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THE NATO GUIDELINE
FOR
GNSS USER EQUIPMENT
STANDARDIZED FIELD
TEST SCENARIOS

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THE NATO GUIDELINE FOR GNSS USER EQUIPMENT STANDARDIZED FIELD TEST SCENARIOS

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1. BACKGROUND

STANAG 4665 describes the characteristics required for a modelling and simulation capability to make predictions on the degree of protection provided by NAVWAR anti-jam equipment. In order to gain confidence in the ability and accuracy of this capability, it is necessary to compare outputs from the model to real-world data collected during field trials. This Allied Navigation Publication 5 (ANP-5) describes common test scenarios, instrumentation, and data collection requirements for obtaining the appropriate data needed to perform a validity assessment of the model.

2. INTRODUCTION

The ability to effectively conduct NAVWAR modelling and simulation is a great asset to the warfighter. These tools can be utilized to quickly run different scenarios and assess the effect of GNSS interference on fielded navigations systems. This, in turn, enables mission planners to modify or generate mission plans according to this data. The model described in STANAG 4665 can be implemented at Basic or Enhanced levels. The anticipated fidelity is a function of its complexity. The model must undergo a validation process in order to:

1) Determine that the underlying theories and assumptions used in the model have been correctly implemented.
2) Indicate to the user the degree of fidelity of the model.

The model validation process is an extensive task in which real-world data is compared to model outputs. A frequent cause for model validation failure is that real-world "truth" data itself is not valid. This document will describe the standard test scenarios and data collection techniques to ensure that the data is sufficient, accurate and appropriate to use in the model validation process.

3. ASSUMPTIONS AND LIMITATIONS

The assumptions and limitations made in this document are as follows:

a. ANP-5 will describe standard test scenarios for gathering field test data used to validate modelling and simulation tools.

b. The test scenarios will provide data to compare with the outputs generated by the models described in STANAG 4665.

c. This document will provide common measures of performance to enable member nations to validate the model. It will not provide absolute values for each measure to be used as a pass-fail test for validation.

d. A non-GNSS based Time Space Position Information (TSPI) source will be available for truth data on the system under test.

e. For simplicity, the fundamental model uses a $\frac{1}{r^2}$ free-space path loss equation, which has limitations for ground-to-ground propagation. For the fundamental model, only ground-to-air propagation should be compared.

f. An airborne platform which is capable of carrying an instrumented GNSS receiver, FRPA, CRPA system, and spectrum analyzer or RF power meter will be available for the test scenarios described in this document.

g. Some GNSS jammer vulnerability knowledge of the instrumented GNSS receiver should be known. This data should include the J/S or C/No thresholds at which the GNSS receiver switches from one tracking state to another.

h. The calculation of the spectral separation coefficient may be adversely impacted by the presence of RF filters in the receiver.

Jammer vulnerability knowledge of the instrumented GNSS receiver is critical in evaluating the accuracy of the model. It is recommended that laboratory testing be conducted to understand the basic receiver design characteristics including precorrelation bandwidth, tracking filter characteristics, where No is being measured and what it represents.

Testing should also be conducted to evaluate the receiver response (including C/No estimates) as a function of jammer waveform characteristics since thresholds at which the receiver changes states may differ for various jammer waveforms. Once determined, this data can be used as inputs to the models described in STANAG 4665.

Furthermore, the FRPA, CRPA and Antenna Electronics (AE) also need to be well characterized. Antenna pattern measurements should be made on the test aircraft to account for antenna gain, body masking, multipath and creeping wave effects.

4. ANALYSIS APPROACH

Analysis includes all of the processes and procedures associated with calculating measures of performance (MOP) which will be used to determine the accuracy of the model. Defining the MOPs will, in turn, define the Integrated Data Requirements List (IDRL). The IDRL specifies instrumentation used to generate the required data and provides the basis for developing test scenarios.

4.1. Issues and Sub-Issues

Normally, issues and sub-issues will drive the MOPs for an analysis plan. For this plan, the only issue is: How accurate is the NAVWAR model when compared to real-world data?

The sub-issues which will be answered are:

1) How accurate is the satellite azimuth and elevation prediction?
2) How accurate is the satellite signal power prediction at the platform?
3) How accurate is the azimuth and elevation prediction of the incoming jamming signal?
4) How accurate is the jamming signal power prediction at the platform?
5) How accurate is the jamming signal power prediction at the receiver after body masking and FRPA gain effects?
6) How accurate is the jamming signal power prediction at the receiver after body masking and CRPA gain pattern effects?
7) How accurate is the predicted number of CRPA gain pattern nulls generated?
8) How accurate is the GNSS receiver tracking state?
9) How accurate is the C/No for each satellite being tracked?
10) How accurate is the propagation model with terrain interference?

4.2. Measures of Performance

Data collected during the trial along with outputs from the model will be used to calculate the MOPs and the MOPs will be used to answer the sub-issues. The following table details the MOPs that will be used to answer the sub-issues.

Sub-Issue		MOP
1	Satellite Azimuth and Elevation Error	Average Standard Deviation Median, 25th and 75th Percentile
2	Satellite Signal Power at Platform	Percent of predicted measurements within 3dB of actual measurements
3	Jammer Azimuth and Elevation Error	Average Standard Deviation Median, 25th and 75th Percentile
4	Jammer Signal Power Error at Platform Position	Average Standard Deviation Median, 25th and 75th Percentile
5	Jammer Signal Power Error at Receiver with FRPA	Average Standard Deviation Median, 25th and 75th Percentile
6	Jammer Signal Power Error at Receiver with CRPA	Average Standard Deviation Median, 25th and 75th Percentile
7	GNSS Receiver Tracking State	Percent of Samples that Predicted equalled Measured
8	C/No Error	Average Standard Deviation Median, 25th and 75th Percentile
9	Enhanced Propagation Model Jammer Signal Power Error	Average Standard Deviation Median, 25th and 75th Percentile

Table 1: Sub-issues and MOPs

4.3. Integrated Data Requirements List

A complete list of data elements required to calculate the measures is included in the following IDRL. This list will be used to define the instrumentation for field tests.

MOP		Data Element	Data Source
1	Predicted Satellite Azimuth – Measured Satellite Azimuth	Satellite Azimuth	GNSS Receiver
2	Predicted Satellite Elevation – Measured Satellite Elevation	Satellite Elevation	GNSS Receiver
3	Predicted Satellite Signal Power – Measured Satellite Signal Power	Measured Satellite Signal Power	RF Power Meter
4	Predicted Jammer Azimuth – Calculated Jammer Azimuth	Calculated Jammer Azimuth	TSPI
5	Predicted Jammer Elevation – Calculated Jammer Elevation	Calculated Jammer Elevation	TSPI
6	Predicted Jammer Signal Power – Measured Jammer Signal Power	Measured Jammer Signal Power	RF Power Meter
7	Predicted Jammer Signal Power at Receiver with FRPA – Measured Jammer Signal Power at Receiver with FRPA	Measured Jammer Signal Power	RF Power Meter
8	Predicted Jammer Signal Power at Receiver with CRPA – Measured Jammer Signal Power at Receiver with CRPA	Measured Jammer Signal Power	RF Power Meter
9	Percent of Time that Predicted GNSS Receiver Tracking State Samples Match Measured Tracking State Samples	Measured GNSS Receiver Tracking State	GNSS Receiver
10	Predicted C/No – Measured C/No	Measured C/No	GNSS Receiver

Table 2: Integrated Data Requirements List (IDRL)

5. INSTRUMENTATION AND DATA COLLECTION

Using the IDRL in Table 2, the instrumentation can be defined to provide the required data elements. This instrumentation can be broken down into five primary sources of data:

1) GNSS Receiver
2) TSPI
3) RF Power Meter
4) CRPA System
5) Jammer

In order to standardize the data products to be shared by the member nations, the post-processed data from each of these sources should be in a delimited ASCII format with column headers in the first row.

Timestamps for each data sample are necessary in order to accurately process the data for the model validation. Timestamps should be in Coordinated Universal Time (UTC).

5.1. GNSS Receiver

Most GNSS receivers have an instrumentation port and are capable of generating a variety of performance data. There are many different industry and military standards for the type and format of data which is output by GNSS receivers. For this trial, it is necessary for the GNSS receiver to have an instrumentation port, and for the tester to have access to the Interface Control Document (ICD) which defines the data available on that port. The output of the instrumentation port should be connected to either a laptop or some other type of data logger capable of collecting all the data which is output by the GNSS receiver. This data might be in a binary format and should ultimately be converted to a standard ASCII delimited file which can be imported by a variety of software programs and shared between member nations.

The data recorded from the GNSS receiver should include the following data elements:

a) UTC Time
b) Overall GNSS Receiver Tracking State
c) Overall GNSS Receiver FOM
d) Latitude
e) Longitude
f) Altitude
g) Velocity
h) Individual Channel SVN Number
i) SVN Azimuth

j) SVN Elevation
k) Individual Channel Tracking State
l) Individual Channel C/No
m) Individual Channel Frequency Tracked
n) Individual Channel Code Type

It is important to know where the C/No is measured in the receiver. If this is not known, it could induce errors in this sub-measure that will affect the accuracy of model outputs.

The majority of this data is required for the MOP calculations; however, other data elements listed are not necessary. These data elements are collected for informational purposes only. Since time and expense has been invested to perform these tests, the extraneous data is collected to provide useful vulnerability data on the GNSS receiver under test.

5.2. Time Space Position Information (TSPI)

TSPI data is the positional truth data that is required in order to run the model in the same position and at the same time as the real-world data. With the advent of low-cost and accurate GNSS receivers, most of the TSPI data gathered today is based on a GNSS system. This is problematic for test scenarios where the GNSS system will be jammed. There are a few possible solutions to generating accurate TSPI data including, but not limited to the following examples.

Instrumentation radar systems can provide the required TSPI data. A single instrumentation radar can provide data accurate to about +/- 100 meters. If a second radar is also available and the ability exists to combine the data from both to provide a blended solution, the position solution can be tightened to about +/- 25 meters. Modern instrumentation system radars utilize GNSS for timing. It is important to note that the radar systems must have a backup timing system which will work in the event that the GNSS jammers affect the radar timing receivers.

Multilateration systems are another alternative to providing TSPI data. Multilateration is the process of locating a platform by accurately computing the time difference of arrival (TDOA) of a signal emitted by the platform and received by three or more ground stations. A multilateration system can provide X-Y data accurate to +/- 25m but the Z axis data is usually accurate to only about +/- 100m.

Another alternative for TSPI data is to have an anti-jam GNSS system on-board the platform. This system must be able to track GNSS signals and provide TSPI information within specified performance in the presence of jamming/interference. The TSPI system shall have a greater resistance to jamming/interference than the instrumentation receiver.

This might be possible when the receiver under test is using a FRPA antenna, but if testing equipment with a greater anti-jam margin, other sources of TSPI will have to be used.

The data recorded from the TSPI system should include the following data elements:

a) UTC Time
b) Latitude
c) Longitude
d) Altitude
e) Velocity
f) Roll
g) Pitch
h) Yaw

5.3. RF Power Meter

An RF power meter will be used to measure the received satellite signal power and also the received jammer signal power. Measuring the satellite signal power is a difficult task and is further addressed in Section 6.6. The power meter should be capable of measuring integrated channel power over the entire bandwidth of the signal being measured.

The data recorded from the RF Power Meter should include the following data elements:

a) UTC Time
b) Total Power Integrated Over Bandwidth at Center Frequency 1
c) Total Power Integrated Over Bandwidth at Center Frequency 2
d) Total Power Integrated Over Bandwidth at Center Frequency N

5.4. CRPA System

The controlled reception pattern array antenna electronics (AE) unit should be capable of outputting data to a data logger or computer. The data recorded from the CRPA system will not directly support the calculation of any measures, but output analysis will increase understanding of CRPA system operation.

5.5. Jammer

Although the jammer transmits power and spectral properties are not used directly in the calculations of the MOPs, the jammer must be instrumented to ensure that the jammers are operating correctly during the entire trial.

The instrumentation on the jammer should consist of a spectrum analyzer measuring the transmitted signal prior to the transmit antenna. This can be accomplished by inserting a directional coupler in between the final power amplifier and the transmit antenna. Care needs to be taken to ensure that the coupled port is attenuated enough so that its output does not exceed the spectrum analyzer's maximum input value.

The spectrum analyzer should be connected to a data logger or computer with datlogging software installed. The data recorded from the spectrum analyzer should include the following data elements:

a) UTC Time
b) Total Power Integrated Over Bandwidth at Center Frequency 1
c) Total Power Integrated Over Bandwidth at Center Frequency 2
d) Total Power Integrated Over Bandwidth at Center Frequency N

The spectrum analyzer should also be able to capture either a picture or digital data which represents the spectrum over the entire bandwidth covered by the jamming signal. This data will not be used directly to calculate measures, but is supporting data which documents the signal transmitted.

It is important to have the jammer transmit antenna fully characterized. This characterization should include antenna gains as a function of azimuth and elevation. The jammer transmit antenna should be installed on a mast or tower as high off of the ground as practical in order to reduce errors induced by interactions with the earth.

5.6. System Calibrations

In order to produce the most accurate data possible in the field trial, the CRPA, FRPA, AE and GNSS receiver must be calibrated. The calibration of the system should include measurements of all cable losses, as well as a characterization of the system noise figures.

Aside from the calibration of the instrumentation and equipment, the model requires calibration as well. The following test scenario is proposed.
Test Scenario: Reference Scenario (without jammers or terrain masking)

Objective: To calibrate the model and to have reference MOPs for comparison during the jammer related test.

Description: In order to have a reference scenario, a test without any jammer or terrain masking must be done. In this simple scenario, the following sub-issues can be answered:

1. How accurate is the satellite azimuth and elevation prediction?
2. How accurate is the satellite signal power prediction at the platform?
3. How accurate is the GNSS receiver tracking state?
4. How accurate is the C/No for each satellite being tracked?

Platform Configuration: The platform should be configured with the following instrumentation:

1. Instrumented GNSS receiver with any antenna (e.g., FRPA, CRPA)
2. TSPI

These systems were described in Section 5.

Platform Route: For this scenario, the platform under test can follow a route that must be defined with the objective to calibrate the model. This route should be repeated in order to gain statistical significance in the data.

6. TEST SCENARIOS

This section will describe the test scenarios used to generate the real-world test data used to validate the model. The following scenarios are suggestions only and represent generic scenarios which can be used to answer the MOPs. The Digital Terrain Elevation Data used in all figures are only examples. Any relatively flat terrain could be used. These may be modified to match the calibration scenarios mentioned in STANAG 4665.

Using the Sub-issues and MOPs from Section 4, it is determined that there are five scenarios which will be used to collect the required data. These scenarios are:

1. Single Jammer without Terrain Masking using FRPA Antenna
2. Single Jammer without Terrain Masking Using CRPA Antenna
3. Single Jammer with Terrain Masking
4. Ring of Jammers
5. Satellite Signal Power Measurements

6.1. Single Jammer Without Terrain Masking Using FRPA Antenna

The single jammer scenario without terrain masking using the FRPA antenna consists of a single jammer placed in a topographic area where mountains or other terrain will not interfere with the transmission of the jamming signal to the platform under test. This is the simplest scenario presented but six of the ten sub-issues can be answered from data generated from this scenario. The following sub-issues can be answered:

1) How accurate is the satellite azimuth and elevation prediction?
2) How accurate is the azimuth and elevation prediction of the incoming jamming signal?
3) How accurate is the jamming signal power prediction at the platform?
4) How accurate is the jamming signal power prediction at the receiver after body masking and FRPA gain effects?
5) How accurate is the GNSS receiver tracking state?

6) How accurate is the C/No for each satellite being tracked?

6.1.1. Jammer Laydown

The main requirement for this laydown is that the platform under test can fly a route in which it will initially be tracking GNSS satellites and fly into the jamming field where there is enough power to cause the GNSS receiver to lose lock. During this entire route, there should be no blockage of the jamming signal to the platform due to terrain masking. Figure 1 shows a theoretical jammer laydown and route with these characteristics.

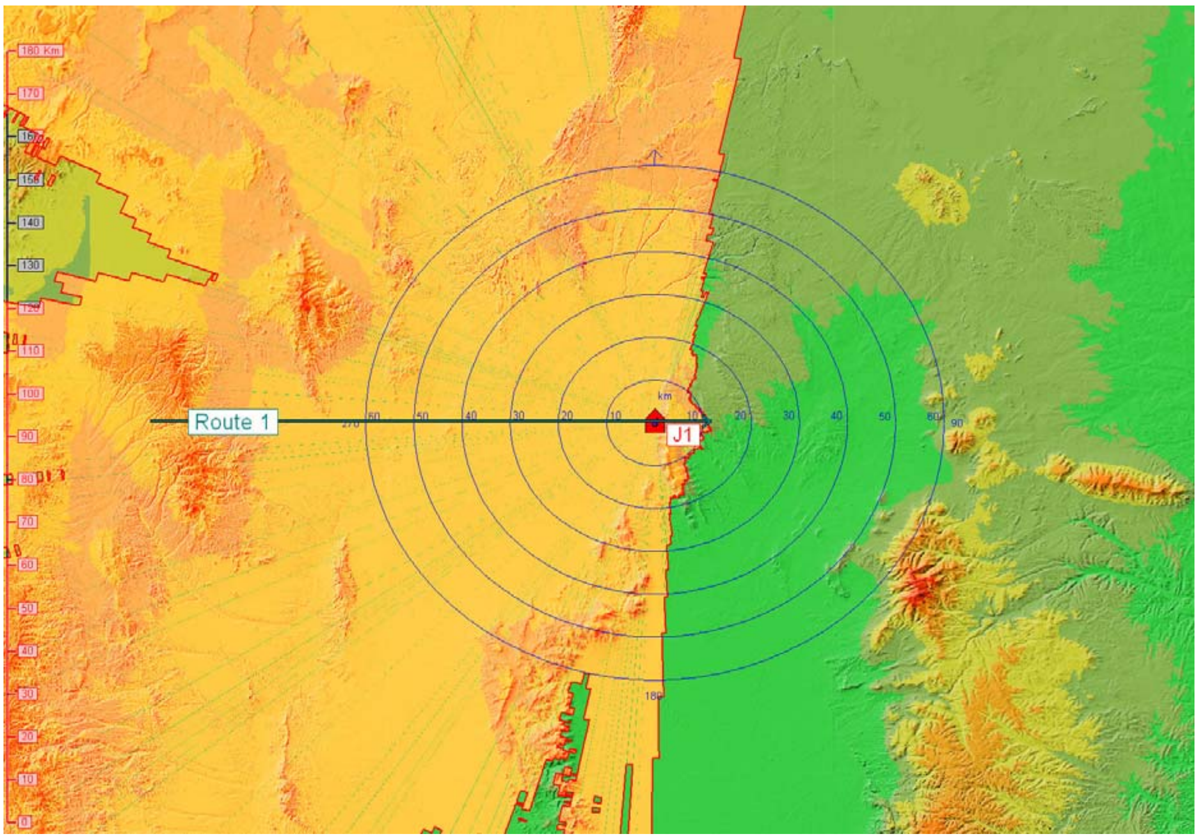

Figure 1: Single Jammer Laydown and Platform Route

In this figure, J1 is the jammer. The portion of the figure that is shaded on the left is the area that has line of sight with the jammer at 1500 m AMSL. The line labelled “Route 1” is the theoretical route. As can be seen, the platform has line of sight to the jammer during this entire route. Therefore, any effects from the jammer are not interfered with by the terrain.

The jammer power level should be set to provide enough power to cause the platform GNSS receiver to lose tracking lock at some point during the route. In order to determine the jammer power setting, there are two variables that need to be defined. First is the distance at which the calculation should be made. The second is the power level required at that distance required to jam the GNSS receiver.

The C/No thresholds at which the GNSS receiver channels change tracking states must be known for the platform GNSS receiver. If these thresholds are stated as C/No numbers, they must be converted to J/S values in order to set the GNSS jammer power level. The recommended algorithm for this conversion is given in Appendix 1.

Since the model is a static model, there will be errors, due to velocity, in the thresholds at which the GNSS receiver changes state.

The power level required to drive the GNSS receiver tracking from state 3 to state 0 as defined in STANAG 4665 Section 5.8 is used to determine the jammer power level.

The following equation is used to define the jammer effective radiated power:

$$P_j = 20\log_{10}(Df) + P_v + 32.4 \quad (1)$$

Where P_j is the jammer effective radiated power in dBW, D is the distance between the platform GNSS receiver antenna and the jammer antenna in km, f is the center frequency in MHz, and P_v is the received power at which the GNSS channels switch from state 3 to state 0.

This power setting was calculated without any body masking effects. If body masking information is available, the jammer ERP should be increased to compensate for the maximum body masking exhibited by the platform in order to ensure that the jammer has enough power to cause the channel state change.

In order to standardize these test scenarios, the jammer waveform will be set up to transmit a 20 MHz Gaussian noise signal.

6.1.2. Platform Configuration

The platform should be configured with the following instrumentation:

1. Instrumented GNSS Receiver with FRPA Antenna
2. RF Power Meter (2)
3. TSPI

These systems were described in Section 5.

For this scenario, there should be two RF power meters to measure received jammer power with and without body masking and antenna gain effects. The data generated from these two meters will be used to answer sub-issues 4 and 6.

The first RF power meter should be inserted in between the GNSS receive antenna and the GNSS receiver. This will give the true jammer RF power measurement that is being seen at the GNSS receiver front-end after body masking and FRPA antenna effects.

The second RF power meter should be connected to a separate antenna which will measure the jammer RF power at the platform without body masking and antenna effects. This antenna should be bottom mounted and the gain pattern should be as close to isotropic as possible. Any antenna gain effects will induce measurement errors in the data.

6.1.3. Platform Route

For this scenario, the platform route must have line of sight with J1 at all times.

In order to evaluate sub-issue 10, "How accurate is the GNSS receiver tracking state?", it is desirable to have the GNSS receiver on-board the platform start with an initial condition of having at least four channels in state 5 as defined in STANAG 4665 Section 5.8. Using this initial condition, the platform must then fly towards the jammer. The platform will eventually pass the two thresholds T2 and T1, where the GNSS channels will drop from state 5 to state 3 and from state 3 to state 0. In order to define the distance from J1 to the initial start point for the route the following variation of the free-space path loss equation will be used:

$$D = \frac{10^{\left(\frac{P_j - P_v - 32.4}{20}\right)}}{f} \qquad (2)$$

Where D is the direct line of sight distance from the platform to the jammer in km, P_j is the effective radiated power of the jammer in dBW, P_v is the power level of interest in dBW received at the GNSS receive antenna, and f is the center frequency in MHz.

Knowing the vulnerability thresholds of the platform GNSS receiver, one can calculate the maximum and minimum distance between the platform and J1 needed during the route.

The maximum distance, Dmax is calculated using equation 2 using the T2 C/No value. The minimum distance, Dmin is calculated using equation 2 using the T1 C/No value. Again, the C/No values are converted to J/S values as outlined in Appendix 1.

To execute this scenario, the platform starts on the route with separation between the platform and J1 of at least Dmax. The GNSS receiver should have at least 4 channels tracking in state 5. The jammer power is turned on. The platform begins its route towards J1. The platform continues until its separation from J1 is less than Dmin. At this point, the GNSS receiver should be in state 0.

This route should be repeated in order to gain statistical significance in the data.

6.2. Single Jammer Without Terrain Masking Using CRPA Antenna

This scenario is similar to the scenario described in Section 6.1 in that there is a single jammer placed in such a way that terrain will not interfere with the transmission of the jamming signal to the platform GNSS receive antenna.

The following sub-issues can be answered with the data generated from this scenario:

1) How accurate is the satellite azimuth and elevation prediction?
2) How accurate is the azimuth and elevation prediction of the incoming jamming signal?
3) How accurate is the jamming signal power prediction at the platform?
4) How accurate is the jamming signal power prediction at the receiver after body masking and CRPA gain effects?
5) How accurate is the GNSS receiver tracking state?
6) How accurate is the C/No for each satellite being tracked?

6.2.1. Jammer Laydown

The main requirement for this laydown is that the platform under test can fly a route in which it will initially be tracking GNSS satellites and fly into the jamming field where there is enough power to cause the GNSS receiver to lose lock. During this entire route, there should be no blockage of the jamming signal to the platform due to terrain masking. The jammer laydown for this scenario can be the same laydown used for scenario 6.1 as shown in Figure 1.

The jammer power level should be determined using the same procedures and formulas used in calculating the jammer power level in scenario 6.1. The only difference will be that the jammer in this scenario will also have to overcome the CRPA antenna. The amount of jamming resistance that the CRPA antenna adds to the GNSS system should already be known. The jammer effective radiated power (ERP) for this scenario will have to be increased by this margin in order to ensure that the GNSS receiver tracking states are affected.

The jammer waveform for this scenario will be set up to transmit a 20 MHz Gaussian noise signal.

6.2.2. Platform Configuration

The platform should be configured with the following instrumentation:

1. Instrumented GNSS Receiver with CRPA Antenna
2. Instrumented CRPA System
3. RF Power Meter (2)
4. TSPI

These systems were described in Section 5.

For this scenario, there should also be two RF power meters to measure received jammer power with and without body masking effects. The data generated from these two meters will be used to answer sub-issues 4 and 8.

The first RF power meter should be connected to a FRPA antenna on top of the aircraft as close to the CRPA antenna as possible, without interfering with the CRPA. This will give the true jammer RF power measurement that is being seen at the CRPA antenna after body masking.

The second RF power meter should be connected to a separate antenna which will measure the jammer RF power at the platform without body masking and antenna effects. This antenna should be a bottom mounted antenna and the gain pattern should be as close to isotropic as possible as any antenna gain effects will show up as measurement errors in the data.

6.2.3. Platform Route

For this scenario, the platform route must have line of sight with J1 at all times.

Just as in scenario 6.1, it is desirable to have the GNSS receiver on-board the platform start with an initial condition of having at least four channels in state 5 as defined in STANAG 4665 Section 5.8. Using this initial condition, the platform must then fly towards the jammer. The platform will eventually pass the two thresholds T2 and T1, where the GNSS channels will drop from state 5 to state 3 and from state 3 to state 0. The distance for the route start point should be calculated as in Section 6.1.3 using Equation 2.

Care must be taken in performing these calculations due to the fact that the CRPA antenna will reduce the amount of jamming power that gets to the GNSS receiver.

To execute this scenario, the platform starts on the route with separation between the platform and J1 of at least Dmax. The GNSS receiver should have at least 4 channels tracking in state 5. The jammer power is turned on. The platform begins its route towards J1. The platform continues until its separation from J1 is less than Dmin.

This route should be repeated in order to gain statistical significance in the data.

6.3. Single Jammer With Terrain Masking

The single jammer scenario with terrain masking uses the FRPA antenna and consists of a single jammer placed in a topographic area where mountains or other terrain will interfere with the transmission of the jamming signal to the platform under test. This scenario is dedicated to answer the following sub-issue:

10) How accurate is the propagation model with terrain interference?

6.3.1. Jammer Laydown

The main requirement for this laydown is that the platform under test can fly a route in which it will initially be tracking GNSS satellites and will be shielded from the jamming signal due to terrain. The platform will then fly out of the terrain blocked area and into the jamming field. The jamming field should be powerful enough at this point to cause the GNSS receiver to lose lock. Figure 2 shows a theoretical jammer laydown and route with these characteristics.

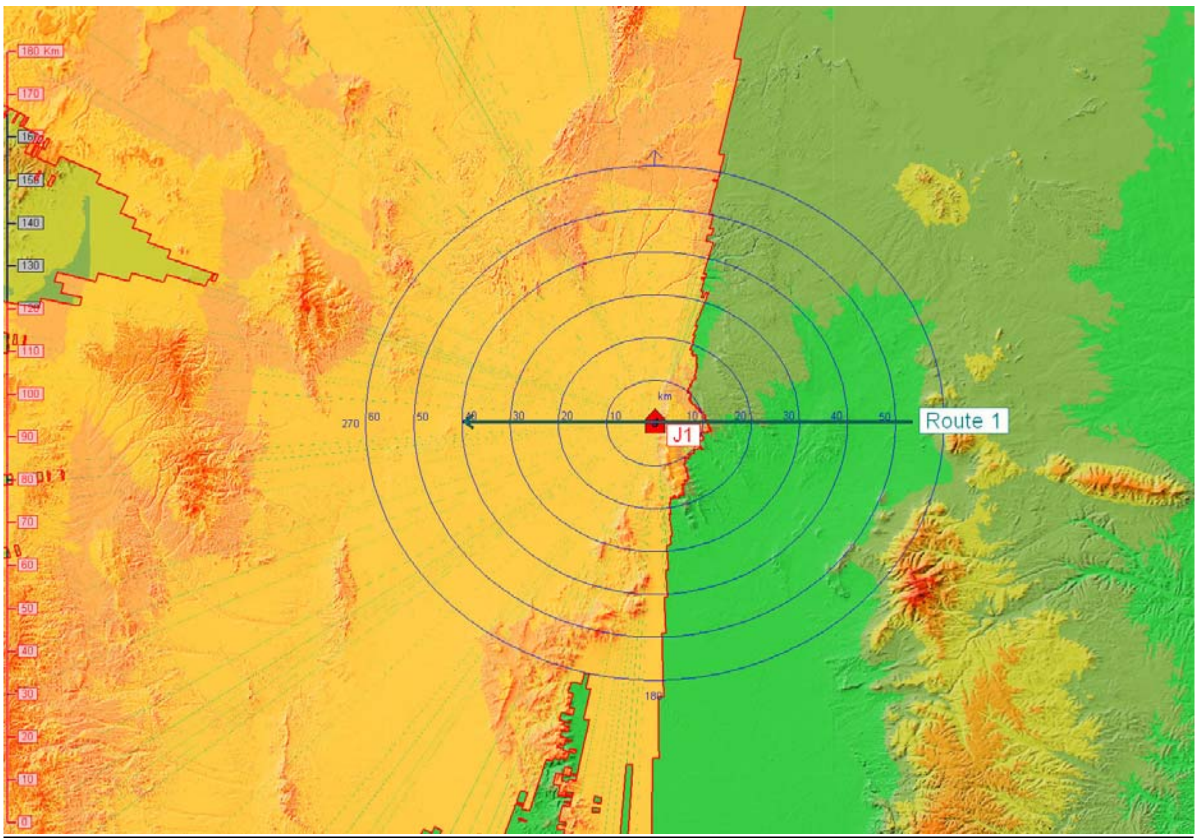

Figure 2: Single Jammer Laydown with Terrain Masking

In this figure, J1 is the sole jammer. The portion of the figure that is shaded on the left is the area that has line of sight with the jammer at 1500 m AMSL. The line labelled “Route 1” is the theoretical route. As can be seen, the platform begins the route in an area where it does not have line of sight with the jammer J1. It then flies over the area of terrain masking, in this case caused by a line of mountains, and into the jamming field. When the platform enters the jamming field, the received jamming RF power is high enough that the receiver switches to state 0 as defined in STANAG 4665.

The jammer power level should be set to provide enough power to cause the platform GNSS receiver to lose tracking lock when it comes over the line of sight horizon. The jammer power level should determined using the same procedures and formulas used in calculating the jammer power level in scenario 6.1.

The jammer waveform for this scenario will be set up to transmit a 20 MHz Gaussian noise signal.

6.3.2. Platform Configuration

The platform should be configured with the following instrumentation:

1. RF Power Meter
2. TSPI

These systems were described in Section 5.

The RF power meter should be connected to an antenna which will measure the jammer RF power at the platform without body masking and antenna effects. This antenna should be bottom mounted and the gain pattern should be as close to isotropic as possible as any antenna gain effects will show up as measurement errors in the data.

6.3.3. Platform Route

For this scenario, the area of interest is that in which the platform loses and gains line of sight with the jammer. Therefore it is desirable for the platform to enter and exit this area as many times as possible in order to collect as much data as possible. This being the case, the platform should set up an orbit in which the platform will transition in and out of line of sight with the jammer.

6.4. Ring of Jammers with FRPA Antenna

The ring of jammers scenario uses the FRPA antenna and consists of a ring of several jammers placed in a topographic area where mountains or other terrain will not interfere with the transmission of the jamming signal to the platform under test. This scenario will answer the following sub-issues:

1) How accurate is the satellite azimuth and elevation prediction?
2) How accurate are the azimuth and elevation predictions of the incoming jamming signals?
3) How accurate is the aggregate jamming signal power prediction at the platform?
4) How accurate is the aggregate jamming signal power prediction at the receiver after body masking and FRPA gain effects?
5) How accurate is the GNSS receiver tracking state?
6) How accurate is the C/No for each satellite being tracked?

6.4.1. Jammer Laydown

This scenario will answer the same sub-issues as other scenarios, but it will do so with the inclusion of multiple jammers. The platform route will start outside of the ring and fly into and out of the ring of jammers. Figure 3 shows a theoretical jammer laydown and route with these characteristics.

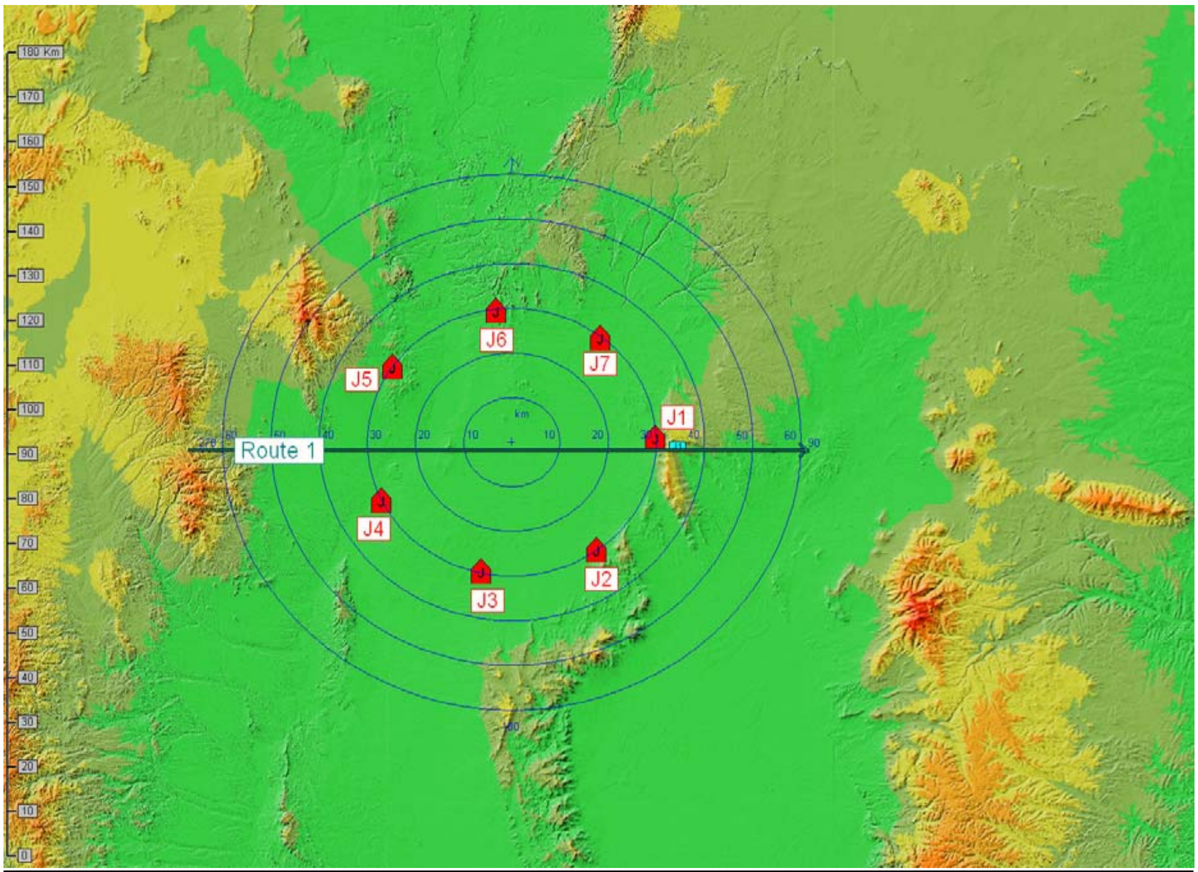

Figure 3: Ring of Jammers

The line labelled “Route 1” in figure 3 is the theoretical route.

The jammer waveform for this scenario will be set up to transmit an asynchronous 20 MHz Gaussian noise signal.

The jammer power levels should be set to provide enough power to cause the platform GNSS receiver to lose tracking lock somewhere inside the ring of jammers. The jammer power level should be determined using the same procedures and formulas used in calculating the jammer power level in scenario 6.1. In this theoretical laydown, seven jammers are used. In this scenario, given the nature of the waveform, all of the jammer signals will be additive. Therefore, at the center of the ring, the power received should be seven times or 8.45 dB as great as the power received from a single jammer.

6.4.2. Platform Configuration

The platform should be configured with the following instrumentation:

1. Instrumented GNSS Receiver with FRPA Antenna
2. RF Power Meter (2)
3. TSPI

These systems were described in Section 5.

For this scenario, there should also be two RF power meters. The data generated from these two meters will be used to answer sub-issues 4 and 8.

The first RF power meter should be inserted in between the GNSS FRPA antenna and the GNSS receiver. This will give the true RF power measurement that is being seen at the GNSS receiver front-end after body masking and FRPA antenna effects.

The second RF power meter should be connected to a separate antenna which will measure the jammer RF power at the platform without body masking and antenna effects. This antenna should be a bottom mounted antenna and the gain pattern should be as close to isotropic as possible as any antenna gain effects will show up as measurement errors in the data.

6.4.3. Platform Route

For this scenario, the area of interest is the area inside the ring of jammers where the GNSS receiver switches from state 5 to state 3 and from state 3 to state 0 as defined in STANAG 4665.

Just as in scenario 6.1, it is desirable to have the GNSS receiver on-board the platform start with an initial condition of having at least four channels in state 5 as defined in STANAG 4665 Section 5.8. Using this initial condition, the platform must then fly towards the ring of jammers. The platform will eventually pass the two thresholds T2 and T1, where the GNSS channels will drop from state 5 to state 3 and from state 3 to state 0. The distance for the route start point should be calculated as in Section 6.1.3 using Equation 2, bearing in mind that there are now seven jammers instead of one.

6.5. RING OF JAMMERS WITH CRPA ANTENNA

The ring of jammers scenario uses the CRPA antenna and consists of a ring of several placed in a topographic area where mountains or other terrain will not interfere with the transmission of the jamming signal to the platform under test. This scenario will answer the following sub-issues:

1) How accurate is the satellite azimuth and elevation prediction?
2) How accurate are the azimuth and elevation predictions of the incoming jamming signals?
3) How accurate is the aggregate jamming signal power prediction at the platform?
4) How accurate is the aggregate jamming signal power prediction at the receiver after body masking and CRPA gain effects?
5) How accurate is the GNSS receiver tracking state?
6) How accurate is the C/No for each satellite being tracked?

6.5.1. Jammer Laydown

The platform route will start outside of the ring and fly into and out of the ring of jammers. This scenario can use the same jammer laydown as scenario 6.4, a sample of which is shown in Figure 3.

The jammer waveform for this scenario will be set up to transmit an asynchronous 20 MHz Gaussian noise signal.

The jammer power levels should be set to provide enough power to cause the platform GNSS receiver to lose tracking lock somewhere inside the ring of jammers. The jammer power level should be determined using the same procedures and formulas used in calculating the jammer power level in scenario 6.1. It must be kept in mind that, in this example, there are now seven jammers instead of one. In this scenario, given the nature of the waveform, all of the jammer signals will be additive. Therefore, at the center of the ring, the power received should be seven times or 8.45 dB as great as the power received from a single jammer.

It must also be kept in mind that the anti-jam margin of the CRPA system must also be overcome with this scenario. Therefore, the amount of anti-jam that the CRPA system has should be added to the jammer ERP.

6.5.2. Platform Configuration

The platform should be configured with the following instrumentation:

4. Instrumented GNSS Receiver with CRPA Antenna
5. Instrumented CRPA System
6. RF Power Meter (2)
7. TSPI

These systems were described in Section 5.

For this scenario, there should also be two RF power meters. The data generated from these two meters will be used to answer sub-issues 4 and 8.

The first RF power meter should be connected to a FRPA antenna on top of the aircraft as close to the CRPA antenna as possible, without interfering with the CRPA. This will give the true RF power measurement that is being seen at the CRPA antenna after body masking effects.

The second RF power meter should be connected to a separate antenna which will measure the jammer RF power at the platform without body masking and antenna effects. This antenna should be a bottom mounted antenna and the gain pattern should be as close to isotropic as possible as any antenna gain effects will show up as measurement errors in the data.

6.5.3. Platform Route

For this scenario, the area of interest is the area inside the ring of jammers where the GNSS receiver switches from state 5 to state 3 and from state 3 to state 0 as defined in STANAG 4665. Another item of interest for this scenario is the amount and depth of nulls produced by the CRPA system. When the platform is inside the ring of jammers, there should be multiple nulls in which to exercise the CRPA system.

Just as in scenario 6.1, it is desirable to have the GNSS receiver on-board the platform start with an initial condition of having at least four channels in state 5 as defined in STANAG 4665 Section 5.8. Using this initial condition, the platform must then fly towards the ring of jammers. The platform will eventually pass the two thresholds T2 and T1, where the GNSS channels will drop from state 5 to state 3 and from state 3 to state 0. The distance for the route start point should be calculated as in Section 6.1.3 using Equation 2, bearing in mind that there are now seven jammers instead of one, and that the anti-jam margin of the CRPA system must be overcome.

6.6. Satellite Signal Power Measurements

In order to answer sub-issue 2, “How accurate is the satellite power prediction at the platform?”, it is necessary to measure the actual satellite signal strength. This measurement is difficult because the power of the GNSS spread spectrum RF signals is well below the thermal noise floor.

This scenario will independently measure the satellite signal power. Due to the instrumentation requirements for this scenario, it cannot be combined with the previous scenarios.

6.6.1. Instrumentation

The instrumentation for this scenario consists of an RF power meter, a well characterized high-gain antenna, and an accurate antenna control system which can direct the antenna given an azimuth and elevation.

For example, IS-GPS-200 states that the minimum received signal level for the L1 C/A code signal is -158.5 dBW. The thermal noise floor in the C/A signals 2.046 MHz bandwidth is -144 dBW. This means that the received GPS signal is 14.5 dB below the thermal noise floor. In order to see this signal the high-gain antenna must have a very narrow beamwidth which will add gain to the incoming satellite signal, as well as reduce the antenna noise temperature.

In order to achieve the most accurate measurement, the antenna should have as much gain as feasible. If the antenna has 34.5 dBi of gain, then the received GPS signal would be 20 dB higher than the thermal noise. This would mean that the thermal noise would only introduce approximately 1 percent of error in the measurement. If the antenna has 24.5 dBi of gain, then the thermal noise could introduce 10 percent of error.

The following data is required to compare the received satellite signal power to the predicted satellite signal power:

1) UTC Time
2) Accurate Antenna Position
3) Accurate Antenna Azimuth and Elevation Angles
4) Received RF Power

The high-gain antenna should be set up to track a GNSS satellite. RF power measurements should be made while tracking. All data should be time stamped with UTC time.

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APPENDIX 1 — CALCULATION OF JAMMER-TO-SIGNAL RATIO GIVEN CARRIER-TO-NOISE DENSITY IN A RECEIVER CHANNEL

1. CALCULATION OF CARRIER-TO-NOISE RATIO

As was shown in STANAG 4665 Appendix 1, when a single jammer is present, the effective c/no figure can be calculated via the following formula:

$$\left(\frac{c}{n_o}\right)_{ef} = \frac{1}{\frac{1}{\left(\frac{c}{n_o}\right)_{uj}} + I} \qquad (1)$$

Where $\left(\frac{c}{n_o}\right)_{uj}$ is the unjammed carrier-to-noise density and I is given by:

$$I = \frac{j}{s} * \frac{1}{Qf_c} \qquad (2)$$

Where $\frac{j}{s}$ is the jammer-to-signal (scalar) ratio, Q is the spread spectrum processing gain adjustment factor (dimensionless), and f_c is the GNSS code chipping rate.

If a vulnerability threshold for a GNSS receiver is defined as a C/No ratio, it is sometimes necessary to convert that to a J/S ratio.

2. CALCULATION OF JAMMER-TO-SIGNAL RATIO

Using Equations 1 and 2 and solving for J/S, J/S can be calculated via the following formula:

$$\frac{J}{S} = 10\log\left[Qf_c\left(\frac{1}{10^{(C/\ N_o)_{ef}/10}} - \frac{1}{10^{(C/N_o)_{uj}/10}}\right)\right] \quad \text{(dB)} \qquad (3)$$

Where $\frac{J}{S}$ is the jammer-to-signal ratio in dB, Q is the spread spectrum processing gain adjustment factor, f_c is the GNSS chipping rate in MHz, $(C/N_o)_{ef}$ is the carrier-to-noise ratio in dB, and $(C/N_o)_{uj}$ is the unjammed carrier-to-noise ratio in dB.

3. SENSITIVITY ANALYSIS OF UNJAMMED CARRIER-TO-NOISE RATIO

An estimate of the unjammed carrier-to-noise ratio can be calculated via the following equation:

$$\frac{C}{N_o} = S + G_R - L_{proc} - N_o - N_f \text{ (dB-Hz)} \qquad (4)$$

Where S is the received satellite signal power at the antenna, G_R is the antenna gain in dB, L_{proc} is the receiver's signal processing loss in dB, N_o is the power spectral density of thermal noise in dBW-Hz, and N_f is the noise factor of the GNSS receiver in dB.

We will assume an antenna gain of 0 dB for this analysis, and we will use the following typical numbers for L_{proc}, N_o, and N_f:

L_{proc} = 2 dB
N_o = -204 dBW-Hz
N_f = 4 dB

As an example, we will also look at the expected range of the GPS L1 C/A code signal on earth. IS-GPS-200 states that S can range from -158.5 dBW to -150 dBW.

Using the aforementioned values, the C/No on earth will range from 39.5 to 48 dB-Hz.

Using Equation 3 with the GPS C/A code chipping rate of 1.023 MHz and a Q equal to 1, the following figure shows the sensitivity of the J/S vs C/No equation to the unjammed carrier-to-noise ratio.

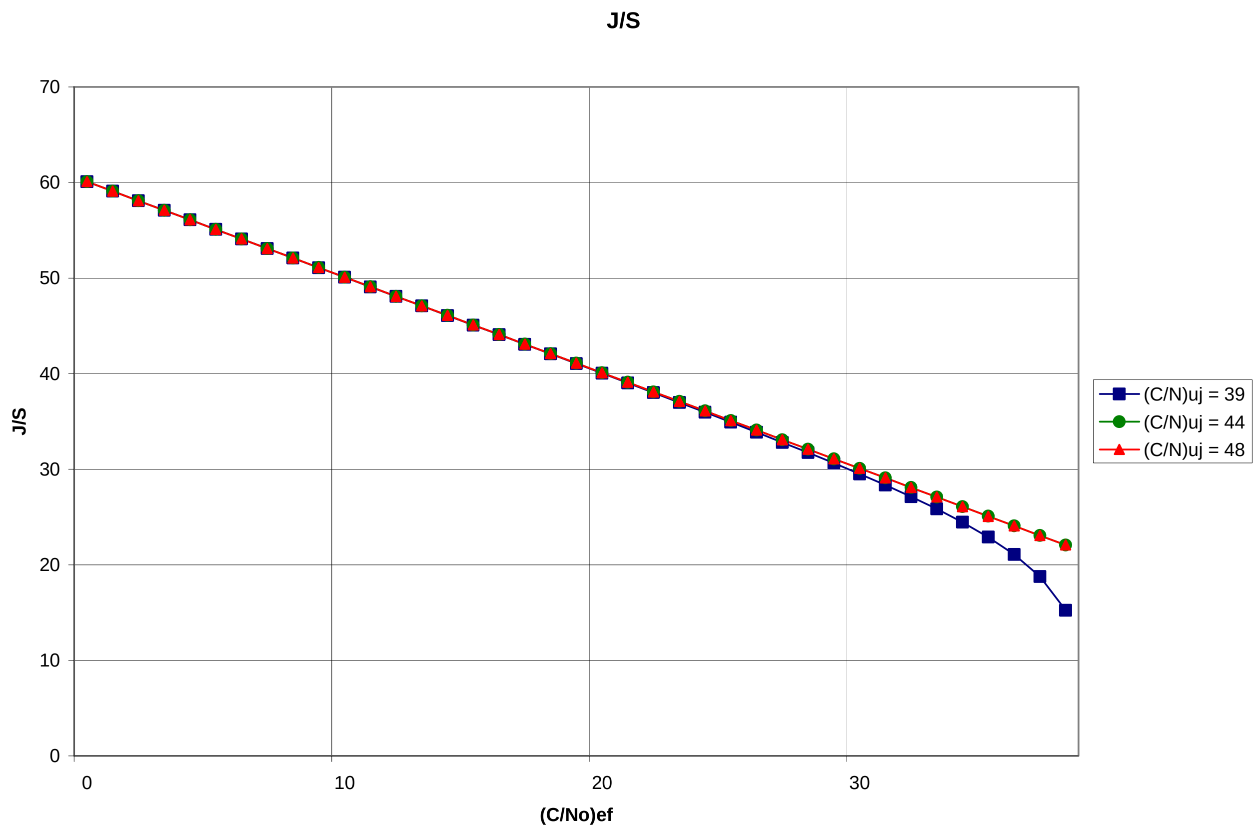

Figure 1: Sensitivity of C/No vs J/S to unjammed carrier-to-noise ratio

As can be seen from Figure 1, at the expected unjammed carrier-to-noise ratios, the J/S and C/No relationship is linear where J/S is above 30 dB. In fact, this equation shows that in this region the following is true:

$$\frac{J}{S} + \frac{C}{N_o} \approx 60 \qquad (5)$$

Normally, the region where J/S is greater than 30 dB is the region of interest in GNSS receiver vulnerability analysis, so Equation 5 can be used as an accurate and quick conversion between J/S and C/No.

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