Sensor Collection and Analysis of Radio Frequencies (SCARF)
LtCol Jeff Boleng, Thorsten Wirges, Dr. Dennis Schweitzer
US Air Force Academy, Colorado, USA
jeff.boleng@usafa.edu
thorsten.wirges@usafa.edu
dennis.schweitzer@usafa.edu

Seana Hagerman and Dr. Ramakrishna Thurimella
University of Denver, Colorado, USA
shagerman@comcast.net
ramki@cs.du.edu

Abstract
In today's net-centric warfare environment, effective management and use of the electromagnetic spectrum is critical. Increasing demands on wireless spectrum from radio traffic, unmanned aerial vehicle (UAV) communication, wireless networks, improvised explosive device (IED) jammers, and sensor networks result in sources competing for, and at times conflicting over, limited frequency spectrum. From an intelligence perspective, having a clear understanding of the RF environment, both friendly and foe, is an important essential of battlefield management. This paper presents the Sensor Collection and Analysis of Radio Frequencies (SCARF) system with a focus on the information processing requirements of the sensors and various system components. The overall architecture, sensor processing and fusion challenges, visualization algorithms, and current implementation status are discussed.

Keywords: RF collection, visualization, data fusion, system integration

1. Introduction
The Academy Center for Information Security (ACIS) at the US Air Force Academy (USAFA) has undertaken research, design, and development of a Radio Frequency (RF) collection, fusion, and visualization system. Our approach emphasizes the innovative integration of largely commercial off the shelf and open source components. The specific mission of ACIS is “to enhance cadet education by providing innovative research opportunities to students and faculty...” As a result, our focus on system integration of available solutions and technologies supports our educational mission well and allows us to maximize the involvement of our student population at a baccalaureate only institution such as USAFA.

This paper will provide the system and project goals, discuss the commercial and open source components and related work in the area, and present several possible system uses. Additionally, the system level design will be presented followed by our current status and challenges in visualization and signal fusion. We conclude with a brief discussion of what is next for the project and research group.

2. Goals
Our goal is to design and build a prototype system of systems (SoS) in order to provide operational and tactical battlefield commanders with a user defined operational picture (UDOP) that characterizes the radio frequency (RF) spectrum in a tactical/operational battlefield area. The design and architectural approach will allow the system to scale to include the RF characterization of an entire theater of operations. There are four primary areas of research requiring integration in order to achieve an operational RF UDOP system. These are:

1. distributed RF sensors,
2. signal collection, analysis, characterization, and identification,
3. mobile ad-hoc network (MANET) for communication of sensor data and Autonomous Vehicle (AV) Command and Control (C2), and
4. sensor data fusion and visual display/representation.
The distributed RF sensors are primarily composed of aerial-based autonomous vehicles (AV). Non-mobile sensors can also be employed to augment the AV sensors. These non-mobile sensors can be inserted/placed by the aerial AV's.

The RF sensors themselves are being designed and built to be extremely frequency and waveform agile in order to cover the broad spectrum of anticipated sources and threats. This requirement has pushed the research in the direction of software defined radios (SDR) for signal collection. Currently we are evaluating GNU radio software (GNU Radio 2008) and the Universal Software Radio Peripheral (USRP) as implemented by Ettus Research (Ettus 2008).

Once RF signals are received, signal collection, analysis, characterization, and identification must be performed. Our goal is to achieve much more than just a mapping of received power levels, by frequency, at differing geographic locations. Rather, the system will characterize the RF parameters such as duty cycle, waveform, encoding, presence of encryption, analog/digital data, etc. in addition to just receive power, frequency, and location. This will significantly aid in the characterization and identification of the signal source, capabilities, and purpose.

The distributed sensor network of autonomous vehicles and strategically placed non-mobile sensors requires a secure, reliable, robust, and resilient communication network in order to both transfer sensor collection data back to a processing location and provide effective Command and Control (C2) of the sensor assets. Significant research and solutions have been accomplished in the area of mobile ad-hoc networks (MANETs) and sensor networks (Wikipedia 2008 and IETF 2008). This project will apply the best of breed from the existing body of research in both areas (MANET and sensor networks) to implement a common, multi-hop networking solution to connect the AVs, sensors, and collection points/ground stations.

As the raw sensor data is communicated back to a central collection point/ground station, it must be fused into a cohesive representation of the RF environment being monitored. The research challenges here include both data fusion and effective data visualization/representation. A first step will be to design and implement a net-centric data store of the RF information collected by the sensors. Next, a distributed and flexible display system will be developed that allows any number of user-defined views. This collection of RF environment data can serve multiple communities of interest/practice. Depending on the audience and intended use, the database will facilitate everything from management of friendly frequencies, to identification of GPS jamming, to Intelligence Preparation of the Battlespace (IPB) for Electronic Warfare (EW) or Cyberspace operations.

3. Commercial/Open source components and related work
Maximum use of existing solutions and technologies is one of our stated goals. As a result, our design and implementation makes use of the following commercial and open source components.

- openMap (http://openmap.bbn.com)
- Wi-spy (http://www.metageek.net/)
- IMOM
- VisiWave (http://www.visiwave.com/)
- Kismet (http://www.kismetwireless.net/)
- Cyberbug (http://www.cyberdefensesystems.com/)
- GNU Radio and Universal Software Radio Peripheral (USRP)

3.1. OpenMap
OpenMap is a JavaBeans based open source GIS program for viewing and manipulating geospatial data. It was developed by BBN technologies and released as open source in 1998. OpenMap is a suite of functions that understand geographic coordinates. These functions can be used to display map data from several different sources. The data can either be derived from fixed files or dynamically served up from web sites. OpenMap is also easily configurable to handle user input events to manipulate geospatial data. Data is handled in a layer format to simplify activating/deactivating particular views.

OpenMap is currently being used in various applications including modeling freight transport flows, modeling flight planning and generating navigation logs, and modeling and calculating tidal and current data to derive optimal marine paths. OpenMap is supported by a large community of users with an active mail-list of information.
SCARF uses OpenMap as the underlying GIS platform with interactive layers of RF visualization data overlaid. This allows the integration of existing geographic data and visualization techniques to be incorporated into the system.

3.2. Wi-spy
Wispy is a commercially available USB-connected spectrum analyzer. It has an extremely small footprint as shown in Figure 1, which makes it suitable for UAV applications in which weight and physical size are primary considerations.

Figure 1. Wi-spy frequency analyzer

Wi-spy operates in the 2400 to 2495 MHz frequency range. Its sweep time of 165 milliseconds collects data at more than sufficient data rates for this application. The Wi-spy is connected to a resident processor on the UAV that performs data filtering and consolidation prior to transmission to a ground-based collection station.

3.3. IMOM
Similar to SCARF, the Improved Many-On-Many system (IMOM) is designed as a tactical decision aid to predict the performance of RF devices in the battlefield environment. IMOM was first developed in the 1980’s and has been continually refined to include integration with GIS systems. IMOM was designed specifically with mission planning goals in mind. Knowledge of the location and capabilities of RF-emitting nodes allow for route planning and communication capability prediction. SCARF is being designed and built as a situational awareness tool in which the RF environment is not known a priori and is built from sensor collection and analysis. SCARF will carefully review the capabilities and lessons learned from IMOM while developing its own capabilities. Additionally, RF situational awareness data will be available for export and use in IMOM.

3.4. VisiWave
VisiWave is a commercially available system that interfaces with the Wi-spy to provide visual survey reports of an area. It interfaces with Google Earth and displays RF coverage suitable for wireless system design and debugging. Some of the unique visual approaches provide good examples for SCARF to consider in its visualization approach.

3.5. Kismet
Kismet is free software distributed under the GNU General Public License (GPL) for detecting and analyzing 802.11 wireless signals. It is a passive system that can be used for intrusion detection, network detection, and network monitoring.

3.6. Cyberbug
The current UAV platform for SCARF experimentation is the Cyberdefense Systems CyberBug drone capable of a 25 mph aerial cruise speed, 5 km range, and 65 min endurance. An aerial control ground station is included with the system. The onboard autopilot system is the Kestrel autopilot which provides GPS timing and location to the control processor and sensor payload (Kestrel 2008).

3.7. GNU Radio and Universal Software Radio Peripheral (USRP)
GNU Radio is free software distributed under the GPL for implementing software defined radios (SDR). The USRP is a GPL reference design which can be used to realize hardware that is compatible with GNU Radio. We use the USRP implementation available from Ettus Research. Our use of GNU Radio and the USRP are to create a software defined, rapidly configurable, broad spectrum RF sensor. Initial SDR experience with this combination has shown that it can be effective for our system and capability demonstration.
4. System uses
This RF sensor collection, analysis, characterization, and visualization system can be used for multiple purposes. Some of the applicable scenarios are included below.

4.1. Joint frequency management
As joint forces deploy to common operating locations, cooperative frequency management is often difficult, disjointed, and ineffective. This system would enable the effective collection and mapping of the frequency use by friendly (and adversary) forces in an operating location. The proper characterization of frequency usage would allow the efficient and effective de-confliction of existing units/forces, as well as enabling the quick integration of augmenting/follow-on forces into an existing network/RF environment. Furthermore, the system will interface with existing frequency management and planning systems to visualize the planned spectrum allocation and usage vs. the actual observed RF environment.

4.2. Interference characterization
This system would allow the timely identification of interference and facilitate the rapid resolution of problems. The interference in question could be a result of friendly forces and mis-configuration or a result of accidental or deliberate action on the part of an adversary. In both cases, the RF sensor collection, characterization, and visualization system (RF SCCV) empowers Commanders to properly identify and manage their RF environment.

4.3. Tactical signals intelligence collection
The system outlined above could augment national signals intelligence collection assets and efforts by providing a responsive, focused, tactical capability to survey, collect, characterize, and identify adversary equipment and activities based on their RF emissions. Often times, it is not possible to satisfy local/tactical level Commanders’ collection requirements with national assets as they compete with other global and national priorities. An operationally responsive signals collection capability is possible using the sensors, network, fusion, and display system outlined above.

4.4. Predictive battlespace awareness
The system outlined could facilitate course of action analysis and mission planning by allowing predictive mission scenarios to be executed or “flown” through an existing RF environment. Such a scenario could visualize, predict, and report the EW and EW countermeasure implications of each course of action with respect to the existing, observed, RF environment. This predictive capability would certainly enable ground, naval, or air forces to more effectively ensure mission accomplishment and survival in the presence of a hostile RF environment. Integration with existing planning tools such as IMOM is being considered to avoid duplication of effort and ensure each tool is applied to its intended area.

5. System level design
SCARF consists of the following high level components (figure 2)
- the Sensor Element (SE),
- the Flight and Mission Control Element (FMCE), and
- the Central Fusion Element (CFE).
5.1. Sensor element
The sensor element of the system includes all the hardware and software required to receive RF signals and communicate them back to the mission control element. It is designed in order to make it a generic payload for a variety of transport mechanisms. The primary target platform is an unmanned aerial vehicle (UAV), however we are also developing a generic interface for an unmanned ground vehicle as well. Stand alone operation is possible. Generally, the sensor element consists of an RF sensor, central processing unit, power supply, and network communication device. Several configurations are being tested.

Current options for the RF sensor include either a Wi-spy 2.4GHz sensor or a USRP software defined radio. Each is in a different state of development. The common control and communications architecture being used has been hosted on generic x86 compatible laptop computers and PC-104 form factor embedded processors. Our current efforts are targeted at hosting all the control, signal analysis, and communications software on a gumstix processor (Gumstix 2008). Network, data download, and reach back communications are provided via Ubiquiti Networks’ 802.11 card (Ubiquiti 2008) at 900 MHz or via a serial link using Digi’s Maxstream wireless modem products (Digi 2008).

It is understood that the RF sensors already present on the modern battlefield are too numerous to list. Every effort is being made to allow all present sensors to contribute signal information to the SCARF system. In many cases, signal format, data format, classification level, releasability constraints, etc. may be significant obstacles to inclusion of the signal data already present into the proposed system. In order to build and test SCARF it is essential that we include an RF sensor capability as an integral system component. The system level design includes the ability to incorporate data from external sensors, and it is our hope that such data will be present and available.

5.2. Flight and mission control element
The flight and mission control element (FMCE) consists of two distinct, but co-located sub-systems. The flight control sub-system is responsible for the command, control, and monitoring of the transportation vehicle—in our case, the Cyberbug UAV. The flight control hardware and software are an integrated component of the Cyberbug upon deliver. Interaction between the mission control sub-system operator and the flight control sub-system operator is frequent. Continual communication is required to adjust the UAV flight profile to accommodate the sensor payload and achieve optimal coverage and RF situational awareness. Mechanisms to more fully automate the communication and control between the flight control and mission control sub-systems are under investigation.
The mission control sub-system in the FMCE is responsible for control and interpretation of the RF sensor data. Communication is three-way—to the flight control sub-system operator, to the onboard RF sensor, and to the central fusion element and the central signal database. The mission control sub-system operator is continually investigating received signals and using the visualization tool and central fusion element database to correlate and identify received RF signal data.

System design requires up to four UAVs, each containing an RF sensor, be controlled by one FMCE. This requires four separate UAV’s being flown by one flight control operator, and four RF sensors being monitored and optimized by one mission control operator. A high degree of integration and automation is required for effective operations under this highly task saturated environment. The RF sensor data being monitored by the mission control operator must be presented in a way that aids interpretation and helps the analyst accurately plan and predict subsequent actions and operations for the UAV. Accurate real-time visualization is the key to achieving this level of control.

5.3. Central fusion element
The central fusion element (CFE) can command and control up to ten (10) flight and mission control elements (FMCE) to provide broad tactical or operational coverage of a brigade sized maneuver area with up to 40 UAVs and sensor packages. The current system architecture, automation level, and manning model are targeted at this magnitude of operations, however, there are no technical or design reasons why multiple fusion elements could not be combined to possibly provide theater level coverage and RF situational awareness. This scaling is one element of future research.

Just as with the FMCE, automation of command and control as well as accurate real-time visualization is essential for control and execution of an operational RF situational awareness mission. During mission execution there is a constant exchange of commands and sensor data between the operators and databases at the CFE and the mission and flight control operators at the FMCE. It is anticipated that numerous UAVs and sensors can be introduced and retired from the system continually. Additionally, design provisions are being made to allow for operator hand off. This consideration will facilitate continuous system operation to accommodate real-time RF situational awareness around the clock if required.

As previously mentioned, every effort is being made to accommodate external RF signal data sources and databases. It is acknowledged that a great wealth of SIGINT information is available. If classification level and releasability constraints are met, the system design allows for the inclusion of amplifying information from any number of external data sources and databases to help the fusion and mission control operators ensure the UAVs and sensors are controlled in the most optimal manner possible to provide the highest clarity situational awareness.

Throughout mission execution, the central fusion element (CFE) will continually provide a tailorable operational picture. This operational picture will continue to evolve and refine as UAVs and sensors explore the battlespace. Mission control and fusion operators/analysts will be constantly augmenting the raw database content with a running estimate of the situation. There will be no incremental updates to external situational awareness views. Rather, the tailored view of the RF database available at the CFE will be viewable continuously for a real-time monitoring and situational awareness capability.

6. Approaches to visualization
A key component of SCARF is a highly configurable, interactive, near-real-time visualization system. Effective visualization systems follow the mantra overview first, zoom and filter, and details on demand (Shneiderman 1996). It is important, especially for situational awareness applications, to provide the user with complete control over what information is displayed, how it is displayed, and the level of detail presented along with a higher level context. Some of the key ideas for the SCARF visualization are presented below.

6.1. OpenMap
One of the advantages of using OpenMap as the underlying GIS platform is the built-in visualization techniques for geospatial data. Capabilities such as panning, zooming, and turning on/off terrain features are standard in the OpenMap system. SCARF adds additional RF visualization capability by adding layers to the existing platform.
6.2. Propagation models versus interpolation
One of the distinguishing differences between SCARF and other RF planning tools is that when planning a wireless network, locations and characteristics of emitter nodes are specified. Mathematical propagation models can be used to estimate signal strengths and interference effects across a geographic area. A simple model using emitter strengths and distances is presented in (Shepard 1998). A more sophisticated model, such as ray tracing, can be used to account for more complex signal interactions with the environment (Honcharenko 1995). Different visual representations of signal strengths over an area can be used to display the result of these models.

However, for the situational awareness application that SCARF is designed for, there is no initial knowledge of emitter location and characteristics. Rather, sensor data is collected and analyzed to predict coverage over the area. As more data is collected the coverage prediction becomes more accurate. It is important for the user to be able to distinguish between raw collected data versus interpolated estimations of signal coverage.

One approach that SCARF is working on for this issue is to combine propagation models with predictive estimation of coverage. That is, signal collection is used to predict emitter location. Standard propagation models are then used to estimate the effect of the predicted locations. As additional signals are collected, location predictions are updated and new signal propagation visualizations are produced.

6.3. Line of sight representation
Another feature that some propagation models incorporate is the ability to use line-of-sight calculations in determining whether a given point can “see” a specific emitter. Since SCARF is built on OpenMap, digital terrain elevation data (DTED) is available for propagation calculations. A variation of Bresenham’s line drawing algorithm is used to determine if two points can see each other without interference from intermediate terrain (Seixas 1999). As an additional analysis tool, the capability is provided to the user to select any two points on the map and see a two-dimensional elevation representation between the two points as shown in Figure 2.

![Terrain image with line-of-sight display.](image)

6.4. User interaction
To provide full user control over the visualization, extensive use of parameter controls are implemented making extensive use of sliders and other GUI mechanisms. For example, to specify a range of frequencies to view, the user selects both the lower and upper frequency values on a slider device. Similarly, starting and ending time points can be selected on a slider to represent what data samples to include in the image.

6.5. Visualizing RF characteristics
Perhaps the biggest challenge with SCARF is to define meaningful visual abstractions of RF characteristics of interest. Typical systems use color coding to display signal strengths at physical points in space. For situational awareness, additional information, such as signal interference, types of signals, and collected vs. estimated data is desirable. The use of simple toggles with traditional color coding is the initial approach for this project. However, one of the goals of SCARF is to find innovative visual approaches that allow the user to better integrate the available data.

7. Summary and future work
The sensor collection and analysis of radio frequencies (SCARF) system is a comprehensive system of systems aimed at providing real time situational awareness of the RF spectrum to
tactical/operational battlefield commanders. System level, database, and interface design is well established. Several elements of system implementation are under way emphasizing off the shelf components. The UAV transportation system is well established. RF sensor elements are implemented for portions of the frequency spectrum, and broad spectrum sensors are in development. Mission control and visualization software is being developed and innovative approaches to RF spectrum visualization and monitoring is being iteratively prototyped. Mission control software and integration with the visualization and flight control software is in the design phase. Overall, parallel system development is proceeding well, especially considering the resources available for implementation.

Areas of future research are numerous and include:
- Graphical processing units (GPUs) to ensure high fidelity, real time visualization of data from numerous sensors,
- Real time data collection, visualization, and mission control,
- Higher level signal analysis and characterization,
- Software defined radio implementation of a broad spectrum sensor, and
- Integration of external data sources for real time sensor and UAV mission control and operational picture accuracy.

8. References


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