Mitigation Paths for Free-Space GPS Jamming

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BIOGRAPHY

Matt Boggs received his BS in Electrical Engineering from New Mexico Institute of Mining & Technology. While there, he designed and implemented instrumentation for energetic materials testing and atmospheric physics research. Matt has been a member of the GPS/INS Systems Section since 1989, and has been involved with design and implementation of missile hardware-in-the-loop simulations, navigation error analysis and GPS jamming efforts. He is currently tasked in the development and analysis of GPS jammer systems.

Kenea Maraffio received her BS in Electrical Engineering from Arizona State University. Employed by NAWCWPNS, China Lake, in 1991, she worked on development of phased-array antenna control software and radome compensation algorithms. In 1993 Kenea developed software for real-time remote control of the Stanford Telecom 7200 GPS satellite simulator. Kenea is currently developing software for remotely controlling a smart, free-space GPS jammer.

ABSTRACT

Many modern weapon systems depend on Global Positioning System (GPS) to achieve midcourse or terminal accuracy requirements. This reliance on GPS navigation dictates that weapon system test facilities be equipped to create realistic GPS jamming (GPSJ) environments. The Naval Air Warfare Center Weapons Division (NAWCWPNS) at China Lake is developing a system of free-space jammers to create a realistic GPS threat environment. The goal of this effort is to yield a high-degree of commonality among outdoor jamming systems and the ones used in NAWCWPNS' Navigation Laboratory and anechoic facilities.

The ability to successfully conduct free-space GPS jamming tests in the continental US is highly problematic due to extensive civilian use of GPS. This paper begins by discussing the major issue related to conducting free-space GPS jamming tests: interference with commercial and other DoD GPS users. Following this discussion, the paper focuses on proposed mitigation methods modeled after NAWCWPNS' energetic materials testing process. The paper concludes with an analysis of a scenario based on an example free-space GPS jammer.

INTRODUCTION

In the late 1960s and early 1970s the GPS/INS Systems Section (then the Inertial Development Branch) was heavily involved in research and development of new-technology inertial guidance sensors and systems. The focus was development of software and ring laser gyros for advanced navigation systems on Navy attack aircraft.

The group first began its involvement with GPS in the mid-1980s while providing navigation system engineering support for the Standoff Land Attack Missile (SLAM) program. In the early 1990s the Section procured a GPS satellite simulator in anticipation of future missile programs integrating GPS receivers into their navigation systems. This asset ushered in a new set of work focused on satellite navigation including its denial and countermeasures.

NAWCWPNS has been extensively involved with electronic warfare and combat since its inception, via testing on its Land, Sea and Electronic Combat Ranges. This work has been expanded in the past decade to include high-powered, free-space radiating GPS jammers in full-spectrum weapons test scenarios in a highly non-encroached environment.

NONINTERFERENCE: "THE" FREE-SPACE GPS JAMMING ISSUE

GPS is used extensively by the civilian community in commerce and science. Some examples of civilian GPS applications include use as a timing source for utilities and science, tracking devices for the transportation industry, quality assurance tools for agriculture, and navigation systems for civil aviation. Additionally, GPS is used for its original, intended application — military systems. In each of these uses, one commonality exits: the requirement for noninterference of the user community due to DoD testing.

Despite the growing trend of modeling and simulation to reduce the requirement for live-fire testing, final confidence in total weapon system performance can only be established via full-up testing, in a realistic threat environment. Given the United States' need to test these systems in GPS jammed scenarios, the question remains how to accomplish this given the seemingly "impossibility" of the situation.

To provide this realistic threat scenario, GPS jammers must be deployed to exercise the systems' anti-jam or targeting capabilities. Two basic options have been discussed concerning where to deploy these jammers for testing GPS assets: the continental United States (CONUS), or at offshore ranges. Testing in the CONUS has the problem of potential interference with users outside the realm of the test, yet has the advantage of lower costs due to reduced logistical strain. Though offshore testing has the advantage of a highly streamlined frequency clearance process, it suffers from the detraction of the logistics expenses, potentially limited instrumentation (in the case of testing at isolated islands), and requirements for agreement along diplomatic lines. In the current era of cost savings within the DoD, it is arguably paramount to maintain testing capability of these systems at CONUS ranges in order to provide test data in a timely and cost effective manner.

At first glance, the requirement of testing DoD weapon systems in GPS-denied scenarios while maintaining a high level of noninterference with the GPS user community might seem to be mutually exclusive. The GPS user community, both military and civilian, can work together to form a series of compromises to ensure all parties' needs are satisfied with minimal inconvenience to non-jamming participants. Indeed, any GPS jamming work must be carried out in this manner to prevent non-participants from being affected by weapons testing and training exercises conducted by the DoD.

MITIGATION PATHS

Mitigation paths are techniques and technologies designed to minimize the impact of free-space GPSJ testing on non-participants. Effective mitigation paths are necessary due to the very low-power of GPS satellite signals, making them susceptible to high-power jamming signals at rather large distances. Additionally, since a high percentage of the GPS community is civilian, the effect of GPSJ tests is to potentially place the public in harm's way. By utilizing an aggressive mitigation strategy, DoD requirements can still be largely accomplished in the CONUS, while protecting the interests and safety of the general user community.

Mitigation Techniques

Widespread usage of GPS severely limits the manner in which free-space jamming tests can be conducted. The problem can be made much more manageable using processes or methodologies to form techniques capable of achieving test requirements. Such techniques enable weapon system tests to be successfully carried out despite their varied set of unique requirements and problems. GPS jamming testing consists of a set of challenges that can be addressed through the use of proper techniques.

Current Techniques NAWCWPNS has been heavily involved in free-space GPS jamming in conjunction with its weapons test and evaluation efforts. Through these tests, NAWCWPNS has become well aquainted with the current methods for conducting jamming tests. Additionally, an informal survey was undertaken for this paper in the interest of comparing NAWCWPNS' experiences with those of other DoD ranges. The most commonly encountered issue throughout the DoD ranges is that of successfully obtaining a frequency clearance in a timely manner to radiate GPS jamming signals.

Frequency Clearance Due to GPS operation being a type of satellite communications, any action potentially interfering with the system is subject to radio frequency control and management. Frequency clearance to radiate must be obtained prior to performing any free-space GPS jamming. This ensures that the proposed test will not interfere significantly with other system users. It also allows public notification of potentially degraded performance prior to testing. The general frequency clearance process for conducting GPS jamming tests is illustrated in Figure 1.

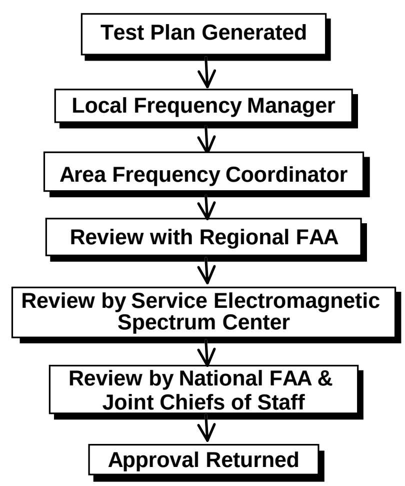

Figure 1 *Generic GPSJ Approval Process*

Unfortunately, specific processes for obtaining GPS jamming clearances vary extensively from base-to-base, and even within bases. The process of obtaining a frequency clearance at some facilities is no different than if one wished to install a two-way radio in a truck. Other ranges require extensive analysis (such as jamming footprint studies) and documentation. A standardized method of conducting jamming tests is needed that addresses the issues of safety and accountability while being flexible enough to meet DoD testing needs.

Proposed Techniques NAWCWPNS has examined the problem of conducting free-space GPS jamming and is implementing new processes for performing such tests at its ranges. These new methods draw extensively on NAWCWPNS' experiences in testing other systems, such as energetic materials and other electronic warfare systems. NAWCWPNS' jamming process is characterized by establishment of GPS Jamming Coordination and Oversight Office, Standard Operating Procedures (SOPs), and a defined Jamming Protocol. This set of methods maintains the high degree of accountability required to conduct successful GPSJ tests, while also providing for a dynamic environment required by the projects and personnel conducting the GPSJ test itself.

GPS Jamming Coordination and Oversight Establishment of a successful GPS jamming test program is very dependent on forming processes that ensure the highest level of safety and confidence of all involved. An important element of this process is the provision for a central point of contact for the oversight of all GPS jamming tests at each command. This position, that of the "GPSJ Coordination and Oversight Office," provides multiple services to members of the affected community. Some of the services provided include:

- Assisting test mangers in designing GPS jamming exercises to minimize external impact while maximizing effectiveness. This includes determination of jammer placement, examination of GPS jammer radiation footprints, antenna beamwidth control, and other analysis on proposed tests to determine potential problems.
- Development of a standard frequency clearance data package in conjunction with GPSJ Coordination and Oversight Offices at other commands, Frequency Management, FAA and JCS. This will help reduce cycle time for obtaining frequency clearances.
- Coordination of frequency clearance paperwork with the test manger and Frequency Management.
- Custodian of SOP, Qualification/Certification and Review processes.
- Maintains corporate history and documentation of all GPSJ tests.
- Issuing notices to appropriate DoD and civilian users of possible degradation of GPS services in the vicinity due to testing.
- Development of standard operating procedures for monitoring, documenting and reporting unauthorized GPSJ radiation within base boundaries. This will raise credibility with external agencies and the civilian user community.
- Keeps abreast of new technologies and techniques that will reduce the impact of free-space jamming on uninvolved parties.
- Keeps informed of all laws and regulations affecting GPS jamming and interference.

This office serves as a "clearinghouse" of expertise on GPS jamming to support all aspects of conducting such tests. The GPSJ Coordination and Oversight Office analyzes GPS-denying scenarios for potential interference problems, while also providing feedback on the proposed test's effectiveness to meet requirements. Equally important, the GPS Jammer Coordination and Oversight Office ensures that all required paperwork and appropriate test plans are in place prior to submitting them to the Frequency Manager.

The GPSJ Coordination and Oversight Office also maintains contact with established, local members of the GPS community that might be adversely affected by GPS degradation due to testing. This coordination extends beyond the normal NTIA/FAA clearance protocols. In the interest of acting as a "good neighbor", channels will be established to facilitate timely communication concerning pending and current jammer tests, to users both in the DoD and civilian communities (e.g. NASA's Goldstone facility or the National Training Center, in the case of NAWCWPNS). Such communication can be accomplished via a wide array of semi-automated avenues, including use of restricted-access web pages, electronic mailing lists and traditional postal services.

Standard Operating Procedures With the current high yields afforded by modern, military explosives and propellants, energetic materials are among the most hazardous items tested by the military. The DoD has developed proven methods to test these materials while minimizing the risk for all involved. Using NAWCWPNS' energetic materials community as an example, risk management is accomplished through use of stringent processes involving utilization of Standard Operating Procedures. These procedures can serve as a model for developing a GPSJ test strategy. A SOP is a clear definition of how a test will be conducted, with analysis and identification of test effects and their respective mitigation routes. SOPs require testers to perform their "homework" prior to testing so that surprises are minimized. The certification of a SOP to a specific test is subject to periodic review by a panel consisting of experts in the field, operators, and management to ensure a sense of oversight in the test approval process. Additionally, use of SOPs allows for effective post-test recreation and analysis — an important capability should the effects and results of a test be called into question later.

Jamming Protocols The analysis and planning process of the SOP furnishes invaluable insight for tailoring the test to provide minimized interference with the rest of the user community. A well-defined jamming protocol is put in place, subject to critique by a review board. This protocol is shown in Figure 2.

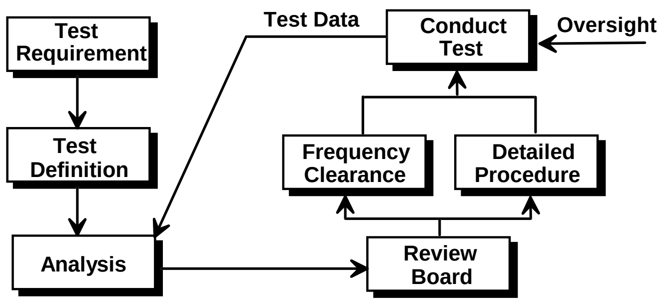

Figure 2 *Jamming Protocol*

The jamming protocol process serves the important role of forcing tests to be adequately planned and reviewed to prevent a potentially inappropriate test from being performed. Each of the blocks in Figure 2 serves a significant role in the jamming protocol process:

<u>Test Requirement.</u> The Test Requirement consists of the basic test concept with objectives and goals defined by the customer. This requirement is usually quite abstract in terms of actual test method.

<u>Test Definition</u> Test Definition is a critical element of the Jamming Protocol process. It describes the methods used for meeting the Test Requirements in conjunction with the test community. Aspects of a free-space GPS jamming test to be defined at this stage include:

- Jammer placement
- Jamming frequencies & bandwidths
- Test duration
- Jammer antenna pattern
- Jammer antenna pointing
- Jammer ERP power
- Jammer profiles

<u>Analysis</u> The analysis stage is where much of the test's "homework" is actually carried out. Ideally, the analysis is integral with the test definition stage. This assures the best possible test formulation in minimal time. Tasks carried out in the analysis portion include:

- Jammer placement and footprint analysis (using validated software packages).
- Identification of potential problems with the test design not meeting test requirements and suggesting alternatives.
- Identification of potential impact to other system users and routes to minimize those jamming effects.

The analysis function is also integrated with other aspects of the jamming protocol process, including the review and oversight stages. Additionally, the actual test should be coupled to the analysis stage by feeding back actual test data. This allows a better understanding of the analysis process (especially the modeling and simulation aspect), since lessons learned can be implemented.

Example areas of test design analysis are jammer placement and control of antenna beamwidths. These two elements contribute heavily to test appropriateness and dictate the level of interference to other users.

- *Jammer Placement* The nature of the GPS signal is such that though the system is sensitive to jamming, the frequency band in which it operates is conducive to exploiting terrain to help control jammer radiation. Given the propagation characteristics of L-band signals, it is possible to place jammers in locations that will be significantly masked from the rest of the user community not involved in the test. In such situations, use of valleys and canyons with significant surrounding elevation gradients provide excellent shielding from ground-based jammers on the valley floor, or look-down jammers directed towards the valley floor. By placing jammers in such a configuration, the problem of affecting huge areas is greatly reduced due to terrain shielding.
- *Controlled beamwidths* In conjunction with careful jammer placement, use of controlled antenna beamwidths further reduces unintentional interference. Though it might be appropriate to characterize a potential GPSJ threat as having a probable omni-direction radiation pattern, for testing purposes use of an omni-direction antenna is not required. Instead, the jammer characteristics can often be simulated by a controlled beamwidth antenna that yields an equivalent effective radiated power (ERP) in the desired direction. This type of controlled beamwidth is often carried out by utilizing a dish-based antenna system, with a beamwidth in the neighborhood of 30^{o} (though this is highly variable per requirements). An additional benefit of using a controlled beamwidth antenna is that of reduced cost. Highly directive antenna beams reduce the net power requirements for the jammer system, resulting in the ability to use lower-power (with corresponding lower price) amplifier.

<u>Review Board</u> The Review Board ensures that adequate planning and analysis has been performed for appropriately defined tests. The Review Board is comprised of a cross-section of the jamming community: test manager, jamming expert, test operator, frequency manager and representation from management.

The Review Board also qualifies, certifies and reviews certification of SOPs and personnel to that SOP. This is performed on an as-needed basis (e.g. formation of a new SOP or after an incident) or annually if the SOP is active. The qualification and certification of personnel and SOPs is a tightly integrated process that, in NAWCWPNS' experience, minimizes extraneous paperwork and nonproductive steps. Despite this streamlining, the Review Board's qualification, certification and review processes still provide adequate documentation for inspections, audits and incident investigations.

Frequency Clearance The frequency clearance process is a superset of the current generic process shown in Fig 1. The proposed mitigation techniques described above provide a standardized "jamming package" for the frequency manager. This package makes full risk analysis and mitigation routes available throughout the clearance process. Additionally, the previous steps help eliminate inappropriate tests from reaching the frequency manager — a streamlining effect.

Detailed Procedure The Detailed Procedure is a parallel process to the Frequency Clearance application process. This step consists of writing a detailed test procedure for the operator's use, based upon the test plan approved by the Review Board.

Test The final stage of the process is actually conducting the test to the procedures and test plan approved in the preceding steps. The test is subject to oversight via frequency monitoring and physical verification by the Review Board. Additionally, test data collected is fed back to the analytical portion of the process in the interest of further refining the analysis database.

Firing Officers An important aspect to the jammer operation procedures is the requirement for trained operators certified to a basic procedure. In addition to requiring operators to be trained, qualified and certified for an operation, responsibility for the actual operations is carried by a primary person trained for the operation: the Firing Officer. The Firing Officer serves as an underpinning to the successful operations of the test by being involved throughout the SOP process from the design and approval stage to the final, on-site operations. By being involved throughout the process, the Firing Officer provides highly relevant feedback from the operations aspect of the test to the rest of the process.

Mitigation Technology

Current The informal survey taken for this report showed that the most consistently utilized mitigation technology is non-integrated frequency monitoring. Most ranges maintain some level of frequency monitoring, often in the form of a van equipped with spectrum analyzers, reference receivers, power meters, etc. Usually, frequency monitoring is not well integrated into the test's data collection or real-time system control capabilities; instead the collected data is used for post-mortem test verification.

Proposed Many potential mitigation technolgies exist that can enable GPSJ tests to be conducted with minimal impact on the user community. These technology routes range from closing the loop of frequency monitoring to alternate jamming methods.

Tightly Integrated Frequency Monitoring. Basic frequency monitoring capabilities usually found on site can be integrated into the test control loop. This capability can provide positive control that safeguards against radiation leakage beyond defined test boundaries. Though a first iteration can be easily implemented through manned operators for datalogging and monitoring equipment, an automated system is the eventual goal for the sake of higher accuracy and efficiency.

Additionally, a series of automated frequency monitoring stations optimized for GPS jamming tests can be implemented. These systems could be developed at a lower per-unit cost than the currently existing broad-band monitoring stations. With the reduced cost of the GPSJ-specific monitoring stations, many of the units can be deployed at strategic points along the ranges for real-time feedback of jammer performance. When a monitoring station receives a higher than expected jamming signal, the data can be fed back to the firing officer as a metric for system performance. If jamming signals were to extend beyond acceptable levels, the firing officer could abort the test due to the excessive radiation.

On-board GPS Jammers A method previously discussed within the GPSJ test community has been the use of an onboard GPS jammer. This system would broadcast jamming signals at an extremely low-power level directly into the weapon system's antenna. The jammer signal is only detectable to the weapon system under test as shown in Figure 3.

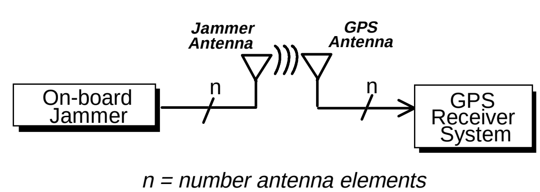

Figure 3 *Onboard GPS Jammer*

This type of jammer system has limitations in its capability to adequately present realistic signals to multiple-element antenna systems. The jammer locations are spatially limited and thus is not capable of presenting a realistic jammer wavefront to the receive antenna. Additionally, this type of system suffers the same problem of other onboard jamming techniques — the requirement for modification of the weapon system.

GPS Jammer Frequency Translation An alternative method to free-space radiation of GPS jamming signals (depicted in Figure 4) is jammer frequency translation. This method broadcasts GPS jammer signals at a non-GPS frequency to prevent interference with nonparticipants. An off-band translator receives the jamming signal and converts it to the appropriate GPS frequency. The GPS satellite and translated jammer signals are then combined prior to the receiver's input. Though the GPS signals could be translated as well, this is not a viable solution for modern, multi-element antenna systems that detect wavefront arrivals — a fielded translator would not be capable of emulating satellite dynamics.

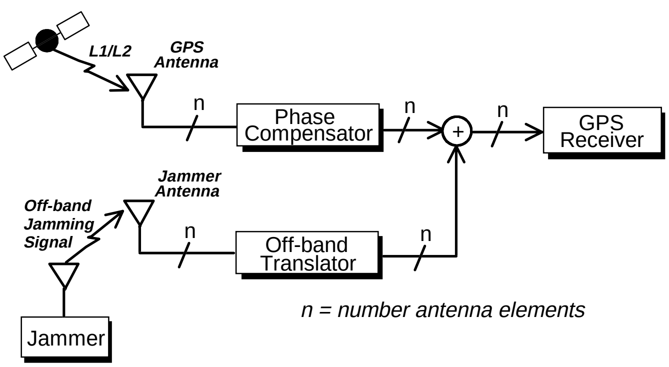

Figure 4 *GPS Jammer Frequency Translator*

A translator solves the problem of broadcast GPSJ signals interfering with other users, though it is does have several drawbacks. Among the detractions of this system is the requirement for an antenna with passband characteristics for the jammer frequency, yet still functionally identical to the original system antenna. An alternative to replacing the original antenna with one that has wider passband characteristics, is to add a second antenna dedicated to receiving the jamming signal. However, this means the antenna is no longer a form-fit-function replacement, thus driving costs up. Also, the addition of a second antenna is not acceptable for applications where physical space is at a premium, as is the case of many weapon systems. Active multi-element GPS antenna arrays require a more complex translator and phase compensator system that allows the antenna electronics to sense angle-of-arrival information. With the increase in complexity of the translator system comes additional costs, for both development and integration. An issue that must be addressed is the economic viability of this type of system against other alternatives, including offshore testing with its high logistical cost.

GPS Jammer Emulator Though not a free-space emitter, a GPS jammer emulator can output a jamming signal to be summed directly with received satellite signals. This requires modeling of the jammer to generate realistic signal levels for the platform's antenna-jammer interactions. In order to accomplish this requirement, a navigation solution must be fed back to the jammer emulator from the platform's navigation system itself. A block diagram of the system is illustrated in Figure 5.

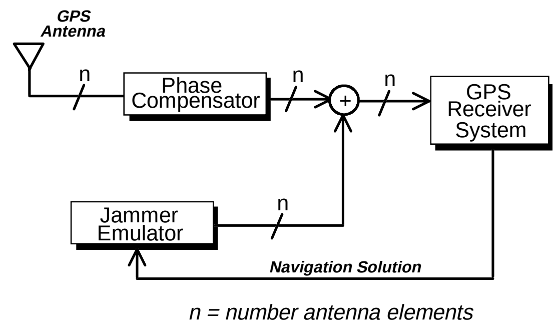

Figure 5 *GPS Jammer Emulator System*

Utility of a GPS jammer emulation system is limited by many of the same factors as GPS jammer frequency translation. The requirement for extensive modification of the user equipment is a major problem for the Jammer Emulator — such modifications will pose extensive costs and logistical problems. As such, use of a GPS Jammer Emulator System will probably be very limited.

CASE STUDY

Techniques such as controlled beamwidth antennas and selective jammer pointing angles are critical to reducing interference effects from GPSJ tests. When used to complement well-placed jammers, controlled beamwidth antennas can be extremely effective in providing a realistic jamming scenario. Two examples using the same jammer with different antenna patterns illustrates the gains afforded through such techniques.

General

For this case study, a 10 kW ERP emitter is placed at the northeast corner of Airport Lake, a playa region of NAWCWPNS' Land Range at China Lake, CA. This area is surrounded by three large mountain ranges: Sierra Nevadas to the west, Cosos to the north, and the Argus Mountains to the east. Additionally, low hills (White Hills) are immediately to the south. The NAWCWPNS Land Range complex lies under the R-2505 airspace (restricted from ground level to space) and is surrounded by the R-2508 airspace (restricted from 20,000' MSL to space). Additional isolation is provided by the highly unencroached area of the upper Mojave Desert. Placement of the jammer system is illustrated in Figure 6.

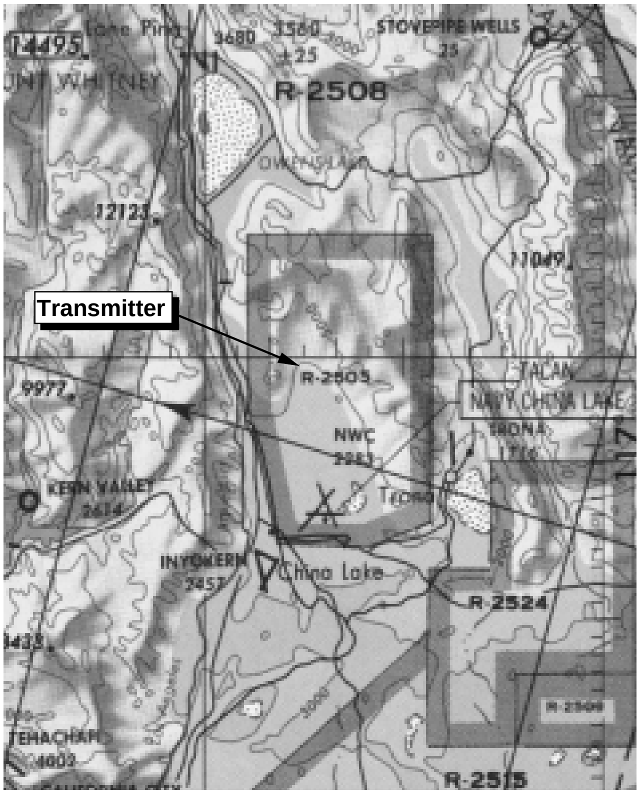

Figure 6 *Placement of Example Jammer*

Propagation modeling of the jammer is carried out using a TIREM-based model, using the parameters illustrated in Table 1.

Jammer Location	**N35° 54' 6.50" W117° 43' 0.30"**
Power	**10 kW ERP**
Antenna Elevation	**2361.5' MSL (Valley Floor)**
Receive Antenna	**Isotropic**
Receive Antenna Elevation	**100.0' AGL**
Frequency	**L1 (1575.42 MHz)**
Prediction Confidence Margin	**0.0 dB**
Atmospheric Absorption	**None**
K Factor	**1.33**
Study Type	**50% Time; 50% Locations**

Table 1 *TIREM Propagation Model Parameters*

The effects of differing polarizations are not included in this study since they are well known and widely documented in published literature.

Directional Jammer

The first configuration for the 10 kW ERP directional jammer utilizes an antenna with 20-degree vertical and horizontal beamwidth as illustrated in Figure 7. The antenna system is oriented 40 degrees east of north, with no elevation applied.

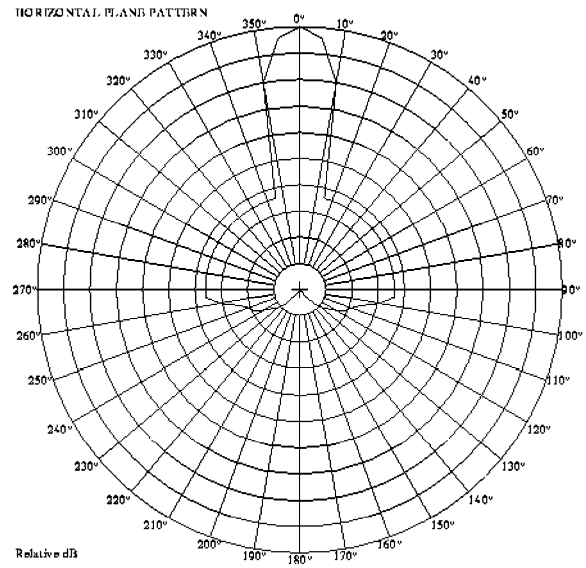

Figure 7 *Horizontal Radiation Pattern for Directional Jammer*

The radiation effects of the directional antenna system are illustrated in Figure 8.

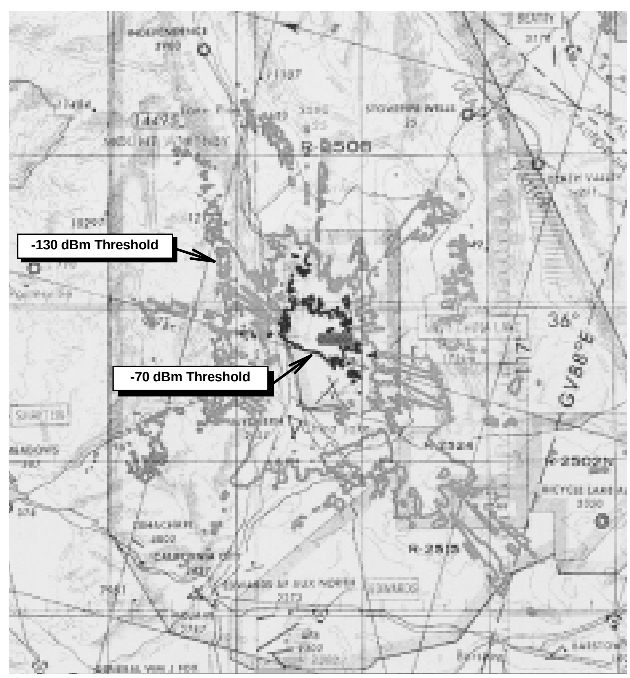

Figure 8 *10 kW Directional Jammer Radiation Pattern*

The jamming signal of the directional system is heavily contained by the natural “bowl” of the Airport Lake basin. This containment is aided through careful pointing of the antenna such that the primary and secondary signal lobes are directed towards mountainous geographic features. In this case, the primary lobe is directed towards the junction of the Argus and Coso Mountains, while the secondary lobes are directed toward the Coso Mountains and the White Hills. The effect of this placement is a high-power jamming signal primarily contained within the NAWCWPNS perimeter, with lower power signal thresholds mostly contained within the R-2508 airspace.

Omnidirectional Jammer

The second configuration for the 10 kW ERP jammer system uses an omnidirectional gain antenna (treated as an isotropic emitter for simplicity) at the same location.

Much like the directional jammer, the omnidirectional jammer signal is heavily affected by the surrounding terrain, as seen in Figure 9. Use of the omnidirectional antenna, however, results in increased signal propagation to the south towards heavily populated Southern California. This is of extreme concern due to the increase in signal bloom at higher altitudes — altitudes subject to commercial aviation approaches to the major airports of Southern California. At higher altitudes the directional jammer is preferable to the omnidirectional system, since the signal bloom is aimed away from critical areas.

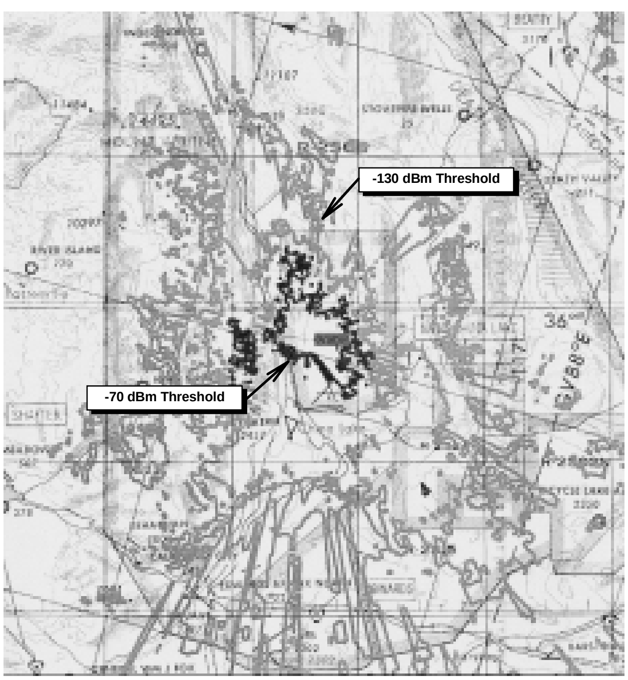

Figure 9 *10 kW Omnidirectional Jammer Radiation Pattern*

Observations

Although both jammer configurations use equivalent power strengths within the defined area of influence, the directional system minimally impacts Southern California. Despite the reduction in signal strength towards urban areas, the limited antenna beamwidth stillexposes the weapon system under test to high-level jamming signals.

CONCLUSION

The goal of this paper is to establish an interaction within the GPS community (both military and civil) that grows into a forum for addressing concerns of the varied users. Hopefully, the requirements of the DoD to successfully test GPS-based weapon systems in denied scenarios will be sufficiently addressed, while also maintaining the high level of safety and confidence the civil user community requires.

ACKNOWLEDGMENTS

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