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Application Note: Co-Location and Jamming Considerations for SSIII Integration

Document No: APNT3004
Revision 1
12/13/04

Author: S. Feeko

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1.0 Background

As GPS receivers become more embedded and integrated with other systems, the immunity to unwanted electro-magnetic interference (EMI) or energy (radiated or conducted) becomes more critical. There will be times when the presence of unwanted energy will be inevitable. The issue is how will the system perform during these times (receiver susceptibility)? Can performance remain intact, or can any ill effects be mitigated (receiver immunity).

It is known that there are several factors contributing to the immunity of jamming of a GPS system. Among these being filtering, grounding, shielding, circuit board layout, component selection and placement, antenna selection and placement, proximity to the jamming source, etc. Susceptibility is a measure of how the performance will be affected or degraded once the unwanted signal gets in.

Radiated EMI can be classified as unwanted electromagnetic energy through free space entering through the GPS antenna. This can occur in environments where high power signals are being transmitted, such as digital or analog cellular towers, weather radars, airport or shipboard radars, or Radio and TV transmitter signals. To these systems, it is signal, to a GPS receiver it is interference.

Conducted EMI can be classified as unwanted electromagnetic energy received through a conducted medium. This can occur in environments where poor engineering practices were followed in the design or when an inadequately shielded GPS receiver is co-located in an enclosure with another circuit or system.
When the antenna is integrated inside the enclosure of the GPS receiver, and there is also another system present as in the case of a cell phone effects of conducted and radiated EMI can occur.

Note: For the purposes of this discussion, in-band jamming is defined as the L1 frequency of 1575.42 +/- 10 MHz and out-of-band is defined as any other frequency.

2.0 PURPOSE

The purpose of this document is to bring to light the importance of jamming and interference considerations during the design of SSIII GPS receivers and to introduce measures that would minimize the effects on performance. The document will characterize the in-band susceptibility and out-of-band immunity of the SSIII GPS receiver. It will discuss susceptibility, and general design practices for isolation. The susceptibility of the SSIII receiver to externally generated continuous wave (CW) noise power at various frequencies of interest was measured by recording the level of C/No degradation as a function of jamming input power level and monitoring any position deviation at chosen test frequencies. The measurements were taken on the standard reference receiver design utilized in the SSIII Evaluation Kit. The document will characterize the resultant behavior of tracking and navigating under these conditions.

3.0 APPLICABLE DOCUMENTS

2010-0119	GSP3e + GRF3w Schematic
2010-0125	GSP3f + GRF3w Schematic
1060-0122	LGA Carrier Board SSIII Schematic
1060-0120	S2SLC100 Evaluation Receiver
	GSP3f Data Sheet
	GSP3w Data Sheet
	GRF3w Data Sheet
APNT3001	SSIII System Design Guidelines and Considerations
APNT3002	PCB Design Guidelines for SSIII Implementations
APNT0022	Integrating Patch Antennas with SiRF GPS Receivers

4.0 THE EFFECTS OF JAMMING

EMI interference causes several problems however for ease of discussion the document will classify them as either jamming or spoofing. Usually the receiver will stop navigating when heavily jammed, meaning it will not continue to provide position updates. When spoofed, the receiver will often output a false velocity and give an incorrect position. Spoofing is the more severe condition.

1. Jamming
    - Receiver is unable to acquire the GPS satellite signals
    - Receiver losses the satellite signals and is unable to reacquire
2. Spoofing
    - Receiver tracks a signal other than the true GPS signal and uses the phase and carrier information to form incorrect measurements for navigation.

In real life conditions, jamming is common and spoofing is rare. This is because a spoofing signal must be very carefully designed to cause damage, and this is very rare.

5.0 MITIGATION

The best available method for increasing immunity to strong out-of-band signals is through proper filtering. In many cases, the receiver may require a pre-select filter before the first stage low noise amplifier (LNA), as well as a filter after the LNA, to prevent saturation and to reduce overall noise power into the receiver through RF band limiting. The only drawback to pre-select filtering is a loss in sensitivity at the system level due to an overall increase in system noise figure.

The best methods for decreasing degradation of performance due to in-band interference entering the receiver are through system implementation and processing.

Earlier in this document it was mentioned that there are factors which could aid in the immunity of jamming of a GPS receiver. Among these being filtering, grounding, shielding, circuit board layout, component selection and placement, antenna selection and placement, proximity to the jamming source. The following is a list of recommended steps that could increase immunity and mitigate the effects of jamming.

- Filtering:

- Filtering for Out-of-Band Signals

- For optimal performance a pre-select filter may often be required before the LNA_IN pin of the RF input of the GRF3w device. A SiRF tested part as seen in the SiRFstarIII reference design may be used. However if another filter is chosen, the following guidelines should be considered. SAW filters are "high-Q" devices with a narrow pass-band. The 30dB rejection point pass-band is approximately 100 MHz. While ceramic filters are "low-Q" devices with a wide pass-band. The 30dB rejection point on ceramic filters is approximately 350MHz. A SAW filter should be selected to anticipate a jamming signal near the 1.575GHz L1 GPS signal. However if the receiver is required to function near an FM radio tower (90~110MHz), then a ceramic will provide a better protection. SAW filters are smaller in size, but have a higher insertion loss.

- Filtering for In-Band Signals

- When integrating the SiRFStarIII receiver with a cell phone handset or other co-located transmitter, it is usually extremely important to add a notch filter on the output of the PA. The phase noise and spurious sidebands generated by the transmitter, which fall inside the GPS band, will severely degrade GPS performance unless measures are taken. Since these are in-band signals, they cannot be removed in the GPS receive path. Therefore they must be removed in the transmit path. A notch filter in the Tx output can control this problem.

- Power Supply Filtering

- Power supply filtering is also an important issue for the control of conducted EMI. This applies to not only filtering on the GPS module but also insure a clean DC supply into the GPS module. Bypass all VCC pins with a filter cap to ground.

- <u>Grounding:</u> Maintain one plane, as your RF GND plane, meaning DO NOT split the ground plane! Use multiple points for connection, meaning use individual vias for ground pins and connections.
- <u>Shielding:</u> Proper shielding in a GPS receiver is a must to eliminate the exposure of the crystal to air current and to provide a path to ground to any possible EMI. A separate RF shield is necessary. Digital shields may be necessary as well if the GPS receiver is housed in the same enclosure as another radio or other device with EMI present. Design initially for "over shielding" and reduce as necessary later. The best material for shielding is metal. Metallic plastic has good aesthetics and is cheaper in both material and production cost, but is not ideal. A two piece shield (wall plus top) is recommended for ease of troubleshooting access during the early stages of development. "Remember good shielding is a must"!
- <u>Circuit Board Layout:</u> "The layout of the GPS receiver will greatly affect its performance". When planning the layout, failure to include EMI considerations as critical factors can lead to several iterations of integrated designs to optimize the EMI problem. Include these recommendations as critical.
    1. Separate the RF and digital sections.
    2. Separate the GPS section with any other circuitry that may be present on the same printed circuit board (PCB).
    3. Isolate the crystal circuit from any noisy source.
    4. Route all the RF circuitry along with the interface lines between the RF IC and the Baseband over the ground plane.
    5. Insure the reference oscillator and loop filter circuitry is also routed over the ground plane.
    6. Route the real time clock (RTC) over the ground plane.
    7. Route clock lines over the ground plane and not near any DC source or path.
- <u>Component Selection and Placement:</u> Consider the SiRF reference design bill of materials (BOM) for critical components. The critical components are the reference crystal oscillator, the voltage regulators and any on board LNA's. For component

placement guidelines refer to APNT3001 and APNT3002. These components have been successfully used, but there may be many other components which can also successfully be used.

- Antenna Selection and Placement: The selection of the antenna and its placement will greatly affect performance. In terms of EMI considerations the preamp in an active antenna should be of good quality and at the proper gain. The placement of the antenna is critical if housed in the same enclosure as the GPS module especially if this enclosure has another radio or other integrated electronics. Place the antenna element in or near the RF section not the digital section and use isolation practices if there are other antennas present. If co-located with a transmitter, try to orient the antennas so that each antenna lies in a spatial null of the radiation pattern of the other antenna. In this way you can achieve some signal isolation at potentially zero cost. The use of a single antenna for the GPS receiver and any other function is not recommended.

- Proximity to the Jamming Source: Radiated emissions can be a problem when the GPS antenna is in the vicinity of the possibility of EMI through free space such as near airports, cell towers, TV or radio broadcasting antennas or repeaters. If this is a suspected problem remove the receiver from this area and retest. If the radiated EMI is coming from inside the enclosure as from a LCD or display than repackaging or a dampening material may be necessary. Conducted emissions can be a problem when energy from an existing source gets coupled to a critical circuit such as the reference oscillator and loop filter areas. This usually can be prevented by good design practices.

6.0 JAMMING TEST OVERVIEW

Jamming immunity and susceptibility are broad subjects. The reason for this is because there are different ways to subject a system to EMI, and different ways to categorize the resulting effects. EMI can be radiated inside a chamber or even through free space and directed at a system, or it can be directly applied (conducted) into a system. This document will focus on only one of the ways to test a GPS system for jamming. That is to directly inject a (simulated jamming) signal directly into the GPS front end of the SSIII EVK while tracking. The tracking can be done with live satellites or a qualified GPS satellite simulator. The test setup shown in Figure 3 is for sample data taken for this document. It should be noted that there was no "notch filter" used for this test. It is not possible to make precise out-of-band jamming measurements without the use of a notch filter or very good tunable band-pass filters because of the in-band harmonics or energy that may come from the jamming source.

As mentioned above the test setup of Figure 3 was used for sample data taken for this document. Figures 1 and 2 illustrate a more precise example for in-band and out-of-band jamming tests

Jamming Immunity

The purpose of this test is to measure the GPS subsystem immunity to jamming due to RF interference. The degradation level defined for test purposes is that displayed C/No will be reduced by 3 dB.

Single Tone Jamming, In Band

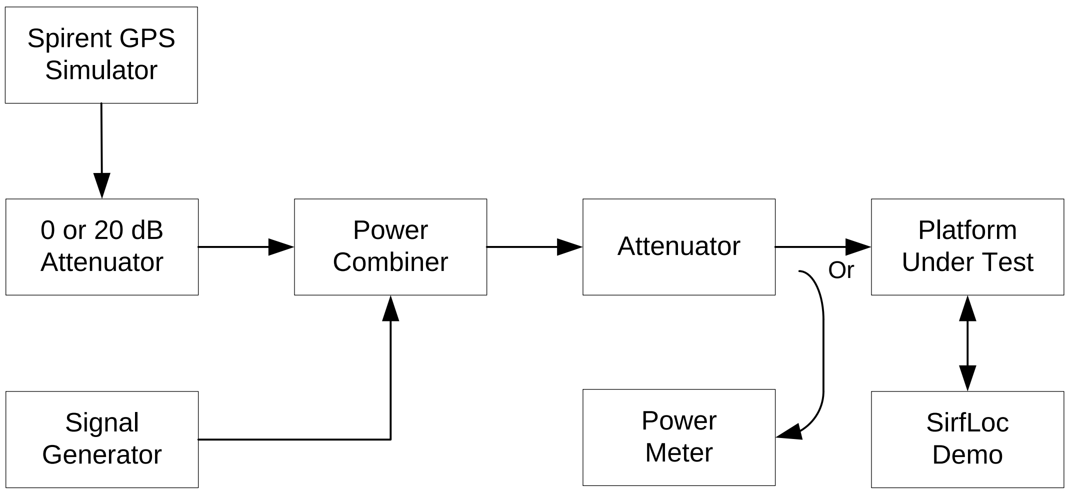


Figure 1 – In-Band Jamming Test Setup

Procedure:

Connect the test setup as shown above.

In-band jamming testing is done in terms of jamming to signal ratio for a nominal signal level. Absolute jamming level in dBm may alternatively be used with suitable modification to the test procedure. Set the GPS simulator for a static scenario with all SV's at equal power and no power modeling. Set the signal generator frequency to 1575.42 MHz. Turn off the GPS satellite power, set the attenuator to zero dB and adjust the signal generator output level to give -60 dBm on the power meter when it is attached to the output end of the cable to the system under test (SUT.) Now set the signal generator to relative amplitude mode. Note: this makes the current amplitude be defined as 0 dB relative. Increase the power of the GPS simulator until the power meter reads -57 dBm. Now the J/S ratio is 0 dB. Reconnect the RF input of the SUT. Set the attenuator to 60 dB. Now the absolute GPS signal level at the input to the system under test is -120 dBm, and the J/S ratio is still 0 dB.

The signal generator should be modulated with 10KHz RMS band limited Gaussian noise or similar modulation. This causes averaging of the GPS fine line structure as would happen in any realistic jamming environment.

Set the Platform under Test to normal mode and acquire. Monitor the C/No. Turn off the signal generator and gather C/No data. Turn on the signal generator and adjust the (relative) amplitude of the signal generator until the C/No is 3 dB less than the previous reading. Record the signal generator relative amplitude. This number is the J/S ratio for these conditions.

Measure the J/S ratio for the signal generator frequency set from 1560.42 MHz to 1590.42 MHz in 1 MHz steps.

Single Tone Jamming, Out-of-Band

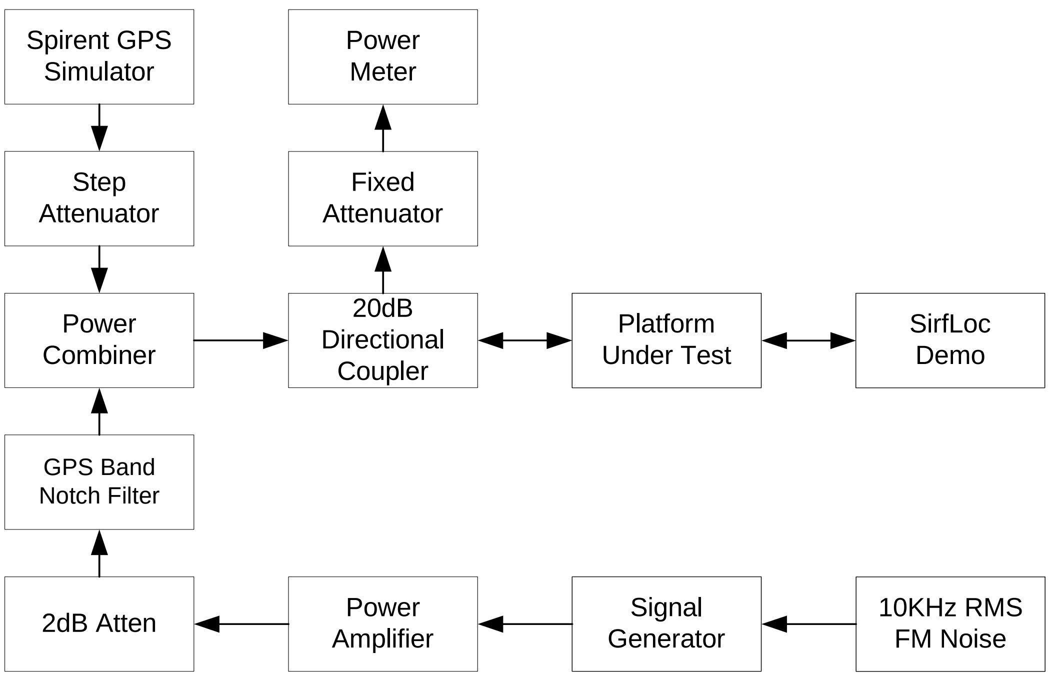


Figure 2 – Out-of-Band Jamming Test Setup

Procedure:
Connect the test setup as shown above. In case the Platform under Test has no RF filters, then the Power Amplifier and the 2dB Attenuator are not necessary. When using a power amplifier, the 2dB pad prevents the power amplifier from being destroyed by total reflection of the output power in the event the frequency is accidentally set to a value which falls in the notch filter rejection band. A typical power output of 2 to 5 watts is adequate for almost all measurements. 1 watt may suffice in many cases. The directional coupler for the power meter is optional; the power meter may be manually inserted at the output of the combiner instead.

Selection of Signal Generator:

The signal generator needs to have spurious no more than -60dBc. The harmonic performance has a choice. Either it must be -60dBc, or one can avoid test frequencies where the harmonic content in the GPS band is greater than -60dBc. The latter can be confirmed by analysis of the signal generator output with a spectrum analyzer. A notch filter in the GPS band is attached to the signal generator output to assure adequate performance of in-band artifacts. The notch filter must provide 60dB of in-band attenuation, thus assuring the combination of signal generator and notch filter together provides -120 dBc of in-band signals from the signal generator.

Testing:

The signal generator should be modulated with 10KHz RMS band limited Gaussian noise or similar modulation. This causes averaging of the GPS fine line structure as would happen in any realistic jamming environment.

Out-of-band jamming testing is done here in terms of the absolute amplitude of the jamming which causes a given amount of degradation of a nominal level of GPS signal. The test setup is as shown above. The power combiner, the power meter and the system under test should be connected with the shortest possible cables. The signal generator cable loss plus notch filter loss must be measured with a power meter or a network analyzer; the cable plus notch filter loss is named "Lsg." Set the GPS simulator for a static scenario with all SV's at the same power, and no power modeling. Turn off the signal generator and set the attenuator to 0 dB. Note the power at the output end of the cable to the system under test. Next reconnect the system under test RF input and adjust the attenuator to the value which will give -130 dBm at the PUT RF input. (This level of GPS power is too small to measure directly.) Note the C/No reading of the receiver. Acquire the GPS signal and set the unit under test to Test Mode 3.

Set the signal generator frequency to 100 MHz and set the amplitude to a low level. Adjust the amplitude upward until the C/No is 3 dB less than noted above. Set the signal generator to display offset amplitude "L+Lsg" dBm less than actual level. "L" is the combiner loss from 4.4.2.1 above. This compensates for the combiner loss. Record the jamming level for 100 MHz to 3000 MHz in 20 MHz steps. Record the jamming level for 1450 to 1700 MHz in 2 MHz steps, except not from 1565.42 to 1585.42 MHz.

SSIII Sample Jamming Data

A simulated jamming signal consisting of a CW from the signal generator was combined with the live GPS satellite signals. The combined signals were directly fed into the GPS receiver RF front end thereby bypassing the antenna. This eliminates any filtering or radiation pattern effects of the antenna and concentrates more on the SSIII GPS receiver. The receiver was allowed to navigate freely before each injection of the CW jamming signal.

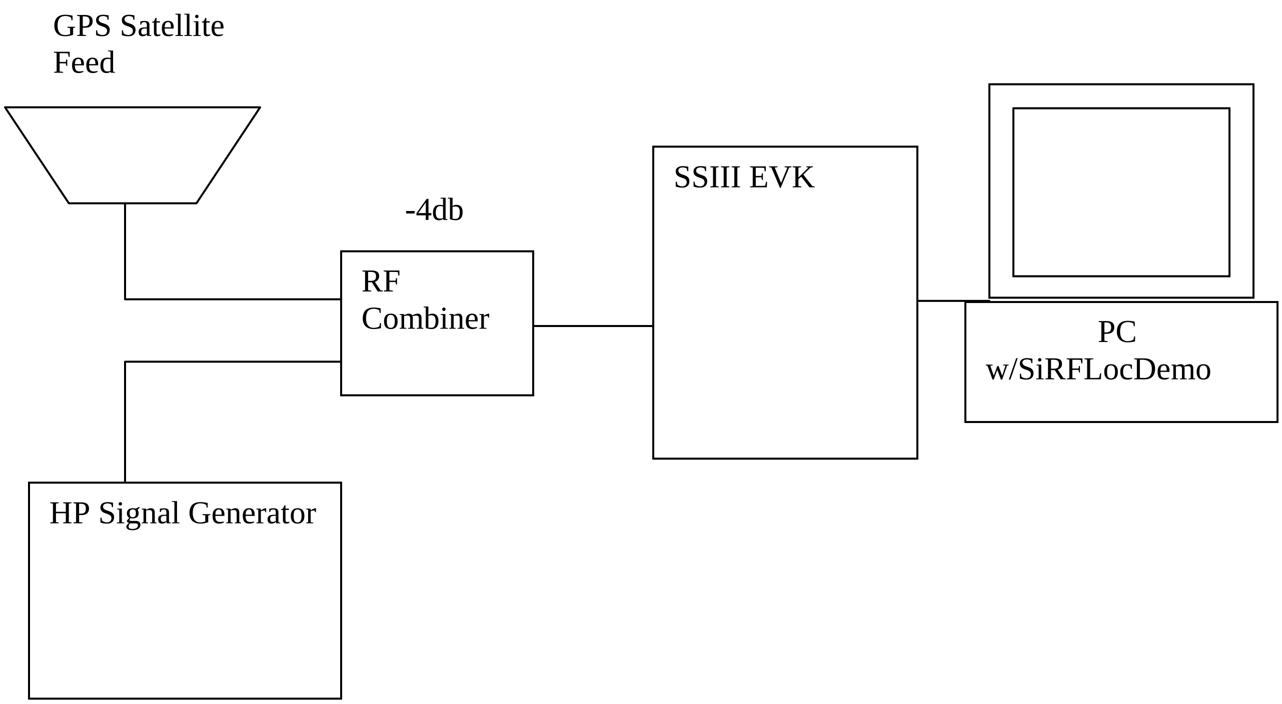
The HP generator was set to various CW frequencies and power levels as follows. The signal generator was tuned to the frequency of interest and the power level was adjusted until a measurable degradation of C/No values were reported on SiRFLoc Demo. The jamming dynamic range was then measured accurately from the point at which degradation was first detected to the point where signal tracking capability in some cases was completely lost.

The following frequencies were chosen for this test:

Table 1: Jamming Test Frequency

Frequency Identifier	Frequency	Application
F1	890 MHz	Cellular Band
F2	1572.42 MHz	Near GPS L1
F3	1575.92 MHz	Near GPS L1
F4	1576.42 MHz	Near GPS L1
F5	1577.0 MHz	Near GPS L1
F6	1640.0 MHz	Out-of GPS Band
F7	1.8 GHz	PCS
F8	2.4 GHZ	802.11 WLAN / Bluetooth

Figure 3: GPS Receiver Jamming Test Setup



Equipment Used:

- SSIII TTB/SLC EVK
- HP 8663 Signal Generator.
- Live GPS Satellite Roof Antenna Feed
- PC with SiRFLoc Demo Monitoring Software
- RF Combiner
-

Procedure

a) The set up test configuration was per Figure 3.
b) The EVK was configured and set-up to operate in an autonomous mode.
c) The receiver was allowed to navigate with no jamming input.
d) The average C/No on SiRFLoc Demo was noted for the highest five satellites
e) The Signal Generator was used to inject the interference signals into the receiver via a Combiner/Splitter. (Note: The Combiner/Splitter has insertion loss of 2.5

and a total set up loss of approximately 4dB. The power levels listed are that as measured at the output of the signal generator. The actual power entering the GPS front end must include the set-up loss).

f) The input power level of the interference source (HP Signal Generator) was varied until SiRFLoc Demo reported C/No degradation. The power level setting at the receiver input and resultant C/No was recorded.

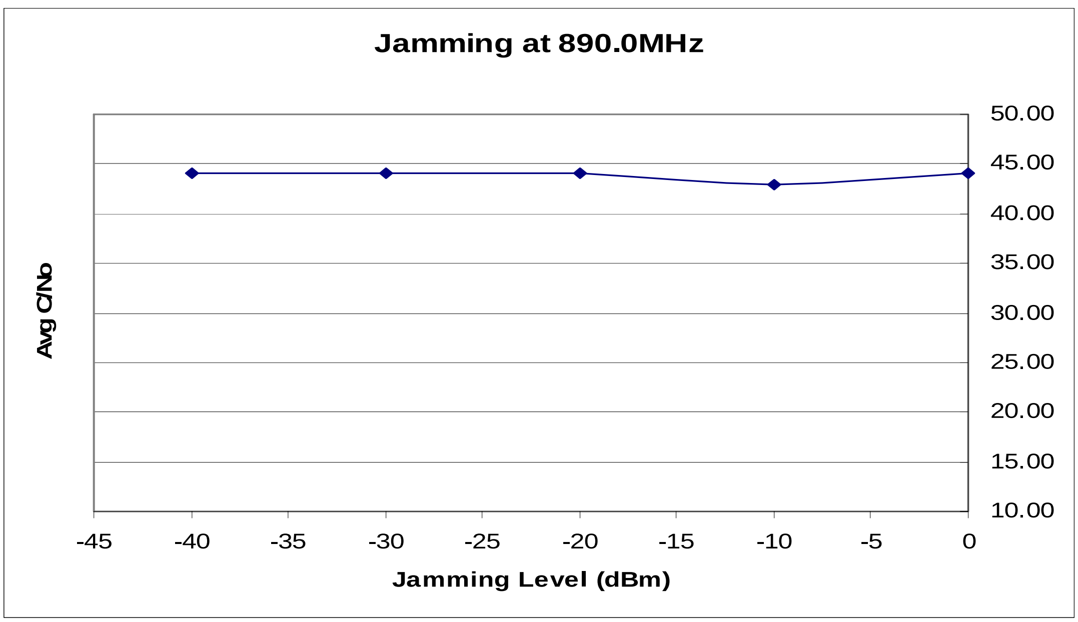
g) The power level of the interference signal was increased from the initial point in even dB increments until the receiver lost satellite track. This was noticed by C/No values decreasing, and the number of satellites being tracked decreasing. The power level setting and C/No was recorded.

h) The measurements were repeated for each of the CW test frequencies of 890MHz, 1572.42MHz, 1575.92MHz, 1575.92MHz, 1576.42MHz, 1577.0MHz, 1640 MHz, 1.8GHz and 2.4GHz.

Summary of Test Results

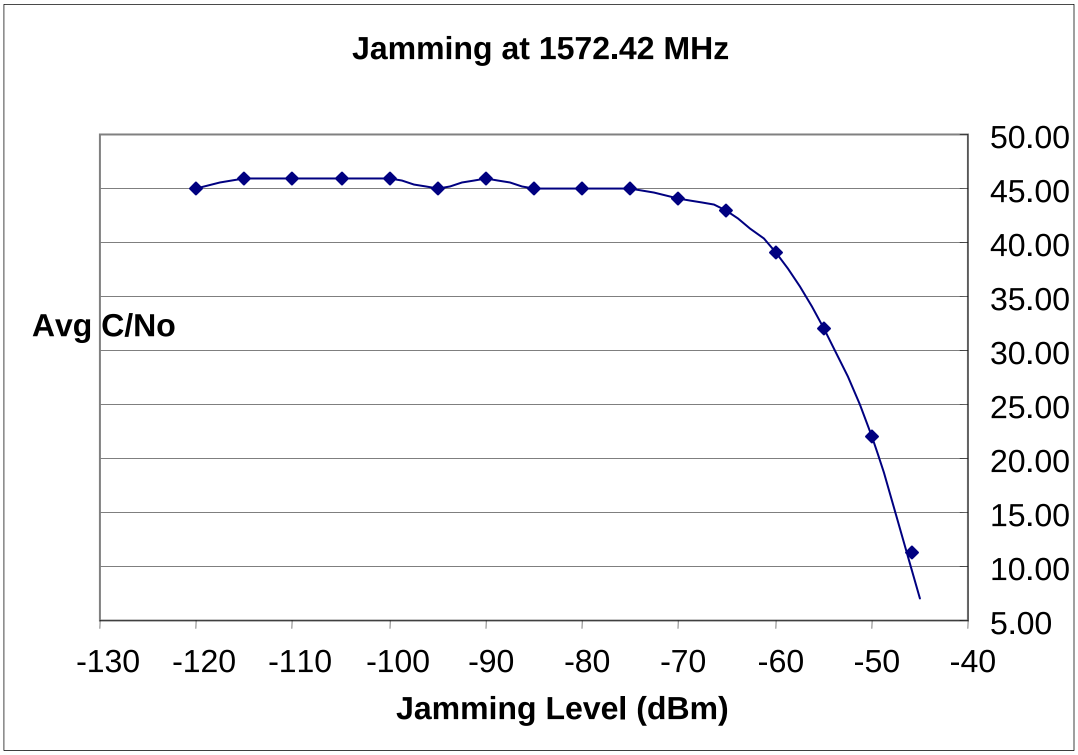
The followings are plots of collected data for the various interference test frequencies.

- **F1 = 890 MHz**

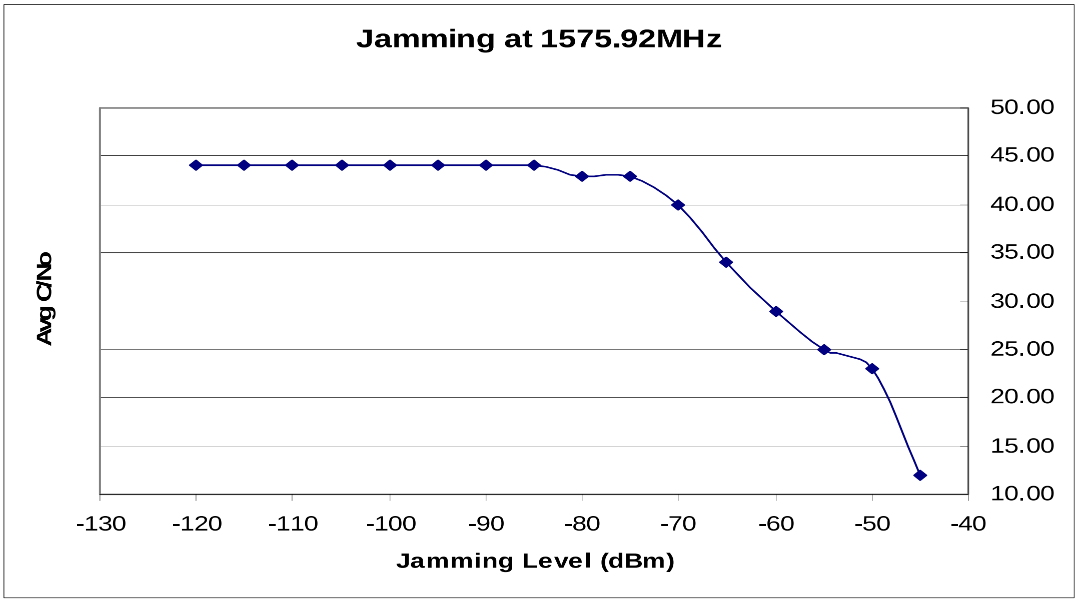


Note: The Avg C/No value for this and all plots below is the average of the four highest strength satellites tracked.

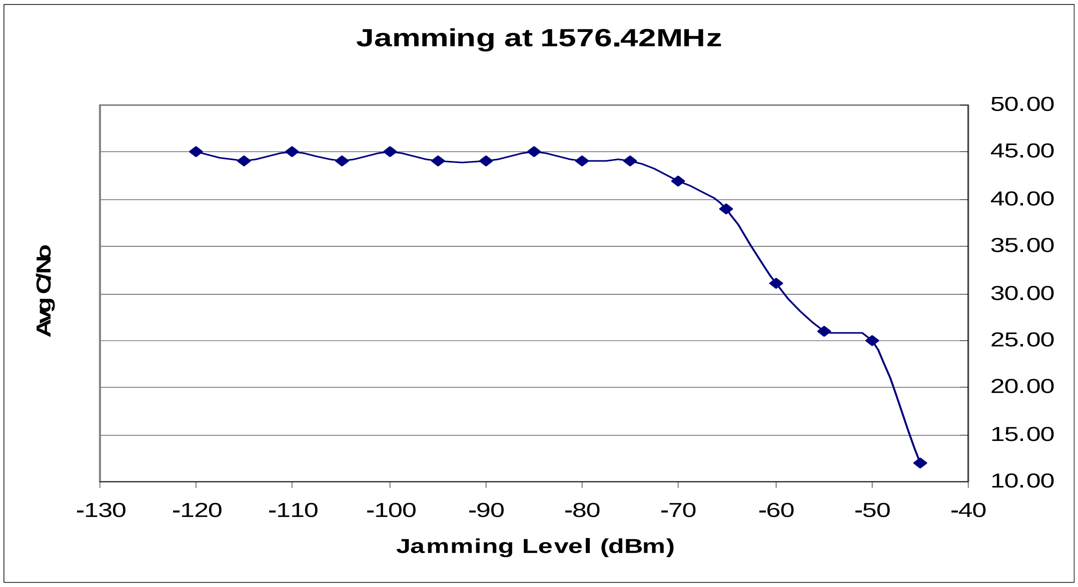
- **F2 = 1572.42 MHz**



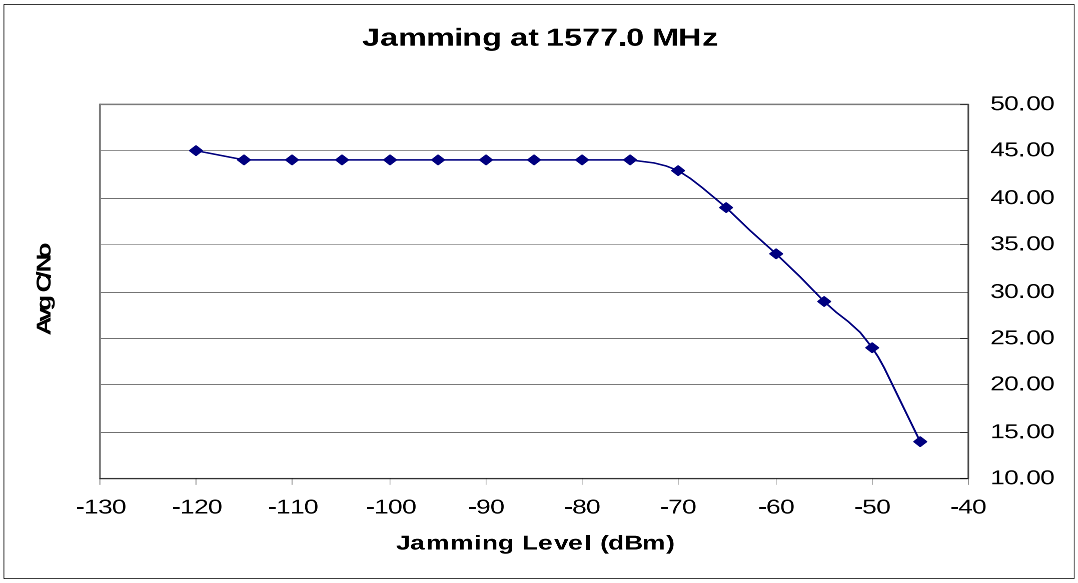
- **F3 = 1575.92 MHz**



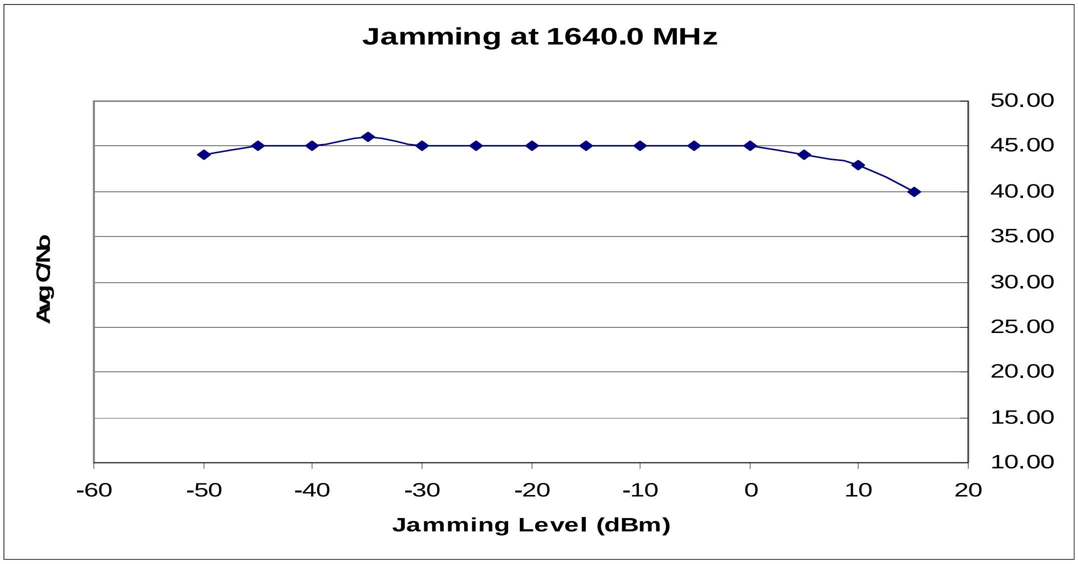
- **F4 = 1576.42 MHz**



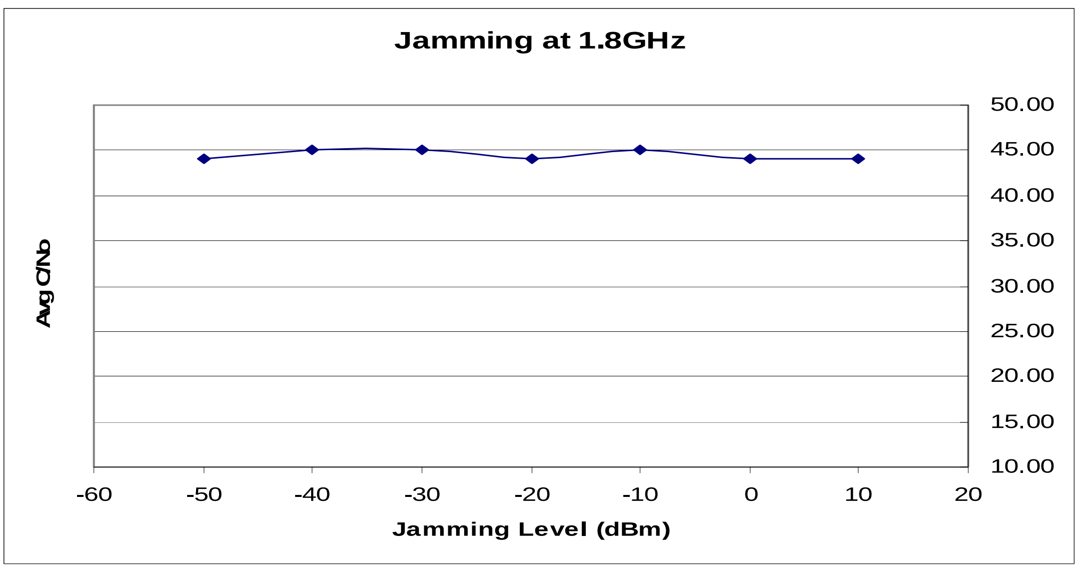
- **F5 = 1577 MHz**



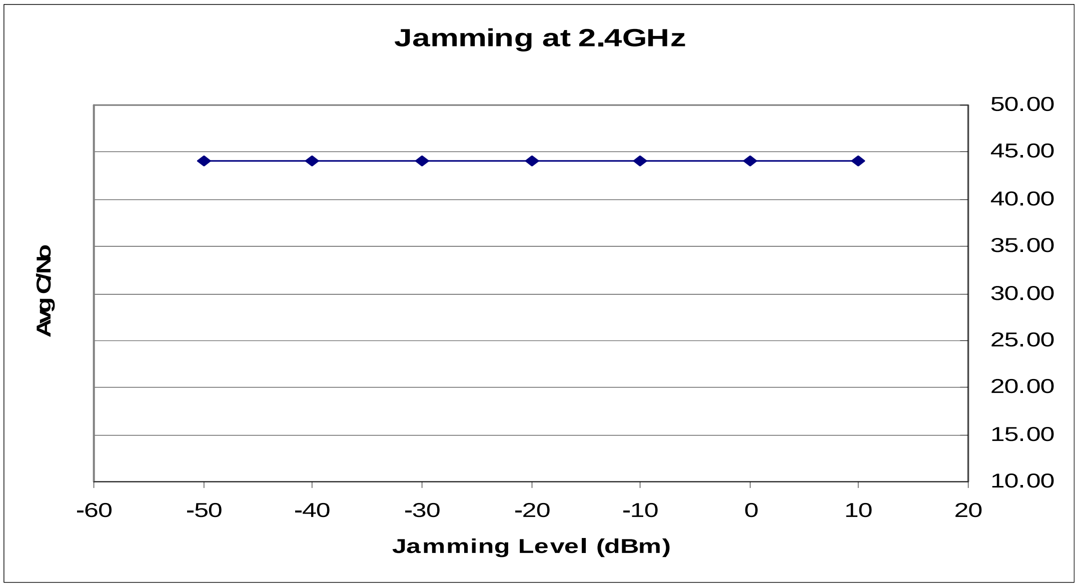
- **F6 = 1640.0 MHz**



- **F7 = 1.80 GHz**



- **F8 = 2.40 GHz**



7.0 CONCLUSION

The test data indicates as expected that in-band jamming will desensitize the SSIII receiver at much lower power levels than out-of-band signals. This is mostly due to the filtering of the out-of-band frequencies. This improvement in out-of-band rejection will be based on the characteristics of the chosen filter implementation.

It is important to realize that this test was only a laboratory simulation of sample data and the results are not absolute. However it is an approximate indicator that in-band frequencies entering the receiver front end will degrade performance. The condition becomes more critical during conditions of weak GPS signal availability.
For a theoretical estimate of in-band or near-band frequencies versus critical power levels of potential jamming signals, consider the following values of maximum allowable power suggested for proper acquisition of weak (~<20dBHz) signals:

a. 1575.42MHz +/- 0 to 1.023MHz, any CW signal s/b below -140dBm
b. 1575.42MHz +/-1.023 to 2.046MHz, any CW signal s/b <-125dBm.
c. 1575.42MHz +/- 2.046 to 3.069MHz, any CW signal s/b <-120dBm.
d. 1575.42MHz +/- 3.069 to 4.092MHz, any CW signal s/b <-115dBm.
e. 1575.42MHz +/- 4.092 to 5.115MHz, any CW signal s/b <-110dBm.
f. 1575.42MHz +/- 5.115 to 10.0MHz, any CW signal s/b <-105dBm.
g. 1575.42MHz +/-10MHz to 20MHz, any CW signal s/b <-95dBm
h. 1575.42MHz +/- 20MHz to +/- 50MHz, any CW signal s/b <-85dBm

In order to interpret measured data in terms of real world operational conditions, the receiver would have to actually be in those conditions. However as an example consider the case of a transmitter in the vicinity of a GPS receiver. The received signal power at the antenna consists of the power density spectrum and the free space path loss due to atmospheric attenuation. What this means is that the closer the GPS antenna is to the source of transmissions, the greater the danger of being jammed. If the jamming frequency (or a strong harmonic of that frequency) gets through the filtering and into the GPS front end, degradation of performance could occur. This is a case of radiated jamming. Proper filtering, isolation techniques, and antenna implementation will be the best line of defense to combat this problem.

The consideration of conducted EMI and co-location is also crucial. Good design practices in terms of layout, proper component selection, grounding, shielding and isolation are the best tools to maximize immunity from self created interference inside a multi-function platform.

In summation, to achieve the proper sensitivity of a GPS receiver along with the desired immunity to jamming, attention must be paid to rejection, isolation, shielding and proper design techniques.

8.0 DOCUMENT MAINTENANCE

8.1 Required Approval for Changes

Changes to this document require the approval of Sales, Marketing, Engineering and Quality.

8.2 Revision History

Rev	Rev Date	CN Number	Description	Author/Editor
1.0	12/13/04	2656	Initial Release	Steve Feeko