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TECHNICAL REPORT
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COMBAT CUEING: GEOLOCATION SYSTEM FOR LOW PROBABILITY OF INTERCEPT SIGNALS

by
Doug Vujcic
and
Kerry Kachejian

Raytheon
Falls Church, VA 22042

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14. ABSTRACT
Raytheon Company has successfully developed and demonstrated a revolutionary new signals exploitation system that weighs 10 times less than conventional technology. Developed under DARPA's Smart Module program, Combat Cueing is a human-portable system that provides radio frequency (RF) situational awareness to small military units, allowing the warfighter to detect and locate in real time low-probability-of-intercept (LPI) transmitters operating between 30 and 88 MHz. Raytheon conducted field demonstrations of Combat Cueing at Ft. A.P Hill, VA. System modules, mounted on HMMWV military vehicles, successfully detected and located threat radios with 250 meter accuracy. The system employed a novel baud-phase time-difference-of-arrival (TDOA) algorithm, which calculated emitter locations by measuring demodulated signal symbol (baud) arrival times at each of the modules. By simultaneously reducing the space, weight, power and cost of conventional systems, these all-weather modules are operational across a broad spectrum of platforms, including tactical ground vehicles, robots, unmanned aerial vehicles, helicopters and ships, or may be left unattended on buildings, towers or the battlefield.

15. SUBJECT TERMS
CUEING RF (RADIO FREQUENCY) GEOLOCATION TDOA (TIME DIFFERENCE OF ARRIVAL
RADIO EMITTER LOCATION PORTABLE LPI (LOW PROBABILITY OF INTERCEPT)
WEIGHT REDUCTION SITUATIONAL AWARENESS SIGNALS EXPLOITATION PROJECT

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PREFACE

Raytheon (formerly Raytheon E-Systems and Raytheon Systems Company) has developed Combat Cueing capability under contract *DAAK60-96-C-3024, CLIN 0001 and CLIN 0002.* The program duration was from May 1996 to November 1999. The program was funded by the Defense Advanced Research Projects Agency (DARPA) ETO (E. Urban).

ACKNOWLEDGEMENTS

Henry Girolamo of the U.S. Army Soldier Systems Center - Natick RDE Center managed the program and provided critical guidance. PM NV/RSTA provided test facilities and personnel to support Combat Cueing field demonstrations and evaluation at Ft. AP Hill, VA. Boeing was a subcontractor on the Combat Cueing program, providing a wearable "User Station" and related software.

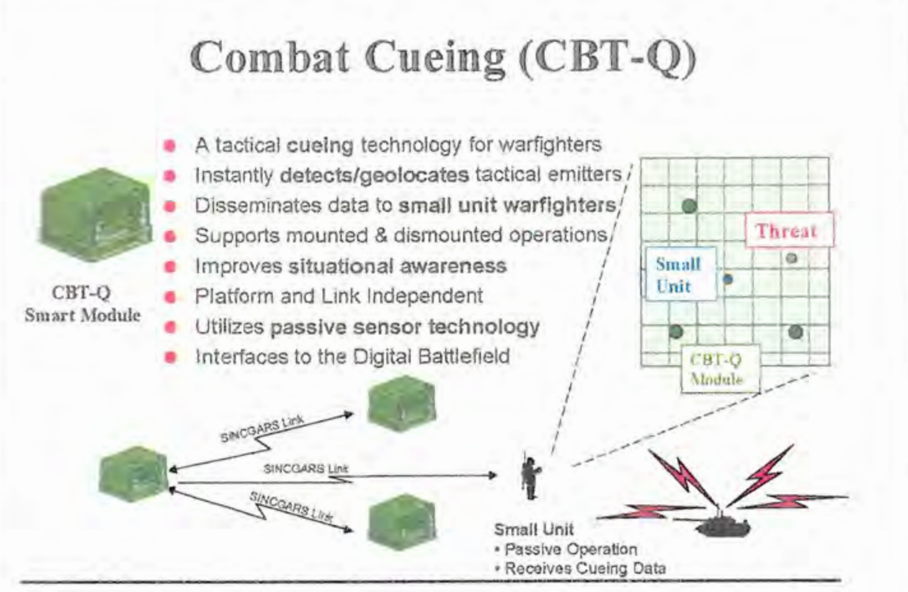
COMBAT CUEING: GEOLOCATION SYSTEM FOR LOW PROBABILITY OF INTERCEPT SIGNALS

1. Summary

The primary objective of this research was to develop and demonstrate a revolutionary signals exploitation module (Figure 1) that weighs 10 times less than conventional technology, uses 1000 times less module-to-module network bandwidth, and provides radio frequency (RF) situational awareness to small military units. Intended functionality allows the warfighter to detect and locate low-probability-of-intercept (LPI) transmitters operating between 30 and 88 MHz, with minimal latency.

Raytheon conducted simulations, hardware design, signal processing algorithm development, demonstrations and tests. Field tests of Combat Cueing were held at Ft. A.P Hill, VA. System modules, mounted on HMMWV military vehicles, successfully detected Panther Radios 8.5 km away. In similar experiments, Panther threat radios were located with an accuracy of 250 meters. The system employed a time-difference-of-arrival (TDOA) location algorithm, which calculated emitter locations by measuring average signal symbol arrival times at each of the modules.

A fully-loaded Combat Cueing module weighs only six pounds and measures 6"x6"x5". By simultaneously reducing the space, weight, power and cost of conventional systems, these all-weather modules are operational across a broad spectrum of platforms, including tactical ground vehicles, robots, unmanned aerial vehicles, helicopters and ships, or may be left unattended on buildings, towers or the battlefield.



Combat Cueing (CBT-Q)

- A tactical **cueing** technology for warfighters
- Instantly **detects/geolocates** tactical emitters
- Disseminates data to **small unit warfighters**
- Supports mounted & dismounted operations
- Improves **situational awareness**
- Platform and Link Independent
- Utilizes **passive sensor technology**
- Interfaces to the Digital Battlefield

Figure 1 - Combat Cueing system enhances battlefield awareness

The Combat Cueing module achieves its miniature size by employing credit card size circuit cards that are compliant with the industry Small PCI and PCMCIA standards. The module houses 10 Small PCI slots and two PCMCIA slots, embedded GPS receiver engine, Pentium® based Embedded Controller, GPS and RF antennas, and power regulators and filters. The system functionality can be extended through insertion of Raytheon's other small PCI and PCMCIA circuit cards.

2. Introduction

The purpose of this report is to describe the execution and findings of DARPA's Combat Cueing (CBT-Q) program. The report is divide in four sections, 3.0 – 7.0, as follows:

Section 3.0, titled ***Methods, Assumptions, and Procedures*** describes six main Combat Cueing tasks:

1. Requirements Analysis and Conceptual Design
2. Algorithm Research and Development
3. Hardware Development
4. Software Development
5. System Test and Evaluation
6. Demonstrations

Section 4.0, titled ***Results and Discussion***, Cueing Program goals and achievements. Section 5.0, titled ***Conclusions***, contains the summary and discussion of the program results. Section 6.0, ***Recommendations***, describes ongoing related research and offers recommendations for future research.

3. Methods, Assumptions, and Procedures

3.1. Task 1 – Requirements Analysis and Conceptual Design

The purpose of this task was to perform the analysis of the military mission relevance of Combat Cueing, determine CBT-Q concept of operation, system requirements, evaluate system partitioning, and perform human factors and user interface analysis.

3.1.1. Military Mission Relevance of Combat Cueing

3.1.1.1. The Problem: Real-time Information for Small Unit Operations

Small unit warfighters are blind in the RF spectrum. Their situational awareness is limited to their eyes, a pair of night vision goggles, and at best a hand held thermal imager with a narrow field of view. Current RF information systems run at the wrong time constant for warfighters involved in small unit operations. Today's RF information systems start by collecting data from various ground and airborne sensors. By the time it is filtered, processed, and disseminated to front line warfighters, the information's tactical usefulness has expired.

Small unit warfighters need combat information systems that provide real-time information on enemy forces. For example, a U.S. tank commander (TC) wants to know "where is an enemy tank, right now!", so he can have his gun barrel pointed in the right direction. If provided with such timely information, warfighters could engage the enemy faster and increase the probability of target destruction. Furthermore, if the information system could identify which tactical targets are highest priority (e.g., command vehicles), these targets could be engaged first. By getting the "first shot" at enemy vehicles and engaging key targets first, U.S. forces will have a strong tactical advantage over potential adversaries.

3.1.1.2. The Solution: Combat Cueing

Combat Cueing (CBT-Q) is a portable (Figure 2), tactical information system concept that assists warfighters involved in small unit operations. CBT-Q modules detect an enemy transmitter and instantly provide the warfighter with the emitter's location. During the "fog of battle", CBT-Q tells the warfighter "Look here, right now!"

Figure 2 - Combat Cueing Module

Utilization of the technology will result in faster target detection and engagement times, greatly enhancing the effectiveness of small unit operations.

CBT-Q technology can support land, sea, and air warfighting operations. The modules are platform independent, which permit their use with wheeled and tracked vehicles, aircraft, ships, or left unattended.

3.1.1.3. Military Advantages

CBT-Q offers a new capability for small unit operations. Utilizing signal processing and advanced packaging, CBT-Q brings information warfare to the cutting edge of the battlefield. CBT-Q has several compelling military advantages for small units:

- Extends situational awareness into the RF spectrum
- Identifies and locates enemy C3I targets
- Open architecture design permits tactical flexibility
- Platform independent
- Link independent
- Utilizes passive sensor technology
- Interfaces to the Digital Battlefield
- Provides affordable, real-time information

For example, the center of Figure 3 illustrates the situational awareness currently available to a dismounted individual on the battlefield. If equipped with night vision goggles or a thermal imager, the individual's situational awareness at night is limited to a narrow sector, out to about one kilometer. If linked to CBT-Q information, the individual's situational awareness could extend out ten kilometers in all directions. For an Army Scout on the forward line of troops (FLOT), this information would allow him to detect and report critical threat activities faster, more reliably, and at longer ranges while maintaining a high degree of survivability. Thus, the Scout's situational awareness in the RF spectrum would be several thousand times greater than in the thermal spectrum. When used together, the broad area RF sensor could be used to cue point thermal sensor to a target.

When CBT-Q is applied to a direct fire engagement (e.g., tank on tank), it can result in faster detection and engagement times. Likewise, reconnaissance forces may be able to quickly locate and report hidden enemy positions that may otherwise have taken hours to find or would have gone completely undetected.

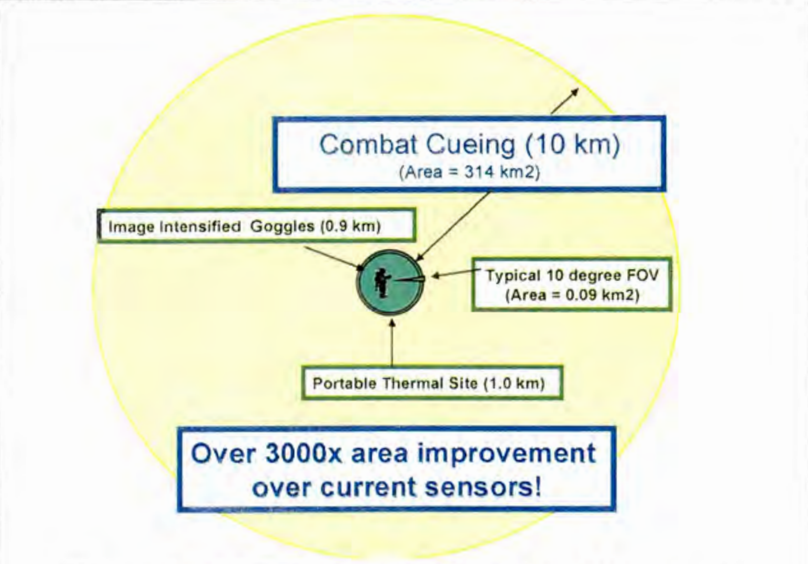


Figure 3 - CBT-Q Extends Situational Awareness

CBT-Q will help disrupt command and control by identifying command vehicles (emitter tanks), enabling their early destruction. Likewise, enemy reconnaissance forces and forward observers would be vulnerable to early detection and destruction, preventing enemy commanders from knowing and effectively reacting to the tactical situation. If the enemy knew that they were up against a CBT-Q opponent, they could adopt strict radio silence. This would still achieve the effect of disrupting their command and control, since enemy commanders could not communicate with their subordinate forces. In essence, CBT-Q permits real-time information warfare to be conducted at the forward line of troops (FLOT).

Finally, CBT-Q is a passive sensor that receives energy from the environment and communicates cueing data to friendly forces over existing LPI tactical radios. The passive nature of CBT-Q offers a distinct survivability advantage over radar sensors that are active and not well suited for forward warfighters.

3.1.2. Concept of Operation

The system concept was developed around the time difference of arrival (TDOA) method. The method uses three spatially separated receivers. Each receiver is equipped with a Global Positioning System (GPS). Signals are received at different times, as illustrated in the figure 4. Using the position of each receiver and difference in the time of arrival, the system calculates the position of the threat emitter.

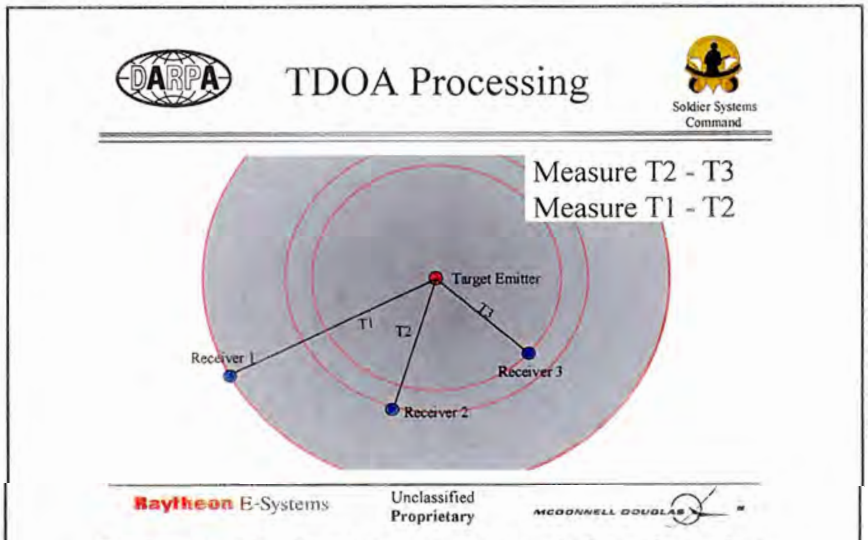
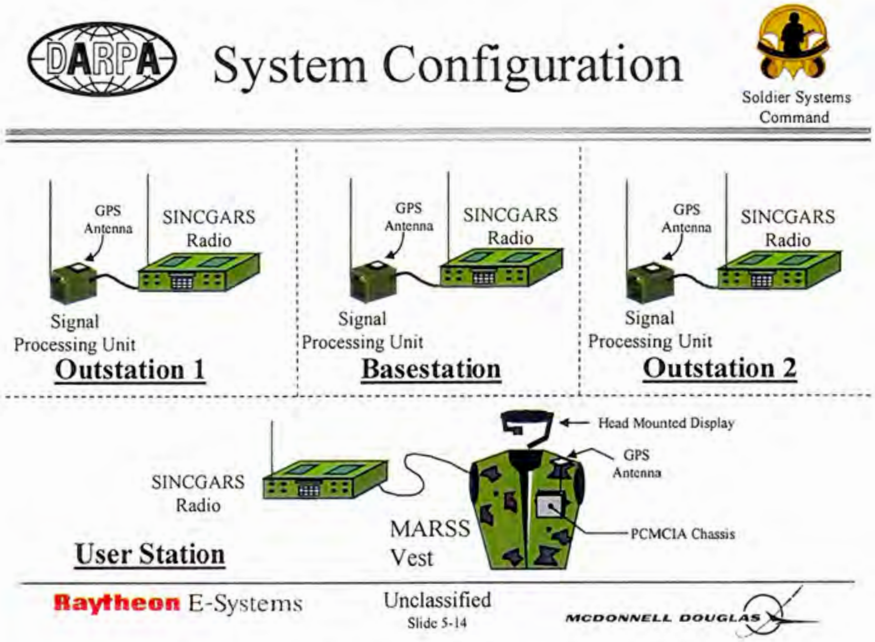


Figure 4 – Geolocation algorithm is based on time difference of arrival of target emitter signal

The system is made up of three receivers and one or more user stations. User Station is the operated by the warfighter. User Station receives target emitter locations and displays the icon on a map in a near-real time.

3.1.3. System Partitioning

As shown in Figure 5, one of the receivers is designated as the Basestation, and the other two as Outstations. Basestation communicates with Outstations and User Stations over the wireless link. A SINCGARS SIP radio was chosen as the wireless link due to its wide military use. Functions assigned to User Station, Basestation, and Outstations are illustrated in Figure 6 and 7.


System Configuration

Soldier Systems Command

Raytheon E-Systems

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Slide 5-14

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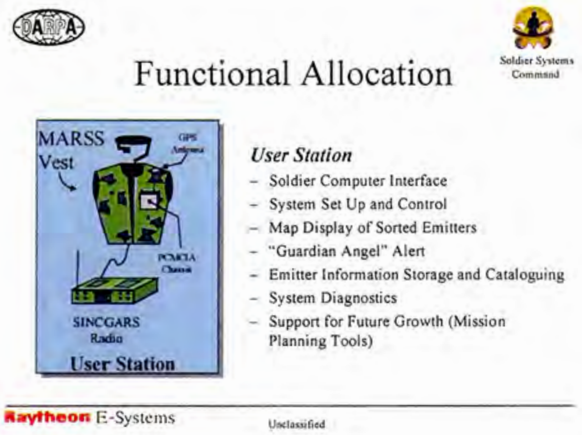
Figure 5 – CBT-Q Components


Functional Allocation

Soldier Systems Command

User Station
- Soldier Computer Interface
- System Set Up and Control
- Map Display of Sorted Emitters
- "Guardian Angel" Alert
- Emitter Information Storage and Cataloguing
- System Diagnostics
- Support for Future Growth (Mission Planning Tools)

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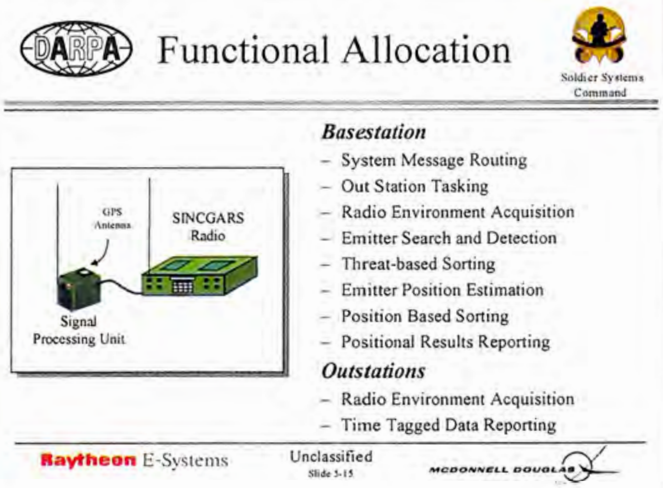
Figure 6 – User Station Functions


Functional Allocation

Soldier Systems Command

Basestation
- System Message Routing
- Out Station Tasking
- Radio Environment Acquisition
- Emitter Search and Detection
- Threat-based Sorting
- Emitter Position Estimation
- Position Based Sorting
- Positional Results Reporting

Outstations
- Radio Environment Acquisition
- Time Tagged Data Reporting

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Slide 5-15

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Figure 7 – Basestation and Outstation Functions

3.1.4. User Interface and Human Factors Analysis

During the system analysis phase, we discussed desirable CBT-Q characteristics with many warfighters[1]. The common "keys to success" were:

- Low false alarm rate
- Simple functionality and intuitive operation
- Range 3 -10 km
- Near real-time performance
- End system must be affordable

As a part of the user interface analysis task, several operational scenarios were developed. Each of the scenarios included behavior of CBT-Q system and its user interface. This analysis was widely accepted by warfighters and became a guiding principle in development of the User Station.

3.1.5. System Requirements

Based on the systems requirements analysis presented in sections 2.1.1 – 2.1.3, a detailed system requirements specification was generated and utilized to guide the system development. System Requirements Specification[2] document for the Combat Cueing System was drafted at the start of the program. The text below is an excerpt from the Overview Section of that document.

"CBT-Q System shall be a portable tactical information system which assists warfighters involved in small unit operations. CBT-Q shall detect a target emitter and "instantly" provide the warfighter with the emitter's location.

The minimal CBT-Q System shall be made up of three CBT-Q "Drop Packets" and warfighter's User Interface Module, as shown in Figure 8. CBT-Q Drop Packets will be placed 3 to 10 km apart from each other in order to accurately detect the target emitter and calculate its location. Typical distances between target emitter and drop packets shall be on the order of 3 to 10 km. The User Station shall be capable of displaying and logging emitter locations.

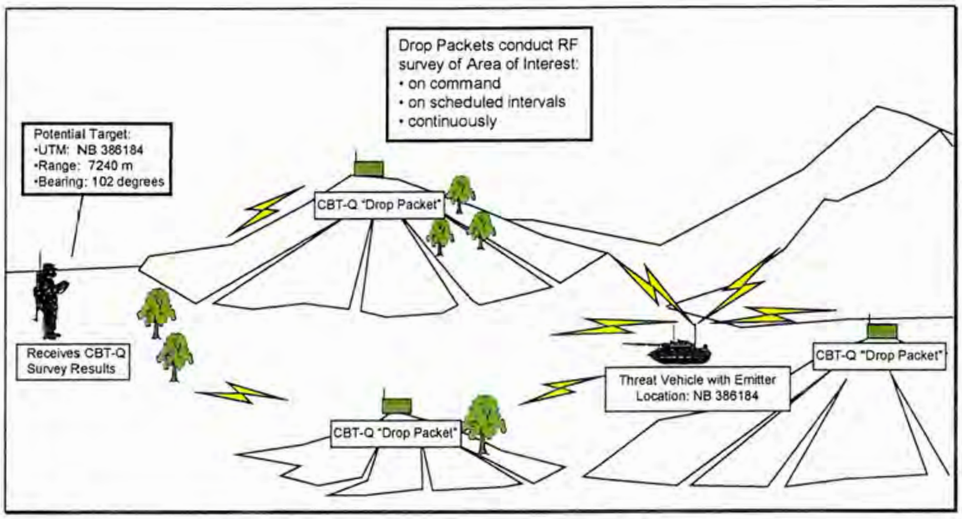


Figure 8 - System Operational Concept

There shall be two types of CBT-Q Drop Packets: Basestation and Outstation. Minimal CBT-Q System configuration shall have 4 subsystems: one Basestation and two Outstations, and one User Station.

Typical communication between the User Station, Basestation, and Outstation (Figure 9) will be accomplished as follows:

1. The Basestation shall accept tasking from the User Station. The tasking may typically include the target emitter type and geographical area of interest (i.e. a 5 by 5 kilometer area). If tasking is not received, default tasking or previously received tasking shall be used.
2. The Basestation and two Outstations shall acquire RF samples.
3. From captured RF samples, the Basestation shall perform target emitter detection.
4. If the target emitter is detected, the Basestation shall request signal timing information from Outstations.
5. Outstations shall respond with target emitter signal characteristics.
6. The Basestation shall accept target emitter signal characteristics and calculate the target emitter position.
7. The target emitter position shall be reported to the User Station if within the user's area of interest..
8. Upon detection of a target emitter, the User Station shall alert the user and display the target emitter on the map and update the target emitter location log file.
9. The system shall periodically perform self diagnostics. Link failures, power disruptions, and self-detected functional failures shall be reported to the User Station.
10. The system shall return to step 1.

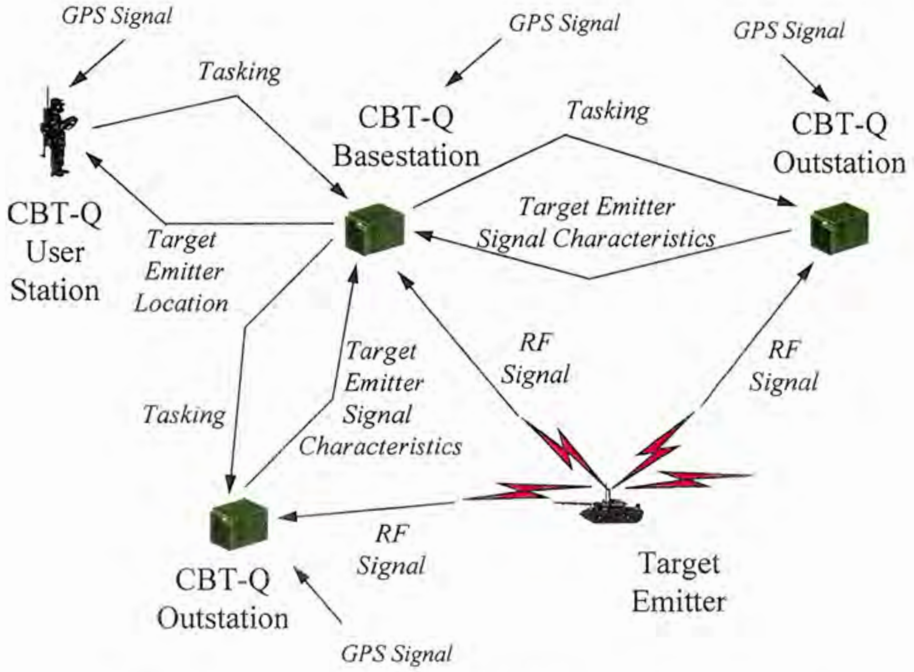


Figure 9 - CBT-Q System High Level Data Flow

Each CBT-Q entity shall have a Global Positioning System Interface in order to determine the time and its own position."

Listed below are key requirements and guidelines.

Guidelines

- Highly Programmable - Supporting Easy Addition of New Signal Types
- Highly Flexible - Supporting Multiple Mission Scenarios
- Low Cost
- Low Power
- Low Profile
- Low Detectability - Minimize RF Emissions

Performance

- System Sensitivity - -105 dBm @ RF Input (all sites)
- Signal Type – frequency hopping in 30 to 88 MHz band
- Probability of Detect (Jaguar - up > 4s) - >95%
- Probability of False Alarm (SINCGARS/FM) - < 1%

- Target Emitter Processing Rate - 12 per minute
- Snapshot Rate - 15 per Minute
- Detect to Display Latency - 5 seconds
- Emitter Storage Time - 12 Hours (8,640 Hits Max)
- Setup Time: < 2 Minutes

Environmental

- Operating Temperature: -25 to +49 C
- Operating Altitude: $\leq$ 10,000 ft.
- Vibration: Will Support Tracked/Wheeled Vehicle Operation (w/ Isolation Mounting)
- Rain: Will Operate for Last 10 Minutes of 30 Minute Exposure to Rain @ 1.8 in./hr. with Wind @ 20 mph
- Orientation: Shall Operate in any Orientation

Physical

- Module Less Than 4" X 4" X 8"
- Module Less Than 4 lbs.
- Employ Industry Standard Format/Bus
- Battery (BA-5590) or Vehicle (HMWWV) Power Source
- Battery Life > 8 Hours

User Interface

- Aplique based

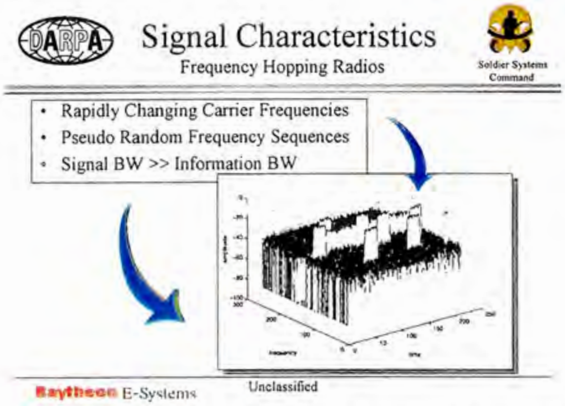
3.2. Task 2 – Algorithm Research and Development

The purpose of this task was to research, develop, and simulate the algorithms required for the CBT-Q signal acquisition, search, sort, and geolocation. The task included determination of the overall system architecture, timing, memory, and processing requirements. Detailed tradeoffs and simulations were performed against other available algorithms and system architectures.

3.2.1. Processing Algorithms

Analysis of processing algorithms is covered extensively in [3]. The information listed below will highlight key findings and decisions.

- Jaguar signal was picked as a target signal due to its wide military use and frequency hopping characteristics.



Signal Characteristics

Frequency Hopping Radios

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- Rapidly Changing Carrier Frequencies
- Pseudo Random Frequency Sequences
- Signal BW >> Information BW

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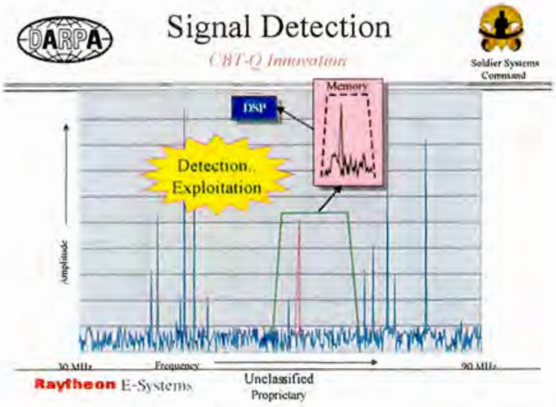
Figure 10 – Jaguar's frequency hopping across 30-88 MHz alludes conventional narrowband search, detect, and track algorithms, which makes it a low-probability of intercept radio

- Jaguar's information bandwidth is only 25 KHz. However, its signal bandwidth is tens of megahertz due to its frequency hopping nature across the entire 30 – 88 MHz band.
- Conventional narrowband scanning search techniques are ineffective for detection of Jaguars due to its rapid frequency agility. (Figure 10)
- Ideal search scheme is to monitor the entire signal band (30-88 MHz) and look for energy bursts. This method was found to be impractical due to a large size of hardware required for its implementation.
- Ambush mode involves "parking" a 10 MHz search and waiting for the Jaguar to hop through. This too was found undesirable since Jaguar hopping sequence need not ever hop through the 10 MHz band.
- The approach chosen for scanning and detection was a hybrid one, which involves rapid searches in 30-88 MHz band in 10 MHz chunks (Figure 11). Specifically, CBT-Q stares between 30-40 MHz for 250 milliseconds, moves over to 40-50 MHz band where it acquires 250 millisecond worth of data, and so on until the entire band is scanned. This method was found to have a high probability of detection for nearly all Jaguar hopping patterns.



Signal Detection

CBT-Q Innovation

Soldier Systems Command

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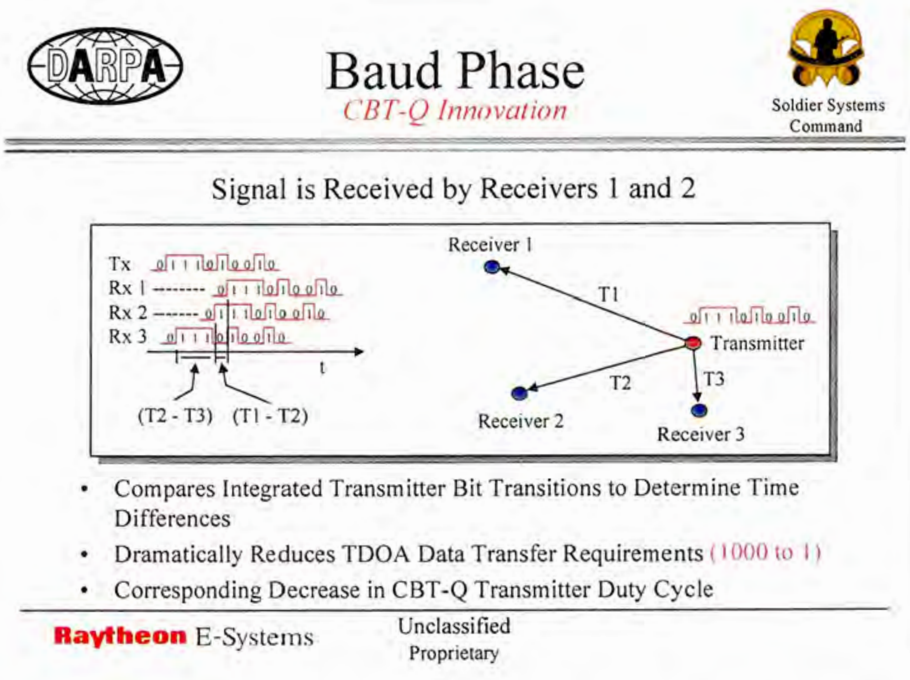
Figure 11 – CBT-Q Algorithm relies on rapid data acquisition across the entire 30-88 MHz band. A sliding 10 MHz scan window covers the entire band in 1.5 seconds. This method has a high probability of detection for most hopping sequences.

- Once the signal is detected, the geolocation calculation uses time difference of arrival method, which is a function of the signal arrival time at each sensor (Basestation, Outstation) and sensor locations. The critical algorithm involves calculation of time of arrival. Two methods were identified: correlation and Raytheon's Baud Phase algorithm.

- Correlation involves passing large amounts of data from Outstations to Basestation where timing differences are calculated. This method was rejected due to was rejected due to a requirement to pass large amounts of data from Outstations to the Basestation. There were several serious drawbacks to this method: (a) amount of time required to send sufficient amount of data was in estimated to be in tens of seconds, and (b) Outstations would flood the RF spectrum with RF energy during data transmissions, thus increasing their own probability of being detected.
- Baud phase method, illustrated in Figure 12, was chosen. This method calculates the relative phase of symbol timing and passes the time from each Outstation to Basestation. Instead of thousands of bytes of data, only tens of bits are passed over the air. Therefore, transmission time and own detectability are minimized by one to two orders of magnitude. Additionally, geolocation response time from Jaguar activation time to geolocation reporting is drastically improved.



Baud Phase

CBT-Q Innovation

Soldier Systems Command

Signal is Received by Receivers 1 and 2

- Compares Integrated Transmitter Bit Transitions to Determine Time Differences
- Dramatically Reduces TDOA Data Transfer Requirements (1000 to 1)
- Corresponding Decrease in CBT-Q Transmitter Duty Cycle

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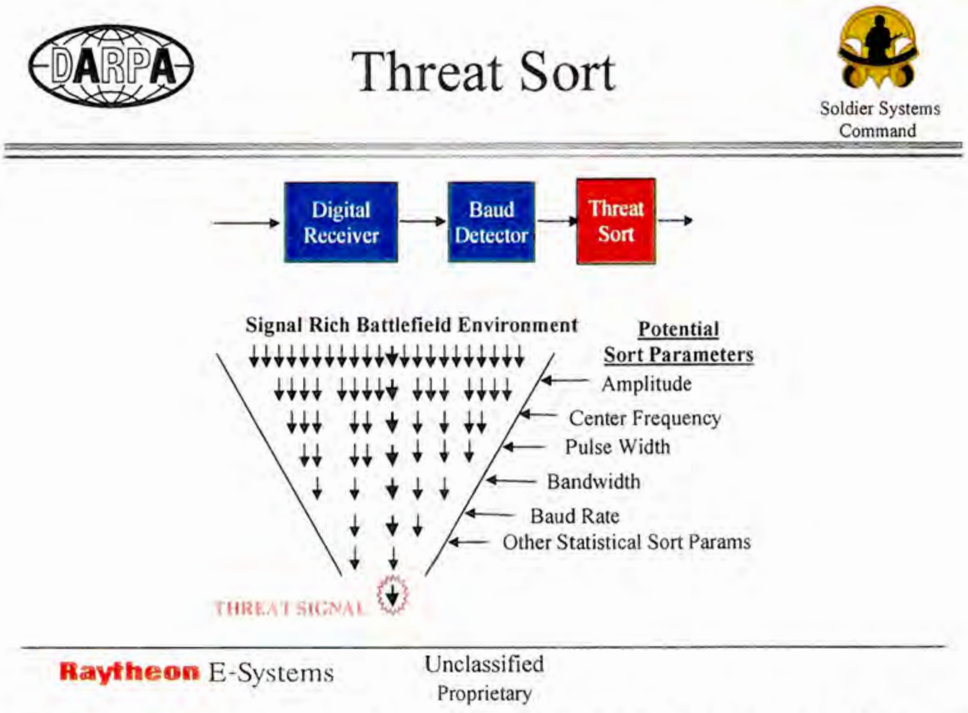
Figure 12 – Baud phase minimizes data transfer times between sensors, decreases own detectability, and dramatically improves geolocation response time to the warfighter.

- Entire processing chain is described in detail in [3]. One key step is the Threat sorting algorithm which determines whether detected energy in the RF spectrum belongs to the Jaguar or some other signal which is not of interest. This algorithm, illustrated in Figure 13, is critical for minimizing false alarm rates.



Threat Sort

Soldier Systems
Command

Digital Receiver → Baud Detector → Threat Sort →

Signal Rich Battlefield Environment

Potential Sort Parameters
Amplitude
Center Frequency
Pulse Width
Bandwidth
Baud Rate
Other Statistical Sort Params

THREAT SIGNAL

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Figure 13 – Threat signal sorting minimizes the probability of false alarms

3.2.2. 20 Questions

On July 23, 1996, DARPA requested answers to twenty questions that covered many topics related to the Combat Cueing topics, which included:

- Technology and innovation
- Signal classes
- Performance Characteristics
- Hardware and software requirements
- Environmental impacts
- System geometry issues
- Tradeoffs

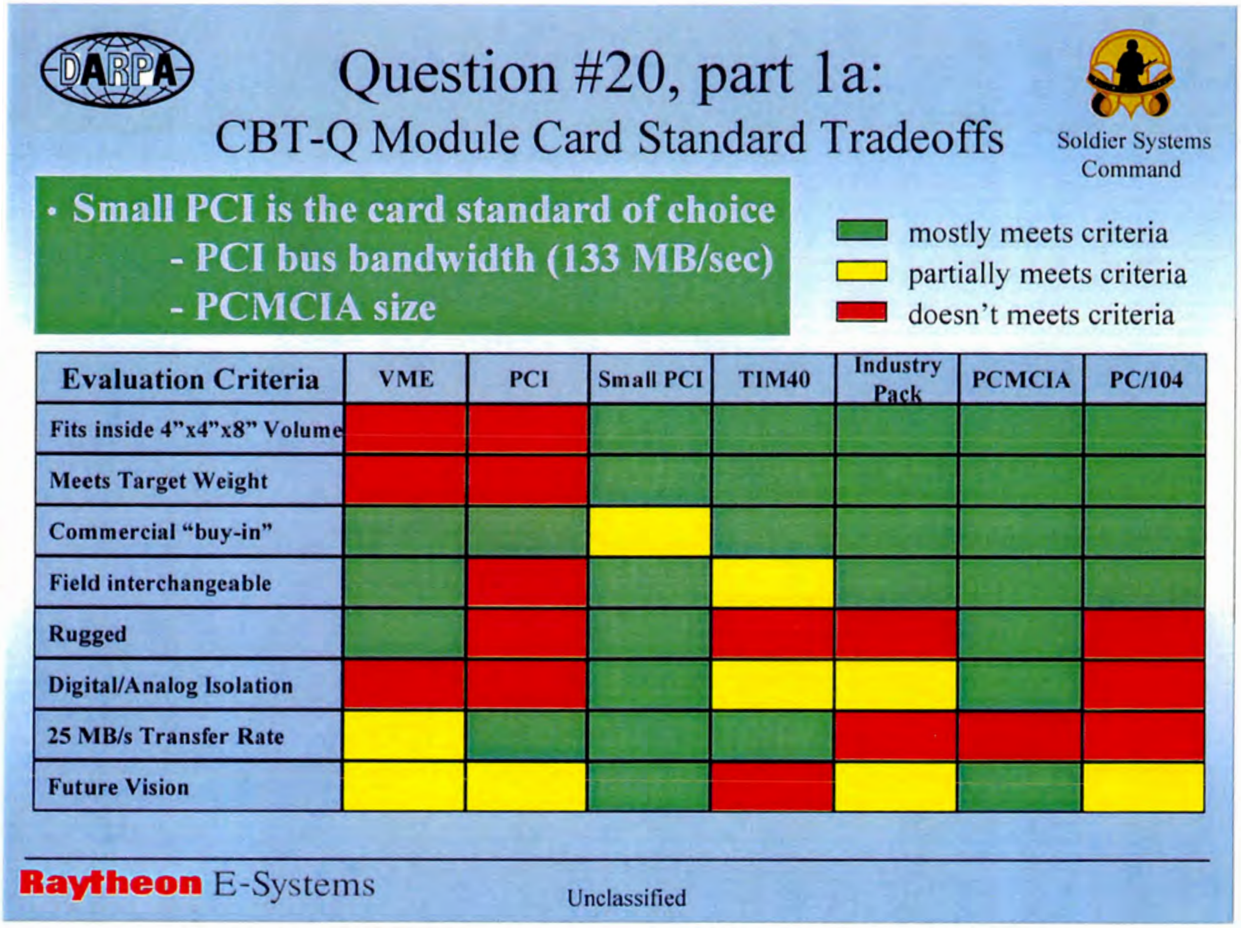
These questions led to valuable research, whose results can be found in [4].

One of the areas analyzed included identification of factors that impact geolocation accuracy. Many factors were identified, including:

- GPS Receiver accuracy
- RF detection sensitivity
- Location of sensor
- Transmit power of threat emitter

- Duration of emission
- Signal to noise ratio of the emitted signal
- Number of hopping pulses detected and processed
- Multipath

Another question dealt with the choice of the bus standard chosen for CBT-Q hardware architecture. Tradeoff analysis (Figure 14) considered several critical criteria and chose Small PCI standard.



Question #20, part 1a:

CBT-Q Module Card Standard Tradeoffs

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- Small PCI is the card standard of choice
  - PCI bus bandwidth (133 MB/sec)
  - PCMCIA size

🟩 mostly meets criteria
🟨 partially meets criteria
🟥 doesn't meets criteria

Evaluation Criteria	VME	PCI	Small PCI	TIM40	Industry Pack	PCMCIA	PC/104
Fits inside 4"x4"x8" Volume	🟥	🟥	🟩	🟩	🟩	🟩	🟩
Meets Target Weight	🟥	🟥	🟩	🟩	🟩	🟩	🟩
Commercial "buy-in"	🟩	🟩	🟨	🟩	🟩	🟩	🟩
Field interchangeable	🟩	🟥	🟩	🟨	🟩	🟩	🟩
Rugged	🟩	🟥	🟩	🟥	🟥	🟩	🟥
Digital/Analog Isolation	🟥	🟥	🟩	🟨	🟨	🟩	🟥
25 MB/s Transfer Rate	🟨	🟩	🟩	🟩	🟥	🟥	🟥
Future Vision	🟨	🟨	🟩	🟥	🟨	🟩	🟨

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Figure 14 – Small PCI standard met most of the evaluation criteria

3.2.3. Simulation

Extensive simulation was performed in order to predict the performance of the system. Results of this study are shown in [5]. Simulation involved many scenarios with varying number of factors that influence geolocation accuracy. These factors include transmitted power, geometry of sensors, and others.

Figure 15 shows the typical impact of geometry on the system geolocation accuracy. Two cases are considered. In a preferred case (left figure), the target emitter is surrounded by CBT-Q sensors (small blue circles). In a less preferred case, the target emitter is not surrounded by sensors. Each ellipse represents an 80% probability curve for detecting the target emitter. Specifically, if the emitter location were in a center of the ellipse, the CBT-Q system would geolocate the emitter inside of the ellipse 80% of the time with an approximate accuracy of 100 meters.

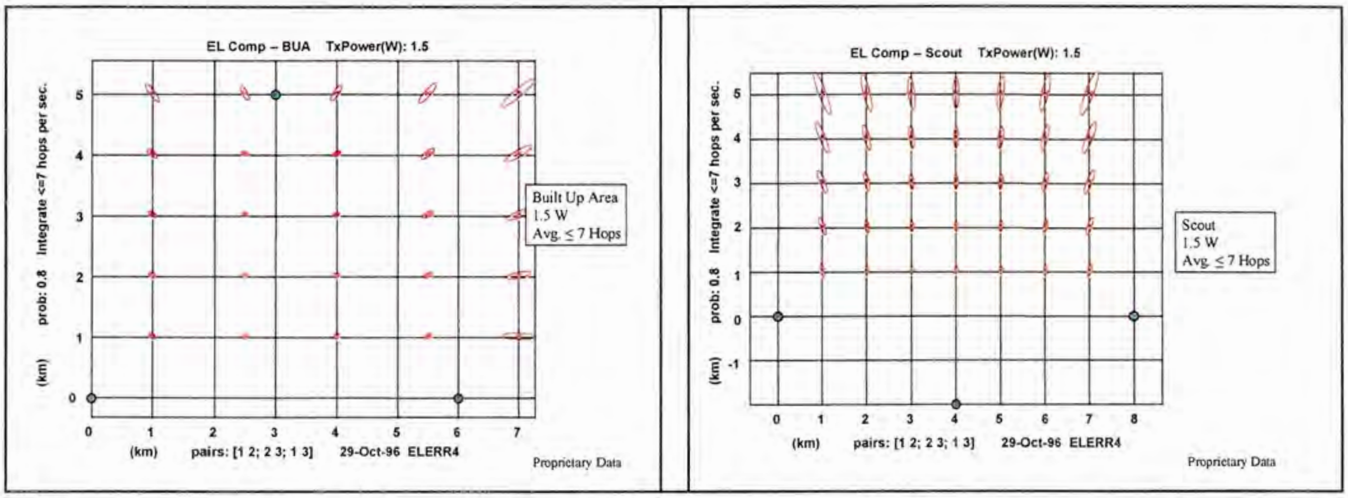


Figure 15– Surrounding target emitter with CBT-Q sensors leads to improved geolocation accuracy.

3.3. Task 3 – Hardware Development

3.3.1. Requirements Analysis

The first part of hardware development included analysis of required resources in order to execute specified Baud Phase based geolocation algorithm. Results of this analysis are shown in [6].

Initial chassis concept is illustrated in figure 16. The concept was based on spatial estimates required to meet demanding processing requirements, illustrated in figure 17. In order maximize the processing power per volume (cubic centimeters), a just-released Texas Instruments TMS320C62 digital signal processor (DSP) was chosen.

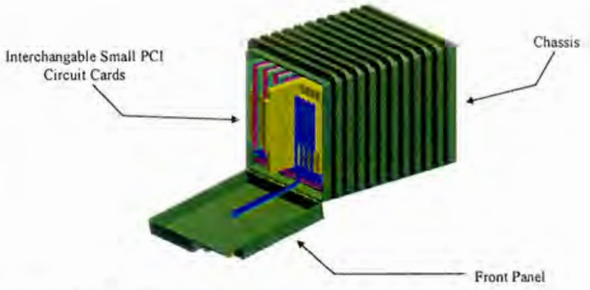
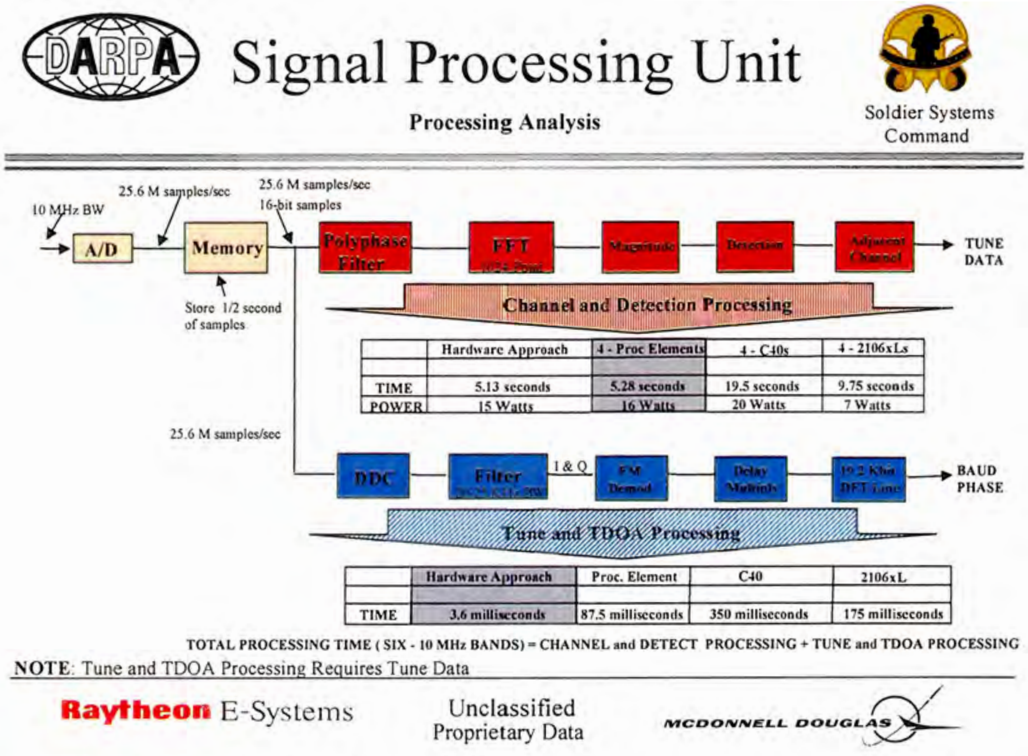


Figure 16 – Initial concept for Combat Cueing Sensor packaging was based on a 4"x4"x6" chassis



Signal Processing Unit

Processing Analysis

Soldier Systems
Command

Channel and Detection Processing

	Hardware Approach	4 - Proc Elements	4 - C40s	4 - 2106xLs
TIME	5.13 seconds	5.28 seconds	19.5 seconds	9.75 seconds
POWER	15 Watts	16 Watts	20 Watts	7 Watts

Tune and TDOA Processing

	Hardware Approach	Proc. Element	C40	2106xL
TIME	3.6 milliseconds	87.5 milliseconds	350 milliseconds	175 milliseconds

TOTAL PROCESSING TIME (SIX - 10 MHz BANDS) = CHANNEL and DETECT PROCESSING + TUNE and TDOA PROCESSING

NOTE: Tune and TDOA Processing Requires Tune Data

Raytheon E-Systems

Unclassified
Proprietary Data

MCDONNELL DOUGLAS

Figure 17 – RF detection and geolocation processing requirements

The system requirements for the Basestation and Outstation [7] and User Station [8] were derived based on overall system specifications.

Figure 18 illustrates the architecture for the Basestation and Outstation sensor.

Termed CBT-Q Module, the module contains all of the necessary functions and interfaces to perform geolocation detection and geolocation functions.

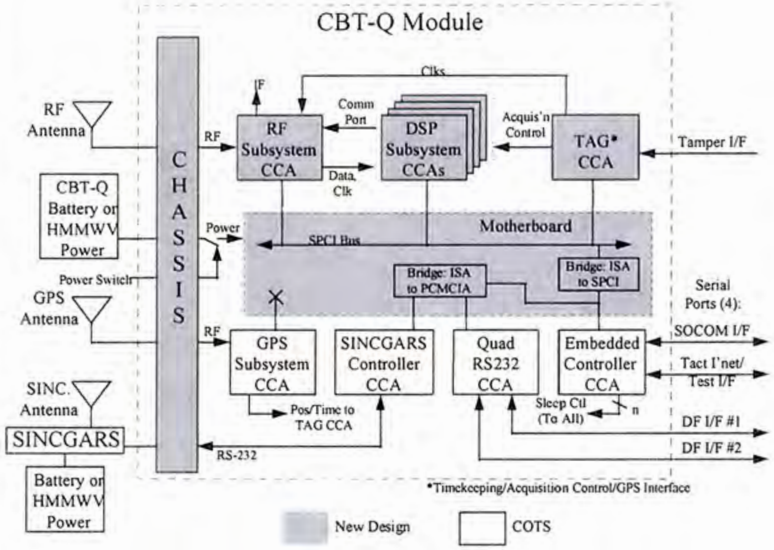


Figure 18 - Basestation/Outstation modules and Constituent Subsystem Electrical/Data Interfaces

User Station, whose block diagram and interfaces are illustrated in Figure 19, is essentially a computer with GPS receiver and a radio subsystem. Boeing MARSS Vest was elected to perform the User Station function.

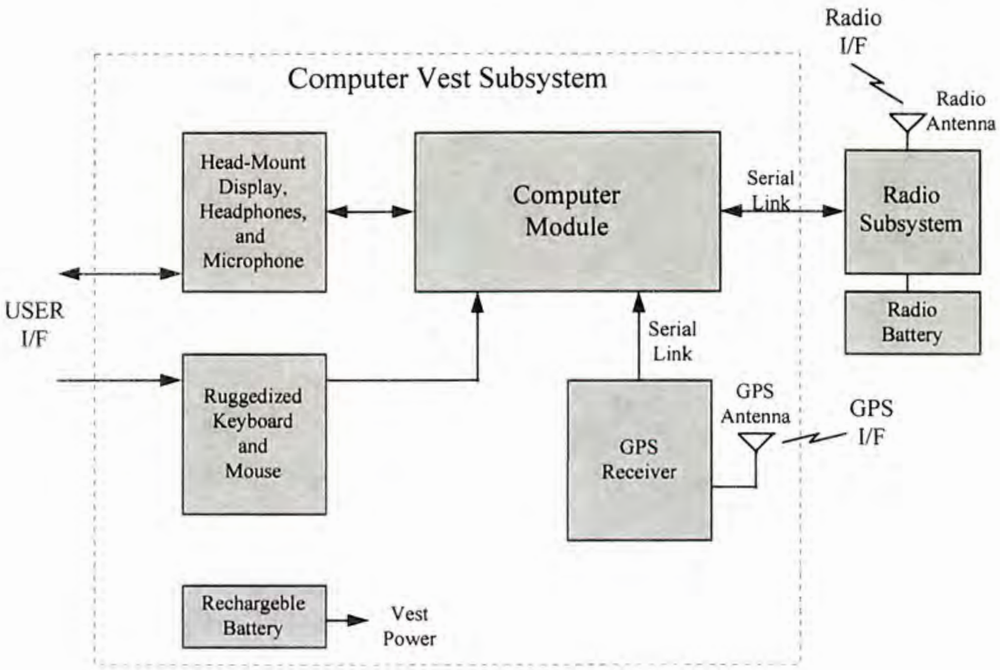


Figure 19 - User Station Block Diagram

3.3.2. Design

Hardware design proceeded. Each hardware block identified during the requirements phase was further specified. These hardware requirements specifications are too numerous to be included in this report. However, they are available upon request.

Detailed design followed. A Critical Design Review [9] was held prior to build and test phase. Mechanical and electrical designs of circuit cards, chassis, cables, and other subassemblies were reviewed.

Figure 20 illustrates the interconnect diagram of CBT-Q module. Major CBT-Q module subassemblies are described below.

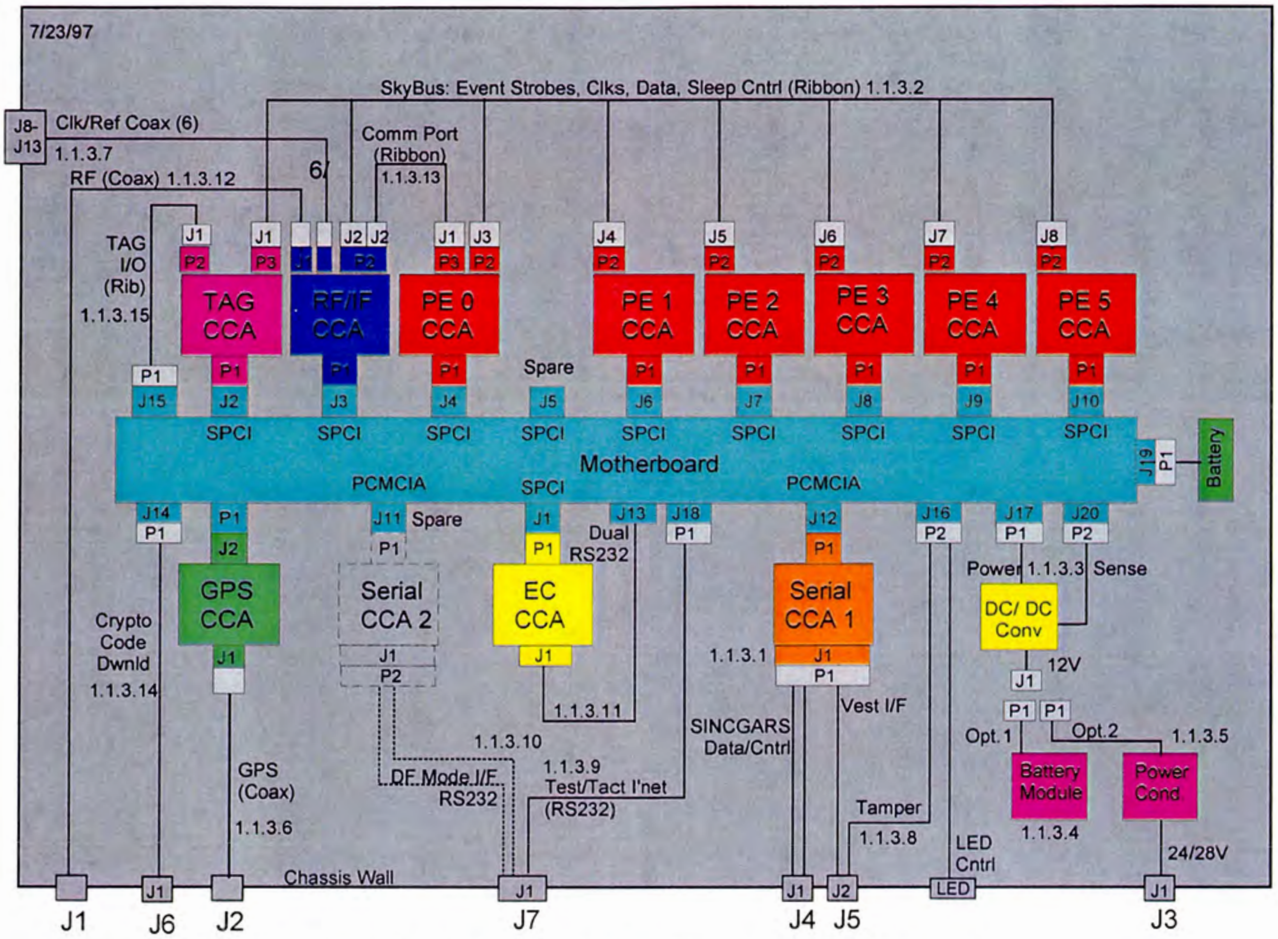


Figure 21 – CBT-Q Module Interconnect Diagram

3.3.2.1. Chassis

Critical characteristics of the CBT-Q Chassis, illustrated in Figure 21, are listed below:

- Miniature construction: 6.6" x 6" x 3.8"
- Weighs only 2.1 pounds
- 10:1 space and weight reduction over VME
- 12 card slots: 10 small PCI and 2 PCMCIA
- Environmentally tight – water resistant to 1m
- Conduction cooled

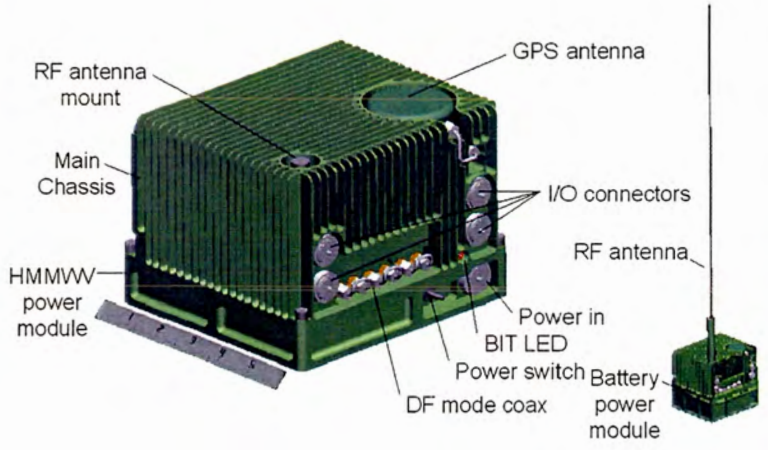


Figure 20 - CBT-Q Module Chassis Features

- Embedded MPE-I™ Miniature PLGR GPS Receiver Engine
- Embedded GPS Antenna
- Integrated RF antenna
- Battery or HMMWV powered.
- Other integrated power conditioning adapters are available.
- Ideal for dismounted, airborne, and covert applications
- A suite of Small PCI circuit cards available for customized applications.

The chassis (Figure 22) contains all essential functions required for your application: a 12-slot motherboard, featuring 10 small PCI slots and 2 PCMCIA slots, embedded GPS receiver engine, GPS and RF antenna and associated wiring. The chassis is rugged and environmentally safe. The assembled unit can be immersed under water or operated in a desert sun.

The chassis is powered by an interchangeable HMMWV Adapter or a Battery Pack (Figure 23).

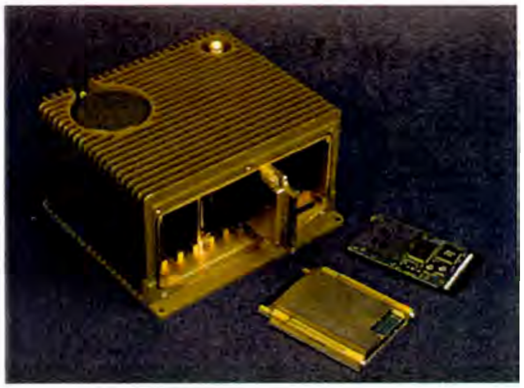


Figure 22 - CBT-Q Module Chassis

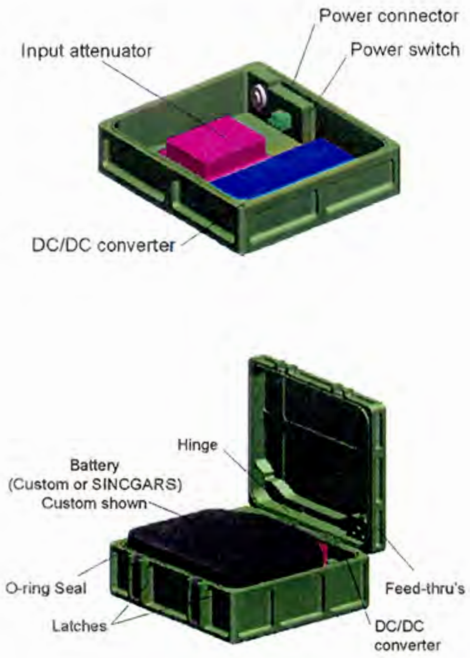


Figure 23 – CBT-Q Chassis' HMMWV Power Adapter (top) and Battery Pack (bottom)

3.3.2.2. Small PCI Cards

Each Small PCI card has a single or a dual (Figure 24) printed wiring board (PWB) construction. Small PCI is a credit-card size, open standard featuring 133 megabyte per second data transfer capability. PWBs are two sided.

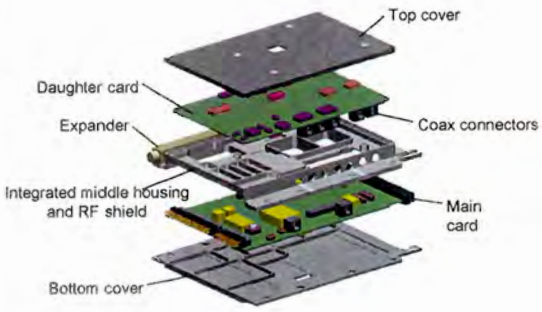


Figure 24 Card construction includes two circuit cards, shields, and housing

PWBs are sandwiched by top and bottom cover. For RF applications, covers may also have built-in compartments for RF shielding and isolation. Cards are designed to provide an efficient thermal path from PWB to the circuit card housing. The expander moves the heat from the housing to the chassis.

Combat Cueing program has developed and or integrated the following circuit card assemblies (CCAs):

Figure 25 – RF-IF Circuit Card Assembly

- **RF – IF CCA (Figure 25)**. This card is a wideband tuner operating in the 30 – 88 MHz band. It outputs 10 MHz wide intermediate frequency (IF) digitized to 12 bits of resolution. Control is accomplished over the PCI bus.
- **Embedded Controller Card (Figure 26)**. Miniaturized through multi-chip module technology, this COTS product features all of the characteristics of a Pentium based personal computer.
- **Processing Element (PE) Card (Figure 27)**. Based on a TMS320C62 DSP, the card accepts wideband IF and can be programmed to perform a wide variety of digital signal processing applications including spectrum analysis, search, demodulation, and others. The card features a digital downconverter, 16 megabytes of IF shapshot memory, and PCI interface capable of bus mastership.

Figure 26 – This Pentium-based Embedded Controller card was never delivered by the vendor. An alternate card from Ziatech was selected an interim solution.

Figure 27 – TMS320C62 portion of the PE CCA

- **Timing, Acquisition, and GPS Card**. Known as TAG, this card provides an interface to the GPS engine. It also contains additional EEPROM, and circuitry for synchronizing RF acquisition with GPS.
- **Quad Serial Card**. This COTS card provides four RS232 connections to the external world.
- **Other PCMCIA Cards.** Two of the 12 PCMCIA slots can house many of the commercially available cards such as Ethernet card, Modem, and others. A PCI-to-PCMCIA bridge chip on the motherboard allows any bus master to access these PCMCIA cards.

3.3.2.3. Thermal Characteristics

CBT-Q chassis is conduction cooled. Covered by heat fins on 5 of the 6 sides, the chassis has a 0.4 degree C per Watt rise when no external air cooling is present. External forced air cooling can improve the thermal performance by almost an order of magnitude.

3.3.3. Build, Integration and Test

Combat Cueing System hardware (Figure 28) was built and tested in accordance with requirements specifications. Exceptions and workarounds are noted below. Some of the workarounds, while not technically preferred, were chosen based on cost considerations. Higher performance implementations were identified but required funding levels that were not available.

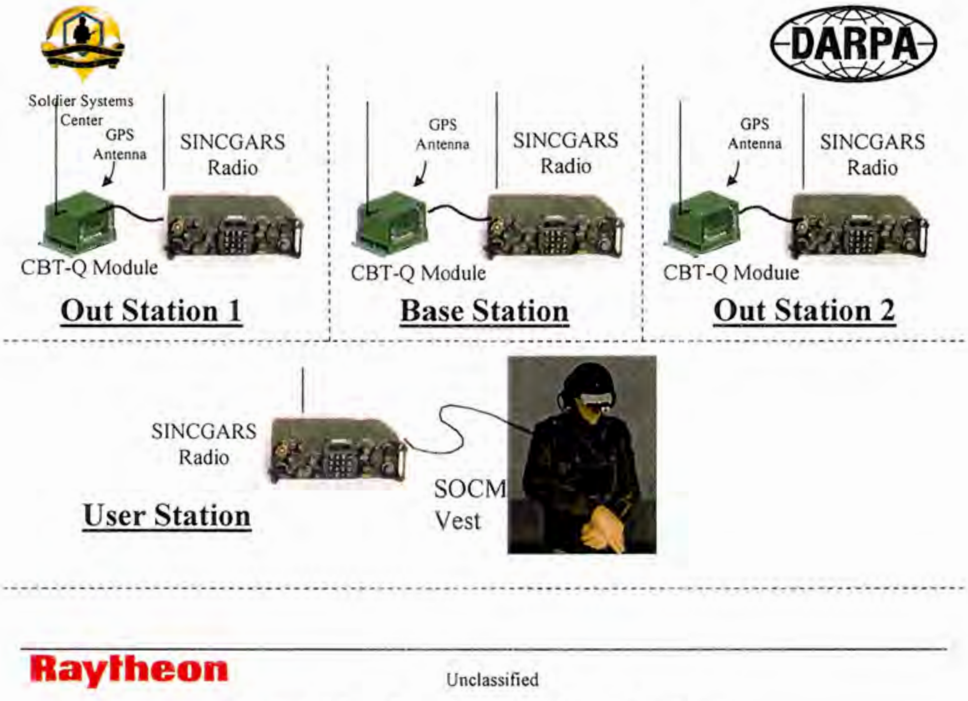


Figure 28 – Combat Cueing Hardware

3.3.3.1. RF-IF CCA

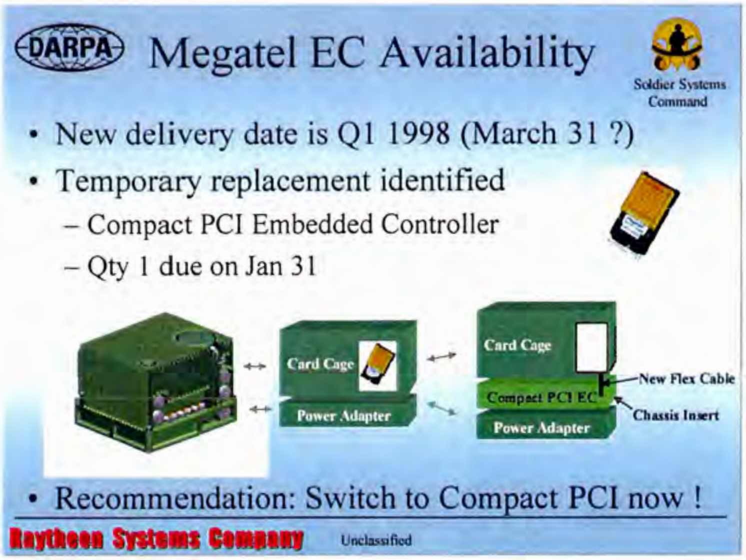
- Initially intended to be a single circuit card assembly, RF-IF CCA was designed on two circuit boards due to its complexity and packaged in one 0.5" housing.
- Sensitivity and dynamic range experienced significant degradation during testing. Analog board was separated from the digital board and housed separately to minimize interference.
- Sensitivity of -105 dbm was not achieved. Instead, -90 dBm was measured in the laboratory environment. This reduction of sensitivity is estimated to have a 50% to 70% impact in CBT-Q sensor range.
- Spur free dynamic range was measured around -65 dB vs. the goal of -75dB.

3.3.3.2. PE CCA

- Initially intended to be a single circuit card assembly, PE CCA was designed on two circuit boards due to its complexity and packaged in one 0.5" housing.
- XILINX field programmable gate array (FPGA) PCI Core did not perform as advertised. Consequently, PCI Initiator function was eliminated. The impact of this change was sign
- C60 Errata sheet identified 45 design problems with TMS320C62 microprocessor. Major problems included loss of 2M byte fast-memory access, unreliable emulator port, memory switching problems. This was a major blow to the CBT-Q performance. The solution included jumpering of additional 256K synchronous burst RAM, lowering the clock speed from 200 MHz to 110MHz, and elimination of pipelined operation. Overall impact was a loss of performance by an approximate factor of 7x. Using today's errata free versions of 'C62 additional performance improvement of 2x could likely be achieved.
- Due to the significant modifications required for enabling PE CCA, only one instead of six CCAs were built and tested per module.

3.3.3.3. Embedded Controller

- Initially a Megatel COTS board was selected to perform this function. The vendor slipped delivery by almost 12 months. An alternate solution was implemented. The new card was also COTS, but came in a Compact PCI format instead of Small PCI form factor. The card is manufactured by Ziatech.
- This modification required a chassis insert and a flex cable, as shown in the Figure 29.
- In order to keep the height of the Ziatech card to a minimum, processor heatsink and some connectors had to be removed. These changes, along with the Ziatech-to-PCI cable presented some serious challenges during debug test and integration phase.



DARPA Megatel EC Availability

Soldier Systems Command

- New delivery date is Q1 1998 (March 31 ?)
- Temporary replacement identified
  - Compact PCI Embedded Controller
  - Qty 1 due on Jan 31

- Recommendation: Switch to Compact PCI now !

Raytheon Systems Company Unclassified

Figure 29 – Megatel Small PCI Embedded Controller was replaced by Ziatech Compact PCI Embedded Controller. This change led to some chassis modifications.

3.3.3.4. TAG CCA

- TAG CCA met majority of its design requirements
- Card-to-card timing

differences, critical to Combat Cueing performance, were measured within 50 nanoseconds, which is above expectations.

- TAG CCA's analog-to-digital clock output had too much distortion and required an external band pass filter.

3.3.3.5. VEST

Instead of the MARSS vest, it was agreed that Boeing would deliver a derivative of Special Operations Combat Management (SOCM) Vest. Capabilities of standard SOCM Vest and Combat Cueing baseline are shown below. SOCM Vest is pictured in Figure 30.

Table 1 – Special Operations CBT-Q Management System Specification

SOCM SPECIFICATION / OPTIONS		COMBAT CUEING CONFIG.
Operating System	Windows™ 95	Windows™ NT
Display	Seattle Sight Systems Hand Held 640x480 or Kopin 640x480	Kopin 640x480
Processor	150 MHz Pentium MMX, upgradeable to 200 and 233Mhz	150 MHz Pentium MMX
Memory	64 Mbytes	64 Mbytes
Weight	11.1 Lbs. basic system, 16.5 Lbs. with PRC-143 radio and GPS	8.9 Lbs. without GPS or Radio
Video Output	VGA and SVGA Compatible	VGA and SVGA Compatible
PCMCIA Slots	3 Total, 2 Type II and one Type III	Disabled Due to Windows™ NT
Hard Disk Drive	340Mbyte PC Card ATA Hard Drive	340Mbyte PC Card ATA Hard Drive
GPS System	Rockwell SOLGR, also PLGR compatible	PLGR (One total for all systems)
Battery Life	4 to 6 hours	4 hours ea.
Battery	6 Amp-hour Lithium Ion Polymer	4 Amp-hour Lithium Ion
Short Range Communications	Proxim RangeLAN2 Wireless LAN Card	N/A
Long Range Communications	Hughes AN/PRC-143 Hand-held Multi-band radio, compatible with AN/PRC-117 and SINCGARS	SINCGARS interface through Serial Cable and Raytheon E-Systems Software

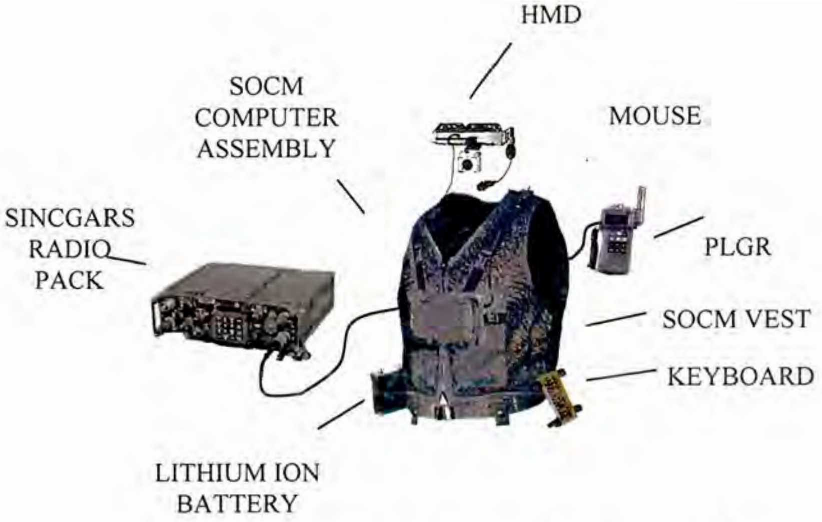


Figure 30 – User Station Vest and Associated Components

The Boeing Company provided Raytheon E-Systems four SOCM systems each configured with the SOCM Computer Assembly, Kopin HMD, mouse, keyboard, vest, two lithium Ion batteries, and a battery charger. The SOCM System is loaded with the User Station Software and interfaced with a SINCGARS radio and PLGR to be used as a Combat Cueing User Station

3.3.3.6. Radios

Four SINCGARS Radios were built along with Vehicular Amplifier Adapters which boost the radio power to 50W. Rechargeable batteries for dismounted operation were also obtained.

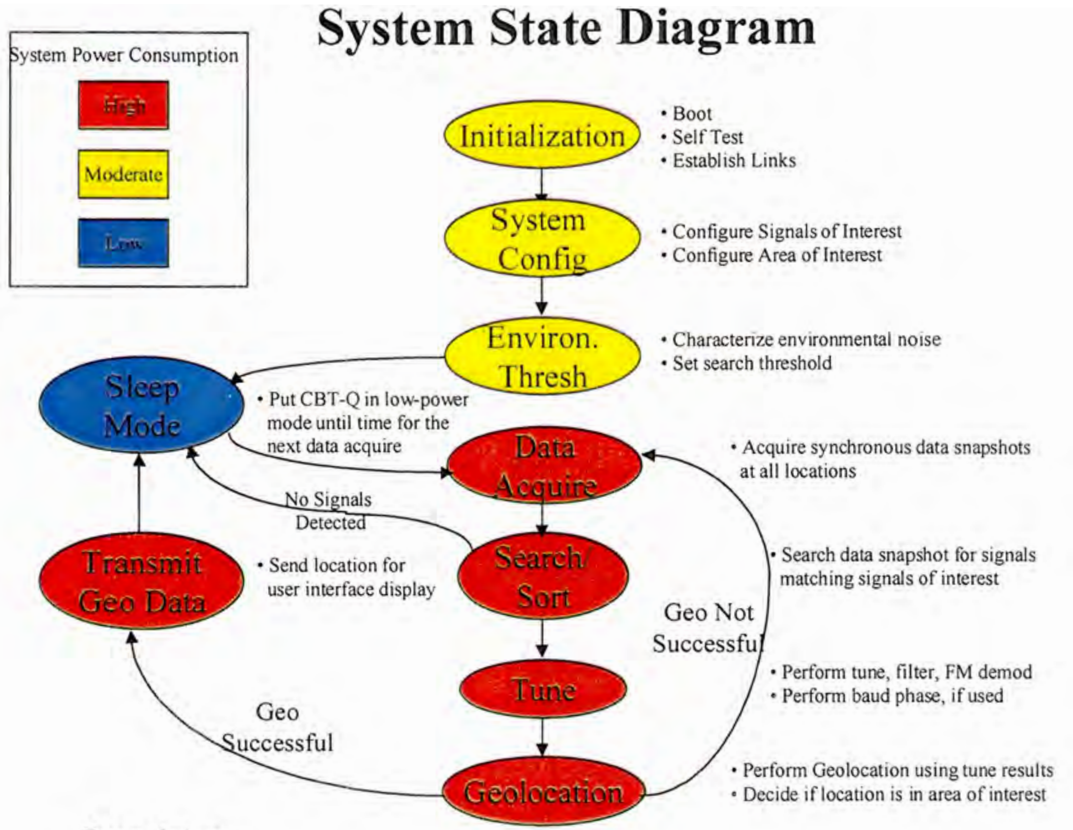
3.3.3.7. PLGR GBS Receiver

A military version of GBS receiver was obtained from Rockwell. PLGR is Y2K compliant. PLGR is attached to CBT-Q Module motherboard. External GBS antenna is embedded in the CBT-Q Chassis.

3.4. Task 4 – Software Development

3.4.1. Requirements Analysis

During this phase of the program, software requirements were established. At a system level, CBT-Q software function is illustrated in the Figure 31. Further high level analysis can be found in [10].



Proprietary

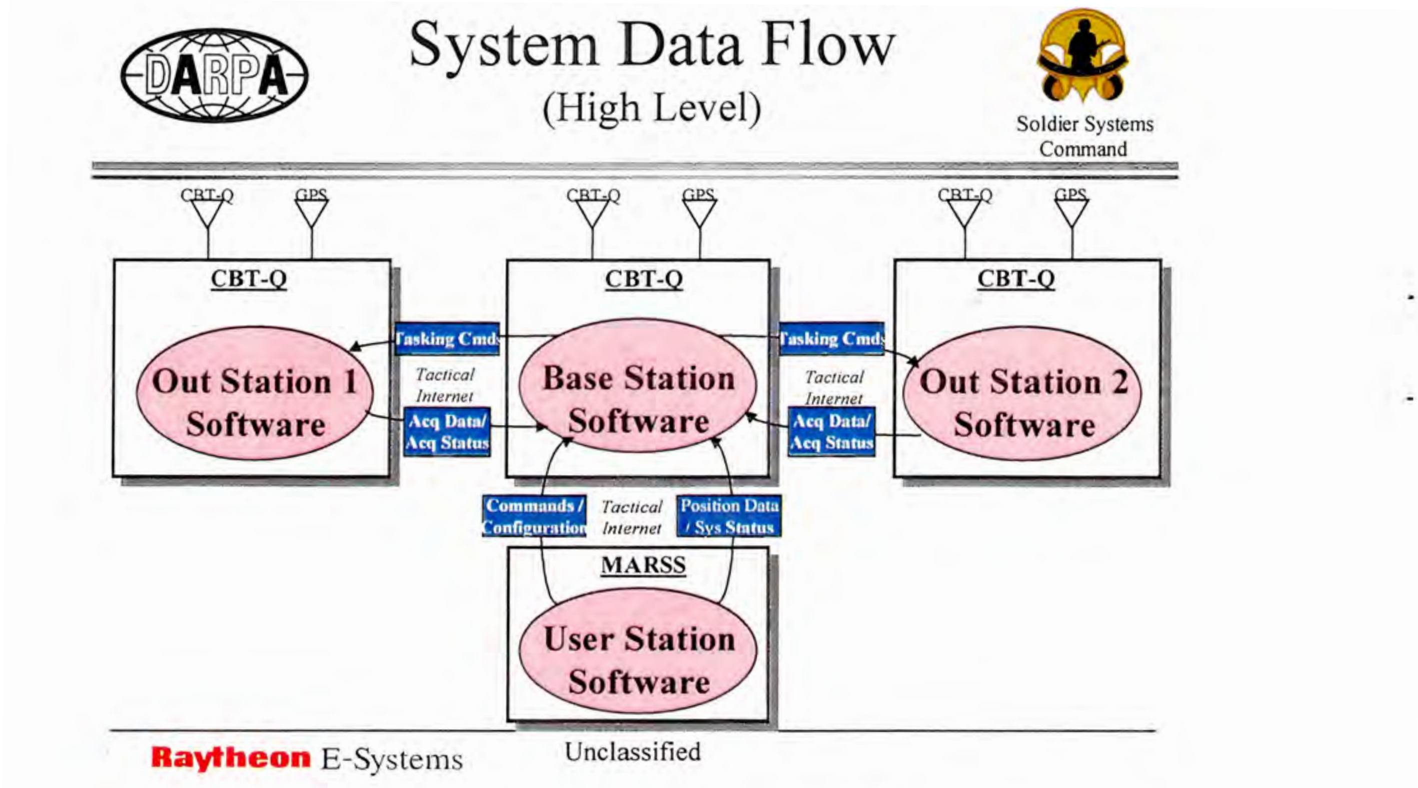
Figure 31 – CBT-Q Software High Level Data Flow

The software runs on the Basestation, Outstation, and User Station concurrently. Software requirements for each are listed in the references as follows:

- Basestation [11]
- Outstation [12]
- User Station [13]

3.4.2. Design

Design was driven by parallel nature of processing. Basestation, Outstations, and one or more User Stations run concurrently. As shown in Figure 32, User Station configures the Basestation, which manages both Outstations relative to RF data acquisition. Geolocation is calculated in the Basestation and reported to one or more User Stations.



System Data Flow
(High Level)

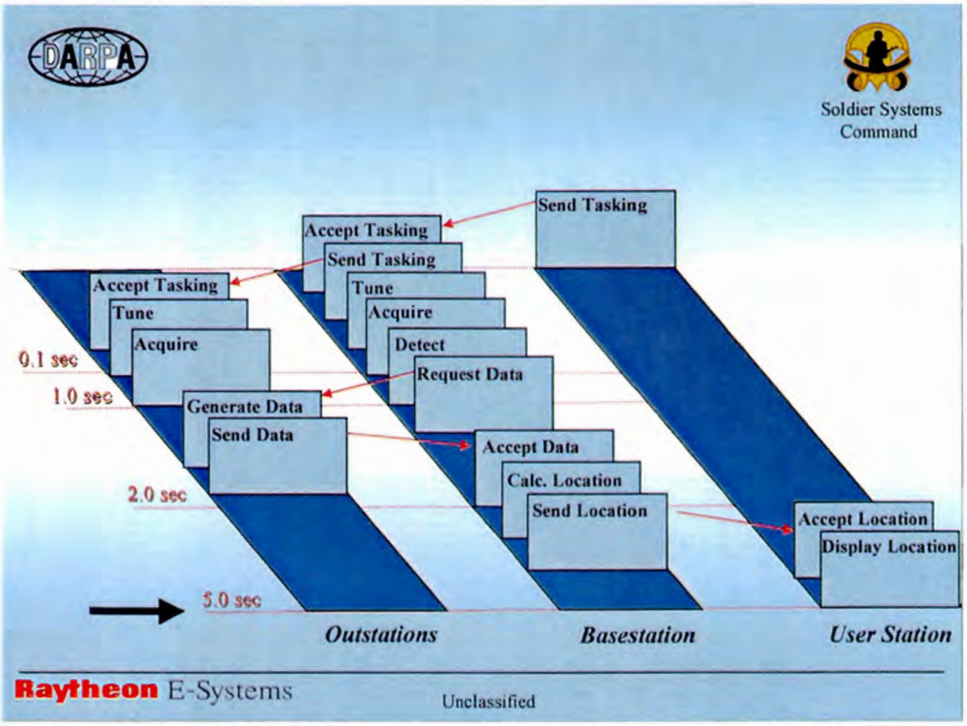
Soldier Systems Command

Raytheon E-Systems

Unclassified

Figure 32 – Basestation manages Outstations

The parallel nature of processing is illustrated in Figure 33. After tasking each of the Outstations to acquire RF data, Basestation itself also acquires RF data and performs search and detection for threat emitters. If a threat emitter is spotted, Basestation requests baud phase information from Outstations. Geolocation is calculated using three sets of baud phases and sensor locations. Location of threat emitter is then reported to the User Station.



Soldier Systems Command

Send Tasking

Accept Tasking

Send Tasking

Tune

Acquire

Detect

Request Data

Accept Tasking

Tune

Acquire

0.1 sec

1.0 sec

Generate Data

Send Data

Accept Data

Calc. Location

Send Location

2.0 sec

Accept Location

Display Location

5.0 sec

Outstations

Basestation

User Station

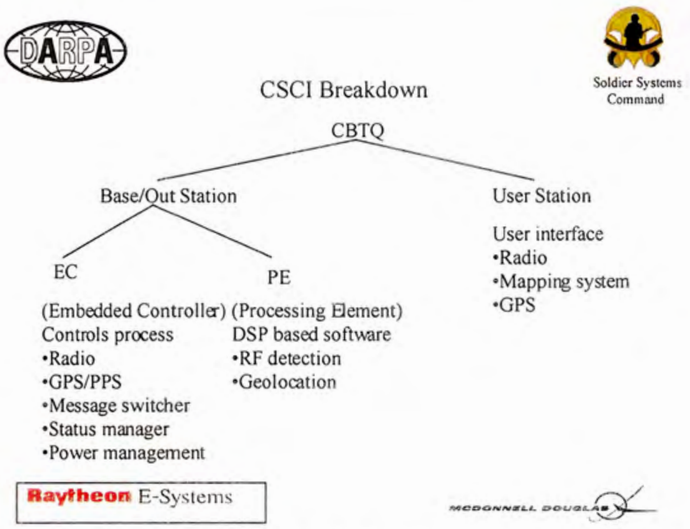
Raytheon E-Systems

Unclassified

Figure 33 – CBT-Q Parallel Processing Timing Sequence

High level software design, illustrated in Figure 34, is described in [14]. Three Computer Software Configuration Items (CSCIs) were defined:

- Base/Outstation Embedded Controller (EC) CSCI, which runs on the Pentium based controller
- Base/Outstation Processing Element (PE) CSCI, which runs on TMS320C62 DSP
- User Station CSCI, which runs on SOCM Vest.



Soldier Systems Command

CSCI Breakdown

CBTQ

Base/Out Station

User Station

User interface
•Radio
•Mapping system
•GPS

EC

PE

(Embedded Controller)
Controls process
•Radio
•GPS/PPS
•Message switcher
•Status manager
•Power management

(Processing Element)
DSP based software
•RF detection
•Geolocation

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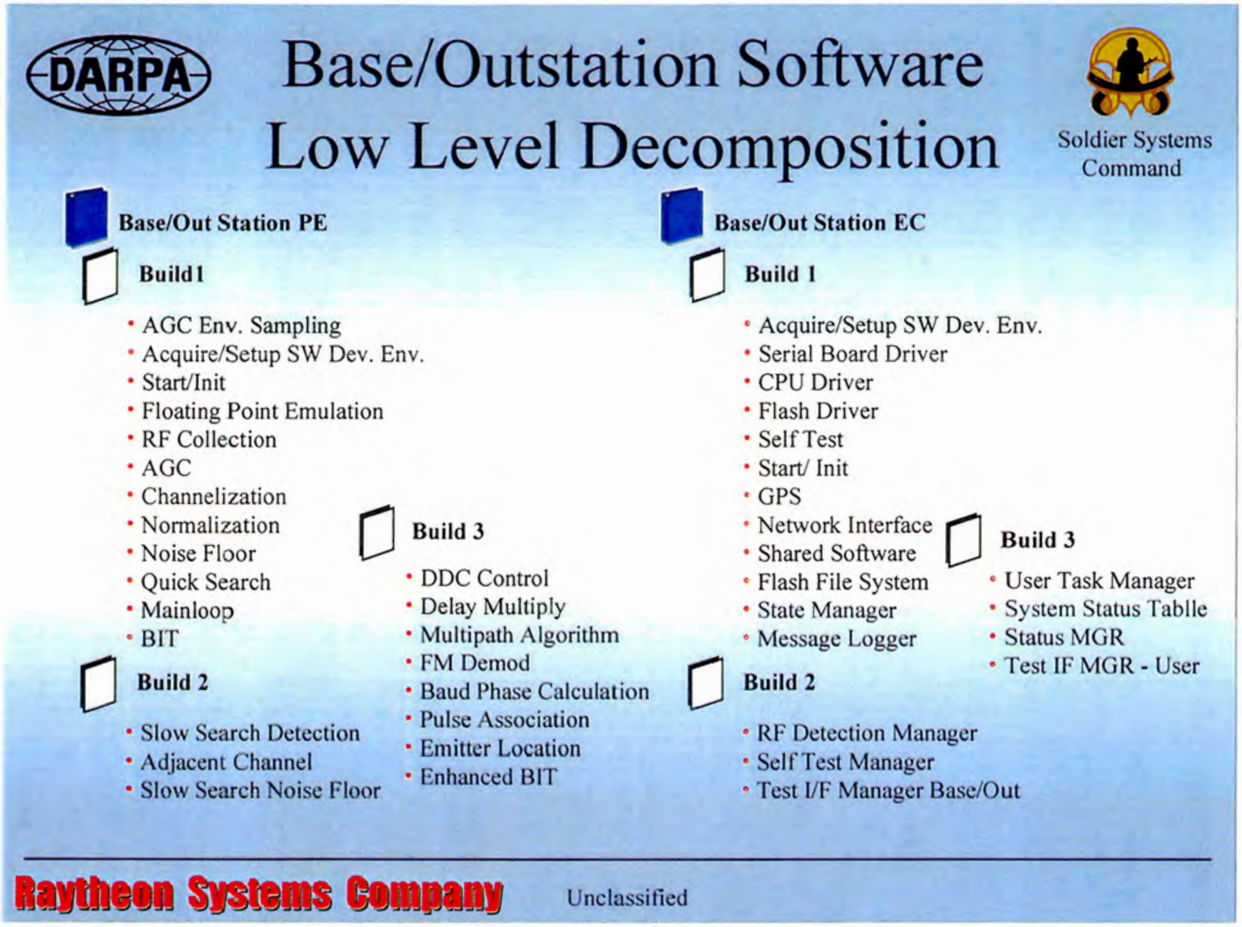
Figure 34 – Software divided into three Computer Software Configuration Items (CSCIs)

3.4.2.1. Base/Outstation

Base/Outstaion software was implemented in three "builds", each adding a maturity level to the previous baseline. Build 1 covered low level interfaces, while Build 3 integrated Geolocation. Figure 35 shows the high level breakout of software.


DARPA

Base/Outstation Software
Low Level Decomposition

Soldier Systems Command

Base/Out Station PE

Build1

- AGC Env. Sampling
- Acquire/Setup SW Dev. Env.
- Start/Init
- Floating Point Emulation
- RF Collection
- AGC
- Channelization
- Normalization
- Noise Floor
- Quick Search
- Mainloop
- BIT

Build 2

- Slow Search Detection
- Adjacent Channel
- Slow Search Noise Floor

Build 3

- DDC Control
- Delay Multiply
- Multipath Algorithm
- FM Demod
- Baud Phase Calculation
- Pulse Association
- Emitter Location
- Enhanced BIT

Base/Out Station EC

Build 1

- Acquire/Setup SW Dev. Env.
- Serial Board Driver
- CPU Driver
- Flash Driver
- Self Test
- Start/ Init
- GPS
- Network Interface
- Shared Software
- Flash File System
- State Manager
- Message Logger

Build 2

- RF Detection Manager
- Self Test Manager
- Test I/F Manager Base/Out

Build 3

- User Task Manager
- System Status Tablle
- Status MGR
- Test IF MGR - User

Raytheon Systems Company Unclassified

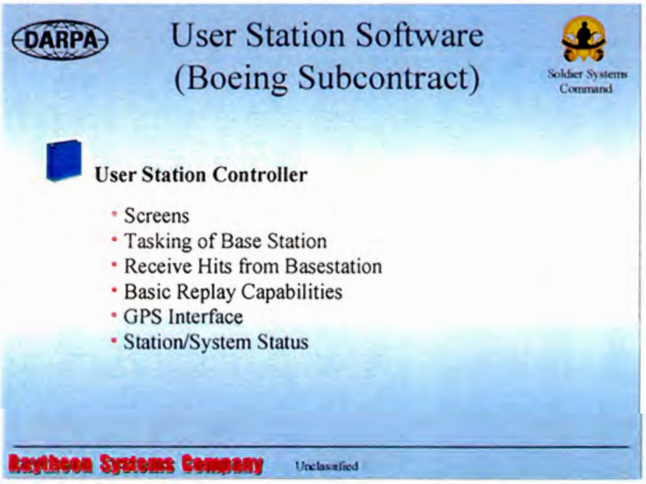
Figure 35 – Basestation and Outstation CSCIs were built in three stages

Base/Outstation EC software was developed using Rational Rose design tool. Programs are coded in C++. VxWorks operating system is employed.

PE Software runs on 'C62 processor. C and assembly languages were employed.

3.4.2.2. User Station

User Station software was developed on SOCM Vest in C++ running under Windows NT environment. Design is made up of functions listed in Figure


DARPA

User Station Software
(Boeing Subcontract)

Soldier Systems Command

User Station Controller

- Screens
- Tasking of Base Station
- Receive Hits from Basestation
- Basic Replay Capabilities
- GPS Interface
- Station/System Status

Raytheon Systems Company Unclassified

Figure 36 – User Station software functions

36.

The most critical aspect of the design was the user interface. At the onset, several user screens were prototyped to highlight the desired features.

The User Station (Figure 37) provides a user interface to control the operations of the Combat Cueing System. It also records the data so analysis of the mission can be done later. The User Station Software initializes when the user powers up the hardware in a normal Combat Cueing System configuration. When activated and running a mission the User Station Software displays the CBTQ User Station Main Window with a mission running. Enemy detections are triangles and friendly detections are square in shape

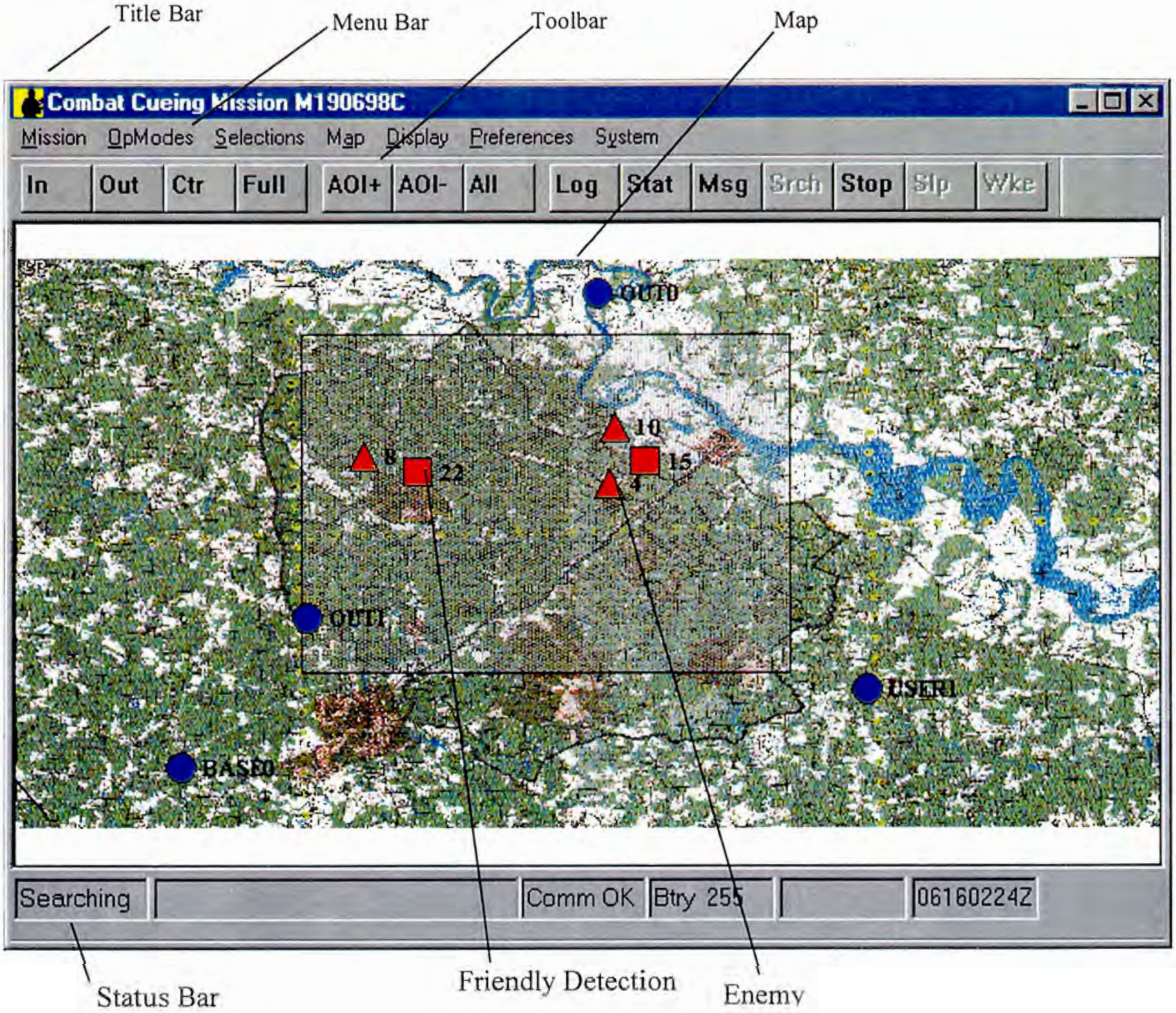


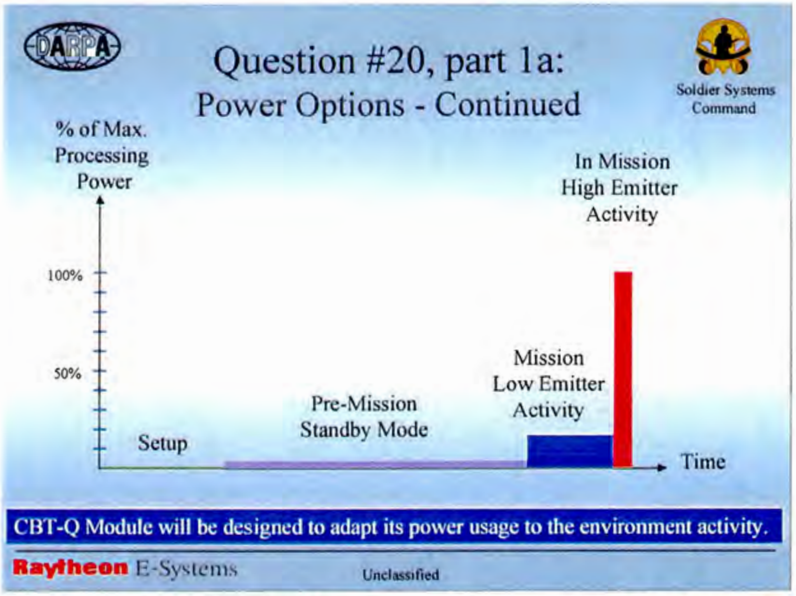
Figure 37 – User Station Main Window

3.4.3. Software Code, Integration and Test

The primary impact on this phase was the hardware limitations PE hardware described previously. EC and User Station software were mostly implemented as planned.

3.4.3.1. PE Software

- Quick Search was eliminated from PE Software. The primary purpose of this function was to lower the overall power consumption. As shown in the Figure 38, during low emitter activity times Quick Search was going to allow CBT-Q module to look for RF energy and, if no energy resembling frequency hopping radios was detected, go to a standby power mode. Additionally, it was shown by analysis that Quick Search increased the probability of detection by allowing CBT-Q to more frequently sample RF environment before the hopping signal went active.



Question #20, part 1a:

Power Options - Continued

CBT-Q Module will be designed to adapt its power usage to the environment activity.

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Unclassified

Figure 38 – PE Hardware problems caused deferment of Quick Search algorithm development. This in turn led to elimination of low power mode during low emitter activity.

- Low power mode, also known as "snooze" mode was also eliminate, since it only made sense in context of Quick Search.
- Since 5 of the 6 PE cards were eliminated from the hardware baseline, it was decide to employ a single card in a less preferred 10 MHz "ambush" mode.
- RF–IF card control, originally planned for PE card, was moved to EC software since PE could not write over the PCI bus into RF-IF registers. This meant that EC Software had to be involved in both tuning and automatic gain control (AGC) processing.
- Geolocation processing was moved from PE to EC since PE integration went very slowly due to errata problems and their fallback solutions, such as NOOP (no-operation) insertion.
- In order to speed up RF Detection, several sections of code were optimized or simplified. Techniques included use of assembly language, floating point operation approximations, and reduction of RF analysis window from 250 milliseconds to 125 milliseconds.

3.4.3.2. Embedded Controller Software

- EC software met most of its requirements objectives
- Additional functionality moved over from PE software included RF-IF card control, tuning and AGC support, as well as geolocation
- EC was also tailored to operate with a single PE card instead of six

3.4.3.3. User Station Software

User Station software mostly met or exceeded its requirements.

3.5. Task 5 – System Test and Evaluation

The objective of this task was to integrate, test, and evaluate CBT-Q system performance. Due to late availability of hardware, field evaluations were performed incrementally at a sub-function level. Four primary sub-functions were tested:

- Radio Network
- Timing Accuracy
- User Station
- RF Detection

3.5.1. Radio Network (Figure 39)

Ability to send data packets over the SINCGARS radio link was tested at AP Hill. Test results showed that:

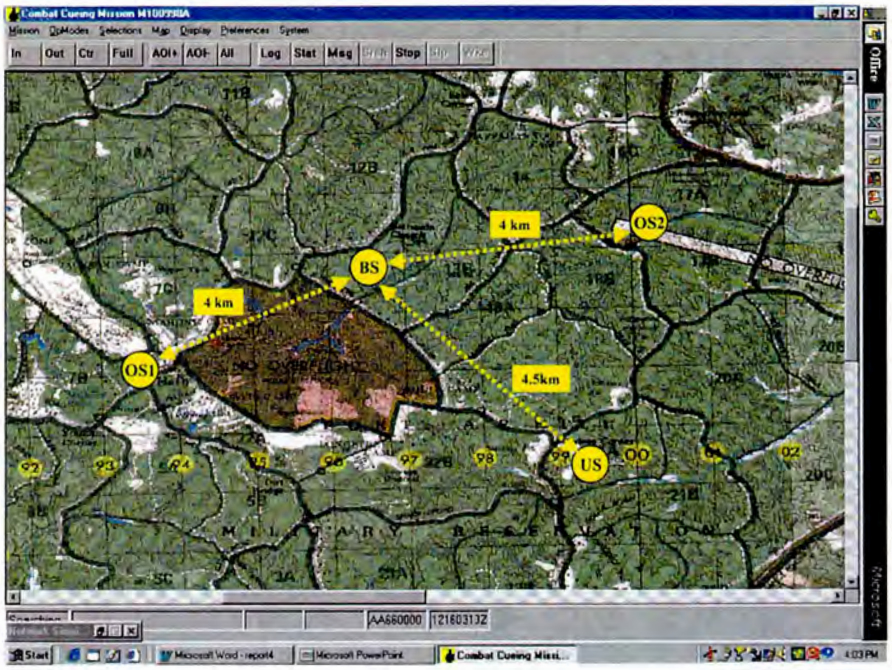


Figure 39 – Radio Network testing at Ft. AP Hill verified that Basestation (BS), Outstations (OS), and User Station (US) could communicate over SINCGARS SIP link if placed in locations highlighted on the map. Yellow lines indicate verified links.

- Radio network communications in distance and foliage settings is sufficient for the needs of the system
- Locations chosen for the Fort A.P. Hill final demonstration activity can be supported for network communications
- Highest reliable radio baud rate for data communications is 4800
- Vehicles in motion generally able to communicate as long as line of site realized

- Effective baud rate of SINCGARS SIP radio is much lower than expected, mostly due to 300 – 400 millisecond carrier ramp-up/down time. Consequently, a 60-byte message takes nearly 0.5 seconds to transmit, reducing the effective baud rate to approximately 1000 baud.

For more information Radio Network testing see test results document [16].

3.5.2. Timing Accuracy

A timing accuracy test was performed to measure the ability of two TAG cards to keep track of time. Minimal absolute time difference between sensors is critical to geolocation accuracy. For every 3 nanoseconds of timing mismatch, additional error of 1 meter may occur in calculation of target emitter location.

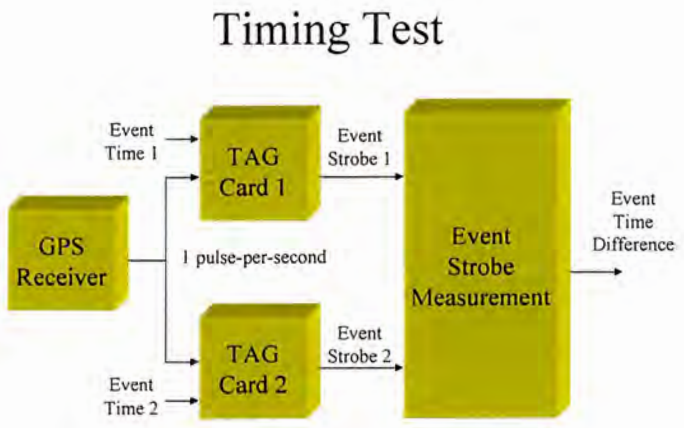


Figure 40 – Timing accuracy test exceeded expectations. 30 nanosecond difference was measured between two TAG cards' Event Strobes. This suggests that the geolocation error caused by CBT-Q sensor internal time keeping will only be about 10 meters.

A simple the test, illustrated in the Figure 40, used a common GPS receiver which provided a 1 pulse-per-second input to two TAG cards. Each TAG card was programmed to generate an Event Strobe at the same time. (Event Strobes are used for synchronization of RF data acquisition and baud phase calculations. Each sensor has a TAG card.) Event Strobes were measured for synchronicity.

The findings exceeded expectations. Differences of 100 nanoseconds were expected. Nominal differences of 30 nanoseconds were measured.

3.5.3. User Station

During the period of 21-23 September 1998, the Combat Cueing (CBTQ) project performed testing at the Fort A.P. Hill test facility. This testing was intended to:

- Confirm operations of system hardware components (module, radios, vests, cabling) in a field environment

- Verify Base Station (BS) installation in the HMMWV (including mechanical, mount, power cabling, radio cabling, and GPS antenna cabling)
- Verify BS to User Station (US) connectivity via radio and direct connect interfaces
- Verify ability of the US to command the BS and receive information from it

In addition to the above goals, the Outstation (OS) radio network and status related software would be tested by installing it on laptop computers and operated in effect as OS simulators. The OS units would then participate in the radio network, accept system control commands, and report status information to the BS. To facilitate the simulation of normal system operations, test data scripts on the BS were initiated by the US. These test scripts sent emitter detection and location reports to the US units.

During periods of the testing the User Station was able to connect to the Base Station via both the radio and direct connect interfaces. During these connection periods, the US was able to successfully command the Base Station software to perform system startup functions and was able to receive system status information from the BS. This system status information consisted of system components (BS and OS) and their position information. The US map did display the correct icons for the BS and OS units in their correct locations. The US unit icons did not appear on the US map. This may have been due to an incorrect GPS receiver setup. The test data scripts executed successfully causing simulated emitter detection and location data to appear on the maps in the planned locations. For more details see [17]. User Station test is illustrated in Figure 41.

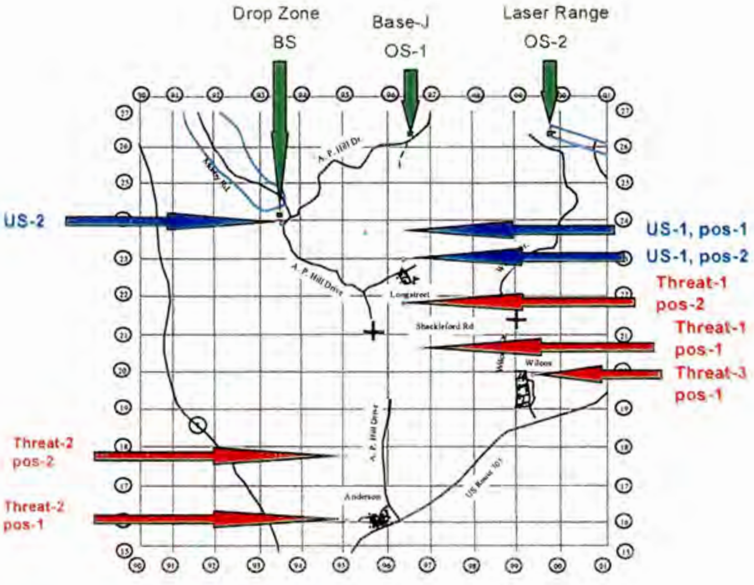


Figure 41 – User Station test was performed at Ft. AP Hill in three positions. Threats were simulated by the Basestation and sent to User Stations, where they were displayed.

3.5.4. RF Detection

3.5.4.1. Laboratory Tests

Ability to detect RF emissions of Jaguar radio was first demonstrated in the laboratory environment. The test involved a Panther Radio (Figure 42) operating in Jaguar mode using a programmable frequency hopping sequence. The radio operated in a low power mode and was connected to the CBT-Q Basestation module's antenna input with a coaxial cable through a variable attenuator.

Figure 42 – Panther Radio is compatible with the Jaguar. It optionally operates in a high power 20W mode.

Despite several software optimizations, CBT-Q Basestation ran RF detection in about 17 seconds, or about 9 times slower than predicted. Majority of this degraded performance is attributable to PE CCA errata problems described in section 2.3.3.2. Consequently, the algorithm was modified to process 125 millisecond snapshot of RF energy rather than 250 milliseconds as originally specified. Although reduced RF snapshot time incurs small reduction in probability of detect, it reduces the detection time 14.3 seconds.

Recognizing that the degradation in RF detection also impacts the Geolocation response time, a message was added from the Basestation to User Station to indicate the detection before the actual geolocation icon is displayed.

Lab tests were conducted in the "ambush" mode by monitoring a single 10 MHz band and letting the Jaguar signal hop through the ambush band. Tests were conducted at all 6 bands.

3.5.4.2. Field Tests

RF Detection was performed at Ft. AP Hill in March 1999. Two fully populated CBT-Q Modules were used in testing. The primary objective of the test was to:

1. Demonstrate the RF detection capability of the CBT-Q system
2. Measure the maximum RF detection distance of the CBT-Q system
3. Measure the minimum signal level required for a successful RF detection
4. Identify Combat Cueing system issues
5. Determine the ability of the RF detection algorithms to discriminate between a Panther radio and a SINCGARS radio.
6. Identify equipment locations and resources required for the Geolocation field test and demonstration.

The test results are described in [18], and summarized in Table 2 and Figure 43.

Table 2 – Ft. AP Hill RF Detection Test Summary

Objective	Results
1. Demo RF Detection	This was successfully demonstrated on two CBT-Q modules.
2. Max Detect Distance	Successful to 8.5 km but foliage and terrain masking caused failures in three locations closer in.
3. Min Detect Level	Successful to -80dBm
4. Identify Issues	CBT-Q modules exhibited failures due to apparent thermal problems.
5. RF Detect Algorithm Discrimination	This objective was not met. SINCGARS hopping mode was not available.
6. Prepare for Geolocation Demo	Locations and equipment were identified and tested.

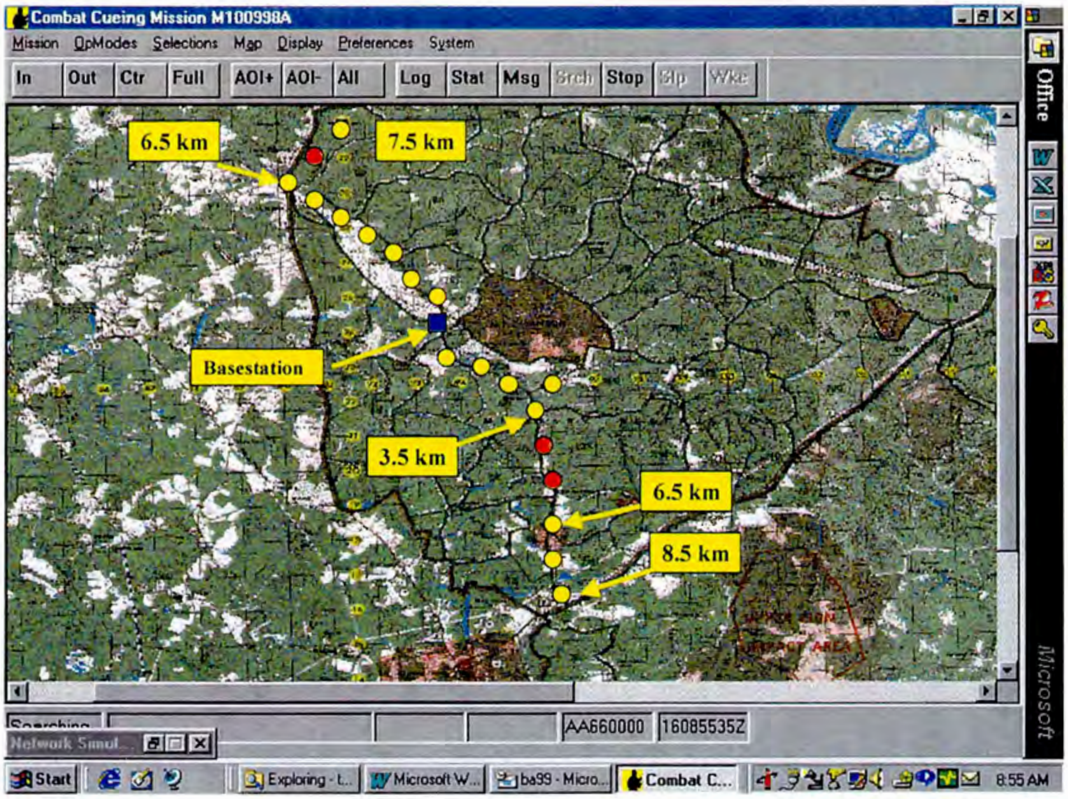
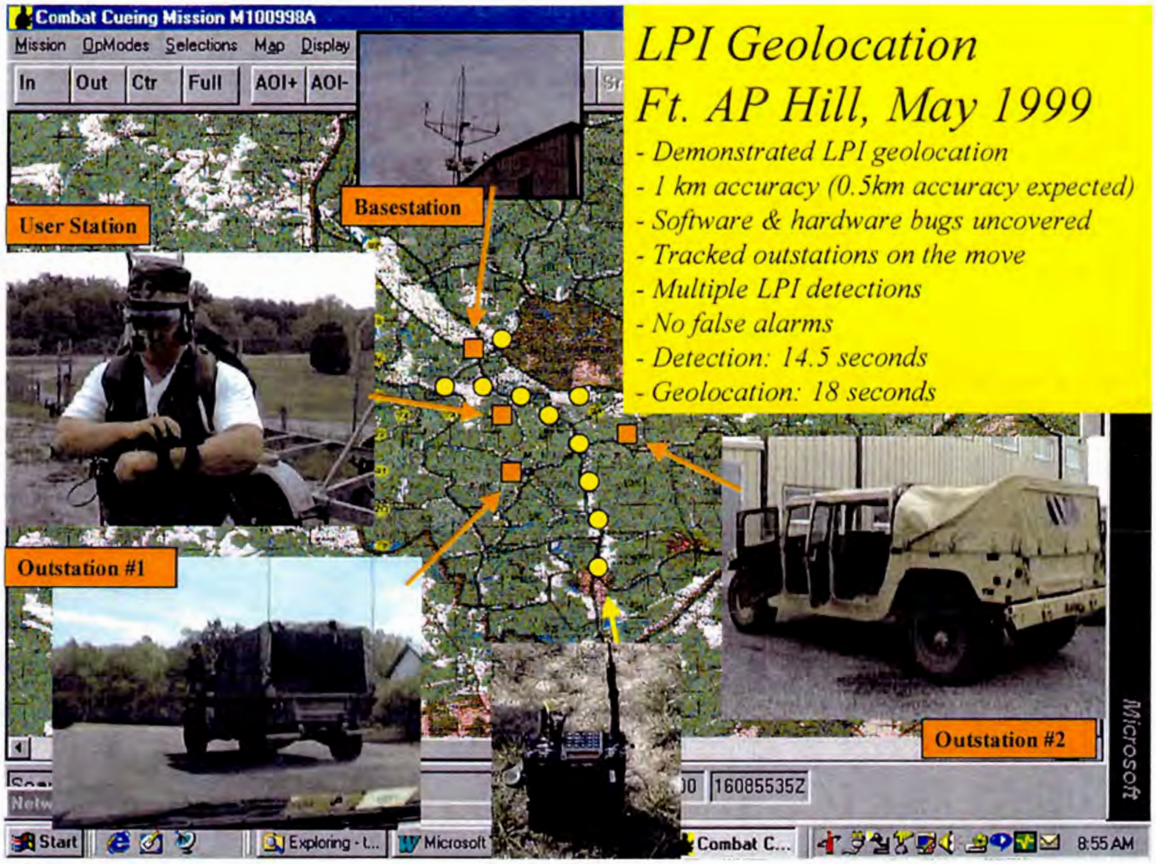


Figure 43 – Yellow dots indicate locations from which the Basestation successfully detected *Panther transmissions. Detection failures (red dots) occurred in low lying, foliage rich* areas with reduced line-of-sight to the Basestation.

3.6. Task 6 - Demonstrations

The purpose of this task was to demonstrate geolocation in the laboratory environment. All field tests were performed at Ft. AP Hill, Virginia. Initial testing of the architecture validated the wireless network approach over SINCGARS radio.

The first test was performed in May of 1999. Results are summarized in Figure 44.



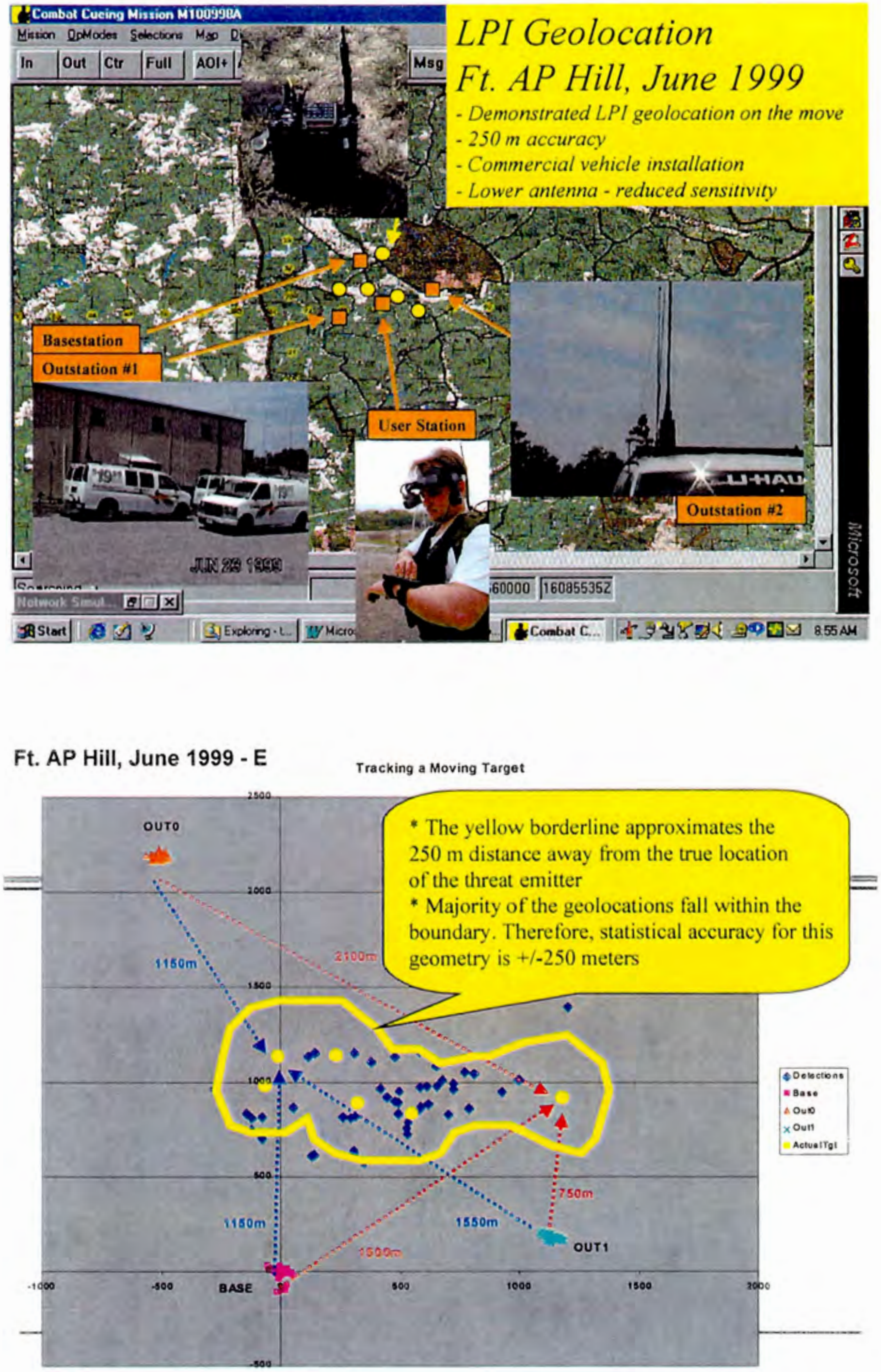
LPI Geolocation

Ft. AP Hill, May 1999

- *Demonstrated LPI geolocation*
- *1 km accuracy (0.5km accuracy expected)*
- *Software & hardware bugs uncovered*
- *Tracked outstations on the move*
- *Multiple LPI detections*
- *No false alarms*
- *Detection: 14.5 seconds*
- *Geolocation: 18 seconds*

Figure 44 - The First CBT-Q Geolocation Demonstration

The second geolocation demonstration, illustrated in Figure 45, corrected some of the algorithm errors and improved the accuracy to 250 meters, a 4x improvement over the initial demonstration. All antennas were mounted on commercial vehicles, resulting in a lower sensitivity.



LPI Geolocation

Ft. AP Hill, June 1999

- *Demonstrated LPI geolocation on the move*
- *250 m accuracy*
- *Commercial vehicle installation*
- *Lower antenna - reduced sensitivity*

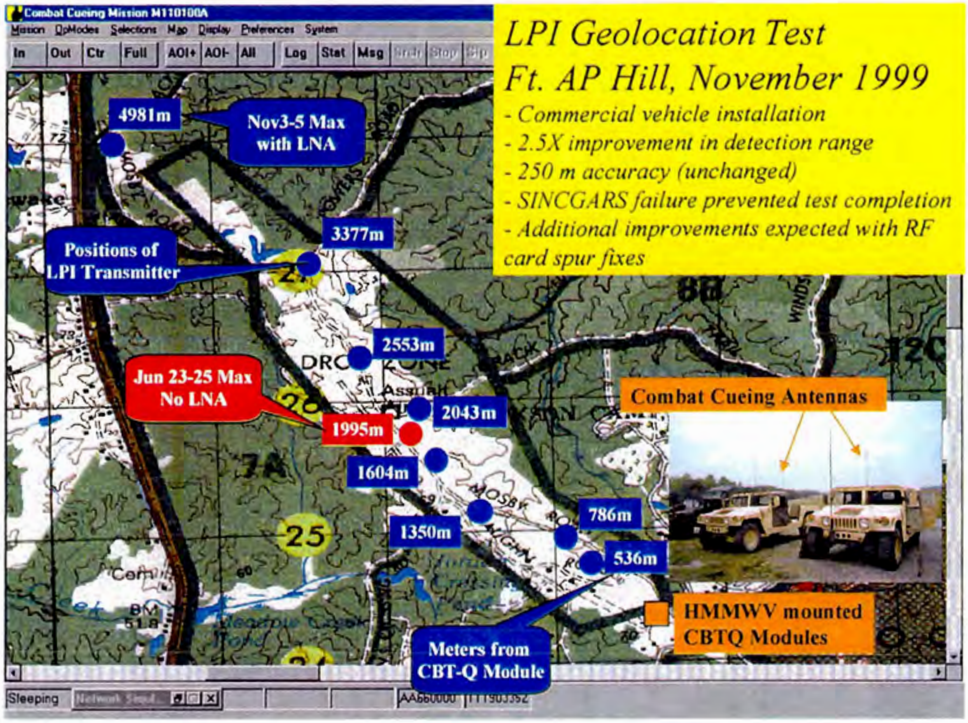
Ft. AP Hill, June 1999 - E

Tracking a Moving Target

* The yellow borderline approximates the 250 m distance away from the true location of the threat emitter
* Majority of the geolocations fall within the boundary. Therefore, statistical accuracy for this geometry is +/-250 meters

Figure 45 - The second CBT-Q demonstration yielded a 250 meter geolocatioon accuracy.

The third and final demonstration took place in November, 1999, is illustrated in Figure 46. This demonstration demonstrated a 2.5x improvement in the sensitivity.



LPI Geolocation Test

Ft. AP Hill, November 1999

- *Commercial vehicle installation*
- *2.5X improvement in detection range*
- *250 m accuracy (unchanged)*
- *SINCGARS failure prevented test completion*
- *Additional improvements expected with RF card spur fixes*

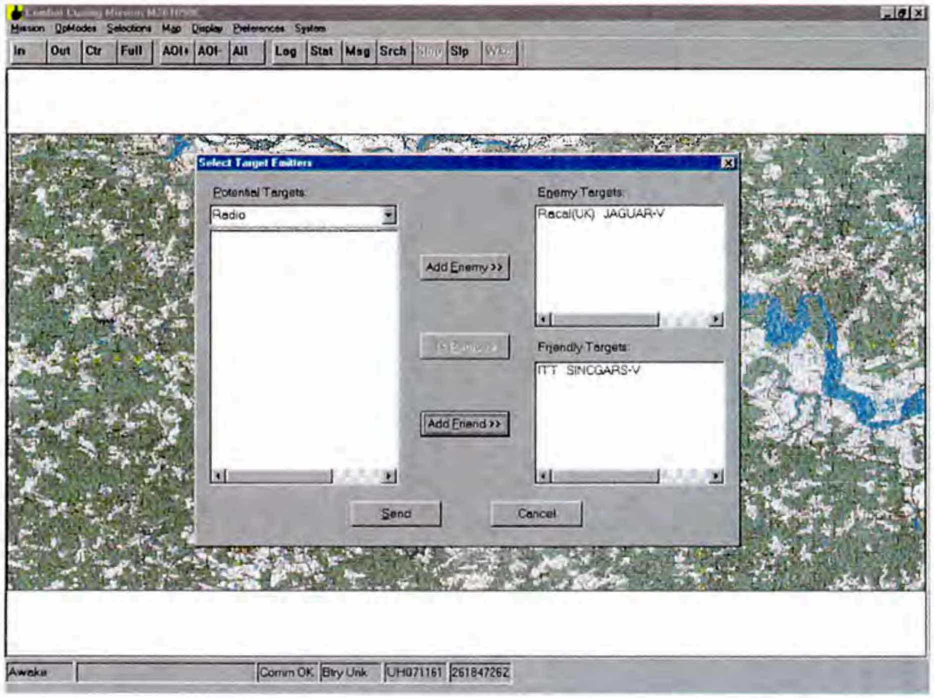
Figure 46 - The third CBT-Q Geolocation test demonstrated a 2.5x improvement in system sensitivity

4. Results and Discussion

This section discusses Combat Cueing System performance against the original program goals.

4.1. Guidelines

- **Highly Programmable - Supporting Easy Addition of New Signal Types**. This objective was **met**. Combat Cueing met this objective. As shown in the Figure 47, CBT-Q User Station allows new enemy and friendly radios to be defined from a list of potential targets.



Potential Targets: Radio

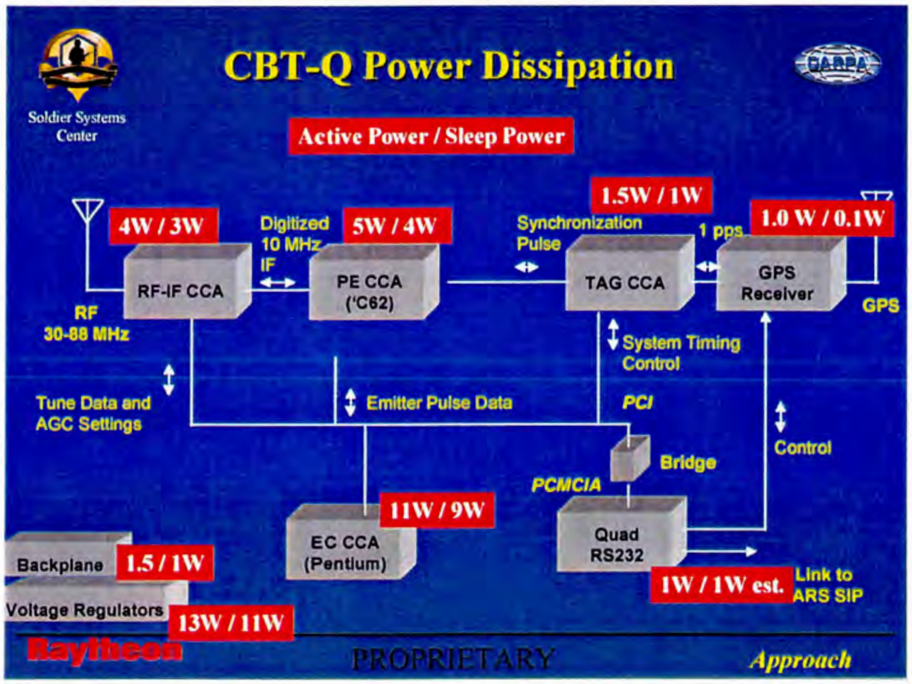
Enemy Targets: Racal(UK) JAGUAR-V

Friendly Targets: ITT SINCGARS-V

Figure 47 – CBT-Q User Station offers a flexible mission setup including reprogrammable definition of enemy and friendly emitters

- **Highly Flexible - Supporting Multiple Mission Scenarios.** This objective was **met**. Many system scenarios were developed and verified with warfighter community. CBT-Q is platform and link independent. CBT-Q offers a flexibility of being deployed in a mounted or dismounted form, powered by HMMWV or battery. CBT-Q sensors can be co-located with User Stations. Multiple User Stations can be supported in a mission.
- **Low Cost.** This objective was **mostly met**. Although the cost per sensor is somewhat higher than the $25,000 goal, the sensor is considerably lower in cost than sensors of similar capability.

- **Low Power**. This objective was **partially met**. While the unit HMMWV based CBT-Q Module operated at only 38.5W (Figure 48) during active mode, its sleep mode power was disappointing 32W. CBT-Q Module is losing approximately 35% of our input power due to inefficiencies in the power supply design. In the current design the 5V, 3.3V and -12V supplies, which comprise 90% of the systems power, are generated by DC-DC converters with 80% efficiency. More importantly, these DC-DCs are daisy-chained to the 24V:12V DC-DC converter that also has an 80% efficiency. This results in a conversion efficiency of 64%. EC CCA ran at higher power than originally selected Megatel CCA.



CBT-Q Power Dissipation

Soldier Systems Center

Active Power / Sleep Power

4W / 3W

RF-IF CCA

RF 30-88 MHz

Digitized 10 MHz IF

5W / 4W

PE CCA ('C62)

1.5W / 1W

Synchronization Pulse

TAG CCA

1 pps

1.0 W / 0.1W

GPS Receiver

GPS

System Timing Control

Tune Data and AGC Settings

Emitter Pulse Data

PCI

Control

Bridge

PCMCIA

11W / 9W

EC CCA (Pentium)

Quad RS232

1W / 1W est.

Link to ARS SIP

Backplane

1.5 / 1W

Voltage Regulators

13W / 11W

Raytheon

PROPRIETARY

Approach

Figure 48 - Primary excessive power dissipations problems were with Voltage Regulators and EC CCA.

- **Low Profile**. This objective was **met**. The HMMWV based system is a 6" cube. Internally, the system houses 10 Small PCI slots, 2 PCMCIA Slots, 1 GPS Receiver Slot, and 1 CPU slot. CBT-Q volume is approximately one tenth the volume of a 14-slot VME system.

- **Low Detectability** – This objective was **met**. The system uses baud phase instead of raw RF samples in order to exchange threat emitter timing data. Sensor-to-sensor transmissions of 1 second or less are typical. Conventional methods require 20 to 100 times.

4.2. Performance

- **System Sensitivity - -105 dBm @ RF Input (all sites).** This specification was **not met** mostly due to lack of time to complete debug of RF-IF CCA. The sensitivity was measured to be in the –80 to –90 dBm range.

- **Signal Type – frequency hopping in 30 to 88 MHz band.** This objective was **met**.

- **Probability of Detect (Jaguar - up > 4s) - >95%.** This objective was **not met** due to PE CCA errata problems described in the hardware section. In order to detect a Jaguar with 95% probability, RF Detection must be accomplished in 2 seconds instead of 14.7. Based on the analysis, CBT-Q should be able to meet this objective with six PE CCAs operating without errata restrictions.

- **Probability of False Alarm (SINCGARS/FM) - < 1%.** This objective was **not verified**. CBT-Q was designed with variable thresholding parameter for sensing RF detections. This parameter can be adjusted based on real-time RF environment in order to minimize false alarm rate.

- **Target Emitter Processing Rate - 12 per minute.** This objective was **not met** due to PE CCA errata problem. Estimated rate is 5 per minute. Based on the analysis, CBT-Q should be able to meet this objective with six PE CCAs operating without errata restrictions.

- **Snapshot Rate - 15 per Minute.** This objective, also referred to RF Detection, was **not met** due to PE CCA errata problem. The measured rate was measured at 7 per minute. Based on the analysis, CBT-Q should be able to meet this objective with six PE CCAs operating without errata restrictions.

- **Detect to Display Latency - 5 seconds.** This objective was **not met** due to PE CCA errata problem. Estimated latency is 18 seconds. Based on the analysis, CBT-Q should be able to meet this objective with six PE CCAs operating without errata restrictions.

- **Emitter Storage Time - 12 Hours (8,640 Hits Max).** This objective was **met**.

- **Setup Time: < 2 Minutes.** This objective was **met**.

4.3. Environmental

- **Operating Temperature: -25 to +49 C.** This objective was **not met**. The unit was operated in the field and laboratory environments ranging between 5 and 25 degrees C with the aid of a fan. Thermal failures were detected without a fan. EC CCA appears to be the primary source of failure. Specific area of failure appears to be Pentium microprocessor, whose fan was removed and replaced with a low-profile heatsink such that the card could fit in the CBT-Q housing. For more details, see Figure 49.

- **Operating Altitude: ≤ 10,000 ft.** This objective was **not verified.** Analysis suggests that the unit meets this objective.

- **Vibration: Will Support Tracked/Wheeled Vehicle Operation (w/ Isolation Mounting).** This objective was **met**. CBT-Q operated in a moving HMMWV environment.

- **Rain: Will Operate for Last 10 Minutes of 30 Minute Exposure to Rain @ 1.8 in./hr. with Wind @ 20 mph.** This objective was **not verified.** Analysis suggests that unit meets this objective.

- **Orientation: Shall Operate in any Orientation.** This objective was **met**.

4.4. Physical

- **Module Less Than 4" X 4" X 8"** – This objective was **not met**. Basic CBT-Q module, excluding battery or HMMWV adapter, measures approximately 6.6" x 6.0" x 4.9" or 194 cubic inches instead of intended volume of 152 cubic inches. The primary reason for not meeting this objective was the addition of the Embedded Controller (EC) housing, shown in the Figure 49.

- **Module Less Than 4 lbs.** This objective was **not met**. The unit weighs 6.5 lbs.

Figure 49 – Embedded Controller CCA insert was added as a fallback to unavailability of Megatel embedded controller card. A large metal plate in mid section of the insert was used to replace the Pentium fan.

- **Employ Industry Standard Format/Bus** – This objective **was met.** Small PCI bus standard was employed.

- **Battery (BA-5590) or Vehicle (HMWWV) Power Source** - This objective **was met.**

- **Battery Life > 8 Hours** – This objective was **not verified.** Based on the battery capacity and measure power dissipation, this objective will likely be met.

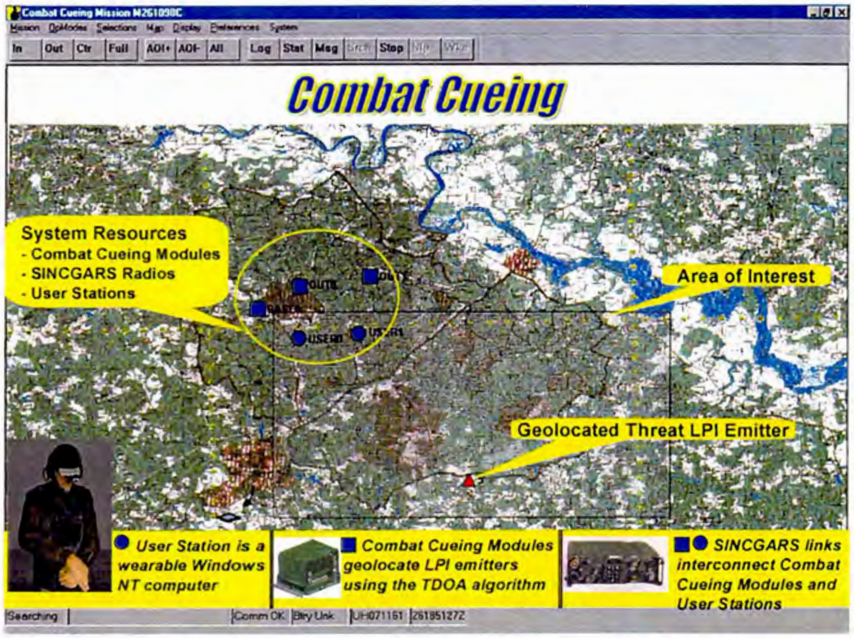
4.5. User Interface

- **Aplique based** – This objective was **not met**. Required by Army Digitization Office (ADO) for Digital Battlefield Applications, Applique is intended to support Tactical Internet and a Common Operating Environment (COE). At the time of User Station development, Applique was not judged to be an open standard. Source code & libraries were not available. Additionally, Applique did not run on Windows NT platform. Despite non compliance, CBT-Q is upgradable to Applique in the future.

5. Conclusions

Combat Cueing, a tactical LPI geolocation system (Figure 50), was developed and demonstrated in the period between 1996 and 2000. The system is made up of two Outstations, one Basestation, and 1 or more User Stations.

The system was developed, built, tested and fielded at Ft. AP Hill, VA (Figure 51).



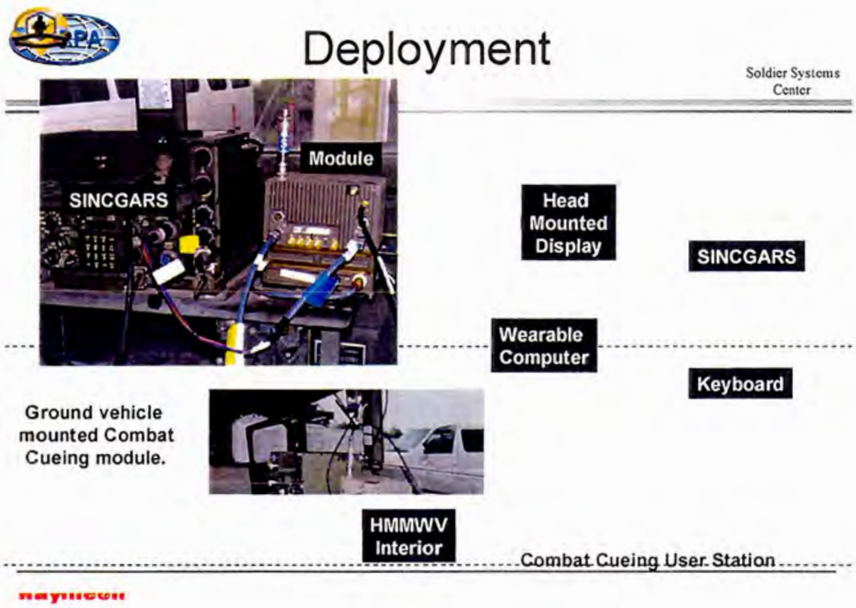
System Resources
- Combat Cueing Modules
- SINCGARS Radios
- User Stations

● User Station is a wearable Windows NT computer

■ Combat Cueing Modules geolocate LPI emitters using the TDOA algorithm

■● SINCGARS links interconnect Combat Cueing Modules and User Stations

Figure 50 – Combat Cueing User Interface displays locations of Combat Cueing assets and detected LPI emitters.



Deployment

Ground vehicle mounted Combat Cueing module.

Figure 51 – Combat Cueing Modules were deployed in HMMWVs and commercial vehicles. User Station functionality was demonstrated on a man-portable wearable computer.

Combat Cueing performance was evaluated against the goals identified at the onset of the program. Combat Cueing partially or fully met 28 of the 29 criteria (Figure 52).

12 of the 29 criteria were partially met due to three primary problems:

- Loss of performance due to TMS320C62 DSP errata problems.
- Increase in size and power consumption due to unavailability of Small PCI Embedded Controller.
- Increase in power consumption due to lack of power management software.

Corrections of above problems would yield a system that meets or exceeds 28 of the 29 criteria.

Figure 53 summarizes major program goals and accomplishments.

Combat Cueing Self-Imposed Goals Revisited

Soldier Systems Center

🟩 **Highly Programmable** - Supporting Easy Addition of New Signal Types
🟩 **Highly Flexible** - Supporting Multiple Mission Scenarios
🟨 **Low Cost**
🟩 **Low Power**
🟩 **Low Profile**
🟩 **Low Detectability** - Minimize RF Emissions
🟩 **Setup Time**: < 2 Minutes
🟨 **Operating Temperature**: -25 to+49 C
🟩 **Operating Altitude**: ≤ 10,000 ft.
🟩 **Vibration**: Will Support Tracked/Wheeled Vehicle Operation (w/ Isolation Mounting)
🟨 **Rain**: Will Operate for Last 10 Minutes of 30 Minute Exposure to Rain @ 1.8 in./hr. with Wind @ 20 mph
🟩 **Orientation**: Shall Operate in any Orientation

🟨 **Size**: < 4" X 4" X 8"
🟨 **Weight**: < 4 lbs.
🟩 **Bus Format**: Industry Standard
🟩 **Power Source**: Battery (BA-5590) or Vehicle (HMWWV) Power Source
🟨 **Battery Life** > 8 Hours
🟥 **Appliqué (FBCB2) compatibility**
🟨 **RF Sensitivity** -105 dBm @ RF Input (all sites)
🟦 **Accuracy**: 500m
🟨 **Range**: 10 km
🟨 **Probability of Detect** (Jaguar - up > 4s) - >95%
🟩 **Probability of False Alarm** (SINCGARS/FM) - < 1%
🟨 **Target Emitter Processing Rate** - 12 per minute
🟨 **Snapshot Rate** - 12 per Minute
🟨 **Emitter Display Latency** - 5 seconds
🟩 **Emitter Storage Time** - 12 Hours (1,440 Hits)
🟩 **Environment** - Soldier Portable Unit

Unclassified Proprietary

🟩 goal met or exceeded
🟨 goal partially met
🟥 goal was not met

Figure 52 – Combat Cueing Program partially or fully met 28 of the 29 goals that were identified at the start of the program.

Combat Cueing Program Summary

Goals

- Provide RF situational awareness for mounted & dismounted forces
- Detect & locate threat LPI radios in real-time
- Achieve 20x reduction in SWaP
- Achieve 1000:1 reduction in Req'd bandwidth
- Platform and Link Independent architecture
- Capable of passive operation
- Affordable, Upgradeable

Accomplishments (Ft. AP Hill Tests)

- Consistent and multiple LPI radio detections
- Low false alarms
- Demonstrated "on the move" operation
- Detection time: <14.5 sec (LPI target)
- LPI Geolocation time: 18 sec (LPI target)
- Geolocation accuracy: 250m (geometry dependent)
- 2x to 3x geolocation accuracy improvement expected with military GPS
- 10x timing improvement expected with 6 DSPs

Raytheon

Figure 53 – Combat Cueing Program major goals and accomplishments

6. Recommendations

6.1. System Level

- **Expanded Capability** - The current configuration of CBT-Q system demonstrates a limited capability in a small, link and platform independent package. Future research should focus toward meeting original CBT-Q goals, expanding the frequency coverage, expanding threat emitter signal types, and adapting CBT-Q to a variety of Command and Control interfaces, as illustrated in Figure 54. Additions of future capability should be done with continuous warfighter community involvement.

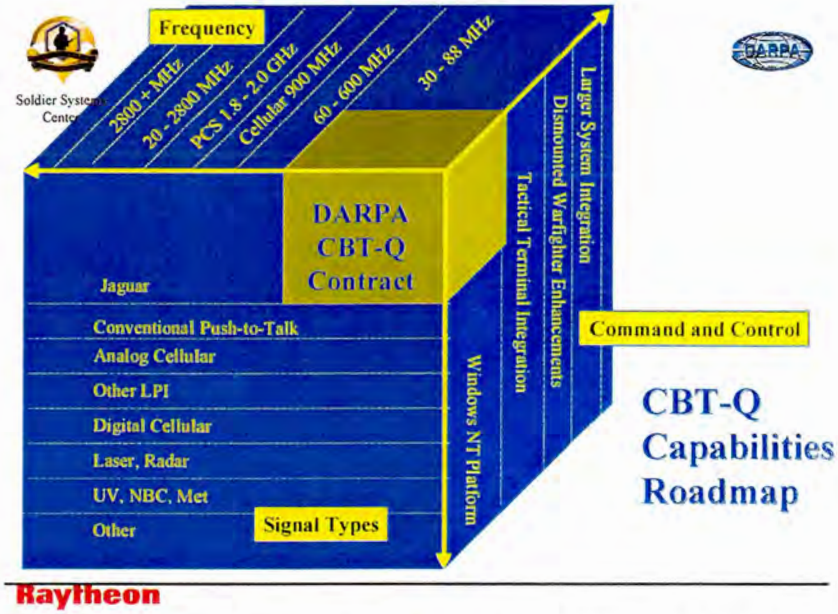


Figure 54 – Current and future capabilities of CBT-Q

- **New Platforms** - Insertion of Combat Cueing to other platforms such as Unamanned Airborne Vehicles (UAVs) should improve the range and utility of the system.

- **Integration** - Integration with other mission enhancing technologies such as Tactical Visualization Module are recommended.

6.2. Hardware

- **Completion of CBT-Q baseline** - Future research should produce and evaluate a hardware baseline capable of running with errata-free DSP.

- **Signal Acquisition Quality** - Further research should be performed in maximizing RF signal acquisition quality in a presence of high speed digital signals.

- **Bus Standard** - Small PCI bus standard should be reevaluated against a set of criteria outlined in figure 14.

- **Rugged Construction** - CBT-Q Module should be ruggedized and further evaluated against militarized environment.

- **Weight and Size** - Further miniaturization and power and weight reduction should be pursued.

- **RF Range** - Capabilities to cover additional frequency ranges should be considered, such as insertion of Raytheon's Ultra Comm Receiver, shown in Figure 55.

Figure 55 – Raytheon's Ultracomm Receiver is a good candidate for enhancing CBT-Q's RF frequency coverage to 20-2800 MHz

6.3. Software

- **Smart Processing** - Future research should focus on *smart* processing algorithms. Smart algorithms maximize the information-to-MIP[1] ratio, or minimize the amount of instructions required in order to acquire necessary information. Key algorithms are RF detection and geolocation. Research of rapid RF search algorithms is critical. One potential method, originally proposed by Combat Cueing, was to quickly search through the RF spectrum for candidate signals, and then follow that up with more precise detection algorithms. This layered, coarse-to-fine method should maximize the DSP asset utilization while preserving a high probability of detection and minimizing the probability of false alarm.

- **Low Power** - By acquiring information efficiently, DSP resources can be placed in standby mode until threat signals emerge. Further research of this type of techniques is required. Desired power profile is illustrated in the Figure 56.

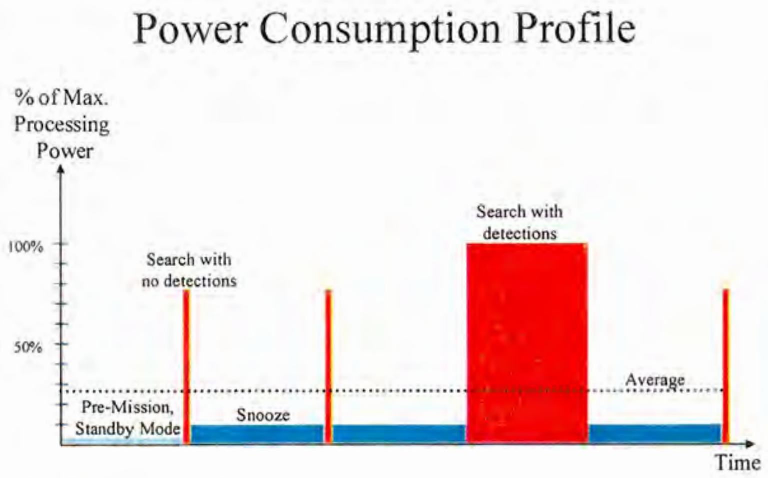


Figure 56 – Power conscious DSP can drastically reduce system power requirements

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[1] MIP stands for *millions instructions per second*

- **Analog Signal Exploitation** – Techniques for processing modern radio signals, such as Baud Phase Timing utilized in CBT-Q, rely on bauded (digital symbol based) nature of the signals to minimize data transmissions between sensors. Similar high-bandwidth efficiency, feature extraction and timing based algorithms should be researched for processing conventional push-to-talk radios.

- **Joint Tactical Radio System (JTRS) Insertion** – As the new military radio of the future is developed, CBT-Q algorithms should be migrated into these radio architectures (Figure 57) for "background" processing of situational awareness algorithms. This theme is currently under investigation on DARPA's Spectrum Supremacy Program. CBT-Q's Geolocation algorithm has been reused on this program.

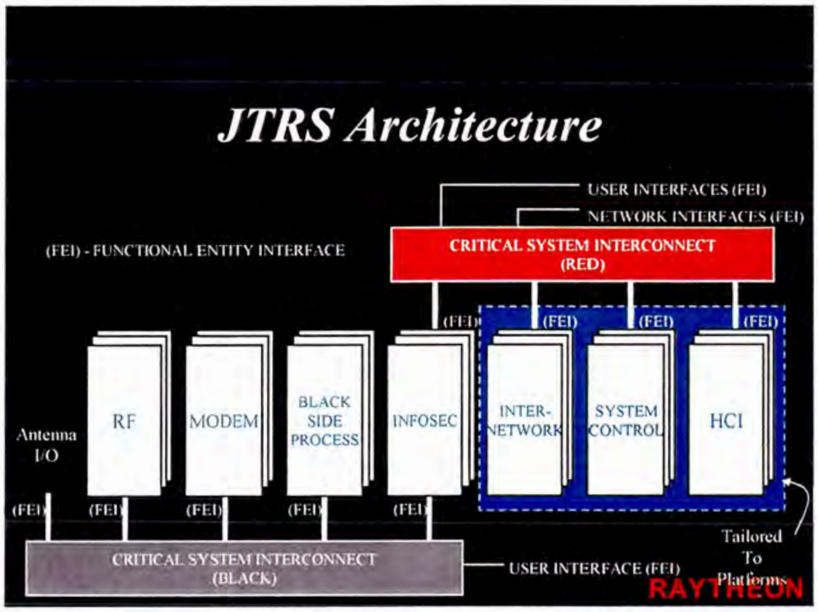

Figure 57 – CBT-Q architecture is compatible with JTRS. Therefore, CBT-Q's software algorithms can be migrated to future tactical radios.

This document reports research undertaken at the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, and has been assigned No. NATICK/TR-00/020 in a series of reports approved for publication.

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8. List of Symbols, Abbreviations, and Acronyms

ADO	Army Digitization Office
AGC	Automatic Gain Control
BS	Basestation
CBT-Q	Combat Cueing
CCA	Circuit Card Assembly
COTS	Commercial off-the-shelf
CSCI	Computer Software Configuration Item
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
DSP	Digital Signal Processor
EC	Embedded Controller
FLOT	Forward line of troops
FM	Frequency Modulation
FPGA	Field programmable gate array
GPS	Global Positioning System
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
IF	Intermediate frequency
LPI	Low probability of intercept
NOOP	No Operation
OS	Outstation
PCI	peripheral communication interface
PCMCIA	personal computer memory card international association
PE	Processing Element
PLGR	Precision Lightweight GPS Receiver
PWB	Printed Wiring Board
RF	Radio Frequency
SINCGARS	Single channel ground and airborne radio
SIP	SINNCGARS Improvement Program
SOCM	Special Operations Combat Management
TAG	Timing, Acquisition and GPS Interface
TC	Tank commander
TDOA	Time difference of arrival
US	User Station