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Standoff Through-the-Wall Imaging Sensor

OJP Grant Final Report

AKELA OJP Grant No: 2007-RG-CX-K016

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This AKELA Draft Final Report is submitted to the OJPs Office of the Comptroller describing DOJ NIJ Grant activities during the Period of Performance Aug 07 – Jan 10 for OJP Grant 2007-RG-CX-K016

Table of Contents

ABSTRACT

The National Institute of Justice (NIJ) and the Department of Defense (DoD) have sponsored AKELA's development of an ultra-wide band radar system to produce an imaging sensor capable of both mapping the internal structure of a building, and locating personnel inside the structure. This capability provides increased situational awareness, in both peace keeping and law enforcement operations, where there is a need not only to determine if there is someone inside a building, but also determine their location and movement within public and correctional buildings. These situations arise during searches for suspects, prisoners, hostage and barricade incidents, and tactical surveillance. While, in many cases, the object is to make contact with a suspect to defuse a potentially violent situation, unfortunately, most operations conclude with physical search and law enforcement (LE) personnel are subject to a high possibility of physical harm.

AKELA's NIJ grant through-the-wall imaging sensor development effort consisted of two phases, in Phase 1 a significant benefit in radar H/W and S/W design was realized by leveraging prior and current AKELA DoD efforts. A baseline NIJ radar imaging system was designed and its performance assessed during laboratory testing. One critical area identified in Phase 1 was the potential program risk of FCC certification.

Phase 2 leveraged Phase 1 results in the area of system design, performance, cost reductions, FCC certification, and LE practitioner evaluation. Technology results included: multiple sensor performance, system, and radar cost reduction analysis, and exploration of alternate FCC certification options. At the end of Phase 2 an imaging sensor system was available that meets operational needs for law enforcement operations.

AKELA's efforts have led to the development of a small, portable imaging prototype system. The system is capable of being quickly deployed with a weight of 17 lbs, has the ability to be operated remotely through either a wired or wireless Ethernet link under battery power for two hours, and is easy to use with control and display functions performed by an off-the shelf laptop computer. Tests of the system have shown that it is capable of imaging the interior of a building, and detecting motion through multiple internal walls and reinforced concrete exterior walls from a standoff range of 30 meters.

1.0 Executive Summary

Hostage rescue, building surveillance, building clearance, and building search operations are a difficult challenge for law enforcement because of reduced situational awareness - a challenge shared by U.S. military forces during hostile urban operations. While early development of through-the-wall detection and imaging systems was supported by the intelligence community, most recent technology development in this area has been focused on LE and military peacekeeping operations. Table 1 describes the operational issues and benefits that through-the-wall surveillance provides for increased situational awareness for both military and law enforcement applications.

Table 1. Through the Wall Surveillance Increases Military and LE Operational Situational Awareness
• Domestic law enforcement and military missions beginning to merge – Active defense domestically – Peacekeeping internationally – Rules of engagement similar • Better tactical surveillance reduces probability for violence – Search, hostage, and barricade incidents – Provides better options for intervention • Personnel safety and operational effectiveness is improved if information of interior features and locations of individuals are available – Implies need for standoff imaging system • The nature of currently available technology and implementation place operational constraints on effectiveness (size, weight, and cost) • Cost effective, reliable solutions for these missions are required

Table 1 Through-the-Wall Surveillance Increases Operational Situational Awareness

The critical technology that enables standoff through-the-wall radar imaging has been the development of a small, low power, software controlled radar sensor module, shown in Figure 1. Software control of the radar allows the user to control emissions both to tailor sensor performance to specific operational requirements, and to simplify compliance with spectrum management regulations. A summary of its capabilities is shown in Table 2.

Figure 1 Single Board Low Power Radar Sensor Module

Table 2. Radar Sensor Operating Characteristics

• Emission – stepped CW
• Frequency range – 20 to 2000 MHz
  – Digital control allows sensitive frequencies to be skipped during sweep
• Frequency hopping rate – 16 user selectable between 5 and 90000 hops per second
• Power input – 12 watts nominal
• Power output – 17 dBm nominal
• Interface monitors system health
  – Low battery warning, low voltage shutoff, over temperature
• Physical characteristics
  – 1.1 lbs: assembly and package
  – 4.25″ wide, 7.5″ long, 1.5″ thick
• Interface – 10/100 Base T Ethernet
  – Setup commands send to radar
• Reliability: 150,000 hours MTBF

Table 2 Stepped Continuous Wave (CW) Radar Sensor Operating Characteristics

Different systems can be configured using this single radar sensor as the common sensing element. Figure 2 shows a long range vehicle system, a short range robotic system, an independent sensor for a networked system, and a short range LE system. Shown in the center is the current single board radar, the key component of all the system variations. The modular nature of the radar allowed the development of special interface and antenna boards that facilitates the implementation of each system. Implementation of each system differs primarily in the number and types of radars employed, and the system control and communication link used. The long range system weighs 120 lbs and uses vehicle power, the short range robotic system weighs 12 lbs, and the short range LE system weighs 17 lbs. The short range systems both use eight AA batteries and operate continuously for a period of two hours.

Figure 2 Radar System Configuration Variations

AKELA's development and experimental activities on a large radar imaging system have demonstrated that the radar sensor has the ability to detect and image both large and small motions through walls of operational interest at significant standoff distances. A long range configuration supporting a DoD program, along with test results, is shown in Figure 3.

By applying the underlying radar technology that is the core enabling capability of these systems, and reconfiguring it specifically for LE application by trading off some performance for cost reductions, under this DOJ (NIJ) program, AKELA has developed a low cost, portable, through-the-wall imaging radar that provides law enforcement personnel the ability to detect, locate, and track individuals in buildings constructed with common building materials, including steel reinforced concrete. The program goals are listed in Table 3. Since the radar hardware has its development heritage in law enforcement applications, it has been designed to be inherently low cost and low risk in meeting program cost objectives.

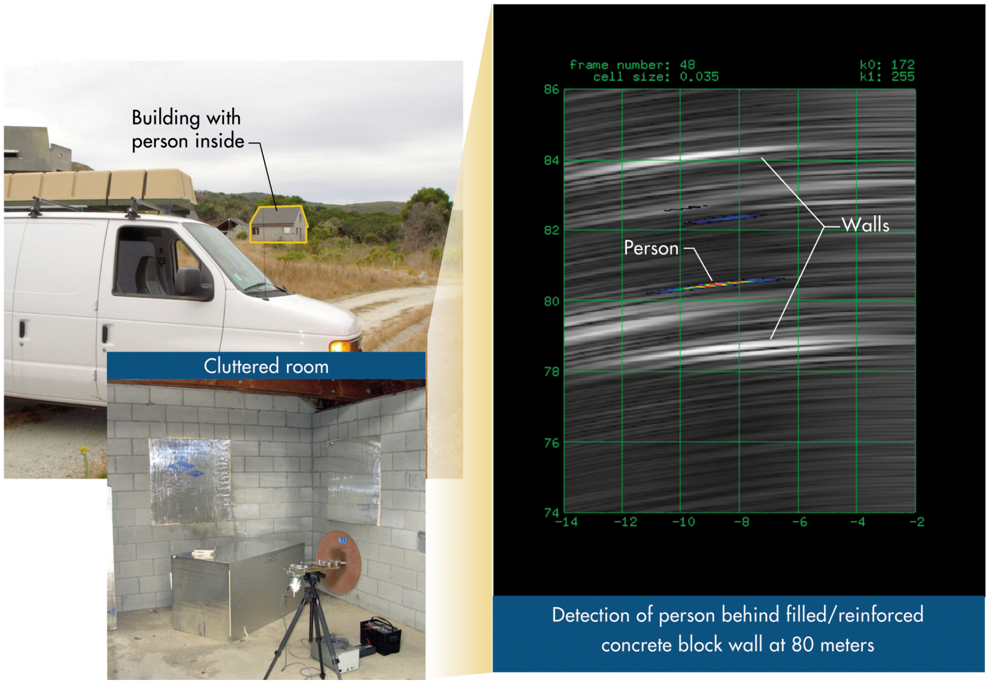


Figure 3 Long Range Radar Imaging System Test Configuration and Test Verification Results

Table 3. NIJ Through-the-Wall Radar Imaging System Program Goals and Benefits		
Feature	**Performance**	**Operational impact**
Weight	~ 15 lbs	Easily carried
Size	54" X 15" X 5"	Fits in car trunk
Power	8 AA batteries	Cost effective operation
Operating time	2 hours continuous	Long mission time
Reliability	150,000 hrs MTBF	Low maintenance Long life
Temperature	-20 C to 50 C	Operational in all environments
Range	30 meters	Through 8" concrete block wall, arbitrary standoff
Image update	Four times per second	Captures both slow and fast motions
Radar control	All digital	No adjustments required
Radar communication	Wired or wireless Ethernet	Remote operation
Cost	Goal: ~ $5000	Affordable

Table 3 NIJ Through-the-Wall Radar Imaging System Program Goals and Benefits

As a direct result of the efforts made under this program, small, portable imaging prototype system was developed and configured, shown in Figure 4. The systems weigh 17 lbs, can be operated remotely through either a wired or wireless Ethernet link, and can operate under battery power for two hours. Performance testing was conducted with the system throughout the program on a variety of structures and in multiple configurations. The test results were used to direct developmental efforts.

AKELA has demonstrated with these systems the capability to image the interior of a building, and detect simulated motion of both stationary and moving individuals through multiple internal walls and reinforced concrete exterior walls at upwards of 30 meters. The sensor control and display functions are performed by an off-the shelf laptop computer.

After FCC approval the prototype units will be evaluated by LE personnel for performance assessment, operational utility and recommended deployment modifications.

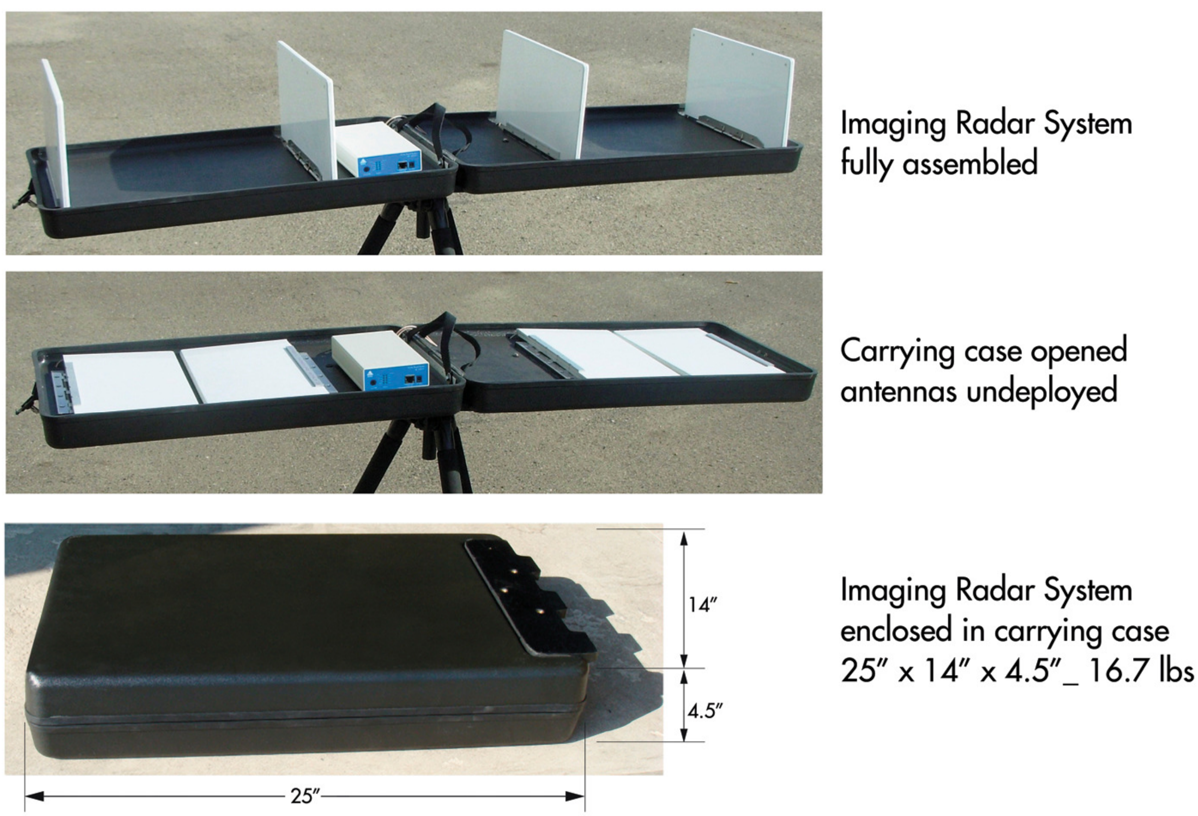


Figure 4 Through-the-Wall NIJ LE Surveillance Imaging Radar System Prototype

AKELA's NIJ grant through-the-wall imaging sensor development effort consisted of two phases, in Phase 1 a significant benefit in radar H/W and S/W design was realized by leveraging prior and current AKELA DoD efforts. A baseline NIJ radar imaging system was designed and its performance assessed during laboratory testing. One critical area identified in Phase 1 was the potential program risk of FCC certification.

Phase 2 leveraged Phase 1 results in the area of system design, performance, cost reductions, FCC certification, and LE practitioner evaluation. Technology results included: multiple sensor performance, system, and radar cost reduction analysis, and exploration of alternate FCC certification options. At the end of Phase 2 an imaging sensor system was available that meets operational needs for law enforcement operations. Concurrent AKELA internal and DoD R&D efforts that have been developing and testing through-the-wall radar system using the NIJ radar sensor design, provided valuable additional information on: 1) the comparison of human subject testing data and breathing machine data and 2) radar sensor performance data on complex building structures.

2.0 AKELA NIJ Grant Background, Goals, and Objectives

Hostage rescue, building surveillance, building clearance, and building search operations are a difficult challenge for LE and correctional institutions due to reduced situational awareness - a challenge shared by U.S. military forces during urban operations. While early development of through-the-wall detection and imaging systems was supported by the intelligence community, most of the recent technology development in this area has been oriented toward LE and peacekeeping operations, and has been supported mainly by the NIJ and DoD. The results of AKELA's participation in NIJ's through-the-wall technology development activities attracted the attention of the DoD in 2004 and resulted in an investment that has significantly advanced the state of the technology.

DoD funding allowed the development of a family of systems for soldier, robot, and mobile vehicle mounted operation that have the capability to work cooperatively. The field ready prototypes are assembled using a common, small, low power, and low cost radar module that has been environmentally hardened and demonstrated to have a MTBF of 150,000 hours. The maximum range of each system is a function of its configuration, with the large vehicle mounted system having demonstrated the capability to detect and locate a stationary person in concrete block structures at a distance of 100 meters. This distance is greater than most LE requirements and the cost of the system used to achieve it is beyond the range of most LE agencies.

Just as the military capitalized on the investment made by NIJ to enable the development of these systems, the current grant has leveraged DoD's recent investment. By employing the underlying radar technology that is the basis for these systems, and reconfiguring it specifically for LE application by trading performance for cost reductions, it is possible to provide a low cost, portable, through-the-wall imaging radar providing LE personnel the ability to detect, locate, and track individuals in buildings made of common building materials including steel reinforced concrete.

The major objectives of the NIJ grant were to redesign the radar sensor module to reduce its manufacturing cost, develop a system package suitable for operational LE deployment, perform system evaluations in concert with law enforcement agencies to identify improvements, incorporate those improvements into the system design, and address the issues that need to be solved in order to ensure that the system can be compliant with the Federal Communications Commission (FCC) requirements for civilian LE use.

Grant goals were to provide an easy to use, battery operated, portable system, weighing less than 15 lbs, with a total system cost of less than $5,000. The system was to be capable of detecting targets through an 8" thick concrete block wall at a range of at least 30 meters, be controllable by a wireless radio to allow remote deployment, and produce images identifying stationary and moving individuals at four frames a second. Providing a robust, low cost imaging system will allow even small LE organizations to increase situational awareness and gain tactical advantage while conducting urban surveillance.

3.0 Technical Approach

AKELA's technical approach encompassed:

- Incremental development of a radar sensor system through iterative testing and design modifications
- Modeling and simulation efforts employing actual sensor hardware (Hardware in the Loop) to achieve high confidence in predictive performance
- Focus on SWAP in trades and analysis efforts for LE deployment
- Leverage DoD investments in sensor design, development, and testing
- Initiation of FCC certification interface early in grant timeline to understand requirements and the certification process
- Consistent feedback loop through user evaluation as a key driver to grant success; LE practitioner interface, acceptance, and feedback for product improvement are critical components of task

3.1 Summary of Phase 1 Tasks

Tasks	Activities	Status
System Design for Law Enforcement	Design for low cost manufacturing	• Single board radar completed • Custom system enclosure manufactured • 4 antenna switch implemented
	Refining performance of standoff array	• Time Division Duplex (TDD) board incorporated • Antenna optimization completed (PR 2 Documentation)
	Package configuration	• Weather resistant lightweight packaging manufactured
	FCC certification	• Simulations and AKELA lab tests completed • Range restrictions for operating conditions identified • Initial interfaces established, requires NIJ coordination
Processing and Display	GUI design	• Initial interface design complete for LE evaluation
	Implementation / refinement	• Baseline operating parameters defined
	Control optimization	• Completed and benched marked
Law Enforcement Evaluation	Evaluation unit assembly	• Three NIJ units assembled and acceptance tested
	Evaluator familiarization	• Initiated Sep 08, final interface with users Jan 09
	Field Evaluation	• Multiple interfaces, Phase 2 Feb 09 for LE evaluation

Table 4 Phase 1 Task Results Summary

The tasks and activities associated with AKELA's Phase 1 effort are summarized in Table 4, and discussed in detail in the following narratives.

3.2 Phase 1 System Design for Law Enforcement

In Phase 1, the task of designing the system for law enforcement was intended to ensure that AKELA's research and development efforts yield a cost-effective, field-ready end product that will prove useful in urban operations. One of the main objectives was to design the array with low cost manufacturing in mind at the outset. AKELA has consolidated the existing multiple-board radar, currently used in systems for the military, to a single board radar configuration, resulting in a significant reduction in assembly cost while incurring no performance penalty. In addition, the implementation of the 4-antenna switch allows a single radar to control all four antennas instead of requiring one radar for every antenna. With these modifications and system reconfigurations, the cost of the radar-only portion, which is the major cost driver for the overall system cost, has been reduced from $5000 to around $1500. The overall cost to produce such a prototype system is estimated to be around $9500. Throughout both phases of this program, AKELA has continued to investigate the cost savings associated with adjustments to hardware components, and has kept track of the tradeoffs by using an internal inventory database. Realistically, it has become increasingly difficult to further reduce the cost of the system without compromising performance. However, during the two phases of this program as well as in other ongoing contracts with the DoD, AKELA has been investigating alternative system configurations that may be significantly cheaper to produce.

Designing a system that would prove useful for law enforcement also relies on characterizing and refining the performance of the standoff array. To enhance the signal-to-noise performance, AKELA designed and completed the Time Division Duplex (TDD) board to control the durations of transmit and receive pulses on the radar, thereby allowing the user to receive only during a time window of interest and effectively reducing the effect of direct paths and known close-range obstacles in the field. The TDD board has been extensively tested and shown to yield significant improvements in target detection. However, during subsequent field testing of the imaging array, it was discovered that even without the use of the TDD board, the system was able to detect stationary breathing targets through two concrete walls at a target distance of up to 22 meters. Although the 4-antenna switch is currently located on the same board as the TDD, whether the TDD circuitry remains a necessity for urban applications with standoff distances no greater than the width of a street is worth investigating in the tradeoffs associated with cost reduction.

In addition to the development and testing of the TDD board, antenna optimization activities have persisted throughout AKELA's Phase 1 effort. Experiments were conducted to measure the antenna radiation patterns, and based on the findings the antenna designs were then iteratively modified such that the antenna directivity was improved. With the latest version of the antenna, the antenna design has been optimized such that clutter objects behind or to the sides of the imaging array would be suppressed in the image reconstruction.

Obtaining FCC certification for the imaging array to ensure that the end product could be used in urban applications is central to the task of designing the system for law enforcement. During the

Phase 1 effort, AKELA conducted in-house measurements of the radar's radiated emissions according to FCC's test guidelines, and determined that the power of the system in the normal operating mode, without any mitigating methods, exceeded the limits set by the FCC for ultra wideband, through-wall devices. The objective of further Phase 1 activities was then to make use of the software-controlled nature of the radar and experiment with restricting the operating parameters, in conjunction with introducing a frequency offset between sweeps, in order to reduce the radiated emissions. The reduction in emission level achieved using the sweep-offset method was significant. With the encouraging results of greatly reduced emissions, AKELA submitted an inquiry to the FCC describing how the mitigation scheme has been implemented along with the new radar emission levels, but the FCC ruled that based on this description of radar operation and the proposed mitigation scheme, AKELA's system would be treated as a swept frequency device. This means that during the compliance testing process, any frequency hopping ability would have to be suspended. AKELA received word of the ruling in November 2008 as Phase 1 was coming to an end, so objectives for the Phase 2 effort were adjusted and reorganized accordingly in order to explore alternate FCC licensing options.

3.3 Phase 1 Processing and Display

The task to optimize the imaging system's processing and display functions was intended to tailor the system according to the needs of law enforcement users. AKELA approached this task by first designing a graphical user interface that streamlines the powerful but complex software AKELA currently uses for radar development purposes. Any status or viewing windows relevant to a LE user, such as the image or texture windows which show the image reconstruction, would appear automatically on screen at startup, while the software capabilities normally reserved for analysis and troubleshooting would be hidden. The redesigned GUI aims to simplify the data acquisition, file saving, and data replay processes to one-click operations wherever possible. In order to accomplish this, AKELA performed a series of experiments in order to determine the optimal operating parameters in situations and at standoff distances typically encountered by law enforcement users in urban settings. The intent was to select certain settings for all evaluation units beforehand so that the law enforcement user would no longer have to configure these parameters before data collection could begin. These parameters include the start and end frequencies of each data sweep, the frequency step size, the data sampling rate, and the detection algorithm resulting in the best image reconstruction.

Efforts were conducted to implement and test a separate detection algorithm devised specifically for the NIJ standoff array. Two factors led to this separate algorithm: 1) In the process of obtaining FCC certification, the end product, the operating parameters had been restricted and differing from the normal AKELA's radar configuration for military applications, such that previous detection algorithms would no longer performed optimally, and 2) it was desirable to develop an algorithm specialized for detecting stationary but breathing targets. In Phase 1, AKELA developed and tested this breathing algorithm, as an addition to existing algorithms, and customized it to suit the operating characteristics of the NIJ standoff array. The algorithm was refined during Phase 2 to reduce the occurrence of noise in image reconstruction.

The results of preliminary testing seemed to indicate that a set of so-called optimal operating parameters is not clearly defined for several reasons: 1) the start and stop frequencies and the frequency step were specifically chosen to allow the system to pass FCC certification testing as a through-the-wall device under Part 15 Subpart F of the FCC rules, but with FCC's ruling that the proposed frequency hopping method to reduce radiated emissions would need to be suspended during compliance testing, AKELA would need to investigate alternate methods to obtain FCC certification, and therefore the restriction on frequency band and frequency step may no longer apply; 2) there may often be more than one setting that works well for a certain test situation; and 3) a small change in the test setup or the type of target to be detected may unexpectedly make one setting perform better than another. In the course of the Phase 1, AKELA, came to the conclusion that rather then providing a single set of optimal system parameters set 'in stone' the evaluation units and the copies of software would be shipped with a default configuration based on optimal parameters, however the user would be allowed to control and change these settings. This allows the user to start using the standoff system immediately but still grants the user the flexibility to test alternate settings that may improve system performance in certain situations. At the end of Phase 1, access to several of the viewing windows has been folded into the software platform so as not to obscure what would eventually become a streamlined LE user interface, yet the software still retains all functionalities.

3.4 Phase 1 Law Enforcement Evaluation

With system and interface optimization activities consuming most resources in Phase 1 and radar modifications continuing, the assemblies of the LE evaluation units were delayed. Contact was made with the Los Angeles Sheriff's Department at the beginning of Phase 1, but scheduling difficulties and the decision to wait to incorporate radar modifications into the evaluation units led to a schedule delays for LE evaluation.

4.0 Summary of Phase 2 Tasks

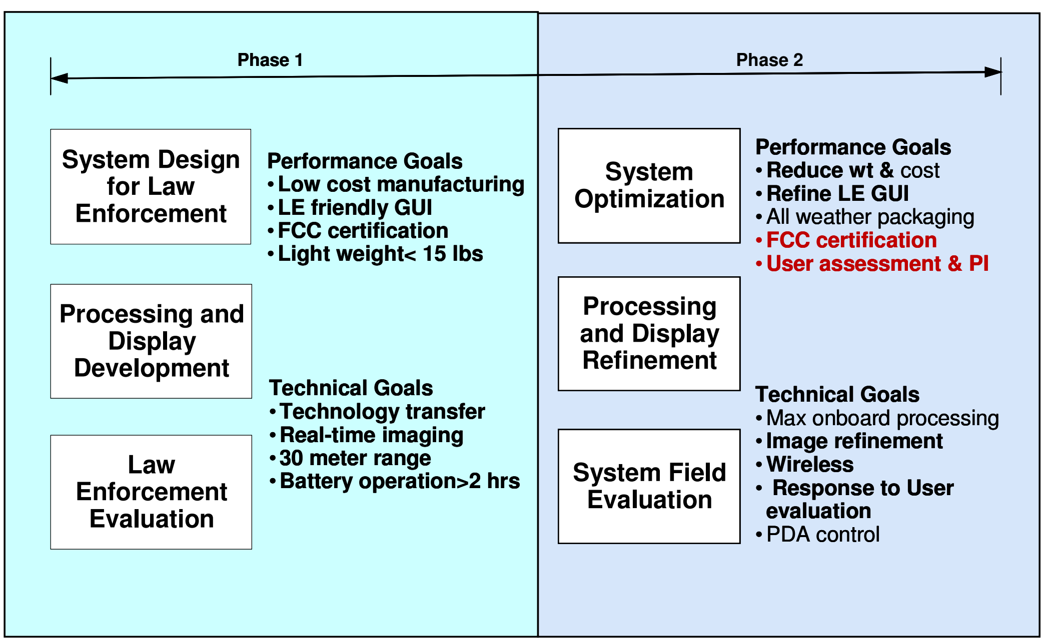


Figure 5 Summary of grant tasks and goals

The tasks and goals associated with AKELA's Phase 2 effort are summarized in Figure 5. In order to allocate more resources and push obtaining FCC certification to the highest priority, as well as continue with user assessment and product improvement, it was necessary to scale back on a few of the planned activities including cost reduction, all-weather packaging for the system, and onboard processing with handheld device control.

4.1 Phase 2 System Optimization

In Phase 2, as part of the task to optimize the system, AKELA investigated the possibility of operating multiple sensor arrays in conjunction with each other in order to boost the imaging and detection capability. As discussed in Progress Report 3, AKELA's radars are designed to function both independently and cooperatively in multi-sensor settings. It was theorized that by adding another imaging array to the default experimental setup, and using information from both units to reconstruct the image, the detection performance and the cross-range resolution would be improved. Preliminary results using multiple units were encouraging. The results of these tests are discussed in detail in Section 5.3 Santa Barbara City fire tower tests.

During Phase 2 field evaluation, law enforcement users emphasized again the appeal of being able to communicate with the standoff imaging array wirelessly. In order to move beyond the wired Ethernet configuration to operating wirelessly, the entire architecture of the communication between the radar hardware and software control program needed to be changed from a synchronous communication mode to an asynchronous mode. The switch to asynchronous communication was done for reliability and robustness in the occurrence of data loss. The details and benefits associated with the switch are discussed in detail in Progress Report 3.

AKELA has also implemented PEDYN, an internal manufacturing and engineering control system that documents and monitors the discrete components and manufacturing processes of any AKELA hardware or software. The NIJ standoff array was one of the first systems to be documented within PEDYN. Throughout Phase 2, AKELA has been using PEDYN to track the cost of the radar system along with engineering and production changes. One of the goals of Phase 2 is to further reduce the cost of the standoff array by identifying components which can either be replaced with less expensive parts or removed from the radar, without sacrificing detection performance. Information about the PEDYN system and the cost reductions that have been made possible are described in Progress Report 3.

4.2 Phase 2 Processing and Display Refinement

The software has been tested across different platforms to ensure that it will work on computers with different processors with the same stability and efficiency. The image texture window, which displays the reconstructed field in a pseudo 3D format, was discovered to be particularly sensitive to hardware configurations.

4.3 Phase 2 System Field Evaluations

A key activity enabler for LE practitioner evaluation has been FCC certification and experimental licensing of the AKELA radar system. The following table is a chronology of the FCC issues and associated organizational interfaces.

SEP 2007	Reviewed FCC certification guidelines with NIJ representatives
JUN 2008	Briefed NIJ on FCC certification issues
JUL 2008	• Assessment of FCC emission requirements • Development of two radar operation methods to address test certification
SEP 2008	Initiated discussions with FCC certification consultant.
OCT 2008	Brief to NIJ FCC certification requirements compliance issues. Submitted anonymous inquiry to FCC's OET Knowledge Data Base regarding emission mitigation methods.
NOV 2008	Received response from FCC that radar's frequency sweep must be suspended during testing.
JAN 2009	• Conducted further performance tests using different unit orientations, multiple breathing machines and multiple walls. Center of Excellence (CoE) visit. Field testing in AKELA's parking lot. Hands on training and demonstration for Los Angeles Sheriff's Department and Clovis Police Department. • NIJ FCC Technical Interface Meeting
FEB 2009	• Consultant spoke with Mr. John Kennedy of the FCC's Experimental Licensing Branch, who recommended filing for an experimental license. • Field experiments at Santa Barbara City Fire Department training facility. • Visited Compliance Certification Services (CCS) lab in Fremont, CA. Discussed next steps for FCC certification with consultant.
MAR 2009	• In-depth testing of asynchronous mode and wireless capability. • Initiated application for Special Temporary Authority (experimental license).

5.0 System Performance Data

The series of performance tests that AKELA conducted over the duration of the NIJ grant will be summarized in the following sections.

Under the NIJ grant, AKELA was not allowed to perform tests with human subjects. However, given the need to determine the system’s ability to detect humans, AKELA constructed a breathing machine which simulated an individual's breathing and involuntary motion by moving a metal plate up to 2” in a rhythmic pattern, at a rate of 12 – 18 cycles per minute[1]. To validate that the breathing machine provided a realistic approximation of a human subject in the tests, results from tests performed with the breathing machine were compared to those from similar tests performed with human subjects under parallel DoD testing efforts. The comparison of results showed that the breathing machine provides a comparable target to human subjects.

5.1 Baseline Acceptance Tests

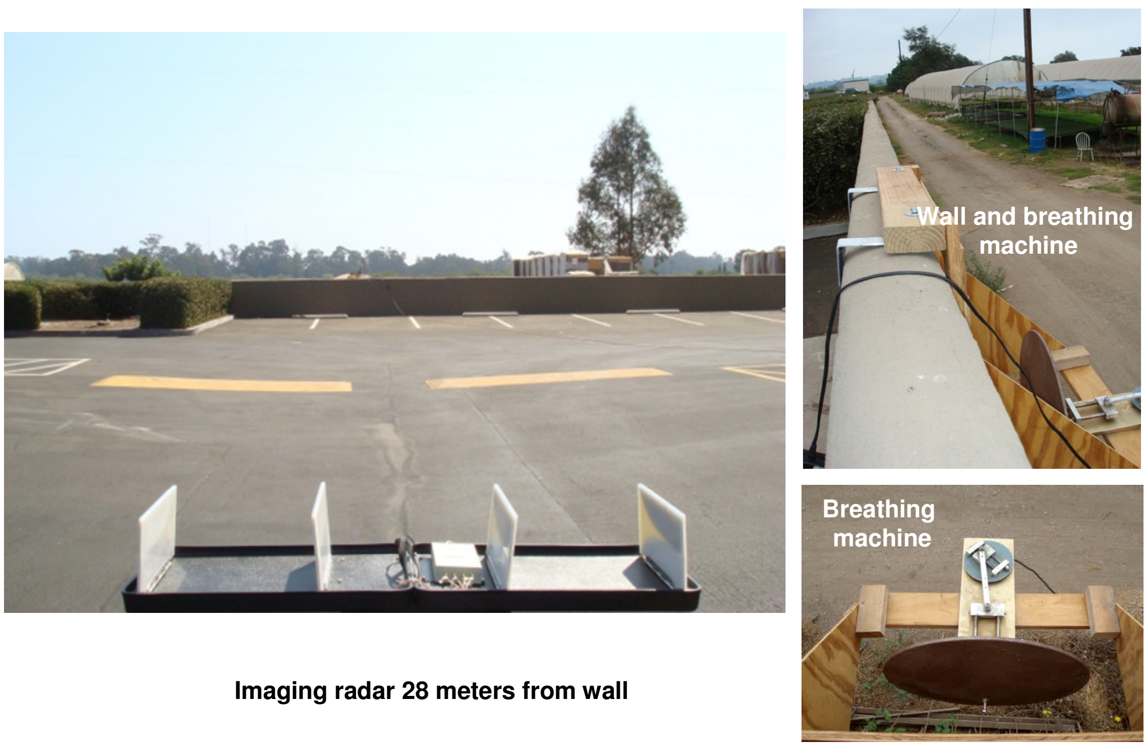


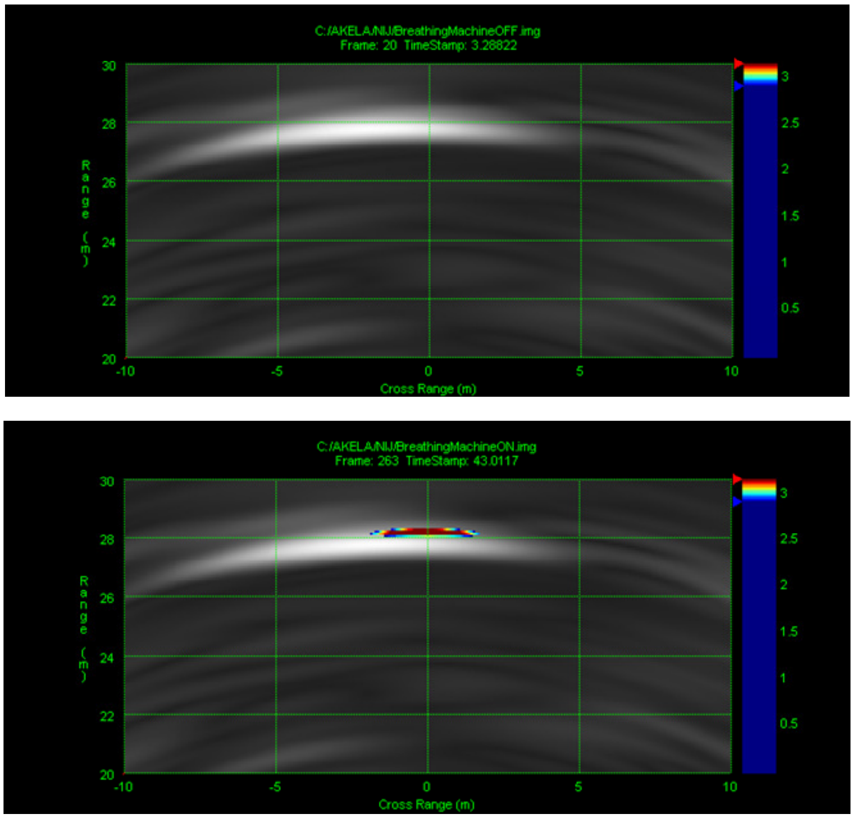
Figure 6 Baseline Acceptance testing experimental setup

Baseline acceptance tests were performed in AKELA's parking lot, with a typical experimental setup as shown in Figure 6. Preliminary results that demonstrate the detection of a breathing machine which was placed behind a 6" concrete wall located 28 meters away from the standoff array were presented at the 2008 S&S Technical Working Group in Atlanta, GA. An example of the detected target is shown in Figure 7.

After the baseline acceptance tests verified the system's ability to detect a breathing target at around 30 meters, further experiments were conducted. These tested various standoff distances up to 45 meters, and multiple breathing machines with variable breathing rates were used. AKELA also conducted in-lab testing to determine the optimal range of operating parameters that would allow the system to meet the performance requirements while simultaneously

[1] The cycle rate was chosen to match the typical breathing rate of an adult human.

facilitating the path to obtaining FCC certification. These parameters include operating frequency range, frequency step size, number of points, and radar sweep rate.



Breathing Machine Off

Breathing Machine On
Image detection through wall

Figure 7 Baseline Acceptance testing detection results

5.2 User Demonstration Tests

AKELA demonstrated the standoff imaging system to users from the Center of Excellence, Los Angeles Sheriff's Department, and Clovis Police Department in January 2009. The array was tested in various configurations to detect up to two breathing targets, as shown in Figure 8. A second wall was then set up in the parking lot, and the imaging system was found to be able to accurately detect targets located between walls and also behind two walls. An experimental setup and result are presented in Figure 9.

Field testing was followed by hands-on training and in-depth discussions of the various features of the user interface and the system setup. The law enforcement practitioners provided useful feedback that shaped the hardware and interface changes AKELA has made during our Phase 2 effort to improve the system.

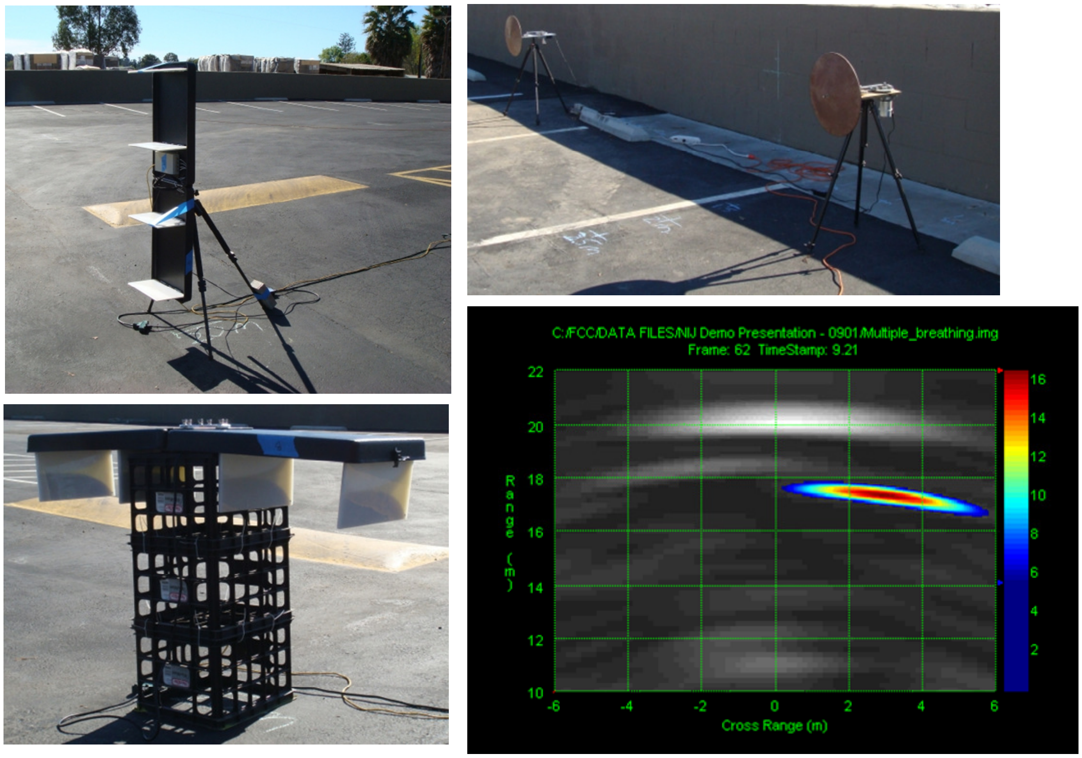
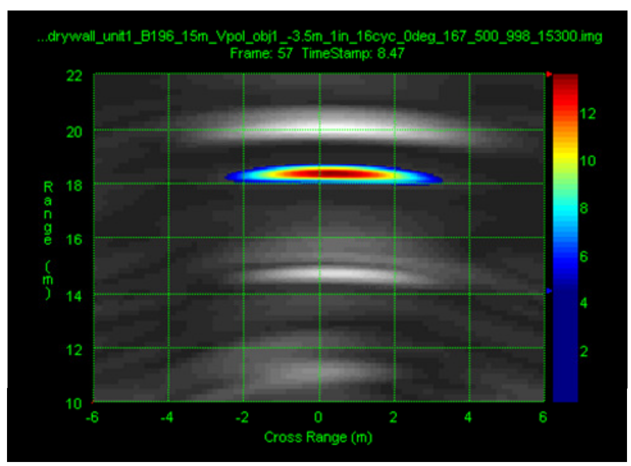


Figure 8 User testing with various array configurations and multiple breathing machines



First wall at 15 meters.

Second wall at 20 meters.

Breathing machine placed 2 meters in front of second wall.

Figure 9 User testing with multiple walls

5.3 Santa Barbara City Fire Tower Tests

To investigate the performance of the standoff array in real-world, complex environments, AKELA obtained permission to conduct testing at the training facility of Santa Barbara City's Fire Department. As shown in Figure 10, the fire tower building consists of four floors, with an adjoining room on the first floor. The walls are approximately 8” thick and constructed of solid poured concrete reinforced both vertically and horizontally with rebar spaced approximately every 12”. The front metal door remained closed during data collection. Figure 11 shows the various clutter objects present on the first floor, as well as the metal staircase and piping that run through all four floors.

Figure 10 Santa Barbara City Fire Department training facility

View from doorway. Interior stairs shown.

To the left: piping, metal door to adjoining room, desk

To the right: filing cabinet, piping, stairs

Figure 11 Interior of first floor showing breathing machine among clutter

The combinations of different radar array configurations and breathing machine configurations that were tested are summarized in Table 5 along with the corresponding experimental results. The array was set up on a tripod 15 meters away from the front of the building. Figure 12 shows three image reconstructions demonstrating the successful detection of a single breathing machine placed at various locations inside a cluttered environment: behind the first wall, in the middle of the room, and behind the second wall (i.e., outside of the fire tower.) When the breathing machine was placed outside of the building, the reconstruction area was adjusted to exclude the strongest return from the metal door and the first wall; the location of the second wall and other reflections from the building interior then appeared in the background of the last image.

Fire Tower Test Configurations		
Radar Array Configuration	**Breathing Machine Configurations**	**Results**
1 Radar Array - Horizontal Orientation	1st Floor, Varying Positions in Room	**Movement Successfully Detected in all Tests**
	Outside of Tower Behind Back Wall	
	2nd Floor, Varying Positions in Room	
	1st & 2nd Floor, Varying Positions in Room*	• **Movement Detected** • **Multiple Detections with Sufficient Spacing Between Machines** • **No Vertical Discrimination**
1 Radar Array - Horizontal Orientation on Van Roof	1st Floor, Varying Positions in Room	**Movement Successfully Detected in all Tests**
	Outside of Tower Behind Back Wall	
	1st & 2nd Floor, Varying Positions in Room*	
2 Radar Arrays – Horizontally Oriented in Positions Around Building	1st Floor, Varying Positions in Room	• **Movement Detected** • **Improved Cross Range Resolution**
	1st Floor, Varying Positions in Room *	

Table 5 Summary of fire tower test configurations and detection results

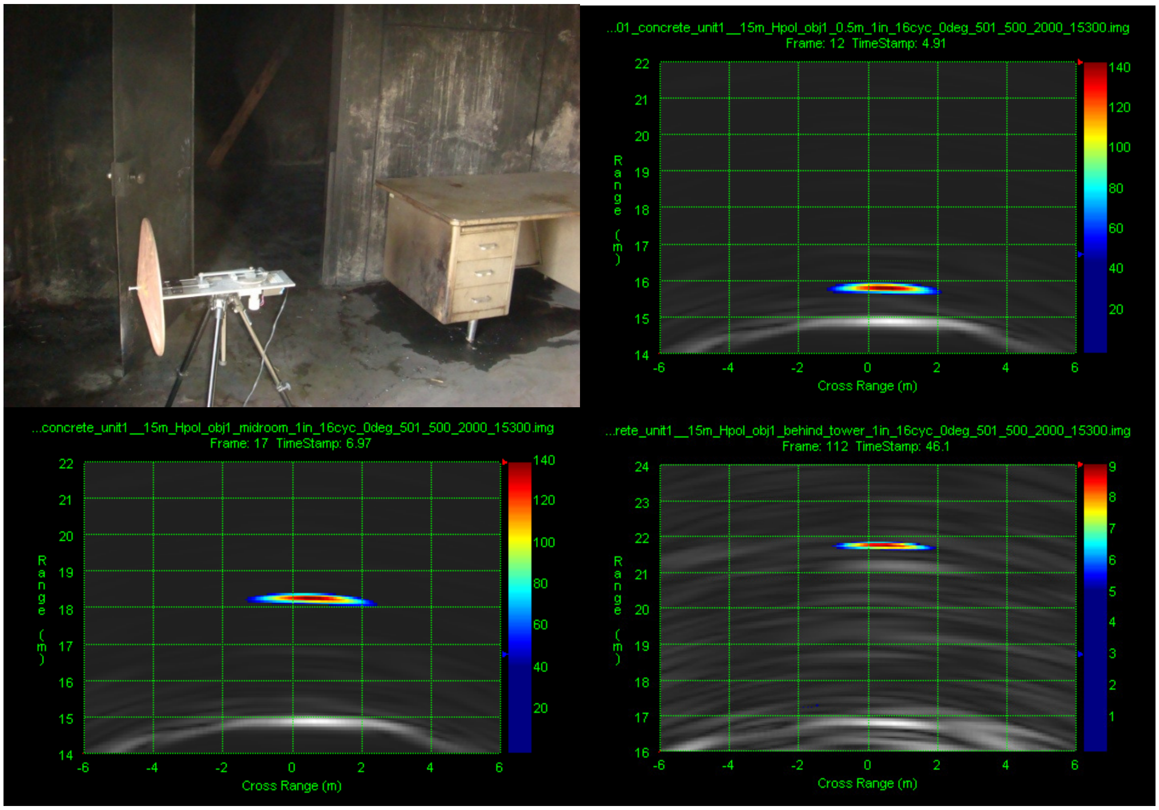


Figure 12 Successful detection of breathing machine placed at various locations in clutter

In addition to testing with a single breathing machine at different locations on the first floor, AKELA also experimented with configurations including the following: positioning a single breathing machine on the second floor, repeating the tests with two breathing machines (one on each floor), placing the standoff array on top of a van, and imaging inside the fire tower with multiple arrays. The breathing machine on the second floor was clearly detected in all the tests, but vertical discrimination was not possible with the array set up in the standard configuration. For example, two breathing machines on different floors separated by a sufficient range offset will appear as distinct detections in the reconstructed image, but there is no way to differentiate between floors unless vertical aperture is provided. If vertical discrimination is required for an application, a practical way to do so might be to orient a standoff array vertically.

AKELA's motivation for testing the performance of a standoff array placed on top of a vehicle was based on feedback from law enforcement officers. The current array can be unfolded and affixed to a tripod in a short amount of time, but the option of placing an array directly on top of a patrol car would make the unit even easier to use and may prove particularly desirable in situations requiring critical response. The technical concern was that strong reflections from the vehicle's surface such a short distance away might negatively impact detection capability, but Figure 13 shows that detection results for a breathing machine behind the first wall in a complex environment were comparable to that of the standard tripod setup.

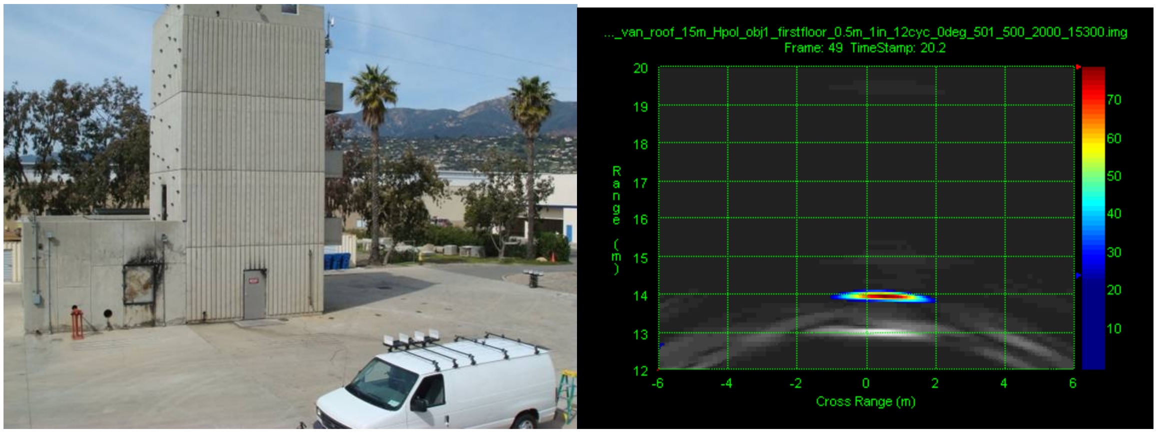


Figure 13 Array mounted on vehicle, successful detection of breathing machine

AKELA was also interested in whether the use of multiple standoff arrays might improve imaging resolution and boost the detection performance. A secondary array was placed on the east side of the fire tower and provided a view of the building orthogonal to that of the first unit. The experimental setup with two arrays is pictured in Figure 14. As demonstrated in Figure 15, when radar returns from the two units are used to reconstruct an image over the area of interest, both exterior walls of the tower show up in the background of the image. The location of the target inside the building is more precisely defined, and the cross-range resolution appears improved. The results of the experiment are promising and indicate that the use of multiple standoff units may provide an advantage in some law enforcement applications as well as in mapping the interior of buildings.

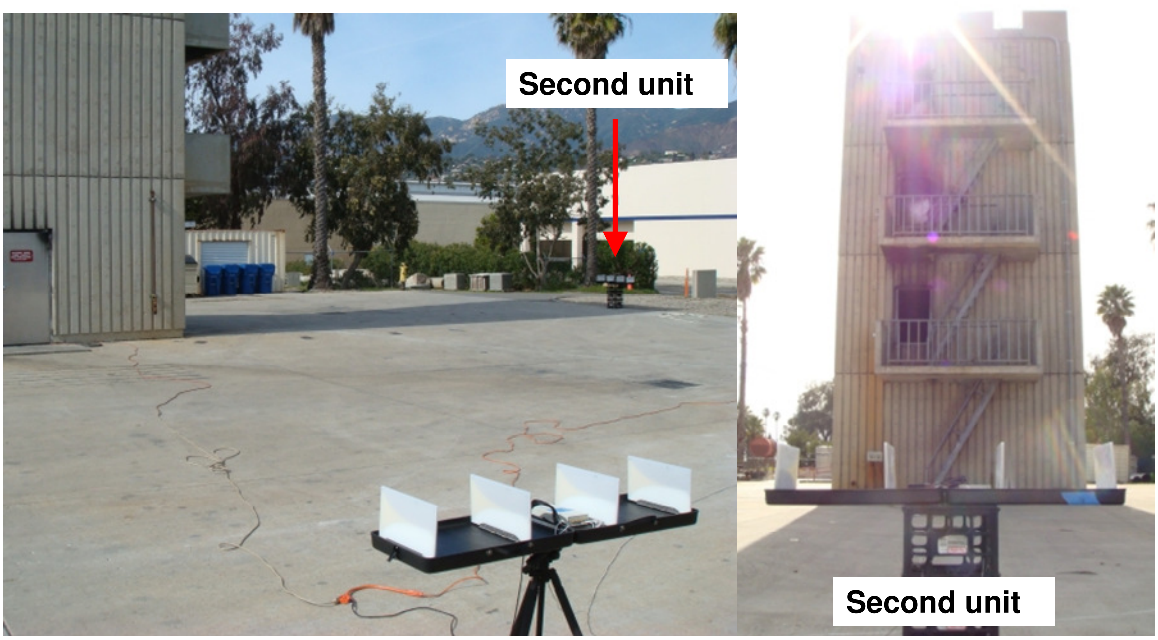


Figure 14 Multiple arrays experimental setup at 90 degrees

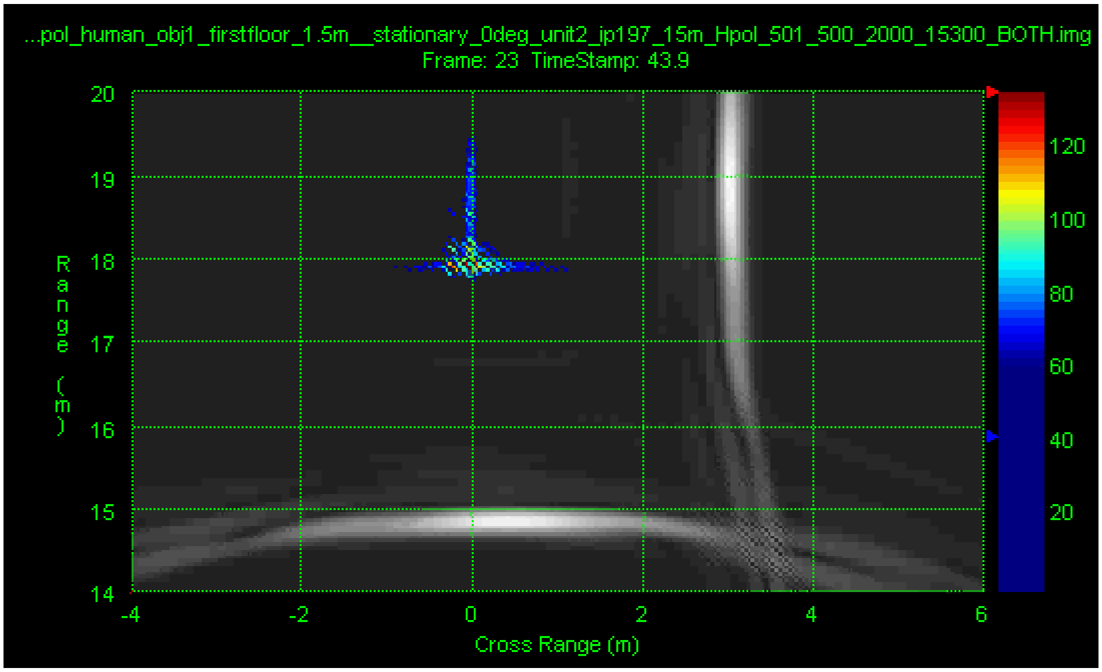


Figure 15 Detection results using multiple arrays

6.0 Relevant Internal AKELA and DoD Test Results

As part of concurrent internal AKELA and DoD efforts, various system configurations, similar to NIJ radar configurations, were investigated to determine through-the-wall detection and personnel tracking performance constraints and improvements.

6.1 NIJ Radar Modifications for Detection Performance Enhancement

To address radar standoff distance, image sensitivities, and associated radar sensor characteristics, the NIJ radar sensor was modified to various system configurations. One of the modified NIJ radar system configurations consisted of multiple radars configured inside a 7"x13"x15" packaging, as shown in Figure 16. This multiple radar sensor demonstration system weighed 12 lbs. Four Vivaldi antennas were mounted on an external 2.9 meters long collapsible array. This system demonstrated successful detection of a breathing machine placed behind a 6" reinforced concrete wall 50 meters away from the system.

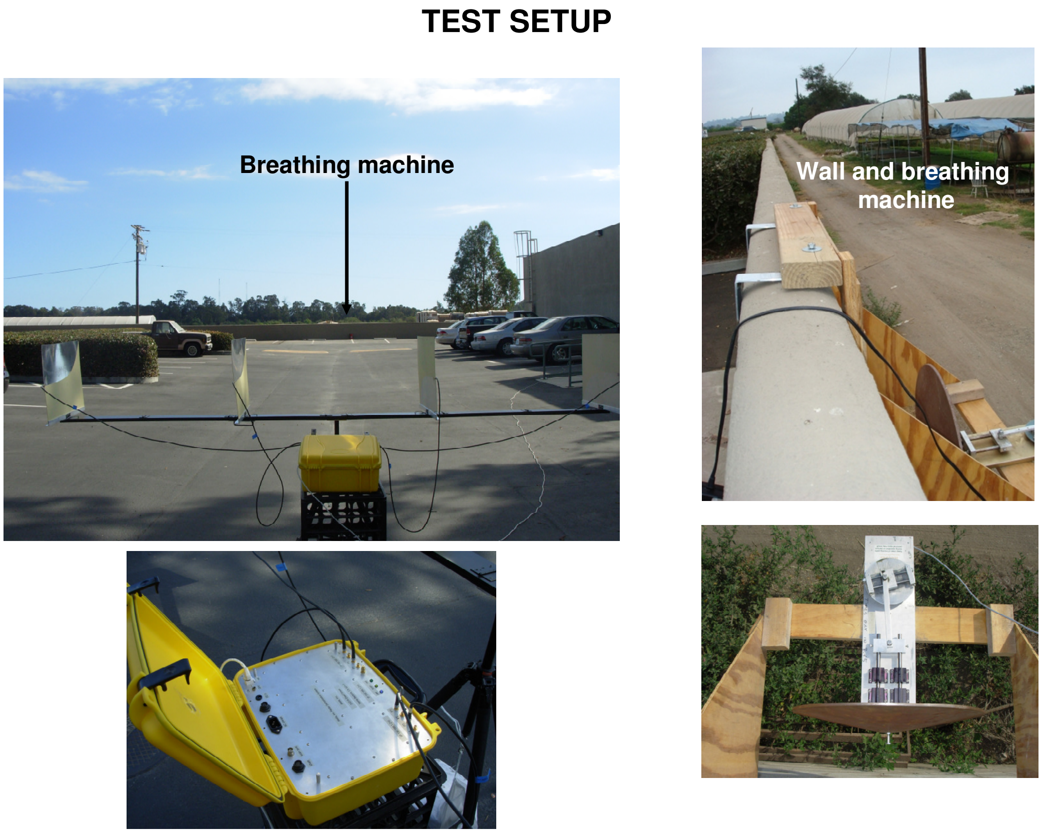


Figure 16 Multiple radar sensor demonstration system

The multiple radar sensor configuration offers significantly improved system performance. In particular, it allows data acquisition at a speed that is approximately twice as fast as what the current NIJ baseline array is capable of. In addition, the Vivaldi antennas used in this demonstration are larger than the standard antennas on the NIJ standoff array and provide more gain; all of these factors contribute to the clear detection of a breathing target, moving with 1" throw, behind a 6" reinforced concrete wall up to 50 meters away.

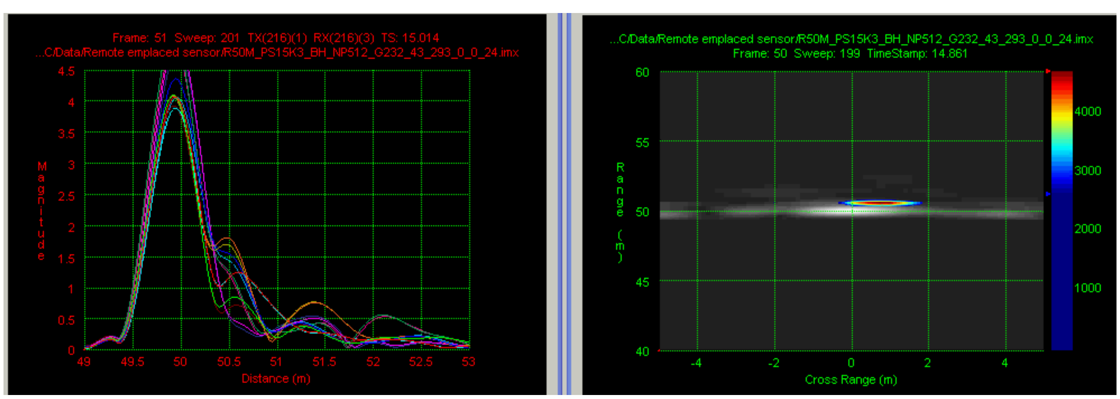


Figure 17 Detection of breathing machine motion (1500 MHz to 2000 MHz)

Figure 17 above demonstrates the detection of the breathing machine over a frequency range of 1500 MHz to 2000 MHz using 512 data points. Different detection algorithms were used with very little change in observed performance. The system detected the breathing machine using all the possible algorithms. The results shown in the figure were obtained using the "NIJ Breathing" algorithm, a specific breathing detection method developed during the course of AKELA's NIJ grant.

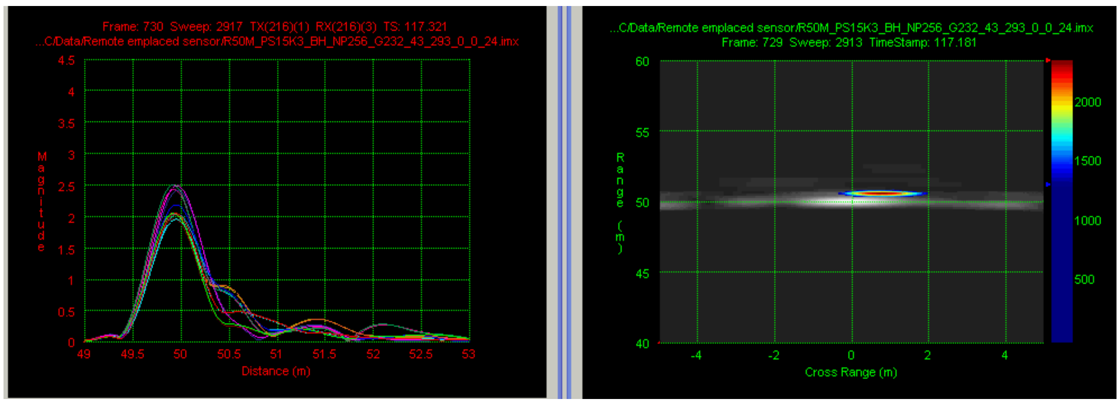


Figure 18 Detection of breathing machine motion (1500 MHz to 2000 MHz)

Figure 18 shows the detection over the same frequency range of 1500 MHz to 2000 MHz, but using only 256 data points. It can be seen from the magnitude vs. distance plot on the bottom left corner that the magnitude of the return due to the 6" concrete wall at 50 meters (as well as the breathing machine placed behind it) has decreased, as should be expected with the use of fewer data points. In this demonstration, the detection algorithm developed for the NIJ grant performed the best of all algorithms attempted. Although aliasing was observed using the other algorithms, in all cases the breathing machine was clearly detected.

This demonstration system was constructed to test the performance of possible alternative configurations. While this system did show marked improvement over the baseline system configuration, the inclusion of multiple radar sensors would significantly increase the cost of the unit over the baseline configuration. Additionally, the antenna array configuration and size would not be feasible for use by LE.

6.2 NIJ Human Subject Simulation Testing

The NIJ grant did not allow human subject testing. In an attempt to obtain permission to perform tests with human subjects, AKELA investigated a review with an Independent Review Board (IRB). AKELA explored various routes to conduct an IRB, and contacts were made with the University of California, Santa Barbara, and two California based private groups that conduct IRBs. While it was concluded by these groups that the AKELA radar presented no human privacy concerns, these groups suggested an IRB may not be the correct forum for the AKELA radar to be evaluated. In response to these comments and the time and scope required to support an IRB, all NIJ testing was conducted with a breathing machine to simulate a human subject motion.

In support of several AKELA concurrent DoD sponsored through-the-wall building interrogation efforts, radar system configurations similar to the NIJ, were approved by the DoD for human subject testing. The objectives of these tests were to detect and track human subject breathing and movement through multi-story reinforced concrete building walls with metallic: doors, windows, and internal furnishings. Testing was conducted with both human subjects and stationary breathing machines. Additionally multi-wall structures were included in the test configurations. Test results of relevant interest to the AKELA NIJ efforts were: 1) the breathing machine provided a motion signature comparable to that of a human subject, and 2) detection of both a breathing machine and a human subject were demonstrated through multiple walls (16" reinforced concrete) at a standoff distance of 21 meters.

7.0 Risk Assessment Review and Mitigation Results

Four major risks were identified at grant initiation: 1) sensor hardware and software development, 2) sensor, antenna and system communication and control prototype integration, 3) FCC Certification, and 4) LE practitioner evaluation. The sensor development and system integration risks were assessed as low due to the prior internal AKELA and concurrent DoD program sensor development tasks. The development and integration risks were mitigated and closed with the delivery of the prototype system and their successful verification performance testing. The FCC risk was initially assessed as medium primarily due to the uncertainty in the FCC certification process associated with a continuous wave (CW) stepped radar sensor and the required FCC certification testing. After FCC certification requirements were identified and discussions with both NIJ and FCC representatives, it became clear that the baseline AKELA sensor operating characteristics would not be applicable with FCC testing configurations and procedures. Although there is a general FCC understanding of the AKELA sensor, the FCC test requirements were developed for pulsed versus a CW sensor. Although paths for FCC risk mitigation have been identified, the risk remains medium until further mitigation efforts are successful.

LE practitioner evaluation risks were initially driven primarily by schedule. LE practitioner evaluation of the AKELA radar sensor system was dependent on design development and prototype development and availability. As the sensor and system development were completed, and prototypes manufactured and available for user evaluation, the requirements for FCC experimental licensing at Practitioner locations halted the process. To mitigate the risk of further delays in practitioner evaluation of the radar sensor system, user demonstration testing was conducted at the AKELA facility to provide: 1) demonstration testing; 2) LE practitioner training; 3) hands on user equipment experience; 4) equipment operational characteristics, and 5) field use deployment adaptability. The LE practitioner demonstrations were invaluable as they identified a number of deployment practitioner issues that could be fixed for field use. These included recording time, image resolution and interpretation, tripod and squad car deployment, multiple sensors, wireless performance and user interface GUI. LE practitioner comments and questions also prompted additions to the test planning efforts, including test objectives, image analysis, and sensor system configurations. Due to the dependence on the FCC certification issues and schedule, the LE practitioner evaluation risk remains at the medium level.

8.0 NIJ Supported Meetings/Conferences/Trade Shows

AKELA has demonstrated the standoff imaging array and presented the latest radar and algorithm developments accomplished under the NIJ grant at the following events:

October 07	S&S Technical Working Group	Orlando, FL
September 08	S&S Technical Working Group	Atlanta, GA
October 08	Technologies for Critical Incident Preparedness	Chicago, IL
May 09	FPED VII	Stafford, VA
September 09	S&S Technical Working Group	Tampa, FL

9.1 Conclusions

- Standoff radar sensor was successful in meeting the grant performance goals of 30 meters detection of personnel through 8" reinforced concrete walls. Accomplishments included:
    - Successful single board radar design, development, and performance verification through testing
    - Four antenna switch design implementation
    - Sensor and system development was aided by both AKELA internal and complementary DoD sensor development efforts
    - Sensor, antenna, and wireless component successfully integrated into prototype
    - Three prototype systems were manufactured, acceptance tested, and available for LE practitioner evaluation
- Radar system protocol has been modified along with restructured software to support asynchronous mode for wireless communication and virtual data storage. Virtual data storage was implemented and a wireless option for the array was extensively tested and verified for 40 meters.
- Size, weight, and power (SWAP) goals status is that the prototype system weighs 16.7 lbs, measures 25" x 14" x 4.5" (enclosed), and powered continuously with AC or eight double AA batteries (2-3 hours).
- The present prototype system costs $9500 to manufacture (goal $5000). A cost reduction methodology has been defined and near term costs saving only reduce to $8500. Other possible system configurations with lower production costs have been identified but require further analysis.
- AKELA's NIJ Standoff Radar System performance was verified in a series of laboratory and complex structure field testing. Data sets with the array arranged in various configurations and simulated personnel detection and tracking through building walls were successfully obtained. Image test data appears to contain additional information of personnel tracking and body movement.
    - User demonstration testing was performed with LE practitioners' participation. Their feedback provided several improvements to graphical user interface, system design, and critical input for radar modification and subsequent test planning and execution.
- The time and resources required to define FCC certification surpassed AKELA's initial expectations. Identifying FCC test requirements and obtaining FCC experimental

licensing caused non delivery of systems for User field testing and delayed plans for coordinating user evaluation.
    - AKELA has obtained an experimental license from the FCC for testing within a 20 km radius around AKELA's office location. The license has been extended to 26 June 10.
    - The path to obtaining FCC certification has been identified, but requires support from LE users and NIJ.
- The NIJ AKELA prototype available at the conclusion of the grant period of performance represents the first generation of LE through-the-wall sensor and surveillance system. Concurrent DoD efforts are providing radar sensor and analyses insights that may increase the AKELA sensor system detection and tracking performance and at the same time reducing SWAP and costs.

9.2 Recommendations

- FCC certification remains a critical issue and risk driver in providing AKELA's through-the-wall-surveillance sensor to LE personnel for LE practitioner evaluation and operational deployment. To address these FCC certification issues in the future will require a continued and concentrated effort on behalf of both NIJ and AKELA.
- User evaluation and feedback is a key aspect for LE operational deployment. As FCC experimental licensing issues are resolved, LE Practitioner testing and evaluation can be completed and the next phase of sensor system design modifications can be continued.
- Imaging data from complex targets suggests that further data analysis could provide additional information on personnel detection and tracking. This effort could provide valuable data and warrants further investigation.
- Additional radar design modifications to higher frequencies should be investigated for penetration of various building material walls and provide potential alternate operating frequency bands to increase the likelihood of FCC certification.
- Multiple radar system deployment can provide greater detection and tracking data. Additional testing should be conducted to investigate performance characteristic of integrated multi-sensors.
- AKELA should continue to leverage DoD sensor system development investment for NIJ. Significant amount of synergy is evident, and to that end, NIJ and AKELA's DoD customers should interact for through-the-wall surveillance technology updates and transfer.
- AKELA's Santa Barbara's Fire Tower testing provided significant radar sensor system data for LE system performance. Further complex building structure testing with various NIJ system configurations should be conducted.