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GIDL: GENERALIZED INTERFERENCE DETECTION AND LOCALIZATION SYSTEM
June 2002

ABSTRACT

The Local Area Augmentation System (LAAS) and the Wide Area Augmentation System (WAAS) are being developed by the U.S. FAA to provide satellite navigation performance compliant with the stringent requirements for aircraft precision approach and landing. A primary design goal of both systems is to insure that signal-in-space failures are detected by ground facilities and affected measurements are excluded before differential corrections are broadcast to users. One such failure is unintentional interference or intentional jamming in the GPS frequency band. To protect integrity, ground facilities must quickly detect the presence of interference that fall within the restricted zone defined by LAAS and WAAS system requirements and thus may be hazardous to users. To protect availability, ground personnel must also be able to locate and deactivate the interference source.

In order to serve this purpose, the prototype Generalized Interference Detection and Localization System (GIDL) has been developed. This prototype includes four antennae and RF sections slaved to a common clock to allow detection and determination of three-dimensional interference location.

The paper describes test results from a real-time demonstration of the GIDL system. In this test, a calibrated wideband noise source is utilized as GPS jammer and is moved around the field between a set of pre-calibrated locations, and the real-time GIDL display provides up-to-date estimates of the location of this interference source to within the limits predicted by the accuracy analysis.

INTRODUCTION

Development and completion of the Global Positioning System (GPS) was the most significant navigational achievement of the 20th century. GPS allows users to know their location anywhere on Earth thereby opening up multiple possibilities for various applications. One of the applications of GPS navigation is aviation. It has been shown that GPS can be seamlessly used for en-route navigation and landing of airplanes.

There are two systems currently under development for this purpose: the LAAS, which primarily targets precision navigation for landing, and the WAAS, which can be used for en-route navigation and non-precision approaches.

Along with these GPS opportunities come some problems associated with GPS signals. GPS signals are very weak and can be easily jammed by unintentional or intentional interference. A solution to this problem is needed. Various approaches to the solution of this problem can be taken: implementation of more robust signal processing algorithms; development of adaptive antennae with null steering; or timely localization and mitigation of the source of interference. This paper addresses the last issue: finding and locating sources of GPS interference.

When GPS was invented, it was designed to be a military system, with only partial utility for civilians. It actually was anticipated that at some point in time the system would be jammed. However, civilians are now the primary GPS users and lengthy outages due to jamming is unacceptable for airplane users. Thus, another part of the system must be developed and tested, such that a jammer presence is both detected and located. This paper proposes a solution to this problem.

Since source localization has been studied almost since the invention of the radio, there are a significant number of algorithms which could be used in the GIDL system. Several ways to implement interference source localization are interferometry, time-of-arrival differential system, spatial spectrum estimation, phased antenna array, etc. The majority of this work concentrates on the interferometric, or time-of-arrival, techniques. Experimental results are included in this paper.

The authors examined possible theoretical solutions to jammer or interferer localization problems, chose the subset of the most interesting solutions, and then developed experimental hardware allowing implementation of these algorithms. Upon completion of the hardware and algorithm development, the prototype system was successfully field tested for the Federal Aviation Administration (FAA).

During the field test, this prototype GIDL was set up at Lake Lagunita on the Stanford campus, along with a conventional optical direction finder. The interference source was placed in various locations in the dry lake bed. The GIDL reported locations of the source, as well as direction to the source from the location of the optical direction finder. GIDL's reported directions and optically observed directions were the same. Mr. Carl McCullough, Director of the FAA's Office of Communications, Navigation and Surveillance Systems was present at the demonstration. He was completely satisfied with the system performance.

SIMPLIFIED GIDL CONCEPT

Let us assume that we have a system containing two antennae and some signal source (jammer) located far enough away such that it is possible to assume that signal wavefronts from this source are planar with respect to the antennae' baseline. This situation is shown in Figure 1.

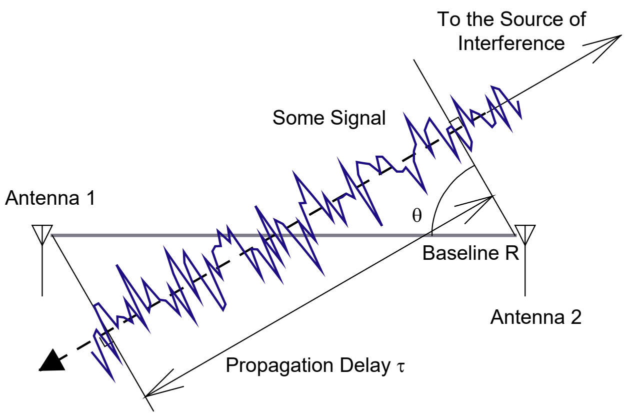

Figure 1: GIDL Concept: Interferometry

If differential signal propagation delay time is measured between these two antennae, and signal propagation speed is known in the media (for example, the speed of light), the range difference (RD) measurement (or time difference of arrival (TDOA) measurement, which differs from RD measurements by a scale factor of propagation speed in the media) can be formed. The RDs are equal to the distance between antennae (the baseline) multiplied by the sine of the angle between antenna baseline and direction of the signal wavefronts (direction to the signal source, or direction of propagation, is orthogonal to the direction of wavefronts, and equal to $90^\circ - \theta$ degrees): $L\sin(\theta) = \tau c$, where c is propagation speed in the media, L is distance between antennae or baseline, τ is the time difference of arrival (or τc is range difference), and θ is the direction of the wavefront with respect to the baseline. L and c are assumed to be known, and τ is the measurement. By inverting this equation, it is possible to find direction of the wavefronts, θ, or direction to the source $90^\circ - \theta$. There is an ambiguity in the solution as signal source can be on either side of the baseline, in a planar case, or on the cone in the case of 3D space. Multiple baselines can resolve this ambiguity.
When the assumption concerning a distant source is not valid it is necessary to take into account the fact that wavefronts from this source are spherical. In this case, it is also possible to form the TDOA (or RD) measurement, but now this measurement

would define a hyperbola of possible source locations in 2D, or hyperboloid in 3D with antennae in the foci of these hyperbolas. This is shown in Figure 2. By intersecting hyperbolas from the multiple baselines, it is again possible to find the signal source location in 2D or 3D space.

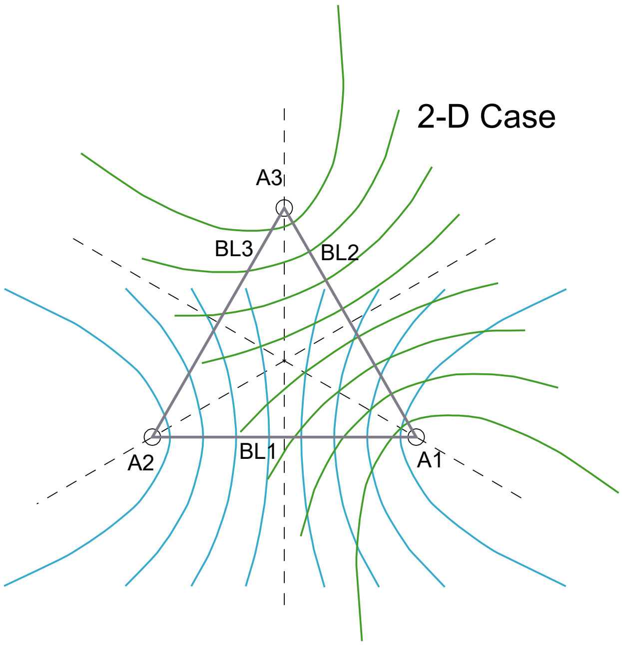

Figure 2: GIDL Concept: Hyperbolic Localization

From this simple concept it is easy to see that it is possible to locate the source of interference by means of a completely static system (without moving parts), through the use of omnidirectional antennae plus signal processing algorithms which let us estimate TDOA measurements.

GIDL HARDWARE CONCEPT

Conceptual design for the prototype GIDL receiver is shown in Figure 3. It consists of four RF inputs, which connect to the four antennae, some RF hardware and a processor to execute receiver processing algorithms. Outputs of the receiver are a jammer detection flag or number of jammers and their estimated location. The actual GIDL receiver follows this conceptual design. It is possible to build a receiver with four RF sections (i.e., with the ability to connect to four antennae). This type of receiver would operate from one common clock, making it a completely coherent system. There are some limitations to this prototype. Namely, it would have only four antennae, and the antenna locations would be limited by cable length from the receiver to the antenna.

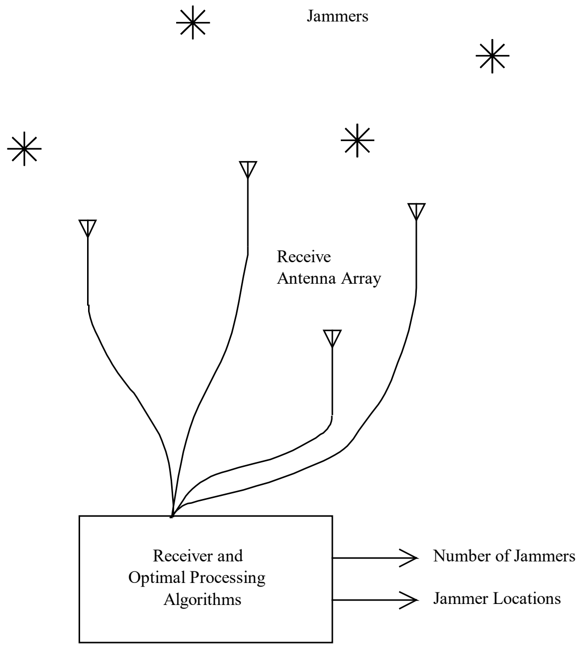

Figure 3: GIDL Realization Concept

EXPECTED GIDL PERFORMANCE

It is possible to calculate expected GIDL performance for the antenna configuration used in the GIDL experiments and demonstrations. For a number of experiments, as described later, a semi-permanent GIDL configuration was used.

For this GIDL configuration, plots of jammer localization using the TDOA method were generated. Hyperbolas corresponding to TDOAs with expected errors of ±0.7m are shown in Figures 4 and 5, with the first figure showing the system as a whole and the second zooming in on jammer location and showing expected localization error boundaries (1σ).

In Figure 6 and Figure 7 it is assumed that a jammer with power –40 dBW/MHz is used during the experiments (as it was) and expected error ellipses for this jammer localization are plotted. Expected localization errors for direction are also plotted with azimuth of 193 degrees. This is an example of how the size of expected GIDL errors depends on the range from the GIDL system.

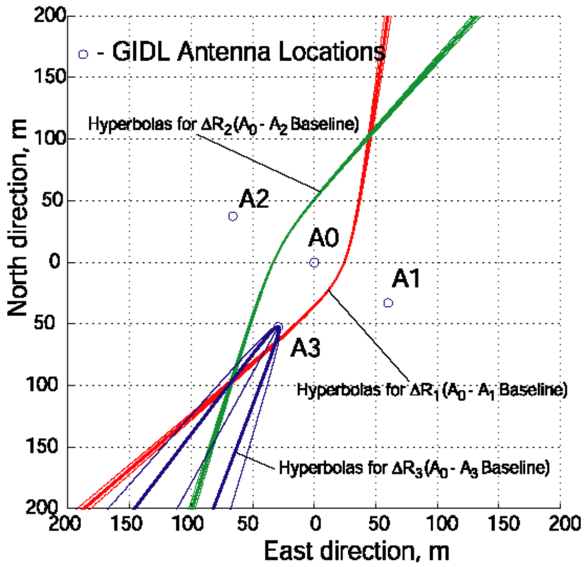

Figure 4: TDOA Jammer Localization. SOP (Hyperbolas) and Error boundaries (±0.7m).

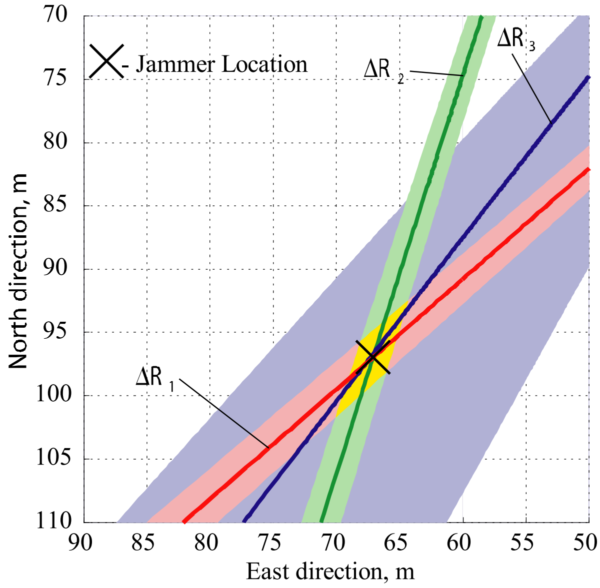

Figure 5: TDOA Jammer Localization. SOP (Hyperbolas) and Error boundaries (±0.7m), Zoomed.

EXPERIMENTAL SETUP FOR FULL GIDL SYSTEM TEST

Full system tests of the GIDL were performed on the dry bed of Lake Lagunita on the Stanford campus. There were a number of reasons for choosing that test location. In particular the lake bed is below ground level with respect to the rest of campus; thus any jammer located in the lake bed would not be visible from the campus or other locations, and would not introduce any unwanted interference to nonparticipating parties. Also, the lake bed is open space and is a reasonable simulation of the real life LAAS installation. It was easy to find an elevated observer spot for independent jammer direction verification. The lake bed is not used for any sports or recreational activities when the lake is dry, so it was safe to install equipment and run cables without any expected interruptions from other users. Lastly, it had the advantage of being located right on the Stanford campus, making it relatively easy to move equipment to and from the laboratory.

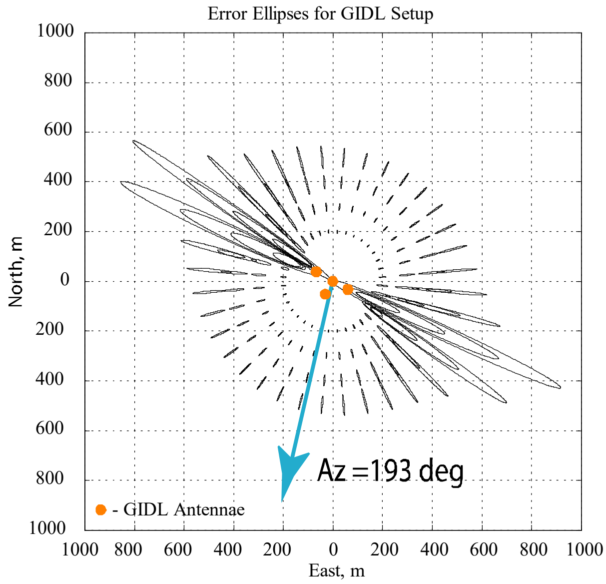

Figure 6: Expected GIDL Performance: Error Ellipses for the GIDL Setup

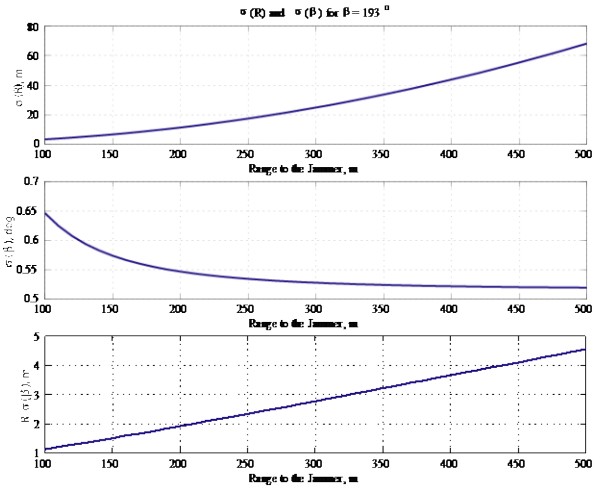

Figure 7: Expected GIDL Performance: Expected Variations of the Errors

There were two installations of the GIDL system on Lake Lagunita. One was temporary and was used only for one day and one series of experiments. It was the first full test of the GIDL system and a verification of the usefulness of the lake-bed setup. This first experiment was performed on August 22, 2000. Large amounts of data were collected and used in post processing for algorithm debugging and system tuning.

Figure 8: Experimental Jammer: -40 dBW/MHz white noise source

Figure 9: One of four GIDL receiving antennae

For all experiments on Lake Lagunita, the -70 dBW/MHz white noise jammer was used with an extra 30 dB amplifier to scale the estimated jamming range to 316 m. The expected GIDL range for a jammer of that power is 505 m. The jamming signal is a white noise centered at the L1 frequency with a bandwidth greater than 24 MHz. This is a realistic type of jammer which could easily be built for under $100 and poses a significant threat to GPS operations. The experimental jammer and amplifier is shown in Figure 8. The jammer power was so low that the GPS receiver installed in the GIDL base station was tracking satellites throughout all jamming experiments. This provided an additional assurance that no other user would be unintentionally jammed while GIDL experiments were being conducted.

NovAtel 401 antennae were used as GIDL antennae for both setups. Each GIDL antenna was connected to the GIDL receiver by an RF cable. The length of the cables was 100 m each, and they were cut to this size. This was done intentionally to allow some experiments to assume that the system delays were equal in each channel and therefore proceed without calibration. Because the cables were of significant length, extra in-line amplifiers after each antenna were used to cope with attenuation and signal degradation in the cables. Belden 9913 cable was used with approximate attenuation of 6 dB per 100 ft at GPS frequency, making each cable attenuation approximately equal to 20 dB. Starlink in-line amplifiers with 21 dB of gain were used. In the first GIDL experimental setup, the antennae were mounted on temporary mounts. In the second, semi-permanent setup, the antennae were installed on mounts permanently fixed in the ground. One of the GIDL antennae with an in-line amplifier attached to it is shown in Figure 9 on a permanent mount.

Location of the antennae and surveyed jammer locations for the first setup are shown in Figure 10. The second setup is shown in Figure 11. As mentioned, this setup was a semi-permanent setup, and numerous experiments were conducted on it. All antenna and jammer mounts in surveyed locations are aluminum posts driven about 70 cm deep into the ground with an antenna thread on top, making them virtually permanent installations.

For proper GIDL operation, it is necessary to know the exact relative geometry of the GIDL antennae, and it is convenient (and necessary for calibration by GPS) to know how internal GIDL coordinates (i.e., antenna geometry) relate to some common coordinate reference. Thus, extra care was taken in surveying the GIDL antenna locations. For both setups, antenna locations were surveyed using Trimble 4000 series survey receivers. Three jammer locations also were marked and surveyed to be used as "truth" for the jammer localization algorithms. The GIDL finds and locates jammers, but it is necessary to know how accurately it is doing its job. Thus, independent ways of locating jammers for test purposes must be available. These surveyed jammer locations were used to collect statistics of GIDL errors in jammer localization.

GIDL Experimental Setup #1, 22.08.2000

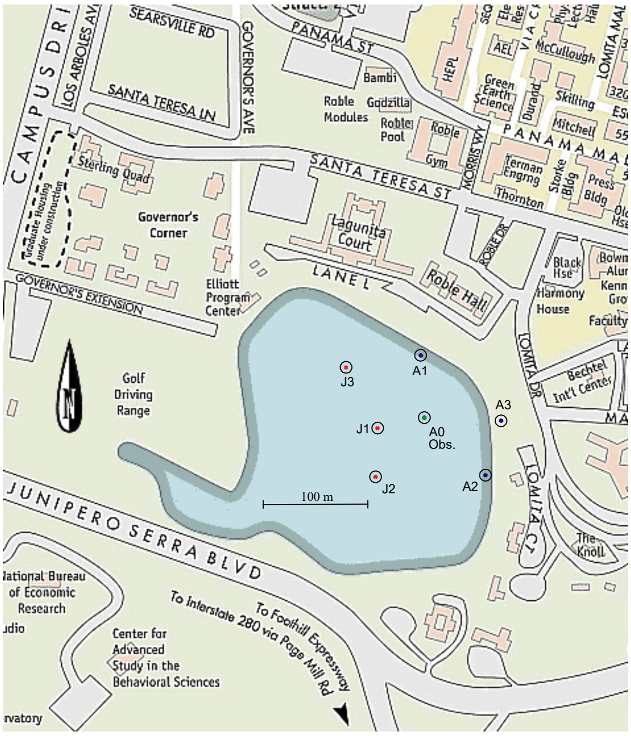

Figure 10: GIDL Experimental Setup for the First Experiment

For the semi-permanent setup, the so-called observer location was also surveyed. For a visual consistency check and for demonstration purposes, an optical direction finder was installed in that location, and all directions to the jammers were calculated relative to this point such that an independent observer can quickly check the GIDL performance. Various views of this direction finder are shown in Figure 12.

After moving all equipment into the field, GIDL antennae were installed on the mounts. One-hundred-meter antenna cables were then run from each antenna to the GIDL base station. For most experiments the GIDL equipment was installed in the back of a truck and consisted of the GIDL receiver, processing computer, and the Garmin GPS receiver (used for calibration and jammer power monitoring), as shown in Figure 13. The base station, i.e., the complete GIDL system, was powered by a gas generator. Thus, it had an independent power source and could be moved to different locations if necessary.

GIDL Experimental Setup #2, 18.10.2000

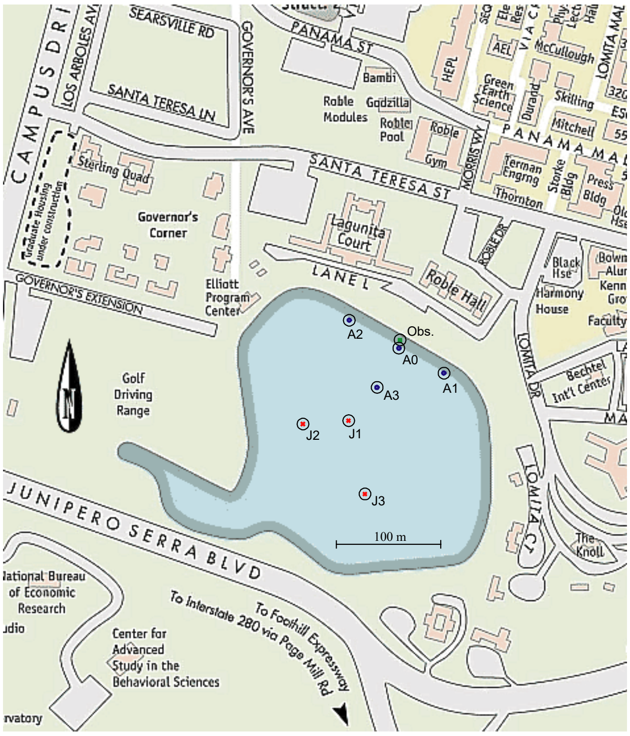

Figure 11: Semi-Permanent GIDL Setup

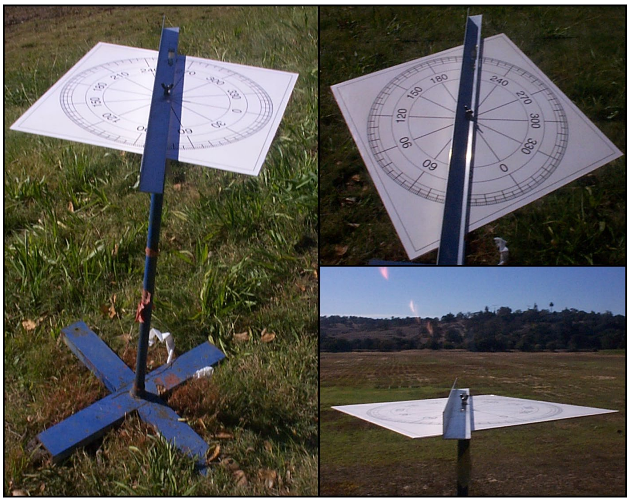

Figure 12: Optical Direction Finder, Used for Independent Jammer Azimuth Verification

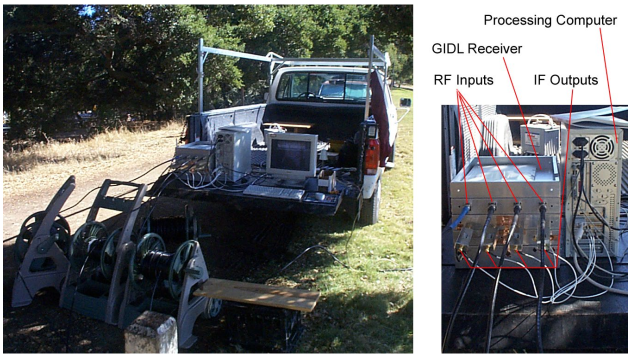

Figure 13: GIDL base station (GIDL receiver, processing computer, etc.) was located in the bed of HEPL truck during experiments at Lake Lagunita

DATA COLLECTION AND DEMONSTRATION MODES

There were two major operation modes for the GIDL system: data collection and demonstration modes. In the data collection mode, software was set up to collect 50 individual data sets for system calibration or jammer localization and to save all raw data to the hard drive for post processing and statistical analysis. The number 50 was chosen due to the limited capacity of the hard drive. When data analysis occurred in post processing or when various algorithms were tested, the following mode of operation was adapted. The GIDL was installed on the test range, and the jammer was turned off. Then 50 calibration data sets were collected. These data sets include raw data from the ADCs in each GIDL channel, time stamped by the GPS time, and satellites in view and ephemeris data from the GPS receiver. The jammer was then moved to the first surveyed location, turned on, and another 50 data sets were collected, this time gathering only raw data from ADCs in each GIDL channel. After this data collection, the jammer was again turned off, and another calibration data set was collected. The jammer was then moved to a second surveyed location and 50 jammer data sets were collected. The same procedure was repeated for the jammer at the third surveyed location. Lastly, another 50 calibration data sets were collected. Using these data, all experimental result plots were generated, and all statistics were obtained. To do so, the first calibration data set was used to calibrate the system clock and biases in the system (by utilizing GPS signals). The jammer data were then processed using the GIDL detection and localization algorithm, taking into account the calibration results.

A second mode of GIDL operation is the demonstration mode. This mode is used to demonstrate system performance, do a quick assessment of the system accuracy, and to “show off” the system. In this mode, a few calibration data sets are collected at the beginning of operation (and could be collected at any time to recalibrate the system during the demonstration) and are then processed and stored as parameters for the real-time jammer localization code. After that, the jammer localization code can be run. One option is to run the jammer detection and localization code continuously. In this case, the GIDL display is shown collects data sets and tries to detect a jammer. If a jammer is detected, location, azimuth and range are displayed on the screen along with expected errors for its location. Another option is to run the algorithm in single runs. Then, on command from the operator, a data set is collected, jammer detection/localization is performed, and results including jammer location (if present) are displayed.

To verify how well the system performs without calibration, it can be run in demonstration mode while setting all calibration coefficients to zero. It takes about 55 seconds to collect and process one data set in demonstration mode, i.e., in that time, data is collected, stored to the hard drive, read into MATLAB, and then processed by the GIDL algorithms implemented in MATLAB. This process could be sped up.

EXPERIMENTAL RESULTS OF JAMMER LOCALIZATION

In Figures 14-19, jammer localization results are shown. The Figures 14, 16, and 18 shows a “bird's-eye” view of the experimental results, and the Figures 15, 17, and 19 zooms in on the jammer which has been localized. Known GIDL antenna locations are shown by the bold circles on the plots, while estimated jammer locations are shown by the regular circles for uncalibrated data and by the small crosses for calibrated data. Also, hyperbolas used for jammer localization are shown (these are so-called “surfaces of position”), along with expected error boundaries for each hyperbola. There is also a predicted 1σ error ellipse shown for the given jammer location.

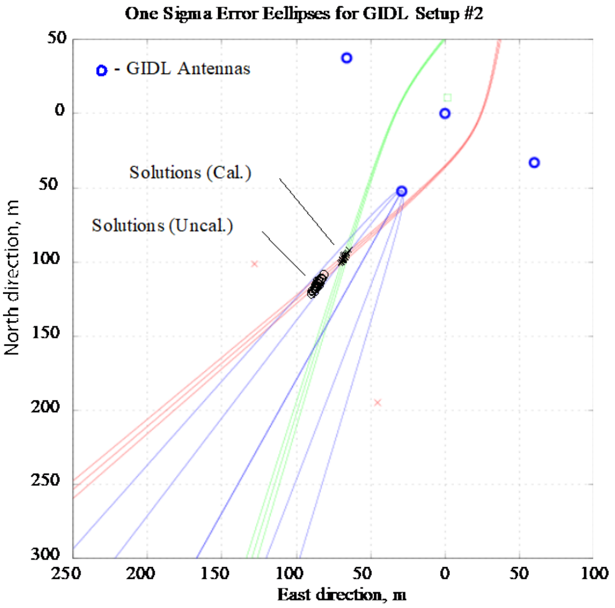

Figure 14: Jammer localization results on October 18, 2000, with jammer at location 1, summary of 50 independent experiments

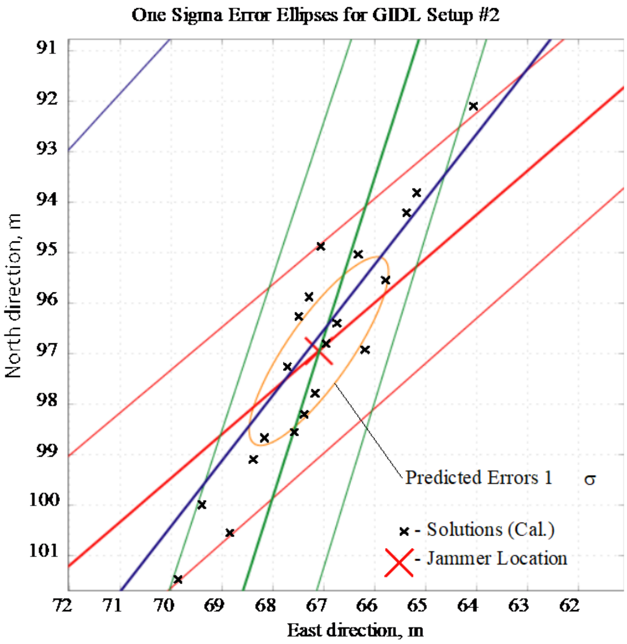

Figure 15: Jammer localization results on October 18, 2000, with jammer at location 1, summary of 50 independent experiments (zoomed)

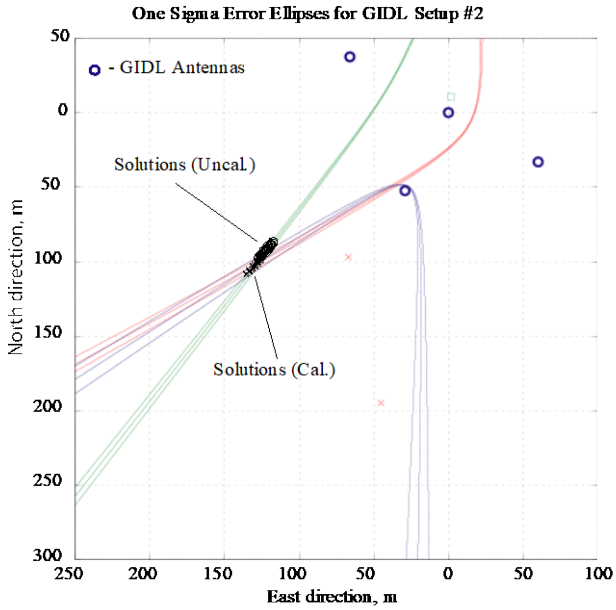

Figure 16: Jammer localization results on October 18, 2000, with jammer at location 2, summary of 50 independent experiments

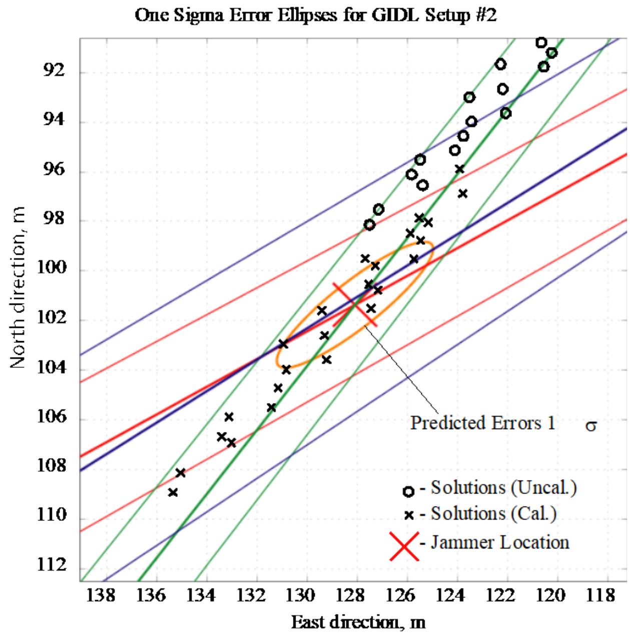

Figure 17: Jammer localization results on October 18, 2000, with jammer at location 2, summary of 50 independent experiments (zoomed)

From these plots, it is easy to see that all calibrated jammer location estimates fell within predicted error boundaries (boundaries on each side of the ellipses of jammer location for each pair of antennae) and correspond to the predicted 1σ error ellipse (these are 1σ boundaries on statistical data, so one would expect about 37% of the data points to lie outside the 1σ boundaries). From the plots it is easy to see that the system performs very well and as predicted.

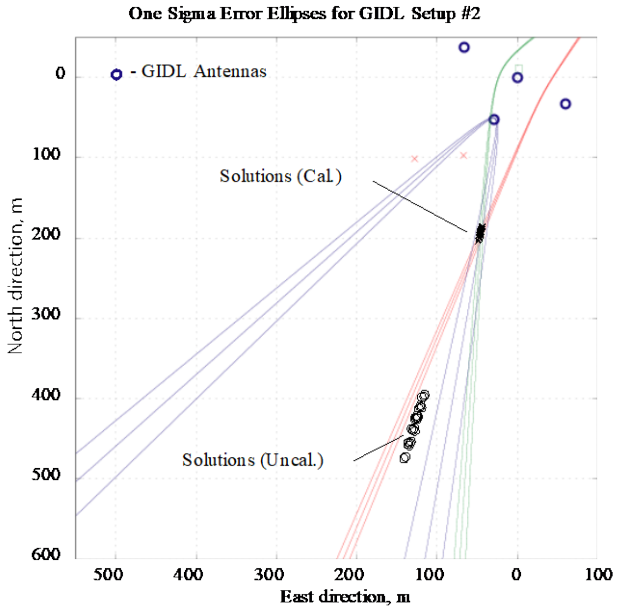

Figure 18: Jammer localization results on October 18, 2000, with jammer at location 3, summary of 50 independent experiments

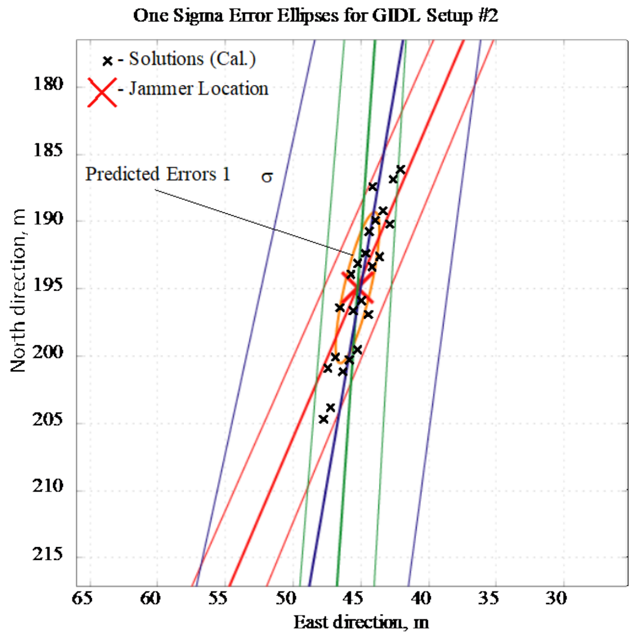

Figure 19: Jammer localization results on October 18, 2000, with jammer at location 3, summary of 50 independent experiments (zoomed)

Looking at the uncalibrated data, it is possible to observe that azimuth estimation remains strong in these results while the ranging information is almost lost. So it is possible to conclude that calibration is more important for finding the range and less important for finding azimuth.

The measured mean and standard-deviation values of jammer localization at each jammer location for 50 data sets are shown in Table 1 and in graphical form in Figure 20, along with the values predicted by the theoretical analysis. In this result, the azimuth and range of the jammer location is referenced to Antenna Number 0 of the GIDL system.

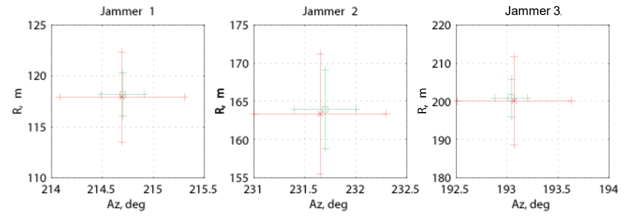

Figure 20: Results of the Experiment Performed October 18, 2000. Surveyed (red ×) and GIDL measured mean location (green ☐) for each jammer with corresponding ±1σ error bars.

Table 2 and Figure 21 shows results obtained in the demonstration mode for jammer localization during the first GIDL experiment at Lake Lagunita on August 22, 2000. To obtain these results, no calibration data were used. Instead, data were obtained immediately after turning GIDL on for the first time on the lake-bed.

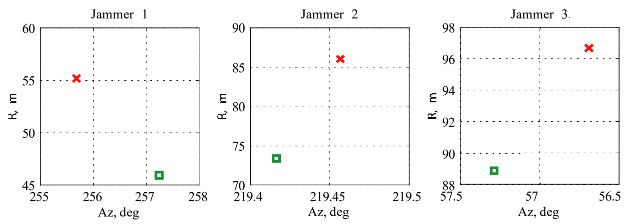

Figure 21: Uncalibrated Jammer Localization in Demonstration Mode During First GIDL Experiment at Lake Lagunita. Surveyed (red ×) and GIDL measured location (green ☐) for each jammer.

Table 3 and Figure 22 shows results obtained in the demonstration mode during the second experiment on the lake. Again, no calibration data were used to obtain these results.

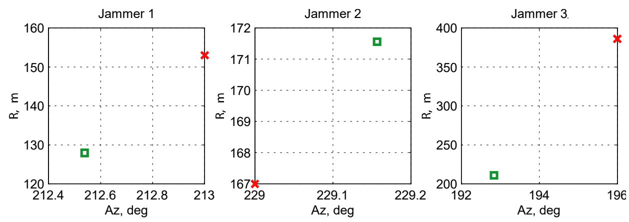

Figure 22: Uncalibrated Jammer Localization in Demonstration Mode During Second GIDL Experiment at lake Lagunita. Surveyed (red ×) and GIDL measured location (green ☐) for each jammer.

	Surveyed		GIDL Measured Mean		Estimated Error		Test Statistics	
	Az, deg	Range, m	Az, deg	Range, m	σ(Az), deg	σ(R), m	σ(Az), deg	σ(R), m
Jam. 1	214.69	117.92	214.70	118.15	0.61	4.39	0.21	2.09
Jam. 2	231.65	163.35	231.70	163.95	0.65	7.83	0.30	5.12
Jam. 3	193.07	200.11	193.04	200.89	0.56	11.51	0.16	4.93

Table 1: Results of the Experiment Performed October 18, 2000. Azimuth and Range Referenced to Antenna 0; Measured values are mean and standard deviation of 50 runs for each jammer location.

	GIDL Reported Location		Surveyed Location	
	Range, m	Az, deg	Range, m	Az, deg
Jammer 1	55.1578	255.6821	45.9234	257.2396
Jammer 2	86.031	219.4568	73.3871	219.4165
Jammer 3	96.6923	-56.6896	88.8767	-57.2878

Table 2: Uncalibrated Jammer Localization in Demonstration Mode During First GIDL Experiment at Lake Lagunita

	GIDL Reported Location		Surveyed Location	
	Range, m	Az, deg	Range, m	Az, deg
Jammer 1	153	213	127.9494	212.5391
Jammer 2	167	229	171.5574	229.1565
Jammer 3	386	196	211.0717	192.8428

Table 3: Uncalibrated Jammer Localization in Demonstration Mode During Second GIDL Experiment at lake Lagunita

These results show that GIDL performs well in finding the azimuth of the jammer even without calibration. This could be useful in localizing jammers, if they are present at the time of GIDL activation. All the data show that the GIDL performs well and as expected in localizing a jammer. This conclusion applies even at ranges when the jammer is not affecting or not completely jamming the protected GPS receiver and with jamming power comparable to the noise floor. It takes only 55 seconds to detect and locate a jammer.

GIDL APPLICATIONS

The GIDL system is built as a four-channel software radio which operates in the GPS frequency band. What it does with received signals completely depends on the software loaded into it. In this work, jammer detection and localization algorithms along with software for this receiver were developed and tested. This receiver and developed software works as an interference detection and localization system. This system originally was in-tended for integration with LAAS as one of the subsystems, to protect airports from GPS interference. But this system has utility on its own and could be used for various other applications. Besides the entire system applying to various applications, the receiver itself proves to be a valuable research platform for a different set of applications.

Applications to LAAS

The GIDL system can be implemented in parallel with a three- or four-receiver LAAS ground facility (sharing some components with the LAAS reference receivers and proces-sors) or as a separate installation to support nearby LAAS and WAAS sites. While LAAS would detect interference on its own, the GIDL would improve overall

LAAS availability through timely detection and localization of a jammer source so that the interference is removed as quickly as possible.

Aircraft Application

It may be possible to use the GIDL on an airborne craft to find sources of interference to GPS. It could be used for flight inspection or for rapid jammer localization in the areas where a GIDL is not permanently installed. (This idea has been suggested by Professor D. Powell during a private conversation.) The GIDL could be installed on the bottom of an airplane forward and back of the fuselage and at the tips of the wings. It could then be used for flight inspection to find the location of any transmitters in the GPS band, particularly sources of interference and jammers.

Currently GIDL data processing is implemented as batch processing. It takes only about 14 ms to collect raw data from the GIDL receiver, and then about 1 minute to process this data by MATLAB software (this processing time could be improved). For airborne jammer localization it also would be necessary to know attitude and location of the aircraft in the moment of data collection. So it is possible to rapidly collect number of data sets in the region of interest and then obtain jammer location in the postprocessing, or to implement number of processors that would process data sets in succession (for example if 10 processors would be utilized with no changes in the current software new data points would be obtained each 6 seconds).

For this application GIDL approach to the jammer localization could be combined with approach studied by Shau-Shiun Jan[1] by providing bearing and Doppler frequency of the jammer. Utilizing jammer range measurements provided by the GIDL could further enhance it.

Another application of GIDL to aviation is the installation of some version of the GIDL system at airports which do not have LAAS but are going to utilize WAAS for navigation and landing. The GIDL system should be inexpensive to install and maintain so that almost any general aviation airport should be able to afford it. Such an installation should increase the protection against interference at this airport. If all airports in the area had a GIDL system installed, then these systems could combine within the network, potentially protecting large regions from jamming or interference.

Other Applications

The GIDL could be used as an interference monitoring, detection and localization tool, whenever it is required. It could be installed on vehicles for use on demand whenever a GPS interference problem is suspected. In this mode of operation, only directional data could be used. By moving the vehicle, it would be possible to triangulate the source of interference.

Temporary interference problems have happened on various occasions. One example is the installation of a remote TV camera on the Durand building on the Stanford campus. For some reason, this camera was transmitting in the GPS frequency band and was interfering with several GPS antenna installations at Stanford. The GIDL was not available then and it took some time to locate this source of interference to GPS. Using the GIDL, it could have been done in a much shorter amount of time.

GIDL Hardware as a Flexible Research Platform

The GIDL receiver has found number of interesting applications in other research conducted in the LAAS and WAAS laboratories. Several people have already used it in their experiments such as: Experiment on Aided GPS Signal Detection[2]; GPS Signal Quality Monitoring Application; GIDL Modifications for Multiple Frequencies; Experiments With New GPS Signals.

CONCLUSIONS

A four-channel, common-clock software defined radio (SDR) that operates in the L1 GPS band has been developed. The primary intended use for this receiver is the Generalized Interference Detection and Localization (GIDL) System and development of new localization algorithms. GIDL signal processing algorithms that allow interference detection, TDOA estimation of weak unknown jamming signals, and their source localization have been developed and tested.

The GIDL receiver is a valuable development platform, first for interference detection and localization and also as a software radio. It can be used for weak GPS signal detection experiments[5], multi-frequency experiments[4] (with slight modifications), and other current and future experiments.

Jammer localization and GIDL interface display software were developed and tested during field experiments and GIDL real-time demonstrations. Field tests of the GIDL demonstrated detection of weak signals as well as determining azimuth and range to their source in real time with experimental results matching the predicted performance. The GIDL demonstrated that it is capable of jammer localization in less than one minute with an azimuthal accuracy better than 0.30 degrees (Table 1) when the largest antenna baseline was 76 meters and distance to the jammer was 200 meters (antenna baseline was 0.38x the distance to the jammer).

The demonstrated GIDL system is compatible with the currently recommended LAAS installation and can improve overall LAAS availability by detecting the presence of a jammer and finding the direction and/or location of detected interference sources.

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