387-5073
Fax: (518) 387-6752
Email: ingraham@ge.com

Technical Contact

Name: Jeffrey M. Ashe
Title: Principal Investigator, GE Global Research
Address: One Research Circle, Niskayuna, NY 12309
Telephone: (518) 387-5302
Fax: (518) 387-5164
Email: ashe@ge.com

1.8 Roles and Responsibilities

Agency shall provide an agency point of contact (project manager) and the necessary staff and resources to solicit informed consent from volunteers, provide resources to perform research program, and provide adequate access to information required to complete the General Tasks, as outlined in Section 1.5, above.

Grantee shall provide the necessary staff and resources to conduct the problem analysis, evaluation design and perform the research program.

2. Funding

Each of the Parties to this MoU will provide the funds necessary to accomplish its respective tasks, as set forth in the Statement of Work (Exhibit A), and for the duration of the Initial Term, as defined in Section 1.4, above.

Nothing in this MoU shall obligate any Party to transfer any funds to any other Party for the work described herein. Specific work projects or activities that involve the transfer of funds, services, or property between the Parties shall require the execution of a separate agreement and shall be contingent upon the availability of funds. Such activities must be independently authorized by the appropriate authorized representatives of all Parties. This MoU does not provide such authority. Negotiation, execution, and administration of such an agreement must comply with all applicable statutes or regulations *(See Section 9. Applicable Law)*.

3. Modification or Waiver

This MoU may be modified, in whole or in part, by the written agreement of the Parties, at any time during the Initial Term.

No part of this MoU shall be modified without the express written consent of the involved Parties. The waiver by one Party of any breach of any term or condition of this MoU shall not be construed as a waiver of any similar or other breach of any term or condition of this MoU. Nor shall said waiver be construed as a continuing waiver of the original breach.

4. Termination

Either party may terminate this MOU for any reason with 14 days notice to the other party. In the event of termination or expiration of this MoU: (i) Agency shall promptly return all equipment not their own and Confidential Information in its possession or control; (ii) Grantee shall promptly return to Agency all Agency Confidential Information *(See Section 6. Confidential Information)* in its possession or control; and (iii) each Party shall provide to the other Party a written statement certifying that it has complied with the foregoing obligations. All rights, benefits and licenses granted by one Party to the other

Parties shall terminate upon such termination.

5. Assignment

This MoU may not be assigned or otherwise transferred by any of the Parties, in whole or in part, without the express prior written consent of the other Parties, which consent will not be unreasonably withheld. The foregoing shall not apply in the event a Party shall change its corporation name.

6. Confidential Information

During the Initial Term of this MoU, the Parties may provide each other with certain information, data, or material, which the disclosing party has clearly marked or identified in writing as confidential in nature ("Confidential Information"). The receiving party shall receive and hold Confidential Information in confidence and agrees to use its reasonable efforts to prevent disclosure to third parties of Confidential Information in the manner the receiving party treats its own similar information, but in no case shall less than reasonable care be exercised by the receiving party. Personal Health Information of volunteer participants in the research program shall be handled as set forth in the Research Protocol.

The receiving party shall not consider information disclosed to it by the disclosing party Confidential Information which: (a) is public information or subsequently becomes such through no breach of this MoU; (b) is rightfully in the receiving party's possession prior to the disclosing party's disclosure, as shown by written records; (c) is disclosed to the receiving party by an independent third party who, to the best of the receiving party's knowledge, is not under an obligation of confidentiality for such information to the disclosing party; or (d) is independently developed by or for the receiving party without benefit of Confidential Information received from the disclosing party as shown by written records.

Each Party acknowledges that the Confidential Information of the other Parties is owned solely by such Party, and that the unauthorized disclosure of such information may cause irreparable harm and significant injury. The degree of such harm or injury may be difficult to ascertain.

Accordingly, each Party agrees that the other Parties will have the right to seek an immediate injunction enjoining any breach of this MoU, as well as the right to pursue any and all other rights and remedies available at law or in equity for such breach.

Grantee, as required by the NIJ in its Privacy Certificate, certifies that data identifiable to a private person will not be used or revealed, except as authorized in 28 CFR Part 22 and as provided in the Research Protocol. Grantee will comply with any Agency rules and regulations regarding the handling of law enforcement information, so far as they do not conflict with Federal statutes. Use and disclosure of limited Personal Health Information

(PHI) in reports and presentations related to the WCI Standoff Cardiorespiratory Monitoring Study is set forth in the PHI Authorization (Exhibit B).

Data collected from Agency during the course of the research activities will be restricted in the following manner:

- Only data pertinent to the completion of the research activities will be collected;
- Data collected will not include any individual identifiers, except as authorized in 28 CFR Part 22 and as provided in the Research Protocol; and
- The data will be used solely for secondary analysis purposes.

For the purposes of the research activities, human subjects are required. Grantee shall be responsible for obtaining and maintaining Institutional Review Board (IRB) approval for the duration of the study. Grantee shall be responsible for any payments or compensation to volunteer program participants.

7. Publicity

The Parties shall not use the name, trade name, trademark or other designation of any of the Parties in connection with any products, promotion or advertising without the prior written permission of the involved Parties.

8. Severability

Should any part, term, or provision of this MoU be declared or determined by any court or other tribunal or appropriate jurisdiction to be invalid or unenforceable, any such invalid or unenforceable part, term, or provision shall be deemed stricken and severed from this MoU. Any and all of the other terms of this MoU shall remain in full force and effect.

9. Applicable Law

This MoU and any disputes concerning it shall be interpreted under the laws of the State of Maryland.

10. Entire Memorandum of Understanding

This MoU, including all documents incorporated herein by reference, constitutes the entire MoU and understanding of the Parties hereto and shall supersede and replace any and all prior or contemporaneous representations, agreements or understandings of any kind, whether written or oral, relating to the subject matter hereof. No changes to this MoU shall be binding upon any of the Parties unless incorporated in a written modification to the MoU and signed by the Parties' contractual representatives.

IN WITNESS THEREOF, the Parties have executed this MoU on the day and year first written above.

FOR AGENCY

_____ _____

J. Michael Stouffer Date
Commissioner
Maryland Department of Public Safety and Correctional Services
Division of Correction

Reviewed for legal sufficiency:

_____ _____

Stuart M. Nathan Date
Assistant Attorney General
Principal Counsel
Department of Public Safety and Correctional Services

FOR GRANTEE

_____ _____

Eric Butterfield Date
Global Technology Leader
Electronic Systems & Controls
GE Global Research

ACKNOWLEDGMENT:

I have read, understand and will abide by the terms and conditions of this MoU.

Technical Contacts:

FOR AGENCY

_____ _____
Margaret E. Reed Date
Chief Psychologist

FOR GRANTEE

_____ _____
Jeffrey M. Ashe Date
Principal Investigator

EXHIBIT A: RESEARCH PROTOCOL

WCI Study Protocol 22JUL2010 V2.0

IRB Protocol for WCI Standoff Cardiorespiratory Monitoring

Jeffrey M. Ashe
General Electric Global Research
Niskayuna, NY 12309
July 22, 2010

Introduction Background

GE Global Research is sponsored by the National Institute of Justice (NIJ), the research and development arm of the Department of Justice, under contract 2007-DE-BX-K176 to evaluate a modified indoor intrusion sensor capable of observing fine movements of the body attributable to heartbeat and breathing. The end goal of the NIJ program is to provide situational awareness on the health or duress of an individual while being monitored by the standoff system in supervised settings such as jails or prisons.

In a previous phase of the NIJ program, GE evaluated the performance of the prototype system in a lab setting with volunteer, informed consent, human subjects participants (GE Employees) under IRC IRB 07189. The IRB study was successfully completed and a continuation phase of the NIJ program has been awarded.

As part of the continuation phase of the NIJ program, GE is to evaluate the performance of the system in a representative user environment. The intent of this protocol is to very closely model the IRB 07189 study protocol while conducting the tests at the Western Correctional Institution (WCI) in Cumberland, Maryland using volunteer, informed consent, human subjects participants from the WCI corrections staff.

WCI does not have an IRB. A memorandum of understanding will be in place between GE and WCI for the study activities. GE will be responsible for obtaining the IRB approval, providing information to WCI for recruiting volunteers, confirming that such volunteers have provided informed consent, conducting the study, and collecting and assessing the study data. Additionally, to participate in the program, volunteers will be asked to execute an Authorization allowing disclosure of their Personal Health Information (as detailed below) in reports of this research.

Study Design

This study will consist of a single population of subjects asked to perform a series of respiratory maneuvers and motions before the motion sensor. The study goal is to evaluate the sensitivity limits of the sensor within the unique layout and construction of a jail cell.

Test subjects will be asked to perform activities of daily living as are typically encountered in the Special Observation Housing (SOH) ward while measurements are recorded with the prototype sensor system.

No prisoners will participate or be exposed to any of the study efforts at WCI.

Inclusion/Exclusion Criteria

Since the study involves the subject performing respiratory and limb maneuvers, exclusion criteria will include whether or not the person has a prior history of chronic respiratory illness that may cause increased discomfort. Controlled respiration by individuals with a history of respiratory illness may cause subject discomfort or temporary dizziness. Excluded subjects will also include those with a history of restrained joint mobility stemming from chronic conditions that may affect range of motion. Such conditions include, but are not limited to, arthritis, tendonitis, or injury.

Included subjects will be those with no prior history or current condition involving long-term respiratory illness and those who are capable of moving the limbs without discomfort while in the seated, supine, or standing position. All subjects of varying characteristics that affect lung capacity are included. This includes subjects of all races and both genders with variations in height, weight, active or sedentary lifestyle, and those who smoke.

Volunteers will be additionally screened for those that are not claustrophobic and who trust their fellow officers to let them out of the cell in a timely manner.

Consent Process and Timing

The consent process will involve the random selection of volunteers from the corrections staff who are employed at the Western Correctional Institution in Cumberland Maryland.

Study flyers will be provided to Corrections Institution officials, who will post them in the corridors and common areas of WCI that are accessible only by the prison staff. There are approximately 500 prison staff at WCI who will be exposed to the flyers throughout the course of the study until a volunteer population size of approximately 10 is obtained.

There are approximately 2 months to complete the evaluation phase of this work. A typical consent process is as follows:

1. Flyers describing the nature of the scientific work will be posted in the corridors and common areas advising those that would like to volunteer to contact the principal investigator by phone or email or to contact the Director of Mental Health at WCI who will refer interested volunteers to the principal investigator.
2. If the subject volunteers, he/she will be advised of the requirements including a detailed description of the respiratory and limb maneuvers required.
3. If the subject is willing to participate, he/she will be mailed a consent form to thoroughly evaluate the inclusion/exclusion criteria on the consent form. The subject shall have approximately 2 weeks to consider participation in the study.
4. An appointment will be made for each subject to meet in person during a PI visit to WCI. Upon discussions and signing the consent form, the PI will schedule study session during the same visit for initial data collection.
5. After completing the first session, subjects will be given an optional schedule for a second session after GE has made system changes in response to learning's from the first session.

Waivers of consent will not be permitted in this study. All subjects monitored must pass through the informed consent process described as above. All consent documentation will be managed and held in private by the principal investigator (PI).

Description and Summary of Procedures

This protocol summarizes the procedure used to acquire data attributable to motion of the individual. To quantify motion as sensed by the radar, the subject will be instructed to remain seated, remain standing, or lying down in the supine position. The subject will then be instructed to move the arms, legs, and head to quantify limb motion. The subject will be asked to perform a series of respiratory maneuvers involving interruption of breathing for no more than 30 seconds or for no more than is comfortable for the subject. The subject will also be asked to perform both respiratory maneuvers and moving of the arms and legs simultaneously for characterizing both motion artifact and meaningful motion in the presence of each other.

The following procedures are generally described to illustrate the flow of the work to be performed by the subject and PI during testing. The description below is not meant to serve as a methodical step-by-step description of each and every action during the study. The approximate time required by the subject will be 90 minutes.

Attachment of Sensors
Approximate time required: 15 minutes

1. A finger-clip pulse oximeter will be attached to the subject. The oximeter will be attached to the data collection system by a lead wire.
2. A spirometer will be introduced to the mouth by the subject holding a breathing tube or, if the subjects prefers, attached over the nose and mouth using a facemask held in place with a quick-release head strap. The spirometer will be attached to the data collection system by a flexible tube.

Respiratory Maneuvers
Approximate time required: 30 minutes

1. Subject will either: stand, be seated in a chair, or assume a supine position on a cot or on the floor.
2. A video camera will be activated to track motion of the subject.
3. A spirometer will be placed by the subject into his/her own mouth.
4. Audible instructions to the subject will be to:
    a. Breathe normally for 3 minutes
    b. Breathe deeply but at normal or comfortable breathing rate for 1 minute.
    c. Breathe normally for 1 minutes
    d. Breathe shallowly but at normal or comfortable rate for 1 minute.
    e. Breathe normally for 1 minute
    f. Hold breath for 30 second or as long as possible
    g. Breathe normally for 1 minute
    h. Hold breath for 30 second or as long as possible
    i. Breathe normally for 3 minutes

Limb Maneuvers
Approximate time required: 30 minutes

1. Subject will repeat steps 1-2 as described in Respiratory Maneuvers.
2. A video camera will be activated to track motion of the subject.
3. Verbal instructions will be provided to move arms or legs in qualitative manner. Audible instructions will be provided to track time and to assist in moving the arms cyclically in a repeatable manner.

No training will be required for this study. Movements and maneuvers such as breathing, withholding of breath, and moving of the arms and legs in simple manner are generally known.

Interested subjects will be shown at a future time of no less than 1 month from recording the waveform results. The qualitative information provided will illustrate whether or not the device can accurately capture motion of the chest attributable to breathing and heartrate.

Data Obtained and Provisions for Subject Confidentiality

To characterize cardiorespiratory motion and motion artifact of the limbs, we rely on traditional monitoring techniques to serve as quantifiable gold standards. Traceable information assignable to an individual will be collected. The data ensemble is summarized below and will be dealt with in the following manner to ensure subject confidentiality. Video data will be stored on DVD optical media under care of the PI.

Measurement Obtained	**Traceable Data**	**Data handling**
Spirometer Data	Tidal volume, flowrate, airway pressure	Subject will execute an Authorization allowing for use and disclosure of Personal Health Information (PHI) in reports of this research; prior to release of any PHI, The Study will remove all descriptors such as name, time, and date from the waveform data.
Oximeter Data	Pulsatile motion related to cardiac cycle	Subject will execute an Authorization allowing for use and disclosure of Personal Health Information (PHI) in reports of this research; prior to release of any PHI, The Study will remove all descriptors such as name, time, and date from the waveform data.
Video Data	Subject Visual Identity	All video will be held on DVD in the sole possession of the PI for PI review only and not used for reports of this research.

Risks, Discomforts, and **Benefits** to Subjects

Benefits to the subject include the development of technology that can be used for simultaneous security sensing and unobtrusive health monitoring. There are no immediate benefits to taking part in the study.

Electrical
Power transmission levels by the radar and sensor transmitters have been limited as mandated by FCC regulations and have already been approved for commercial use. Radar transmit powers are ubiquitous and are on order of common cell phone transmit levels or radar sensors used for indoor lighting activation.

Mechanical
Mechanical exposure involves discomfort in having a spirometer in the mouth for prolonged periods. Any discomfort reported by the subject will result in immediate pausing of the study with cessation of the monitoring episode entirely if desired by the subject.

Chemical
There are no chemical interactions in this study. The spirometer and spirometer mouthpiece is disposable and designed for prevention of bacterial cross-contamination. All mouthpieces are sterile and for single-use only.

Physiological
There may be intermittent dizziness if breath is withheld for any given subject depending on his/her physical condition. Any reported dizziness will result in immediate pause of the study with cessation of the monitoring episode entirely if desired by the subject. A cot, or a blanket on the floor, will be present if the subject prefers to rest due to dizziness. Any reported joint pain will result in immediate pause of the study with cessation of the monitoring episode entirely if desired by the subject.

Stress

In performing activities within the cell with the door closed and/or locked, you may feel a heightened level of discomfort. A corrections officer, either the shift commander or a corrections officer designated by the shift commander, who is not a volunteer participant in the study, will escort us at all times during the study and will open the door anytime at the request of the subject. Any reported intolerable stress or discomfort would result in an immediate pause of the study allowing the subject to exit the cell. The remaining study session may be ceased if desired by the subject.

Cost and Compensation

Subjects will participate on their off-shift time. GE will reimburse the subjects for their time and travel in the amount of $100 per study session.

Data Analysis and Statistical Analysis

Analytical methods to evaluate receiver sensitivity to fine motions of the motion standard and individual subjects will involve harmonic analytical methods such as Fourier analysis or other decomposition techniques involving orthogonal basis functions such as Wavelet decomposition. Other methods widely found in communication, detection, and estimation theory may be used.

References

The following links represent the type of instrumentation to be used in the proposed study and is meant to provide a gauge to the reviewer of the invasiveness to a subject's personal space.

Biopac Spirometer:
http://www.biopac.com/airflow-transducer-60ml-sec
Biopac Pulse Oximeter:
http://www.biopac.com/spo2-pulse-oximeter-amplifier
Intrusion Sensor: radar-based motion sensor:
http://www.gesecurity.com/portal/site/GESecurity/menuitem.f76d98ccce4cabed5efa421766030730?selectedID=1829&seriesyn=true&seriesID=

Contact Information

Jeffrey M. Ashe, Principal Investigator
One Research Circle
Niskayuna, NY 12309
Phone: 518-387-5302
E-mail: ashe@ge.com

EXHIBIT B: PHI AUTHORIZATION

Authorization allowing use and disclosure of Personal Health Information

This authorization form covers volunteer participants in GE research study #10118 under IRB approval from IRC, Inc. The above-mentioned study is in effect from _____ through _____.

This authorization specifically covers the inclusion of selected Personal Health Information (PHI) in reports and presentations related to the WCI Standoff Cardiorespiratory Monitoring Study referred to and labeled as the "WCI Study".

Selected PHI shall include subject physical parameters (gender, age, height, and weight), spirometer waveforms (indicative of breathing rates and patterns), pulse oximeter waveforms (indicative of heart rates and patterns), motion sensor waveforms and information pertaining to where the data was gathered.

All other PHI descriptors, such as name, time, and date of participation in the study will be removed prior to the release of any data.

No pictures or video recordings will be released.

Subject:
By signing, I agree to allow use and disclosure of the above-identified PHI.

Name _____, Date _____

Investigator:
I acknowledge I have explained the above and answered all the subject questions.

Name _____, Date _____

Appendix B5 – WCI Officer Study Protocol

IRB Protocol for WCI Standoff Cardiorespiratory Monitoring

Jeffrey M. Ashe
General Electric Global Research
Niskayuna, NY 12309
July 22, 2010

Introduction Background

GE Global Research is sponsored by the National Institute of Justice (NIJ), the research and development arm of the Department of Justice, under contract 2007-DE-BX-K176 to evaluate a modified indoor intrusion sensor capable of observing fine movements of the body attributable to heartbeat and breathing. The end goal of the NIJ program is to provide situational awareness on the health or duress of an individual while being monitored by the standoff system in supervised settings such as jails or prisons.

In a previous phase of the NIJ program, GE evaluated the performance of the prototype system in a lab setting with volunteer, informed consent, human subjects participants (GE Employees) under IRC IRB 07189. The IRB study was successfully completed and a continuation phase of the NIJ program has been awarded.

As part of the continuation phase of the NIJ program, GE is to evaluate the performance of the system in a representative user environment. The intent of this protocol is to very closely model the IRB 07189 study protocol while conducting the tests at the Western Correctional Institution (WCI) in Cumberland, Maryland using volunteer, informed consent, human subjects participants from the WCI corrections staff.

WCI does not have an IRB. A memorandum of understanding will be in place between GE and WCI for the study activities. GE will be responsible for obtaining the IRB approval, providing information to WCI for recruiting volunteers, confirming that such volunteers have provided informed consent, conducting the study, and collecting and assessing the study data. Additionally, to participate in the program, volunteers will be asked to execute an Authorization allowing disclosure of their Personal Health Information (as detailed below) in reports of this research.

Study Design

This study will consist of a single population of subjects asked to perform a series of respiratory maneuvers and motions before the motion sensor. The study goal is to evaluate the sensitivity limits of the sensor within the unique layout and construction of a jail cell.

Test subjects will be asked to perform activities of daily living as are typically encountered in the Special Observation Housing (SOH) ward while measurements are recorded with the prototype sensor system.

No prisoners will participate or be exposed to any of the study efforts at WCI.

Inclusion/Exclusion Criteria

Since the study involves the subject performing respiratory and limb maneuvers, exclusion criteria will include whether or not the person has a prior history of chronic respiratory illness that may cause increased discomfort. Controlled respiration by individuals with a history of respiratory illness may cause subject discomfort or temporary dizziness. Excluded subjects will also include those with a history of restrained joint mobility stemming from chronic conditions that may affect range of motion. Such conditions include, but are not limited to, arthritis, tendonitis, or injury.

Included subjects will be those with no prior history or current condition involving long-term respiratory illness and those who are capable of moving the limbs without discomfort while in the seated, supine, or standing position. All subjects of varying characteristics that affect lung capacity are included. This includes subjects of all races and both genders with variations in height, weight, active or sedentary lifestyle, and those who smoke.

Volunteers will be additionally screened for those that are not claustrophobic and who trust their fellow officers to let them out of the cell in a timely manner.

Consent Process and Timing

The consent process will involve the random selection of volunteers from the corrections staff who are employed at the Western Correctional Institution in Cumberland Maryland.

Study flyers will be provided to Corrections Institution officials, who will post them in the corridors and common areas of WCI that are accessible only by the prison staff. There are approximately 500 prison staff at WCI who will be exposed to the flyers throughout the course of the study until a volunteer population size of approximately 10 is obtained.

There are approximately 2 months to complete the evaluation phase of this work. A typical consent process is as follows:

1. Flyers describing the nature of the scientific work will be posted in the corridors and common areas advising those that would like to volunteer to contact the principal investigator by phone or email or to contact the Director of Mental Health at WCI who will refer interested volunteers to the principal investigator.
2. If the subject volunteers, he/she will be advised of the requirements including a detailed description of the respiratory and limb maneuvers required.
3. If the subject is willing to participate, he/she will be mailed a consent form to thoroughly evaluate the inclusion/exclusion criteria on the consent form. The subject shall have approximately 2 weeks to consider participation in the study.
4. An appointment will be made for each subject to meet in person during a PI visit to WCI. Upon discussions and signing the consent form, the PI will schedule study session during the same visit for initial data collection.
5. After completing the first session, subjects will be given an optional schedule for a second session after GE has made system changes in response to learning's from the first session.

Waivers of consent will not be permitted in this study. All subjects monitored must pass through the informed consent process described as above. All consent documentation will be managed and held in private by the principal investigator (PI).

Description and Summary of Procedures

This protocol summarizes the procedure used to acquire data attributable to motion of the individual. To quantify motion as sensed by the radar, the subject will be instructed to remain seated, remain standing, or lying down in the supine position. The subject will then be instructed to move the arms, legs, and head to quantify limb motion. The subject will be asked to perform a series of respiratory maneuvers involving interruption of breathing for no more than 30 seconds or for no more than is comfortable for the subject. The subject will also be asked to perform both respiratory maneuvers and moving of the arms and legs simultaneously for characterizing both motion artifact and meaningful motion in the presence of each other.

The following procedures are generally described to illustrate the flow of the work to be performed by the subject and PI during testing. The description below is not meant to serve as a methodical step-by-step description of each and every action during the study. The approximate time required by the subject will be 90 minutes.

Attachment of Sensors
Approximate time required: 15 minutes

1. A finger-clip pulse oximeter will be attached to the subject. The oximeter will be attached to the data collection system by a lead wire.
2. A spirometer will be introduced to the mouth by the subject holding a breathing tube or, if the subjects prefers, attached over the nose and mouth using a facemask held in place with a quick-release head strap. The spirometer will be attached to the data collection system by a flexible tube.

Respiratory Maneuvers
Approximate time required: 30 minutes

1. Subject will either: stand, be seated in a chair, or assume a supine position on a cot or on the floor.
2. A video camera will be activated to track motion of the subject.
3. A spirometer will be placed by the subject into his/her own mouth.
4. Audible instructions to the subject will be to:
    a. Breathe normally for 3 minutes
    b. Breathe deeply but at normal or comfortable breathing rate for 1 minute.
    c. Breathe normally for 1 minutes
    d. Breathe shallowly but at normal or comfortable rate for 1 minute.
    e. Breathe normally for 1 minute
    f. Hold breath for 30 second or as long as possible
    g. Breathe normally for 1 minute
    h. Hold breath for 30 second or as long as possible
    i. Breathe normally for 3 minutes

Limb Maneuvers
Approximate time required: 30 minutes

1. Subject will repeat steps 1-2 as described in Respiratory Maneuvers.
2. A video camera will be activated to track motion of the subject.
3. Verbal instructions will be provided to move arms or legs in qualitative manner. Audible instructions will be provided to track time and to assist in moving the arms cyclically in a repeatable manner.

No training will be required for this study. Movements and maneuvers such as breathing, withholding of breath, and moving of the arms and legs in simple manner are generally known.

Interested subjects will be shown at a future time of no less than 1 month from recording the waveform results. The qualitative information provided will illustrate whether or not the device can accurately capture motion of the chest attributable to breathing and heartrate.

Data Obtained and Provisions for Subject Confidentiality

To characterize cardiorespiratory motion and motion artifact of the limbs, we rely on traditional monitoring techniques to serve as quantifiable gold standards. Traceable information assignable to an individual will be collected. The data ensemble is summarized below and will be dealt with in the following manner to ensure subject confidentiality. Video data will be stored on DVD optical media under care of the PI.

Measurement Obtained	**Traceable Data**	**Data handling**
Spirometer Data	Tidal volume, flowrate, airway pressure	Subject will execute an Authorization allowing for use and disclosure of Personal Health Information (PHI) in reports of this research; prior to release of any PHI, The Study will remove all descriptors such as name, time, and date from the waveform data.
Oximeter Data	Pulsatile motion related to cardiac cycle	Subject will execute an Authorization allowing for use and disclosure of Personal Health Information (PHI) in reports of this research; prior to release of any PHI, The Study will remove all descriptors such as name, time, and date from the waveform data.
Video Data	Subject Visual Identity	All video will be held on DVD in the sole possession of the PI for PI review only and not used for reports of this research.

Risks, Discomforts, and Benefits to Subjects

Benefits to the subject include the development of technology that can be used for simultaneous security sensing and unobtrusive health monitoring. There are no immediate benefits to taking part in the study.

Electrical
Power transmission levels by the radar and sensor transmitters have been limited as mandated by FCC regulations and have already been approved for commercial use. Radar transmit powers are ubiquitous and are on order of common cell phone transmit levels or radar sensors used for indoor lighting activation.

Mechanical
Mechanical exposure involves discomfort in having a spirometer in the mouth for prolonged periods. Any discomfort reported by the subject will result in immediate pausing of the study with cessation of the monitoring episode entirely if desired by the subject.

Chemical
There are no chemical interactions in this study. The spirometer and spirometer mouthpiece is disposable and designed for prevention of bacterial cross-contamination. All mouthpieces are sterile and for single-use only.

Physiological
There may be intermittent dizziness if breath is withheld for any given subject depending on his/her physical condition. Any reported dizziness will result in immediate pause of the study with cessation of the monitoring episode entirely if desired by the subject. A cot, or a blanket on the floor, will be present if the subject prefers to rest due to dizziness. Any reported joint pain will result in immediate pause of the study with cessation of the monitoring episode entirely if desired by the subject.

Stress
In performing activities within the cell with the door closed and/or locked, you may feel a heightened level of discomfort. A corrections officer, either the shift commander or a corrections officer designated by the shift commander, who is not a volunteer participant in the study, will escort us at all times during the study and will open the door anytime at the request of the subject. Any reported intolerable stress or discomfort would result in an immediate pause of the study allowing the subject to exit the cell. The remaining study session may be ceased if desired by the subject.

Cost and Compensation

Subjects will participate on their off-shift time. They will be reimbursed for their time and travel in the amount of $100 per study session.

Data Analysis and Statistical Analysis

Analytical methods to evaluate receiver sensitivity to fine motions of the motion standard and individual subjects will involve harmonic analytical methods such as Fourier analysis or other decomposition techniques involving orthogonal basis functions such as Wavelet decomposition. Other methods widely found in communication, detection, and estimation theory may be used.

References
The following links represent the type of instrumentation to be used in the proposed study and is meant to provide a gauge to the reviewer of the invasiveness to a subject's personal space.

Biopac Spirometer:
http://www.biopac.com/airflow-transducer-60ml-sec
Biopac Pulse Oximeter:
http://www.biopac.com/spo2-pulse-oximeter-amplifier
Intrusion Sensor: radar-based motion sensor:
http://www.gesecurity.com/portal/site/GESecurity/menuitem.f76d98ccce4cabed5efa421766030730?selectedID=1829&seriesyn=true&seriesID=

Contact Information

Jeffrey M. Ashe, Principal Investigator
One Research Circle
Niskayuna, NY 12309
Phone: 518-387-5302
E-mail: ashe@ge.com

Appendix C1 – WCI Inmate Study Protocol

Protocol: WCI Inmate Observation Study

October 9, 2012 V1

Jeffrey M. Ashe, Principal Investigator, (518) 387-5302, ashe@ge.com
General Electric Global Research, One Research Circle, Niskayuna NY 12309

Background

Despite many improvements, inmate suicide remains a longstanding problem for correctional institutions. In addition to the fundamental tragedy of loss of life, suicide incidents place huge burdens on the institution that contributes to the tarnishing of the reputation of law enforcement, increasing the costs of litigation, and driving new needs to continuously monitor inmates. In order to provide increased situational awareness of the confined inmate's status, GE has developed a prototype demonstration system that can measure an inmate's heart rate, breathing rate, and general body motions (level of activity) without being attached to the inmate. The standoff measurement system will not prevent suicide attempts nor will it identify those inmates who are at risk of suicide. It is anticipated, upon successful development and testing, the system will provide new information to augment the in-place observation processes for at-risk inmates.

The contactless measurement system is based upon observing the inmate's ballistogram using a modified version of a Range Controlled Radar (RCR) that was originally designed as a motion detector for home security systems. A ballistogram is the measurement of subtle motions on the surface of the body due to body motion including movements of the arms, legs, head and torso as well as due to the motion of internal components such as the heart and lungs. The detection of the ballistogram required modifications to the RCR hardware for increased physiological sensitivity and the development of new signal processing algorithms to detect and classify features.

The program, funded by the US Department of Justice, is entering its third phase (Phase III) where a system will be deployed to monitor inmates in an operating prison for an extended field-trial. The testing will be performed at Western Correctional Institution (WCI) Cumberland, Maryland in conjunction with the Maryland Department of Public Safety and Corrections Services. Further description of the phases is described below:

- Phase I of this program was completed from 2007 through 2009. This effort involved modifying the radar hardware and developing assessment algorithms to extract states of activity, breathing rate and heart rate from the non-contact radio-frequency sensor. Testing of the system in this phase was performed under IRB on 20 volunteer employees in a lab setting at GE Global Research. Volunteers were asked to wear an electrocardiogram (ECG) monitor and a spirometer (breathing) monitor while performing set of activities under the observation of the experimental radar sensor

and a video camera. The sensitivity and specificity of the algorithms to detect and classify states of activity (three states: motion, still & concern) was assessed by comparison of the processed radar signals to the activity recordings (as extracted from video). The accuracy of heart rate and breathing rate estimates was assessed by comparison to physiological recordings (as extracted from ECG and spirometer). Subject demographics (gender, age, height & weight) were collected for further segmentation of the data results. Under this phase, the state classification algorithms obtained high sensitivity (82% for motion, 80% for still and 90% for concern) and high specificity (97% for motion, 85% for still and 94% for concern) with an overall diagnostic accuracy of 83%. Additionally, the heart rate and breathing rate estimation algorithms had accuracies of 9.9% and 18.5% respectively, during still states. This high sensitivity/specificity and high rate accuracy enabled a follow-on study to explore performance with a different population in a different setting.

- The Phase II follow-on of this program was completed from 2010 through 2011. This effort involved testing the system under IRB on 10 volunteer corrections staff in a cell in the SOH unit at WCI. Volunteers were asked to wear a pulse oximeter (SpO2) monitor and a spirometer (breathing) monitor while performing set of activities under the observation of the experimental radar sensor and a video camera. The sensitivity and specificity of the algorithms to detect and classify states of activity was assessed by comparison of the processed radar signals to the activity recordings (as extracted from video). The accuracy of heart rate and breathing rate estimates was assessed by comparison to physiological recordings (as extracted from SpO2 and spirometer). Subject demographics (gender, age, height & weight) were collected for further segmentation of the data results. Under this phase, the state classification algorithms obtained high sensitivity (86% for motion, 81% for still and 96% for concern) and high specificity (100% for motion, 90% for still and 91% for concern) with an overall diagnostic accuracy of 86%. Rate estimation accuracies ranged from 5% to 10% better than the 20% goal during periods of relative stillness. An alerting algorithm was developed to detect when periods of concern (activity=concern or activity=still with abnormal heart rates or breathing rates) persisted for a length of time. The alerting algorithm detected all events (no missed events) while achieving false alert rates less than 5%. These successful results enabled a follow-on study to explore performance in real-world prison operating conditions.

- The technical effort on the Phase III follow-on of this program began in 2012. The goal of this phase is to investigate the performance of the alerting algorithm under long-term operational conditions in a real-world prison environment. In other words, the system will be used to monitor inmates during their normal activities when housed in the SOH unit at WCI. For this this operational assessment, the RCR will be

the only sensor used in the study - no video or other physiological (e.g. ECG, SpO2 or spirometer) recording will take place. This effort will package the prototype system for inmate safety, install the packaged system into 3 operating cells and evaluate the performance of the alerting system (e.g. missed events and false alerts) for a 3-month period of time.

Consent

This study will require participating inmates to comprehend and provide informed consent. Since there are several unique considerations for studies regarding inmates, the consent process is as follows:

- Studies will be conducted in the SOH unit at WCI. There are approximately 10 cells in the SOH of which typically 3 to 5 cells are occupied at any one time. Inmates may be housed in the SOH for periods from 1-3 days up to several weeks as needed. There is full time observational staff in this facility that provides scheduled or continuous observation. This setting is desirable for the study since observational activities logs are to be used as the metric to assess the prototype system performance and many different inmates will be cycling through the unit. Other areas of the prison do not have as comprehensive observation nor do permanent housing units have frequent changes in occupancy.

- Inmates will be referred to the SOH by normal WCI processes. Inmates may be referred to the SOH for a variety of reasons including mental health issues, depression, risk of suicide or self-harm and other reasons. Due to these issues, some inmates may not have the capacity to comprehend the study or the capacity to provide informed consent. Some inmates who are housed in the SOH may be there for other reasons such as seeking temporary relief from the unit population, awaiting medical or legal appointments. These inmates are likely to have the capacity to provide informed consent.

- Before being made aware of the study, the inmates will be housed in non-instrumented cells of the SOH. Given historical population rates at WCI, there is ample number of non-instrumented cells available so that only fully consented inmates will be housed in instrumented cells.

- The WCI mental health professional counselor supervisor will screen the inmate history for signs that would indicate the inability to comprehend or provide informed consent. While a portion of these evaluations are based upon subjective factors, the professional capability of the mental health professional counselor supervisor will be used for the final determination including assessment of these factors:
    - Inmates with a chronic history of mental illness will be excluded from consideration for the study.
    - Inmates with severe acute depression or risk of suicide will be excluded from consideration for the study.

  - Inmates who's condition is likely to be worsened (e.g. paranoia) will be excluded from consideration for the study.
- The mental health professional counselor supervisor will have a one-to-one discussion with those inmates who are deemed capable of providing informed consent. The mental health professional counselor supervisor will describe the study at a comprehension level commensurate with the inmate's capability. The mental health professional counselor supervisor will discuss what rights the inmate has, what is to be expected for participation, the risks and benefits of participation, the study is completely voluntary, no special treatment or compensation will be obtained and no recourse will be taken if the inmate decides not to participate.

- After the discussion with the mental health professional counselor supervisor , if an inmate expresses interest in participating in the study, the mental health professional counselor supervisor will review the consent form. After confirming the inmate has comprehended the study and understands their rights, the mental health professional counselor supervisor will obtain the inmates signature. The consent form will remain in the locked possession of the mental health professional counselor supervisor.

Study Design

The study will be an observational study of the prototype sensor to evaluate the performance of the alerting system. The inmates will not be required to do anything different than their normal daily activities.

Three prototype sensors will be installed in prison-approved lighting fixtures in three cells of the SOH at WCI. Prison maintenance and electrician staff at WCI will install the fixtures and route the cables to a PC at the officer's console outside the cell. As the in-room equipment will be installed and contained in an approved fixture, it is not anticipated the inmates will be able to access any contents of the equipment.

The officer's console will provide an indicator that the system is running, but will not display any of the activity or physiological estimates or alert states. The console will provide status in plain text that each unit is powered on and that the system is recording data. The console will record raw data and processed data for remote analysis by the GE staff. The officer's will follow their standard shift protocol. The officer's will not have access to nor use any study data to affect their normal shift protocol tasks, actions or decisions. Signage will be affixed to the officer console indicating "For experimental data collection only. System status is not an indicator of inmate safety."

The officers will observe inmates at 15 or 30 minute intervals and record a log of the prisoner activity during the observation (e.g. sleeping, exercising, pacing, reading, etc.) and the position/location of the inmate (e.g. supine on bed, supine on floor, standing, sitting, etc.). The logs will be identified by date/time and cell number. The logs are currently in use as standard practice in the SOH of WCI. The mental health professional counselor supervisor will obliterate any specific identifiable data before sending acopy

of the logs to GE. No inmate specific identifiable data shall be received in the logs provided to GE.

Periodically (daily, weekly, etc.) the electronic data from the prototype system and the officer-generated log data will be provided to GE for offline performance assessment and analysis. The data will be associated by date, time and cell number. All data accessed by GE will be de-identified of prisoner-specific information.

Occasionally, in the presence of GE or UTRC personnel, the officer console will be opened up to show the data collection and algorithm results in real-time. This is for demonstrations purposes in obtaining feedback on the usefulness and presentation of the data and analysis. For these short-term activities (15-30 minutes), the cells may be occupied by an inmate or by a corrections officer. In the case of an inmate occupying the cell, there will be no interaction between the GE or UTRC personnel and the inmate.

Equipment

The in-room sensor unit contains the radiofrequency motion detector and a data acquisition unit. The radiofrequency motion detector is a narrow-band Doppler radar operating at 5.8 GHz (Model RCR-50 Range Controlled Radar, United Technologies Corporation, Fire & Security, Bradenton, FL). It has been modified to be capable of sensing motion for moving objects in the range from 0 to 15 feet using an external pulsing circuit and an external antenna. Data acquisition and communication is performed by an Arduino Nano (Gravitech, Claremont, CA) processing unit which communicates over Ethernet. Power is supplied to the in-room unit using power-over-Ethernet sharing the same communication wires.

The systems used in previous phases and for the proposed phase are shown in the pictures below. The table below enumerates the differences between the equipment used in previous IRB studies as compared to the inmate observation study.

Table 1: Comparison of modifications being performed to consolidate the instrumentation and package for safe use with inmates.

Component	Previous Phases (Phase I & Phase II)	Inmate Observation Study (Phase III: this study)	Comments
Motion Detector	RCR-50	RCR-50	No Change
Antenna	Dipole or 17 dBi Dish	11 dBi Patch	Lower Power/Smaller
Pulser	Function Generator	Custom Circuit	Lower Power/Smaller
Acquisition	BioPac/Agilent	Arduino	Lower Power/Smaller
Communication	Ethernet/USB	Ethernet	Long Distance to Console
Power	Power Supply	Power-over-Ethernet	Shares Wires with Ethernet
Fixture	Temporary Tripod	Permanent Prison-Rated Light Fixture	Increased Prisoner Safety

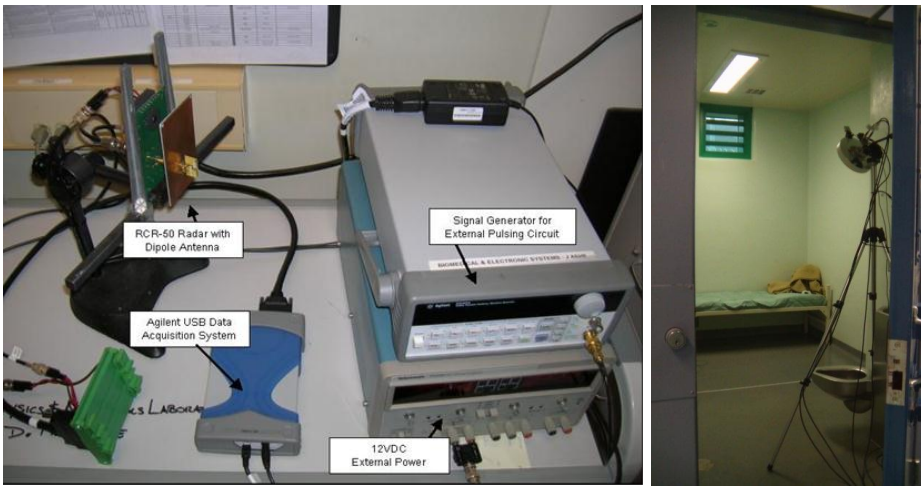


Figure 1: Experimental system previously in Phase I and Phase II of the program. Modifications are being performed to consolidate the instrumentation and package for safe use with inmates.

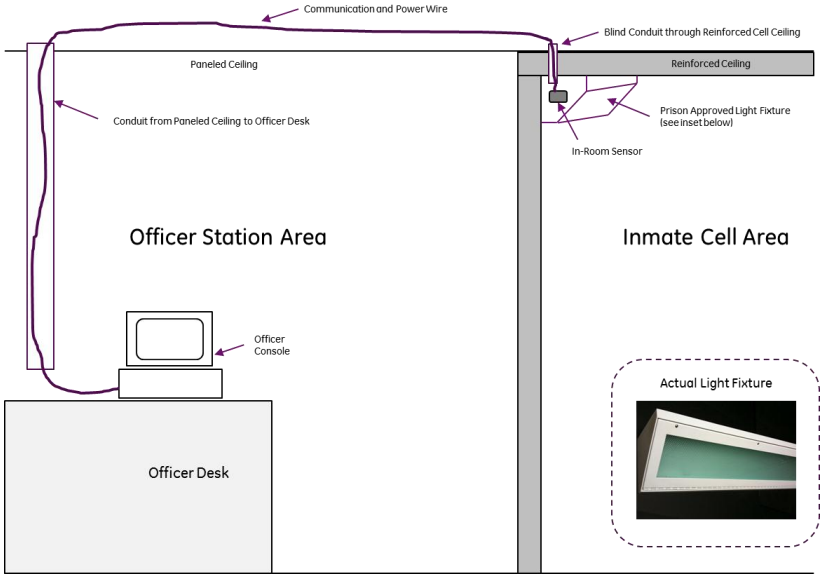


Figure 2: Experimental system proposed in Phase III (this study) with in-room portions of the system packaged in a prison-approved light fixture for inmate safety.

Risks

Decision Making

To ensure decision making is not influenced by the prototype system, the officer console will not display any information about the activity state, heart rate, breathing rate or alert status of the inmates. The officer console will only allow the officers to observe status

that the system is running and to execute a routine to save and/or send data to GE. Corrections officers will be instructed by the WCI shift commanders to follow their normal SOH protocols which do not involve the use of information from the prototype system. Signage will be affixed to the officer console indicating "For experimental data collection only. System status is not an indicator of inmate safety."

RF Safety
To ensure safety from radiofrequency exposure, each unit will be tested to meet conformity with FCC OET-65 Bulletin "Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields" prior to installation in the prison. The units will be required to meet the limits for uncontrolled exposure (the most stringent limits because the subject cannot remove themselves from the exposure area). The RCR radar, sold as a commercial motion detector, already meets these limits. Testing prior to shipment will ensure modifications of the pulse circuit, antenna and enclosure still meet the requirements. Test results will be reviewed and approved by the Principal Investigator and the GE Global Research Human Subjects Protection Administrator. Similar modified units have been tested and previously approved for use in Phase I and II of the NIJ program.

Fixture Safety
To ensure safety from the physical enclosure, each unit will be housed in a prison-rated enclosure and each unit will be installed by the WCI facilities and electrical staff. The housings are designed so they cannot be tampered with and so there are no exposed edges or gaps from which an inmate could support a ligature. The WCI facilities and electrical staff will install the units in compliance with the prison policies.

Suspicious Findings

The data will not be reviewed for diagnostic purposes. The capability of the prototype system may be able to observe conditions related to breathing and heartbeat. These conditions may include sleep apnea, bradycardia or tachycardia. Although the capability of the system may be able to observe suspicious findings, this protocol does not provide any actionable, real-time information with respect to these conditions. System data may or may not be reviewed for purposes of conducting the research. In the event a suspicious finding is observed in the data reviewed, GE will report the cell number, date and time of the finding to the mental health professional counselor supervisor of WCI who oversees the SOH unit.

Benefits

This is an observational study of a prototype monitoring system. There are no immediate benefits to the inmates or to the corrections officers who are participating in the study. Upon successful commercialization of an unobtrusive monitoring system, the results from the study will provide long term benefits. These benefits include:

- For inmates: such monitoring systems and response protocols will increase inmate safety. Unobtrusive systems will increase inmate privacy and reduce interruptions with the intrusive nature of observations.
- For corrections officers: such monitoring systems will increase effectiveness by providing data to augment existing observation protocols. Incorporating noncontact systems in the cells will increase officer safety by reducing the need to enter the cell during observations.

Confidentiality

To protect inmate privacy, all data accessed by GE will be de-identified of prisoner specific information. Correction officer initiated cell occupancy and activity logs will be de-identified to contain no inmate specific identifiable data and consist of only cell number, date, time, prisoner activity during the observation (e.g. sleeping, exercising, pacing, reading, etc.) and the position/location of the inmate (e.g. supine on bed, supine on floor, standing, sitting, etc.). Information regarding the identity of the inmate will not be kept nor associated with the study materials provided to GE.

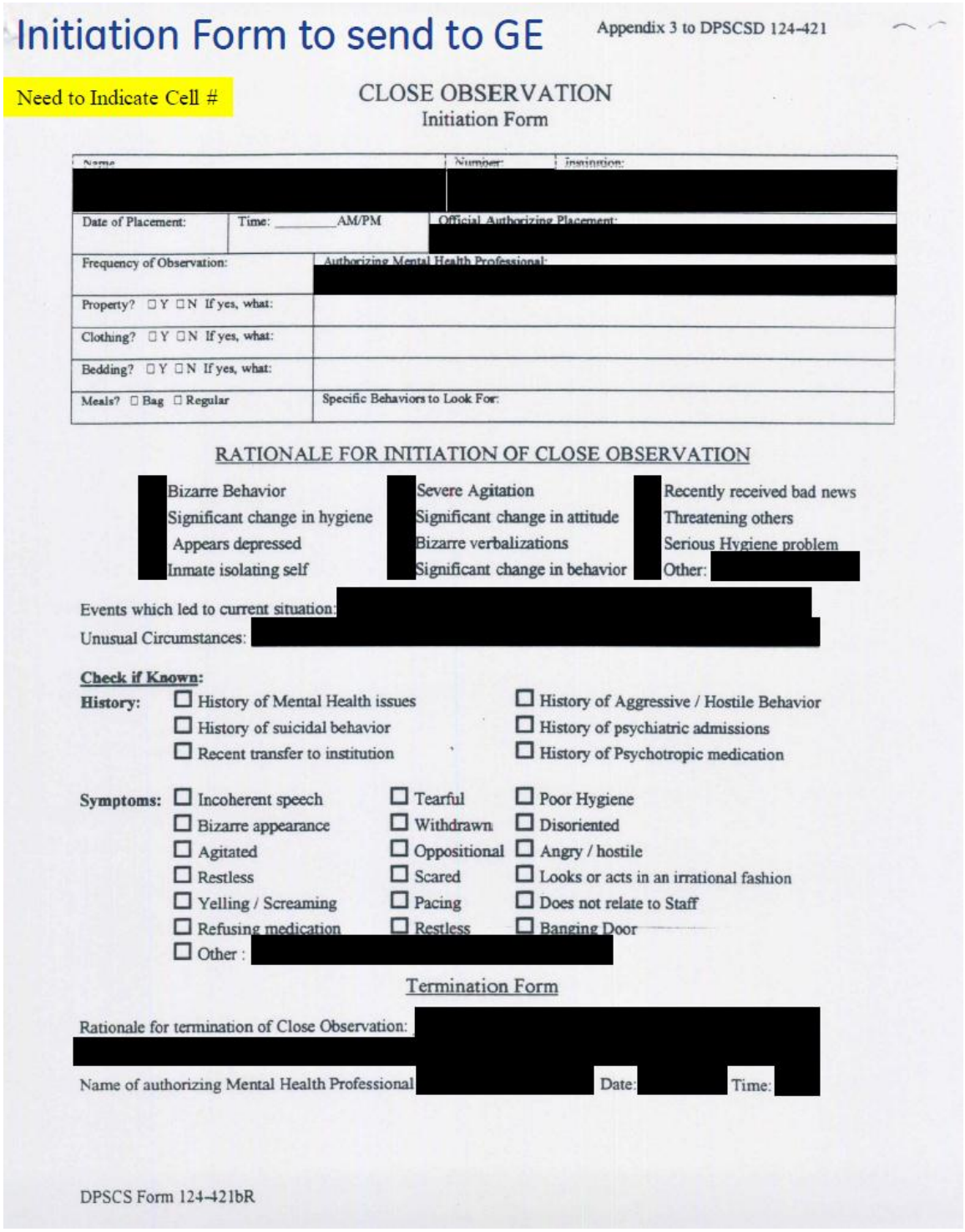
Compensation

There will be no compensation for the study. Inmates will not receive compensation for the study. Corrections officers will not receive compensation for the study.

Data Assessment

Study data will be assessed to determine the performance of the prototype system in providing accurate situational awareness of in-cell activities. The system activity classification data will be compared to the officer generates activity logs. The sensitivity and the specificity of the classification algorithm will be assessed. The false alarm rate of the alerting algorithm will be assessed.

EXHIBIT B: INMATE OBSERVATION FORM



Initiation Form to send to GE

Appendix 3 to DPSCSD 124-421

Need to Indicate Cell #

CLOSE OBSERVATION
Initiation Form

Name [redacted]	Number:	Institution:
Date of Placement:	Time: _____AM/PM	Official Authorizing Placement: [redacted]
Frequency of Observation:	Authorizing Mental Health Professional: [redacted]	
Property? ☐Y ☐N If yes, what:		
Clothing? ☐Y ☐N If yes, what:		
Bedding? ☐Y ☐N If yes, what:		
Meals? ☐Bag ☐Regular	Specific Behaviors to Look For:	

RATIONALE FOR INITIATION OF CLOSE OBSERVATION

[redacted]
Bizarre Behavior
Significant change in hygiene
Appears depressed
Inmate isolating self

[redacted]
Severe Agitation
Significant change in attitude
Bizarre verbalizations
Significant change in behavior

[redacted]
Recently received bad news
Threatening others
Serious Hygiene problem
Other: [redacted]

Events which led to current situation: [redacted]

Unusual Circumstances: [redacted]

Check if Known:

History:
- ☐ History of Mental Health issues
- ☐ History of suicidal behavior
- ☐ Recent transfer to institution
- ☐ History of Aggressive / Hostile Behavior
- ☐ History of psychiatric admissions
- ☐ History of Psychotropic medication

Symptoms:
- ☐ Incoherent speech
- ☐ Bizarre appearance
- ☐ Agitated
- ☐ Restless
- ☐ Yelling / Screaming
- ☐ Refusing medication
- ☐ Other : [redacted]
- ☐ Tearful
- ☐ Withdrawn
- ☐ Oppositional
- ☐ Scared
- ☐ Pacing
- ☐ Restless
- ☐ Poor Hygiene
- ☐ Disoriented
- ☐ Angry / hostile
- ☐ Looks or acts in an irrational fashion
- ☐ Does not relate to Staff
- ☐ Banging Door

Termination Form

Rationale for termination of Close Observation: [redacted]

Name of authorizing Mental Health Professional [redacted] Date: [redacted] Time: [redacted]

DPSCS Form 124-421bR

Observation Log to send to GE

Appendix I

Need to Indicate Cell #

OBSERVATION LOG

Name [redacted]	Number:	Institution: [redacted]
Date of Placement:	Time: _____AM/PM	Official Authorizing Placement: [redacted]
Frequency of Observation:	Authorizing Mental Health Professional: [redacted]	

Date/Time	Observer's Initials/Title	Comments/Observations
	[redacted]	

Attach Additional Pages as Necessary

Distribution: Inmate Medical File

Page ____ of ____

DPSCS Form 124-420-3

Appendix C2 – WCI Inmate Study Consent

Consent to be a Research Subject

Inmate Motion Detection Study

Purpose	We are evaluating a motion sensor to monitor inmate activity using a sensor placed in a light fixture within a cell. The sensor is based on a Doppler radar which is commonly used to turn on lights or for security systems. The sensor can provide information about your level of activity and about your breathing and/or heart rates. The study will help us understand if the sensor can improve existing inmate observation in the Western Correctional Institution (WCI) Special Observation Housing (SOH) unit.
Procedures	If you agree to be in the study, your motions will be recorded by the motion sensor while you are housed in the SOH. While in the SOH you will be expected to perform your normal daily activities. You will not need to perform any special procedures.
Risks and Discomforts	The motion sensor in the cell uses high frequency radio waves. The system has been designed and tested to ensure your radio wave exposure is less than FCC regulations for the general public.
Benefits	There are no immediate benefits to you. In the future, inmates may benefit from improved observation procedures which may provide more safety and added privacy.
Alternatives	If you do not want be in the study, you may be housed in a standard SOH cell which does not contain motion sensors.
Cost and Compensation	There is no cost to participate and you will not receive any money or special treatment. Your parole will not be affected by participating or not participating.
Privacy and Confidentiality	To protect your privacy, all motion sensor data collected during the study will not be associated with your name or with your WCI record.
Inclusion & Exclusion Criteria	You must not have a history of mental illness or be in a depressed condition where the study will aggravate your condition. The head of the WCI psychology department will assist you in making this determination.
Questions	Any questions may be directed to Ronald S. Weber in the WCI psychology department. If you have complaints or questions about your rights, you may contact an impartial reviewer, E&I Review at subject@eandireview.com or 1-800-472-3241.
Rights	You have the right to refuse to participate. Once in the study, you have the right to withdraw. You may refuse to participate or withdraw from the study at any time without fear of retribution.
Funding Agency	This research is sponsored by the General Electric Company through a funding grant issued by the National Institute of Justice, which is the research, development and evaluation agency of the US Department of Justice.

Please sign this form if you agree to be in this study. A copy of this form will be placed in your records.

	Inmate	Person who explained the study
Signature		
Printed Name		
Date		

Appendix C3 – WCI Inmate Study MD DPSCS DRC Application

Department of Public Safety and Correctional Services

RESEARCH APPLICATION

Researcher's Name	Jeffrey M. Ashe
Title and Work or School Affiliation	Principal Investigator/Senior Electronic Systems Engineer General Electric Global Research Center
Mailing Address	One Research Circle Niskayuna, NY 12309
Telephone Number	(518) 387-5302
Email Address	ashe@ge.com
Title of Research Study	Inmate Motion Detection Study
Main Research Hypothesis and Purpose of Study (why it will advance knowledge or practices in the criminal justice or related fields)	Corrections officials are ultimately responsible for the health, safety and welfare of their inmate populations. This includes protection for harm from others and/or for self-harm. Inmates who are deemed at risk of suicide are provided counseling, increased oversight and special observation. Unfortunately, it is not practical to have inmates wear medical monitors. Our hypothesis is that new standoff monitoring systems can provide additional situational awareness for corrections staff. This awareness includes non-contact measurement of motion for assessment of inmate activity level, breathing and heartbeat which can augment typical scheduled visual observations. Additional situational awareness will improve the inmate's level of care and provide corrections officers with better information for timely interventions. The performance and usefulness of new standoff monitoring technologies is not known in real-world operating prison conditions. The purpose of this study is to assess the performance and usefulness of the technology by monitoring inmates in an extended 3-month field trial.
Methodology(ies)	A summary of the methodology is provided here. The detailed methodology is provided in the proposed Memorandum of Understanding (attached). Prototype non-contact sensing systems will be installed in prison-rated light fixtures in three cells of the Special Observation Housing (SOH) unit at the MD DPSCS Western Correctional Institution (WCI). The SOH unit is unique in that it provides close observation that is needed for assessing the system performance in this study. Seven cells in the SOH will not be instrumented to allow for capacity to support inmates that are ineligible or do not wish to provide informed consent. For those inmates that participate in the study, WCI will provide de-identified activity logs to GE for data analysis. It is expected the number of subjects who may give consent over the three-month study period may be as many as N=30. For statistical consistency with prior study IRB collection on employee

volunteers, at least N=10 subjects will be required.

The system will measure motion of the inmate using a low-power Doppler radar (RCR-50, United Technologies, Bradenton, FL). The motion signals will be interpreted by algorithms to classify inmate activities into three categories: Motion – there is motion in the cell, Still – there is a small amount of motion corresponding to breathing and/or heartbeat, and Concern – there is a lack of motion. In the Still state, the signals will be further analyzed to determine breathing and/or heart rates. If the Concern state persists long enough, an alert will be issued. Similarly, if the breathing and/or heart rates are abnormal, an alert will be issued. For the purposes of this prototype study, the prototype system will not provide any information to the corrections officers. The corrections officers must follow their normally prescribed protocols for inmate observation and handling. Data analysis will be performed offline by comparing the system states and alerts with the de-identified activity logs.

Consent:

Informed consent will be required for participation. The department head of the WCI psychology department will be responsible for determining eligibility and obtaining informed consent. Inmates will be referred to the SOH by existing WCI processes. Inmates housed in the SOH may not have the mental capacity to comprehend the study nor to give informed consent. The psychology department head will screen the inmates to determine which ones have the capacity to comprehend and give informed consent. While a portion of these evaluations are based upon subjective factors, the professional capability of the department head will be used for the final determination including assessment of these factors:

- Inmates with a chronic history of mental illness will be excluded from consideration for the study.
- Inmates with severe acute depression or risk of suicide will be excluded from consideration for the study.
- Inmates who's condition is likely to be worsened (e.g. paranoia) will be excluded from consideration for the study.

The department head will have a one-to-one discussion with those inmates who are deemed capable of providing informed consent. The department head will describe the study at a comprehension level commensurate with the inmate's capability. The department head will discuss what rights the inmate has, what is to be expected for participation, the risks and benefits of participation, the study is completely voluntary, no special treatment or compensation will be obtained and no recourse will be taken if the inmate decides not to participate.

After the discussion with the department head, if an inmate expresses interest in participating in the study, the department head will review the consent form and obtain the inmates signature. The consent form will remain in the inmate's record and only accessed by qualified WCI personnel.

Data Recording:

During the study, officers will observe inmates at 15 or 30 minute intervals and record a log of the inmate activity during the observation (e.g. sleeping, exercising, pacing, reading, etc.) and the position/location of the inmate (e.g. supine on bed, supine on floor, standing, sitting, etc.). The logs will be identified by date/time and cell number. No inmate specific

identifiable data shall be in the logs provided to GE.

Periodically (daily, weekly, etc.) the electronic data from the prototype system and the officer-generated log data will be provided to GE for performance assessment and analysis. The data will be associated by date, time and cell number. All data accessed by GE will be de-identified of prisoner-specific information.

Occasionally, in the presence of GE personnel, the officer console will be opened up to show the data collection and algorithm results in real-time. This is for demonstrations purposes in obtaining feedback on the usefulness and presentation of the data and analysis. For these short-term activities (15-30 minutes), the cells may be occupied by an inmate or by a corrections officer.

Risks:

Decision Making - To ensure decision making is not influenced by the prototype system, the officer console will not display any information about the activity state, heart rate, breathing rate or alert status of the inmates. The officer console will only allow the officers to observe status that the system is running and to execute a routine to save and/or send data to GE. Corrections officers will be instructed by the WCI shift commanders to follow their normal SOH protocols which do not involve the use of information from the prototype system. Signage will be affixed to the officer console indicating "For experimental data collection only. System status is not an indicator of inmate safety."

RF Safety - To ensure safety from radiofrequency exposure, each unit will be tested to meet conformity with FCC OET-65 Bulletin "Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields" prior to prison installation. The units will be required to meet the limits for uncontrolled exposure (the most stringent limits because the subject cannot remove themselves from the exposure area). The RCR radar, sold as a commercial motion detector, already meets these limits. Testing prior to shipment will ensure modifications of the pulse circuit, antenna and enclosure still meet the requirements. Test results will be reviewed and approved by the Principal Investigator and the GE Global Research Human Subjects Protection Administrator. Similar modified units have been tested and previously approved for use in Phase I and II of the NIJ program.

Fixture Safety - To ensure safety from the physical enclosure, each unit will be housed in a prison-rated enclosure and each unit will be installed by the WCI facilities staff. The housings are designed so they cannot be tampered with and so there are no exposed edges or gaps from which an inmate could support a ligature. The WCI facilities and electrical staff will install the units in compliance with the prison policies.

Suspicious Findings:

The data will not be reviewed for diagnostic purposes. The capability of the prototype system may be able to observe conditions related to breathing and heartbeat. These conditions may include sleep apnea, bradycardia or tachycardia. Although the capability of the system may be able to observe suspicious findings, this protocol does not provide any actionable, real-time information with respect to these conditions. System data may or may not be reviewed for purposes of conducting the research. In the event a suspicious finding is observed in the data reviewed, GE will report the cell number, date and time of the finding to the chief psychologist of WCI who oversees the SOH unit.

	Benefits: This is an observational study of a prototype monitoring system. There are no immediate benefits to the inmates or to the corrections officers who are participating in the study. Upon successful commercialization of an unobtrusive monitoring system, the results from the study will provide long term benefits. These benefits include: • For inmates: such monitoring systems and response protocols will increase inmate safety. Unobtrusive systems will increase inmate privacy and reduce interruptions with the intrusive nature of observations. • For corrections officers: such monitoring systems will increase effectiveness by providing data to augment existing observation protocols. Incorporating noncontact systems in the cells will increase officer safety by reducing the need to enter the cell during observations. Confidentiality: To protect inmate privacy, all data accessed by GE will be de-identified of prisoner specific information. Correction officer initiated cell occupancy and activity logs will contain no inmate specific identifiable data and consist of cell number, date, time, prisoner activity during the observation (e.g. sleeping, exercising, pacing, reading, etc.) and the position/location of the inmate (e.g. supine on bed, supine on floor, standing, sitting, etc.). Information regarding the identity of the inmate will not be kept nor associated with the study materials. Compensation: There will be no compensation for the study. Inmates will not receive compensation for the study. Corrections officers will not receive compensation for the study. Data Assessment: Study data will be assessed to determine the performance of the prototype system in providing accurate situational awareness of in-cell activities. The system activity classification data will be compared to the officer generates activity logs. The sensitivity and the specificity of the classification algorithm will be assessed. The false alarm rate of the alerting algorithm will be assessed.
DPSCS Data or Cooperation Required	WCI staff will support the installation and removal of monitoring systems into several cells of the SOH, support the data collection activities, support transfer of data and provide feedback on aspects of the system performance. The department head of the WCI psychology unit will determine if inmates housed in the SOH have the capacity and comprehension to participate. The department head will conduct the study introduction sessions and obtain informed consent.
Funding Source, if any	US Department of Justice, National Institute of Justice "Unobtrusive Suicide Warning System" Grant #2011-IJ-CX-K003 (awarded)
Study Duration	Oct 1, 2012 through Dec 31, 2012 (anticipated)
Publication Intentions	Study results will be presented to corrections communities through the National Institute of Justice technical working groups and through papers and presentations in technical conferences and journals (IEEE).
Other Required Information	Attachments: Proposed WCI Memorandum of Understanding (including proposed protocol and

	observation collection form) NIJ Proposal (funded) Previous WCI Memorandum of Understanding
Date	September 17, 2012

Questions? *Contact Toni Allegra at tel: 410-339-5019; fax 410-339-4228.*

Appendix C4 – WCI Inmate Study IRB Feedback

Ethical & Independent Review Services
A Shared Commitment to Ethical Research

November 19, 2012

Jeffrey M. Ashe, MScEE
General Electric Global Research
One Research Circle
Niskayuna, NY 12309

RE: WCI Inmate Observation Study – E&I Study #12177-01

Dear Mr. Ashe,

During the meeting on November 6, 2012, the IRB reviewed this study. The IRB asked for more information so that they may have a better understanding of the study. The board will review your responses at a future meeting at which time further questions are possible. Your responses will be placed on the agenda for the next possible full board meeting.

The IRB was grateful for the well-prepared information submitted. The following issues need to be addressed:

PROTOCOL:

1. Page A-4, Consent Section:
   Please specify the consent process for inmates who are removed from SOH and then returned. How long will their consent be valid? Will they re-consent each time? Will their mental health status be evaluated each time they return to SOH?

2. Page A-4, Last Paragraph:
   How will the activity logs be de-identified? Please include these specifics (crossed out with a sharpie or use of whiteout) in the protocol.

3. Page A-5:
   Please clarify the reference to "UTRC." Is this a sub-contractor to GE? How is it that they will have access to the officer console kept at WCI? What are the provisions that will be taken, with regards to confidentiality, when the occasional real-time demonstrations activities occur?

   Please verify this information is appropriately provided in the consent form.

4. Page A-5, First Paragraph:
   This section states that "suspicious finding" will be reported. Please define "suspicious findings." Do they include misconduct by the inmate?

5. Pages. A-5, A-8 and the Recruitment Script, last paragraph:
   Please clarify the role of the correction officers in this study. There are a few references that give the impression they are also subjects.

E&I Midwest Board & Business Office
14400 East 42nd Street, Suite 240
Independence, MO 64055
Phone (816) 421-0008
Fax (816) 356-2227

E&I West Coast Board
100 Tamal Plaza, Suite 158
Corte Madera, CA 94925
Phone: (415) 485-0717
Fax: 485-0328

Ethical & Independent Review Services
A Shared Commitment to Ethical Research

CONSENT:

6. The IRB asked for changes to the consent document. Attached is the re-written consent document. Please review it and let us know if you agree or disagree with this version. If you disagree, please provide your rationale. You may also submit any additional changes you would like to make at this time by showing tracked changes.

OTHER ITEMS:

7. The IRB requested a course completion certificate on the Protections of Human Research Subjects from the WCI Mental Health Professional Counselor Supervisor due to his role in this study. The IRB recommends the course at www.citiprogram.org.

8. When available, please submit E&I Form 33 for the site and E&I Form 35, CV and training for the sub-investigator.

9. Please complete only the appendix A/B (pages 4 through 7) of the attached E&I Form 25C.

10. Please be aware that under sub-part C we may need to certify this study: http://www.hhs.gov/ohrp/policy/populations/prisoncertlet.html

11. As the Maryland DPSCS Department Research Committee approval is a requirement and as their response may affect or alter your current proposal, the board suggested holding your response until you have their reply and can coordinate responses.

To facilitate our review of your responses, please respond to these questions in a point-by-point format. In addition, please incorporate your responses into the appropriate documents. For each document requiring revision please submit a copy with tracked changes and a clean copy. You do not need to resubmit documents that require no changes. If no response is received within 90 days, this request will be withdrawn. Fees will apply.

We look forward to your response and please feel free to contact us to ask questions or discuss ideas.

Sincerely,

Jean Taylor-Woodbury, RN, MS, ANP-BC, IRB Chair
(by) Jenny Ramos, CIP

Appendix C5 – WCI Inmate Study MD DPSCS DRC Rejection

Department of Public Safety and Correctional Services

Office of the Secretary
300 E. JOPPA ROAD • SUITE 1000 • TOWSON, MARYLAND 21286-3020
(410) 339-5000 • FAX (410) 339-4240 • TOLL FREE (877) 379-8636 • V/TTY (800) 735-2258 • www.dpscs.maryland.gov

January 4, 2013

Jeffrey M. Ashe
General Electric Global Research Center
One Research Circle
Niskayuna, New York 12309

RE: DRC #228 "Inmate Motion Detection Study"

Dear Mr. Ashe:

As previously indicated to you, the Departmental Research Committee initially reviewed your Research Application at its meeting on September 18, 2012. Thereafter, the Committee requested additional feedback from within the Department for review at its meeting on November 13, 2012. At that time, it issued a recommendation that has since been reviewed and approved by the Secretary of the Department of Public Safety and Correctional Services.

I regret to inform you that the Committee recommended to decline the Research Application. The merits of this phase of your research, as proposed, do not appear to outweigh the disruption to a segment of the Department's operations, the Special Observation Housing (SOH) unit at Western Correctional Institution (WCI), that is devoted to mitigating the effects of mental disturbances and suicidal thoughts and tendencies. This decision was not taken lightly because we know you conducted an earlier part of your research at WCI. However, this phase of your research cannot be supported by the Department.

Although the Department is unable to help you complete your research, I wish you success in locating another site and in reaching your desired outcomes.

Very truly yours,

Christina Lentz
Executive Director, Office of Grants, Policy, and Statistics
Chairperson, Departmental Research Committee

CNL/ta
CC: File

Appendix D1 – RCR Modification and Testing at UTRC

MODIFICATION AND TESTING OF AN RCR50 FOR USE IN NON-CONTACT HUMAN VITAL SIGN MONITORING

WRITTEN FOR GRC AS PART OF NIJ CONTRACT:

2011-IJ-CX-K003

PO # 400103441

Nicholas Soldner
United Technologies Research Center
411 Silver Lane, MS 129-85
East Hartford, CT 06108
Phone: (860) 610-7781
SoldnenC@utrc.utc.com

Joe Zacchio
United Technologies Research Center
411 Silver Lane
East Hartford, CT 06108
Phone: (860) 610-7910
zacchij@utrc.utc.com

Vijay Lakamraju
United Technologies Research Center
411 Silver Lane
East Hartford, CT 06108
Phone: (860) 610-7672
lakamrvr@utrc.utc.com

Mark Vogel
United Technologies Research Center
411 Silver Lane, MS 129-15
East Hartford, CT 06108
Phone: (860) 610-7051
vogelma@utc.utc.com

WORK FUNDED UNDER NIJ CONTRACT 2011-IJ-CX-K003

TABLE OF CONTENTS

1. Introduction

This report covers the design, fabrication and testing of a 5.8 GHz radar system suitable for non-contact monitoring of inmate vital signs (heart rate, breathing and motion). The system covered in this report consists of the following major components: 1. A modified 5.8 GHz range-gated Doppler radar, 2. 5.8 GHz antenna, 3. Arduino embedded computer and 4. a prison grade fixture housing the entire system.

2. Requirements

The overall system should be capable of reading human vital signals from a range of 3 meters and transmits raw results to a central PC via Ethernet. The radar should be capable of measuring motion between 0 and 10 Hertz and filter out anything outside of that range. In addition, the system should be tamper proof and create not additional safety issues once installed in an inmate's cell.

3. Design and Construction of System Components

At its core, the system is based on the low cost range raging radar that is present in RCR50, a radar based motion sensor sold by Interlogix, a UTC business unit. Although the system uses this commercially available product, several modifications and additions are necessary for this application and are detailed in this section. A selection of manufacturer part numbers is provided in Section 6.

3.1. 5.8 GHz Doppler Radar

The 5.8 GHz radar is the heart of the system and is responsible for transmitting and receiving reflected RF energy from the human target. The commercially available version of this radar, model RCR50, is shown below in Figure 1. The radar uses a 5.8 GHz oscillator circuit and digital timing circuits to achieve finite range sensitivity, beyond which, responses are ignored. The type

of radar can be described as “range gated 5.8 GHz Doppler radar.” Range gating is especially import in situations where objects or persons may be moving in an adjacent room but are not the intended targets.

Figure 1 Image of the commercially available 5.8 GHz radar, model RCR50, which is modified for use as a physical interface for the non-contact vital sign system (left)

For the radar to work in this application, the range is fixed to cover a typical prison cell of 7’x10’x10’. In addition to a fixed range, the internal pulse generator is disconnected and the internal circuitry modified to operate with an external pulse generating circuit operating at 5 MHz with a 50% duty cycle (100 ns pulse every 200 ns). Previous testing of the radar used external laboratory instruments to generate this pulse which isn’t practical in a prison environment. Instead, the team designed and built a compact pulse generator specifically for this application. The prototype pulse generator used to prove out the design is shown in Figure 2. The completed pulse generator is shown in Figure 3.

The pulse generator is functionally comprised of an RC-controlled, free-run oscillator, which drives a buffer amplifier stage. The free run oscillator can be adjusted in the range of 2 MHz to 5 MHz via an adjustable resistor. The buffered amplifier stage drives a clamping inverter which in turn directly gates the 5.8 GHz oscillator section of the RCR.

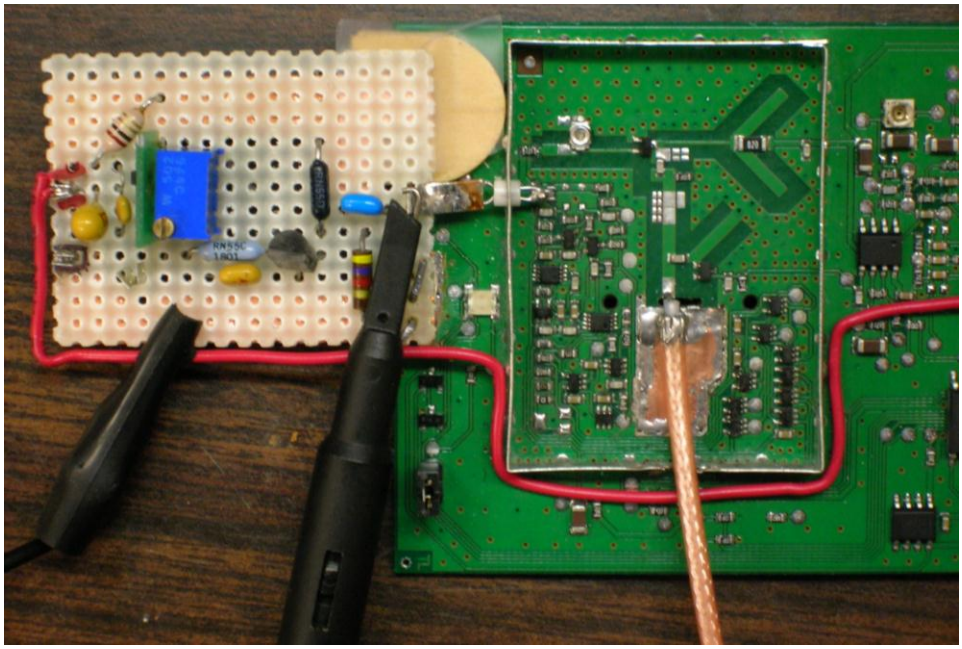


Figure 2 Prototype modified RCR 50 showing pulse generator (left) and modifications in the 5.8 GHz circuitry to enable an external antenna connection (right)

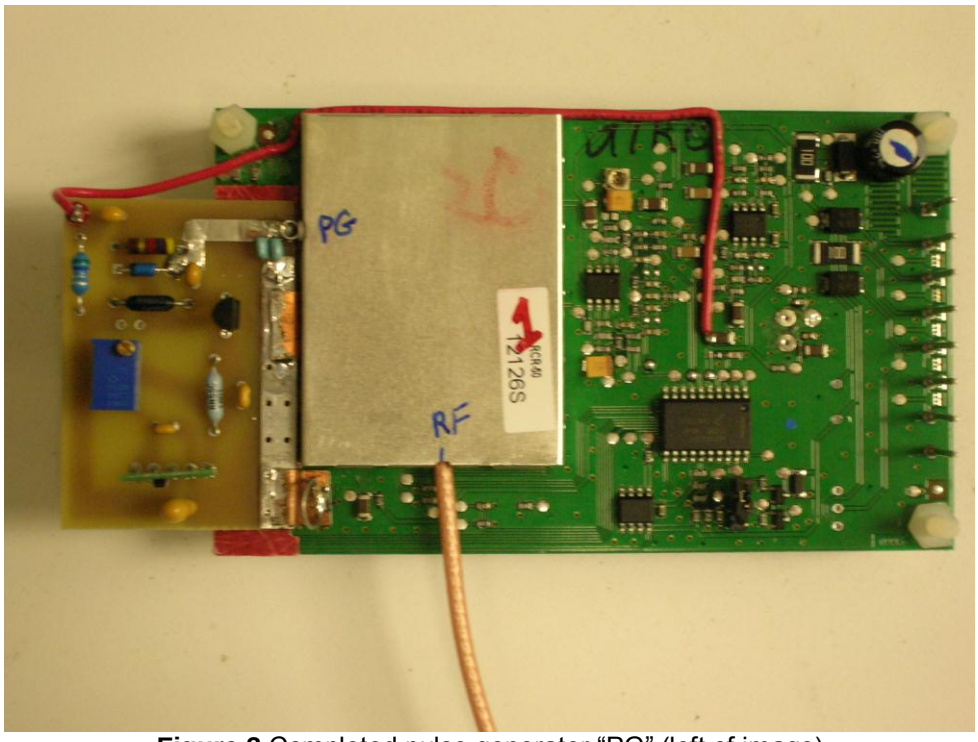


Figure 3 Completed pulse generator “PG” (left of image)

3.2. Integration into Prison-hardened fixture

The team down-selected a prison-hardened light fixture manufactured by Kenall (model # CC 2 1/1 1 17 RS 1 120 3/G 1) which is used to house the radar system. The main reasons for using such a fixture were (1) prior approval by the prison staff for use of such fixtures for lighting (2) strength and space available in the fixture and (3) aesthetics and ability to clone as a simple light fixture. The included fluorescent lamps were removed to make space for the forward facing antenna and other system components. Specifications for the fixture are provided in Figure 4. The fixture uses tamper proof fasteners, a high impact polymer lens and heavy steel construction.

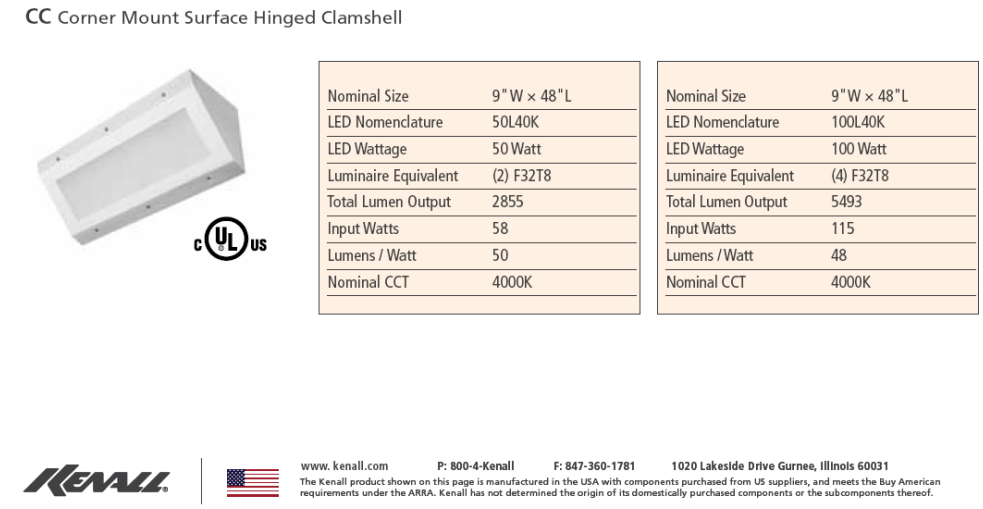


Figure 4 Image and specifications for Kenall prison-grade light fixture which was adapted to house the non-contact vital sign radar

3.3. Antenna Selection

To detect an inmate at any location within the cell, antenna selection was crucial to achieving both range and coverage. The team investigated several potential locations within the cell and selected position #5 as shown in Figure 5. Position #5 is ideal since the antenna main beam points along the cell length, allowing use of an off-the-shelf patch antenna. In addition, this allows the antenna's main beam (highest gain) to be pointed at the bed; one of the most difficult locations to detect vital signs (i.e. inmate sleeping face down).

The team down-selected the HG5811P 11 dBi patch antenna from L-Com primarily because it provided the most gain for a commercially available 5.8 GHz antenna which also meeting our size requirements (fits within the lamp enclosure). A multi-antenna system was considered as well however through testing (shown later), the single antenna performed well. A multi-antenna system is however feasible for cells that may have features or dimensions that a single-antenna system can't cover. The four primary choices for antenna are shown in Figure 6.

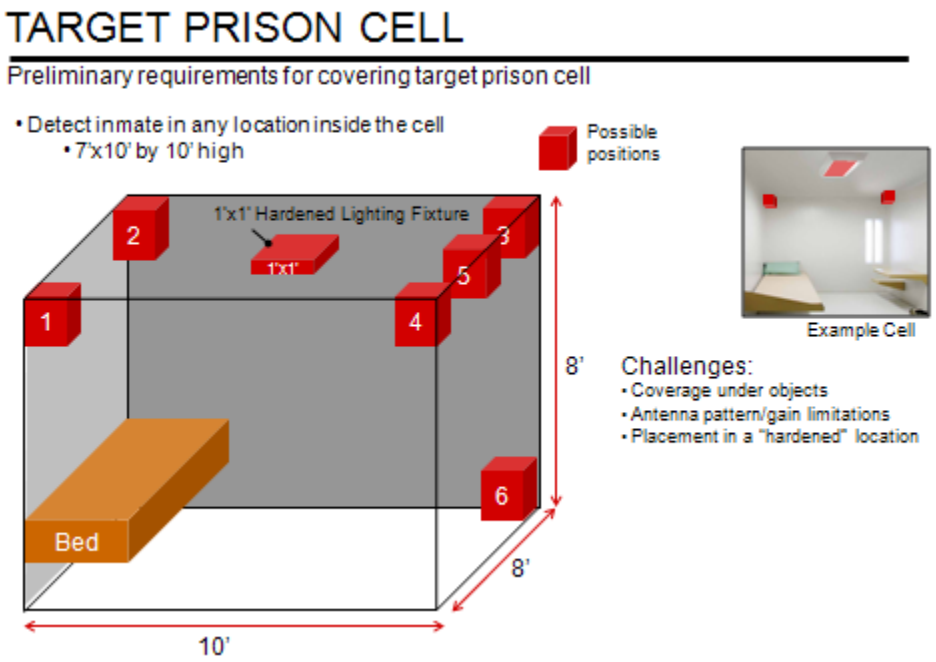


Figure 5 Graphic showing potential antenna locations and potential use of existing lamp fixtures.

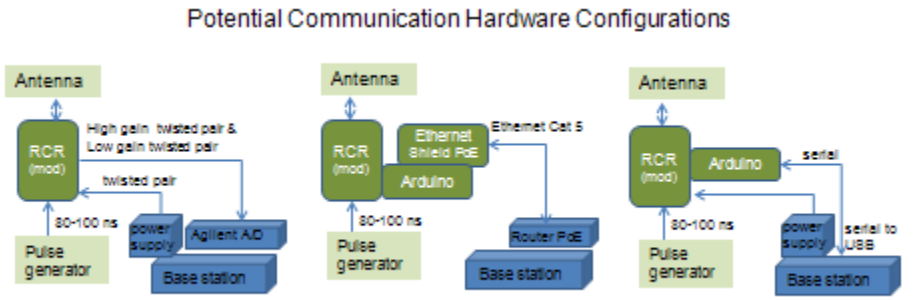
Manufacturer	Gain (dBi)	HBW	VBW	Area
Anyone (Dipole)	2.15			
L-Com	17	25	25	9.7x2.2"
L-Com	11	30	60	4.5x4.5"
L-Com	8	75	60	4.5"x4.5"

Figure 6 Narrowed list of antennas, ultimately the 11 dBi 4.5x4.5" antenna was chosen.

3.4. Processor and Connectivity

In order for the information collected by the radar to be transmitted to a central guard post or monitoring station, a configurable processing element and communications method was selected for integration into each cell. Several options were considered, including both wired and wireless communication as well as centralized and de-centralized signal processing. Due to the unknown signal propagation environment in a prison and the need for obtaining necessary certification, wireless communication was ruled out. Ultimately, Ethernet was chosen primarily because it easily supports the needed bandwidth and has the added advantage of being able to power the system using the Power over Ethernet (PoE) standard. This means that only one cable connection would be needed for each cell, no separate power or data cables required. Figure 7 shows the three primary architectures that were evaluated. “Option 2” was down-selected because it was the most scalable and required the least amount of cabling.

An Arduino UNO Rev. 3 platform processor with PoE capable internet shield was used to sample both the high and low gain channels of the radar and convert the sampled data into Ethernet packets. The architecture is such that several radar systems (one per cell), would send the raw radar data continuously, using UDP, to a central computer. The central computer is responsible for gathering the data streams from multiple radars (one from each of the prison cells) and tasked with applying algorithms to the raw data and providing greater situational/health awareness about the prison inmate. The code running on the Arduino processor inside each cell’s radar is simple, placing most of the burden on the central computer. The Arduino code is shown in Section 5 below.



Trade	Option 1 – Analog (6-wire w/ 2 per output channel & 2 for power)	Option 2 – Ethernet (Arduino and Ethernet Shield)	Option 3 – Serial (Arduino and Serial to USB converters)
Advantages	• No software changes at base station • Lowest cost at sensor • Short implementation time • Highest precision A/D over wide range	• Ethernet provides maturity and scalability • Reasonable sensor hardware cost • PoE	• Arduino serial output easy to implement • Reasonable sensor hardware cost
Disadvantages	• Possible need for line conditioning • Potential signal degradation	• UDP can lose data and ethernet adds complexity • Programming needed at sensor and base station • High coordination between sensor and base station required	• Some serial data can be lost • Programming at base station required • High coordination between sensor and base station required

Figure 7 Three primary communications and digital processing options that were considered. Option 2 was selected due to its bandwidth, scalability, cost and ability to provide power

4. System Testing and Final Assembly

The pulse generator output spectrum and time-domain performance were measured to ensure acceptable RF output power, pulse width and pulse repetition rate. Tests were also conducted in the UTRC electromagnetic anechoic room to evaluate the modified radar's capability to read vital signs at a distance. Electric field strength measurements were conducted and compared to exposure safety limits.

Figure 8 shows the pulse generator output waveform when the pulse generator is loaded by the RCR50 (normal operation). The pulse generator achieved the target 100 ns pulse width at 50% duty cycle (200 ns period). The rise time of the pulses was less than 4ns, which enabled to provide the required performance.

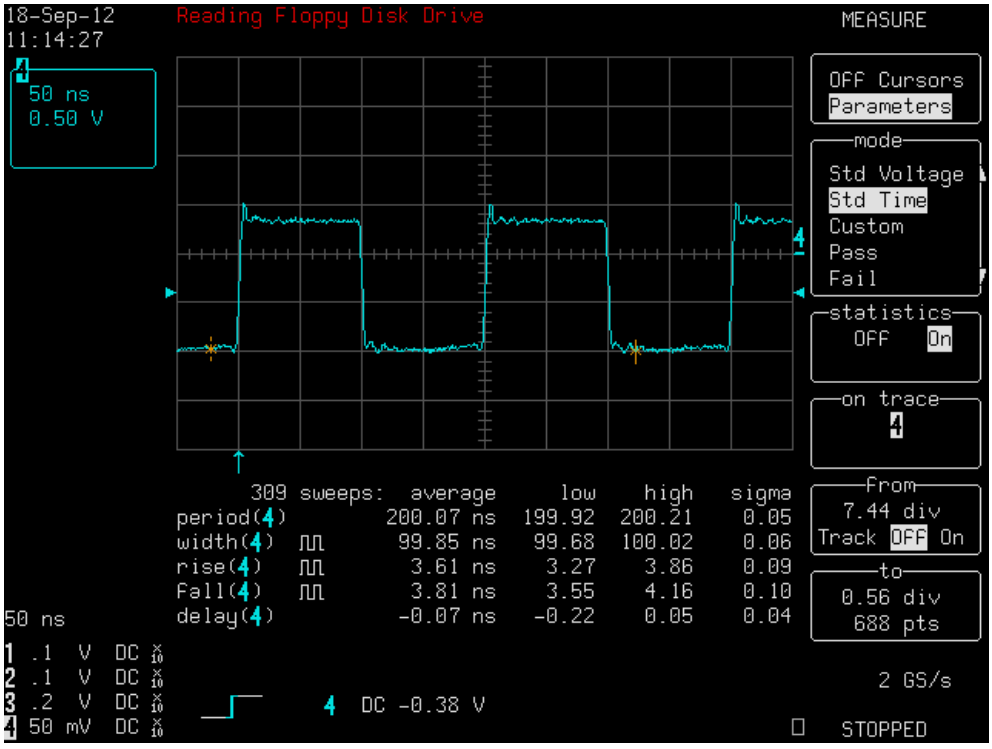


Figure 8 Output of pulse generator when connected to RCR50. Period is 200 ns and pulse width is 100 ns with minimum overshoot and a fast rise time of 3.61 ns.

Figure 9 shows the spectrum output measured at the modified RCR50's antenna output port. The spectrum maintains the 5.8 GHz center frequency of the original RCR50 with a peak power of -4.5 dBm at 5.7986 GHz. The peak power was measured through a coaxial cable with loss of 5 dB at 5.8 GHz. So, the actual power at the antenna jack was 0.5 dBm. In the final construction of the lamp fixture, the connecting coax has a loss of 0.5 dB putting the power level at the antenna port at 0 dBm.

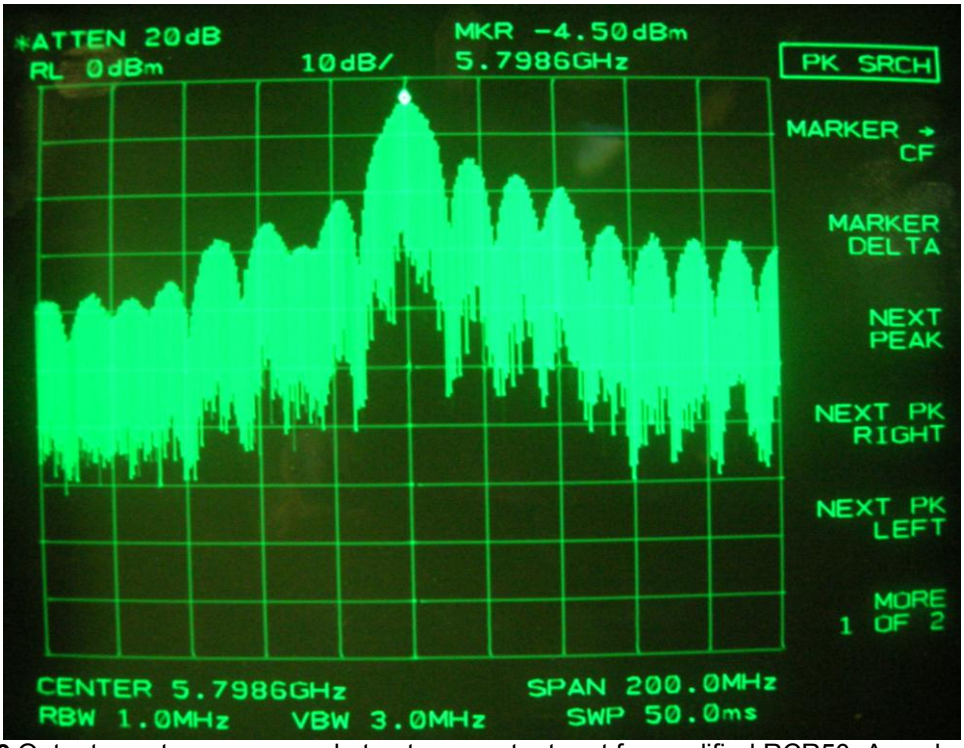


Figure 9 Output spectrum measured at antenna output port for modified RCR50. A peak power of -4.5 dBm was observed at 5.7986 GHz

Figure 10 shows the 3 axis electric field meter used to determine radar field strength at a distance. Figure 11 provides measurement results using the 3-axis field meter at a distance of 0.43 meters (left) and 0 meters (right). The 11 dBi antenna used in the final system was used in all tests and the radar output power was fixed. Comparing the measurement results of Figure 11 to the FCC's Maximum Permissible Exposure (MPE) limits in Figure 12, the measured values are well below limits. These measurements were made to provide a reference for the power density emitted by the radar and should not be considered as a complete safety test.

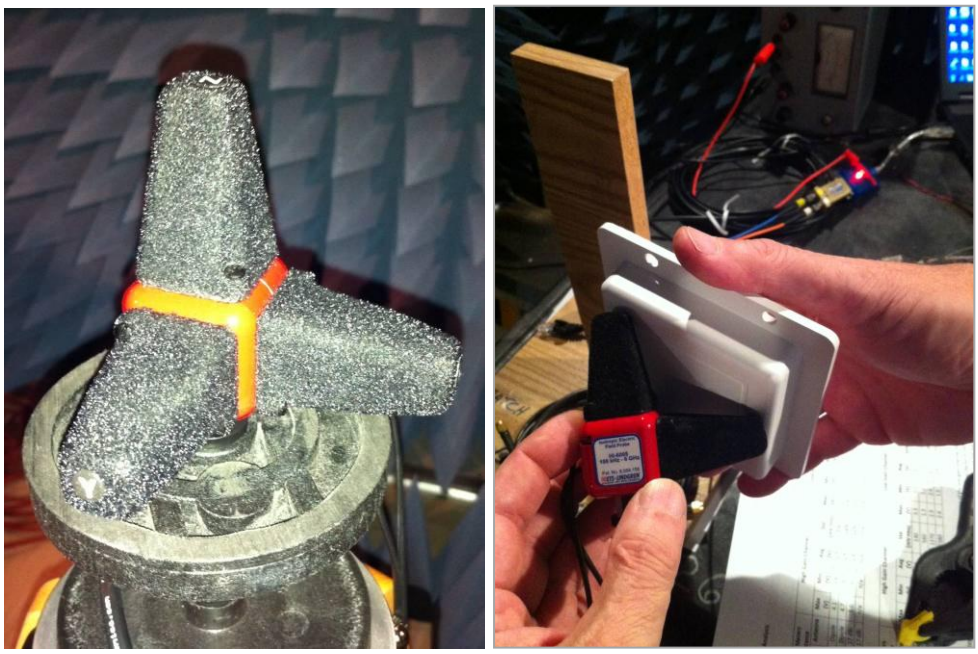


Figure 10 3-Axis electric field probe positioned on tripod (left), field probe as close as possible to the radar antenna

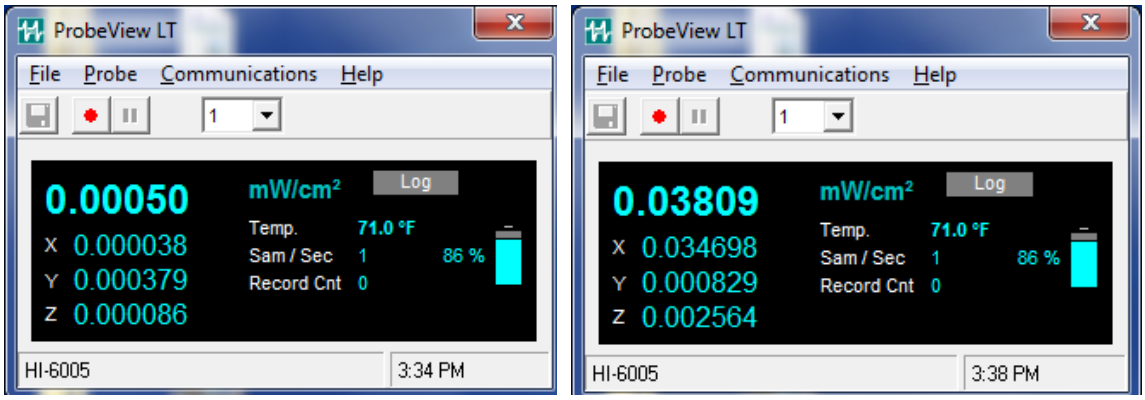


Figure 11 Field power density (0.5 μW/cm^2) measured at 0.43 meters (left), field power density (38.09 5 μW/cm^2) measured on top of antenna (right)

(B) Limits for General Population/Uncontrolled Exposure

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $|E|^2$, $|H|^2$ or S (minutes)
0.3-1.34	614	1.63	(100)*	30
1.34-30	824/f	2.19/f	($180/f^2$)*	30
30-300	27.5	0.073	0.2	30
300-1500	--	--	f/1500	30
1500-100,000	--	--	1.0	30

f = frequency in MHz *Plane-wave equivalent power density

Figure 12 FCC limits for maximum permissible exposure. The values highlighted in red are pertinent to the 5.8 GHz radar system. 1.0 mW/cm^2 is the maximum permissible value.

System testing in the UTRC electromagnetic anechoic chamber used a spherical conductive target provided by GRC as a reference. The target was used to verify that the high and low gain channel output of the radar met or exceeded sensitivity provided by the stock radar. Use of the target also allowed the output of the radar's high and low gain channels to be directly compared with the digitized output of the Arduino. Figure 13 provides a snapshot of the spherical target placed in the UTRC anechoic chamber. The target followed a circular path and rotated at a constant rate.

Figure 13 Initial testing using GRC provided spherical test target. The target was used to baseline radar performance and also to verify that Arduino-digitized data was correct.

With the radar pointed at this target, both the high and low gain channels were monitored using an oscilloscope directly connected to the radar as well as an Arduino which sampled and packetized the data for transmission to an Ethernet connected PC. The results of the target measurement are shown in Figure 14 and it can be seen that the oscilloscope (top) and Arduino (bottom) signals match.

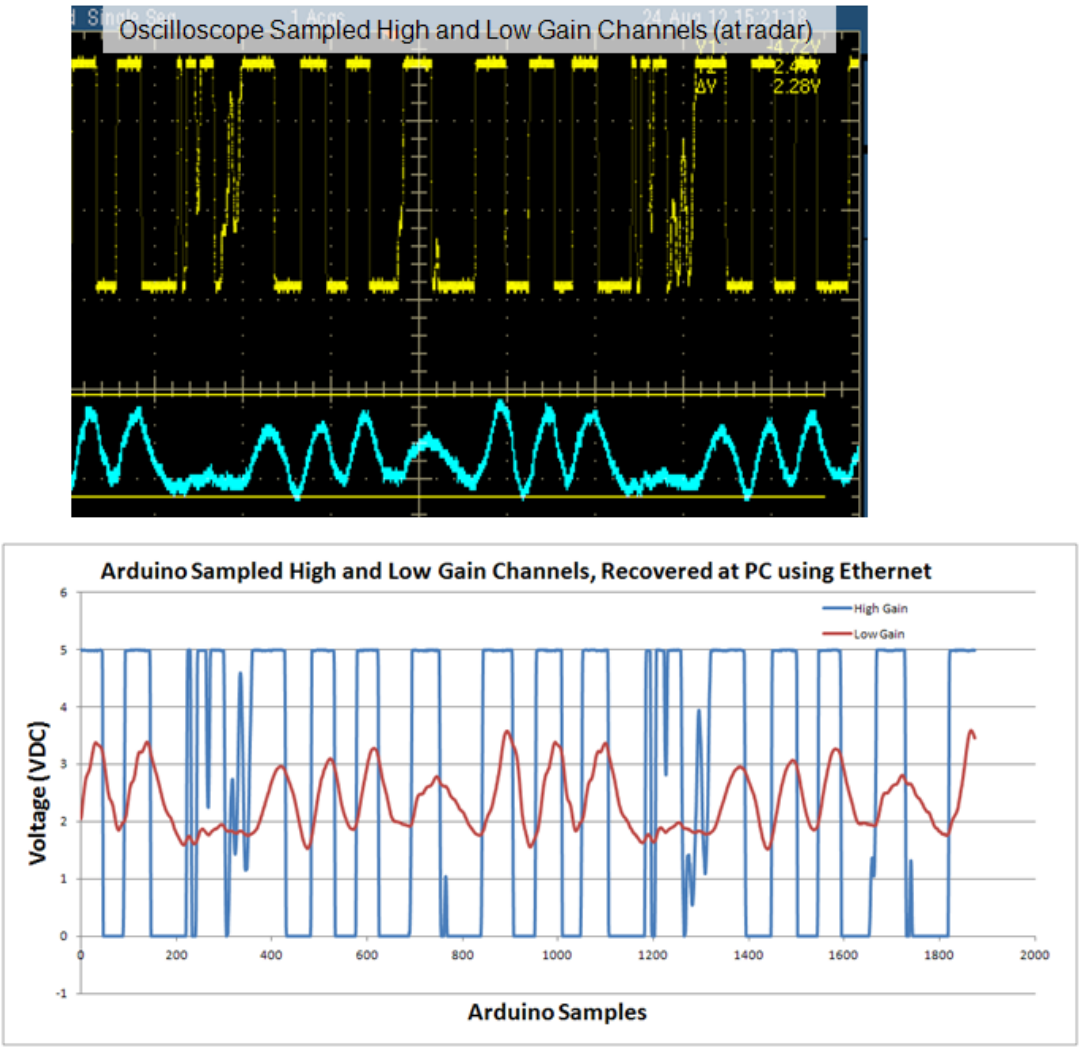


Figure 14 Comparison of high and low gain channels as recovered by direct measurement at radar (top) and after sampling and transport over Ethernet (bottom)

The next set of figures illustrates the final assembly of the fixture intended for in-cell installation.

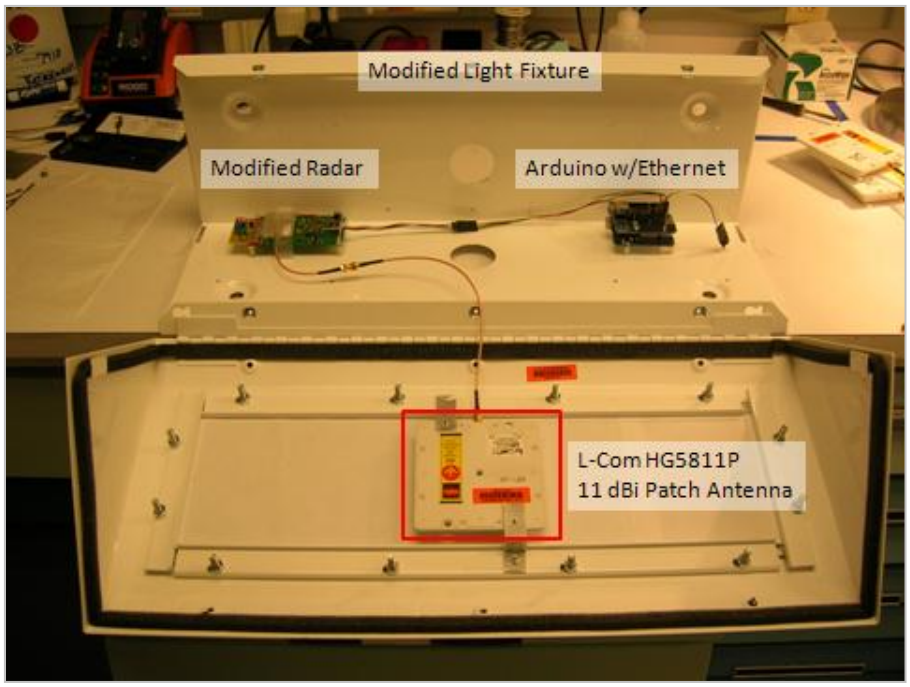


Figure 15 View of completed prison fixture showing rear of 11 dBi patch antenna, modified radar assembly and the Arduino used to transmit raw radar output over Ethernet

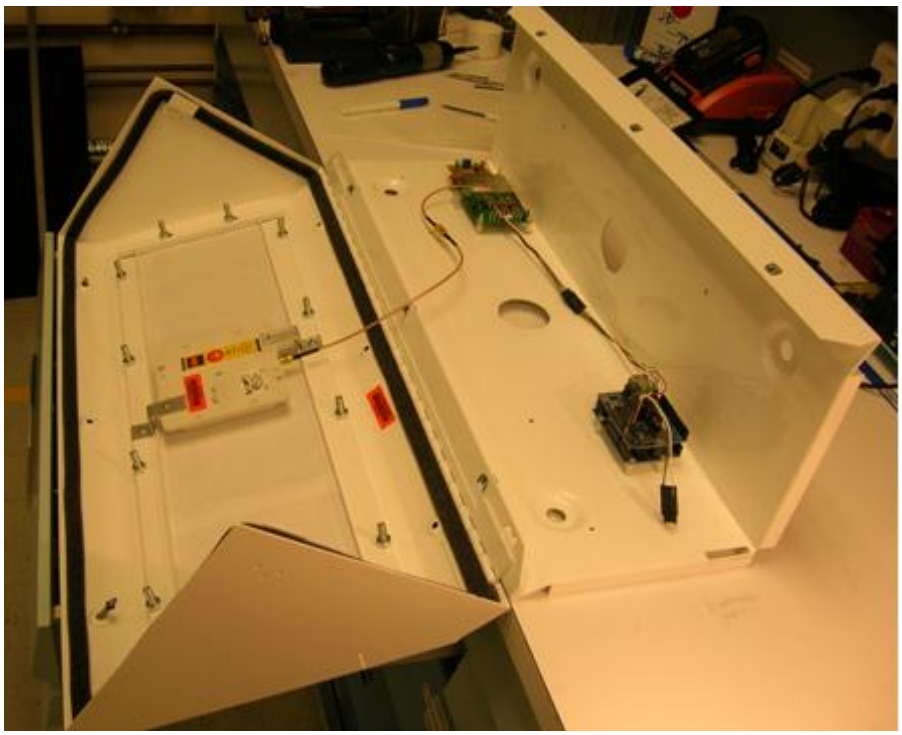


Figure 16 Side view of completed radar fixture

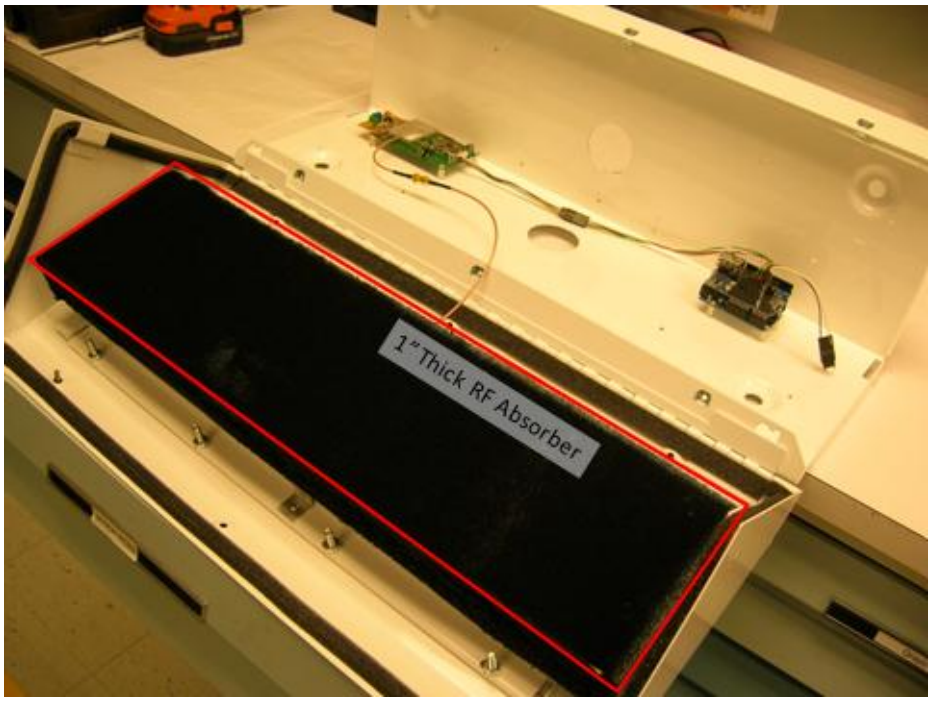


Figure 17 1" Thick RF absorber is installed immediately behind the 11 dBi antenna to absorb any backfire emissions from the antenna and to prevent that from reflecting inside of the lamp enclosure

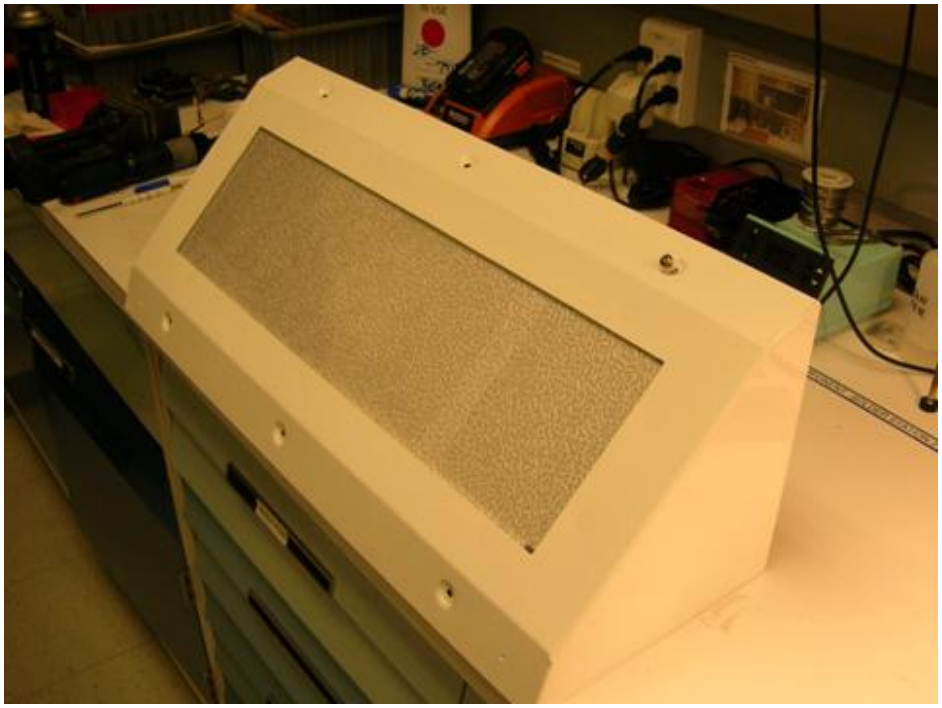


Figure 18 Closed radar fixture showing that radar system is not visible from the outside

5. Arduino Code

Listed below is the Arduino code used to sample the high and low gain channels of the radar and transmit the data over Ethernet via UDP.

```
#include <SPI.h>        // needed for Arduino versions later than 0018
#include <Ethernet.h>
#include <EthernetUdp.h>                // UDP library from: bjoern@cs.stanford.edu 12/30/2008

//#define USE_LED
//#define USE_DHCP
//#define USE_UTRC
//#define USE_STRING

#if defined(USE_UTRC) && !defined(USE_DHCP)
//#define USE_DHCP
#endif

#ifdef USE_LED
#define LED_PIN 13
#endif

#ifdef USE_UTRC
IPAddress serverIP(172,31,7,71);
#else
//IPAddress serverIP(192, 168, 1, 2);
IPAddress serverIP(192, 168, 1, 3);
//IPAddress serverIP(172,31,11,54);
#endif

#ifndef USE_DHCP
```

```
IPAddress localIP(192, 168, 1, 9);
#endif

const unsigned int serverPort = 8888;
const unsigned int localPort = 8888;

// An EthernetUDP instance to let us send and receive packets over UDP
static EthernetUDP Udp;

void setup()
{
#ifdef USE_LED
   pinMode (LED_PIN, OUTPUT);     // enable pin 13 for digital output
#endif

   // The IP address is an arbitrary IP address
   // byte mac[] = {0xDE, 0xAD, 0xBE, 0xEF, 0xFE, 0xED };

   // This is the address in the back of the Ethernet shield
   byte mac[] = {0x90, 0xA2, 0xDA, 0x02, 0x00, 0x3A};

   Serial.begin(9600);
#ifdef USE_DHCP
   if(Ethernet.begin(mac) == 0) { // start ethernet using mac & DHCP
      while(true) {  // no point in carrying on, so stay in endless loop:

      Serial.println("Failed to configure Ethernet using DHCP");
      }
   }
   delay(1000); // give the Ethernet shield a second to initialize
#else
```

```
    Ethernet.begin(mac, localIP);
  #endif
    Udp.begin(localPort);

    IPAddress myIPAddress = Ethernet.localIP();
    Serial.print("This IP address: ");
    Serial.print(myIPAddress);
    Serial.print("This IP address: \n");
  }

  // buffers for receiving and sending data
  static char packetBuffer[UDP_TX_PACKET_MAX_SIZE]; //buffer to hold
incoming packet,
  static int ledState = HIGH;
  static unsigned int count = 0;
  static unsigned short seqNum = 0;
  void loop()
  {
    short v0 = analogRead(A0);
    short v1 = analogRead(A1);

   #ifndef USE_STRING
    unsigned short *p = (unsigned short*) packetBuffer;
    p[0] = seqNum++;
    p[1] = v0;
    p[2] = v1;
    Udp.beginPacket(serverIP, serverPort);
    Udp.write((const uint8_t*)packetBuffer, 6);
    Udp.endPacket();
   #else
    sprintf(packetBuffer, "%u,\t%d,\t%d\n", seqNum++, v0, v1);
```

```
    Udp.beginPacket(serverIP, serverPort);
    Udp.write(packetBuffer);
    Udp.endPacket();
//Serial.print(packetBuffer);
#endif
    delay(10);

#ifdef USE_LED
    if(count++ % 100 == 0){
        ledState = (ledState == HIGH) ? LOW : HIGH;
        digitalWrite (LED_PIN, ledState);
    }
#endif
}
```

6. Selected Component part number list

Below is a short list of components used in the system which may not be readily found through inspection of the system itself.

Component	Manufacturer	Part Number
Antenna	L-Com	HG5811P
Arduino (MCU)	Arduino	A000066
Arduino (Ethernet)	Arduino	A000075
Enclosure	Kenall Lamp	CC 2 1/1 1 17 RS 1 120 3/G 1

7. Summary

A radar systems based on the range controlled Doppler radar in a COTS motion sensor was modified and outfitted with a high performance, small form factor pulse generator circuit to provide the required performance required for

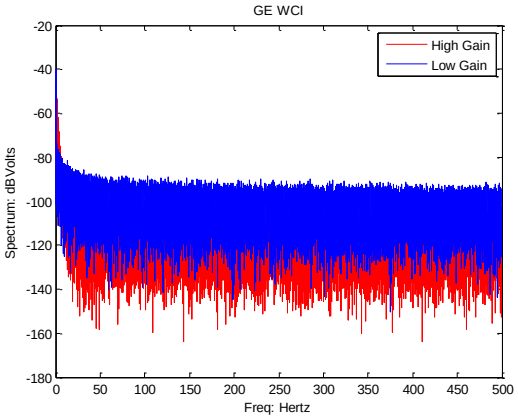
unobtrusive life sign monitoring of prison inmates. The radar system along with a small processor and wired communication module was housed in a prison-approved light fixture to ensure the system is readily installable and provides robust communication of the system to the central processing station.

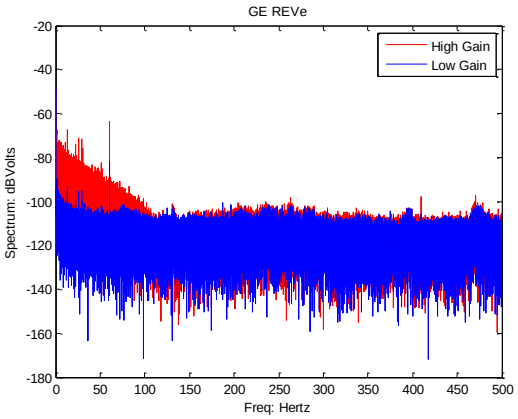
Appendix D2 – RCR Validation and Testing at GEGRC

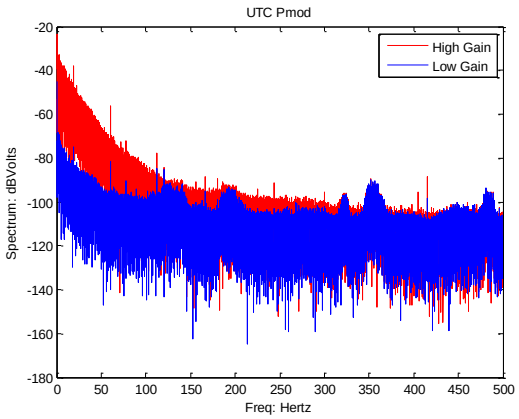
In investigating the limited performance of the UTC modified units, it was discovered that although the UTC units were modified in accordance with the spec provided by GE, there were differences in the units GE had used internally and at WCI. The spec's provided to UTC were based on an in-house unit GE was using for short range experiments (using a 20 ns pulse at less than 1% duty cycle) vs. the actual unit GE had used in prior testing at WCI (100 ns pulse at 50% duty cycle). The differences in design are summarized below:

Circuit	**GE WCI** **(rev D)** **Unit as tested at WCI**	**GE RevE** **Unit as used for UTC Spec**	**UTC #3** **(Pmod)** **Unit as provided by UTC**
Antenna	11 dBi in enclosure #3	11 dBi in enclosure #3	11 dBi in enclosure #3
RF Output Power	+3.5dBm	-15dBm	+7.5 dBm
IF Circuits	Stage 1 Ri=22K Ci=80uF Rf=1M Cf=90,000pF Stage 2 Ri=22K Ci=80uF Rf=680K Cf=90,000pF	Stage 1 Ri=22K Ci=220uF Rf=1M Cf=2,000pF Stage 2 Ri=22K Ci=220uF Rf=500K Cf=2,000pF	Stage 1 Ri=22K Ci=150uF Rf=2.2M Cf=1,000pF series with 22K Stage 2 Ri=22K (10K + 12K pot) Ci=150uF Rf=2.2M Cf=1,000pF series with 22K
50/60 (100/120) Notch Filter	60 Hz with 1 uF coupling	60 Hz with 1 uF coupling	60 Hz with 0.1 uF coupling
Pulse Generator	Agilent 33220A 5 MHz, 50% duty 1.55 Vpp, -725 mVoff	Internal – factory with second pulse disabled, 20 ns, 11 kHz PRF	External – custom circuit made by UTC to mimic Agilent settings
DAQ	Arduino in parallel with Biopac	Arduino in parallel with Biopac	Arduino in parallel with Biopac
DC Power	9V from Arduino PoE	9V from Arduino PoE	9V from Arduino PoE

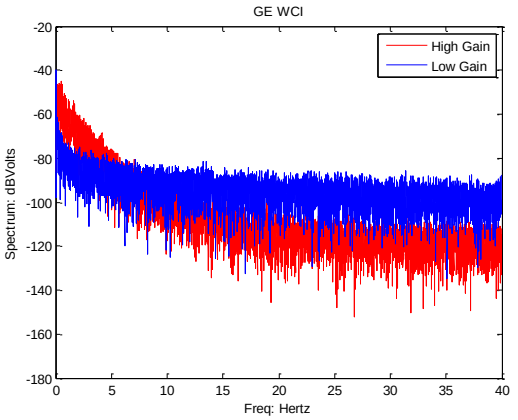
In observing the spectra for noise input, we see the GE WCI unit was much quieter than the GE unit from which the specification was derived and than the WCI modified units.

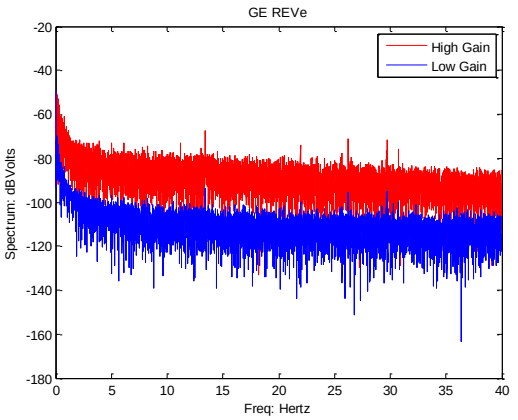


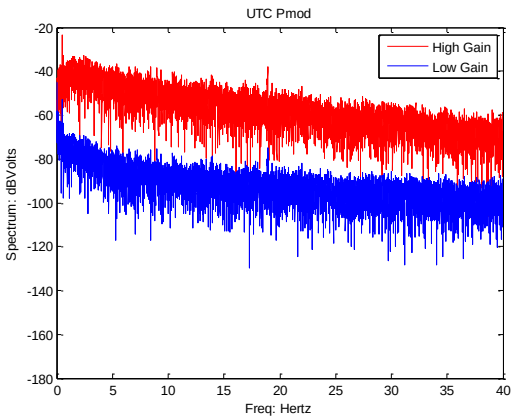




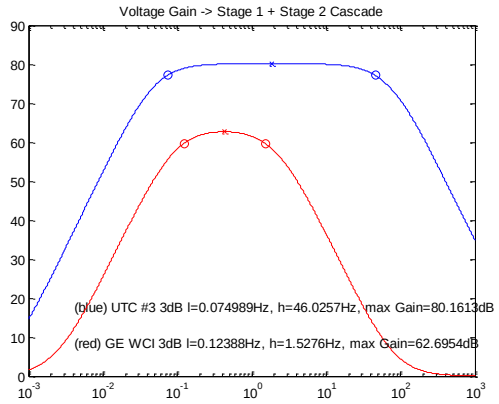
Looking closer at the spectra below 40 Hz, we see that the UTC unit also loses very low frequency gain in the high gain channel.

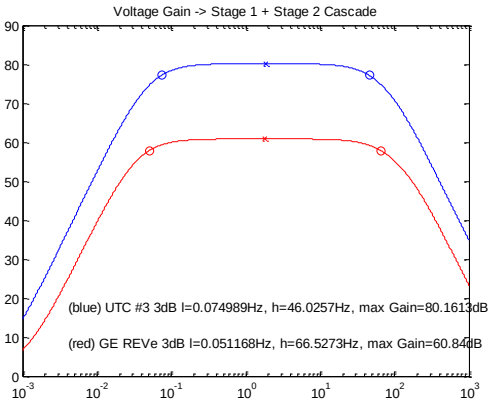


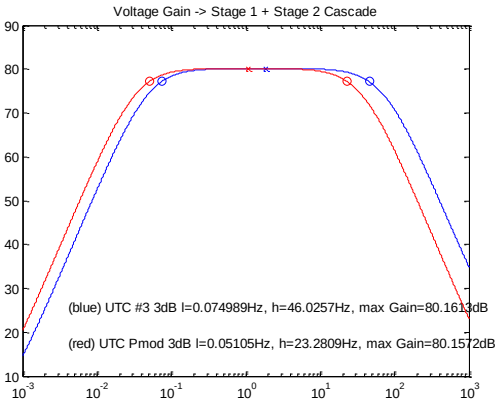




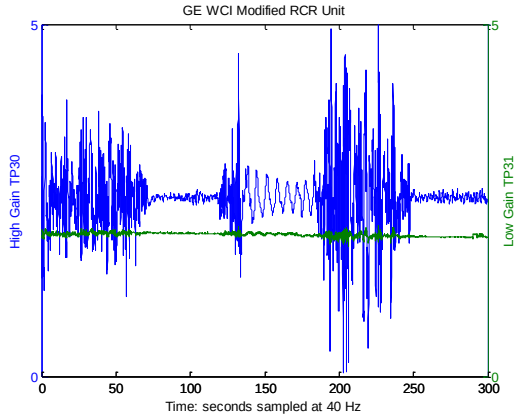
The calculated filter responses indicate that although UTC met the spec GE provided, the spec inadequately represented the actual unit that GE had tested at WCI.

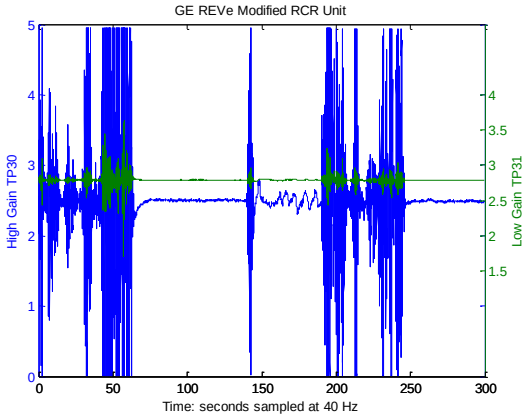


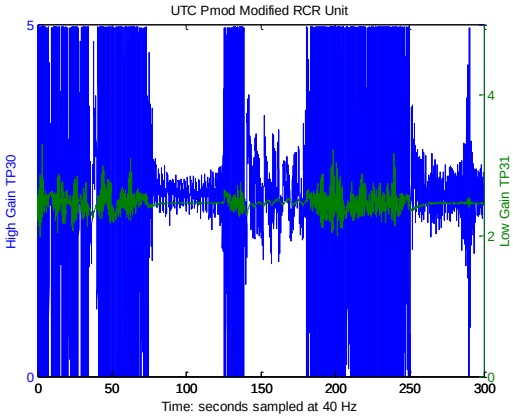




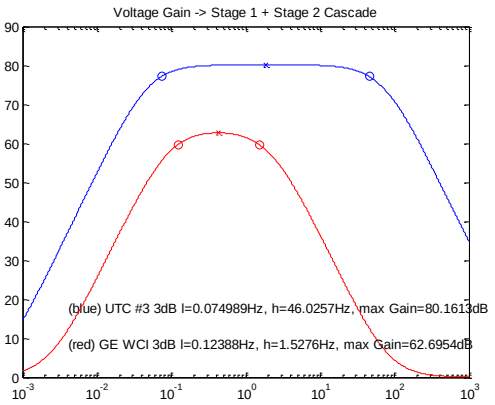
The effect of the differences is seen in the traces of activity (motion -> empty -> motion -> breathing -> motion – empty) in that the UTC units do not provide visibility signal quality.

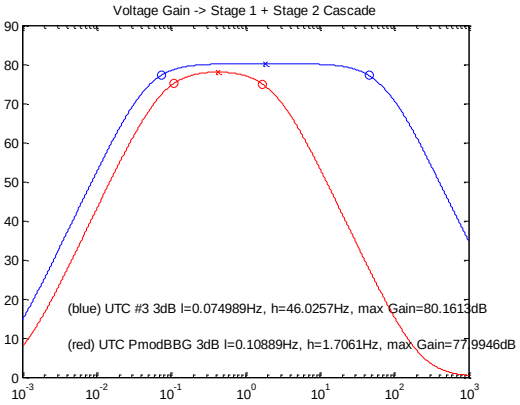






After final modifications, including increasing the gain to compensate for the Arduino input range, the characteristics are as follows:

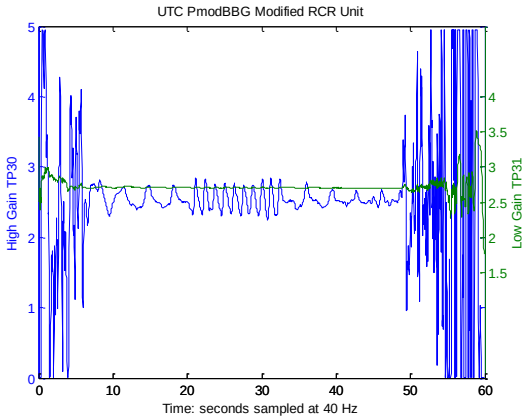


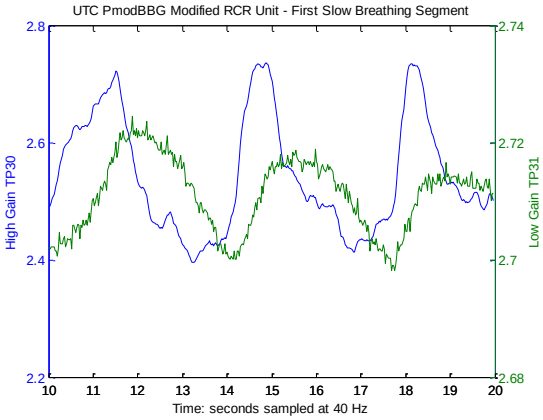


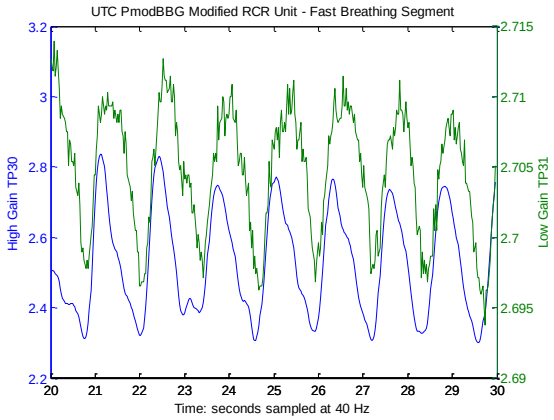
Circuit	**UTC PmodBB**	**UTC PmodBBG**
IF Circuits	Stage 1 Ri=22K Ci=94uF (47+47) Rf=1M Cf=100nF Stage 2 Ri=22K Ci=94uF (47+47) Rf=680K Cf=100nF	Stage 1 Ri=22K Ci=94uF (47+47) Rf=2M Cf=33nF Stage 2 Ri=22K Ci=94uF (47+47) Rf=2M Cf=33nF

The observed data now looks reasonably strong and recognizable but still loses some low frequency response in the high gain channel which can be improved by changing the coupling cap from 0.1 uF to 1 uF.

One Minute of data with 0.1 uF: motion -> slow breathing -> fast breathing -> slow breathing -> motion







One Minute of data with 1.0 uF: motion -> slow breathing -> fast breathing -> slow breathing -> motion **(Final Configuration)**