Advanced Online GNSS RFI Detection and Investigation

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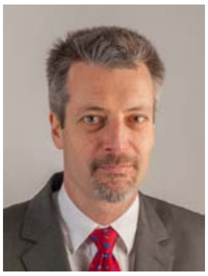

ABSTRACT

The potential for GNSS Radio Frequency Interference (RFI) to degrade air-navigation signal quality is well known and the impact becomes more important as the transition to RNAV/RNP based navigation continues.

Building on research presented at the 2014 IFIS [1], this paper describes an "online" implementation of the methodology and techniques presented, additionally incorporating that which was presented at the ION GNSS Conference 2015 [2].

Consideration is also given to aspects such as:

1. "Periodic Inspection" of GNSS Environment during routine ILS inspections at busy airports
2. Online alerting and reporting of results that indicate the presence of an interference source
3. Characterization and localization of interference sources using fixed wing and/or rotary wing Flight Inspection platforms

The implementation in an Automatic Flight Inspection System (AFIS) is discussed and examples of results observed in real-world conditions are analyzed.

INTRODUCTION

Current GNSS interference detection methods provide for a go/no-go indication as to the presence of GNSS inference and are typically performed only during commissioning Flight Inspection/Validation of a new GNSS (GPS) based procedure.

While this method has proven successfully thus far it does have limitations, in particular in the detection of short duration interference (typically < 10 seconds). Short term interference can easily go undetected in flight unless issues such as lost RTK solution or complete loss of GPS are experienced. The use of spectrum analyzers to capture the GPS spectrum is an improvement, however they typically do not allow for continuous monitoring. Use of GPS performance measures, such as Carrier to Noise Ratio (C/No) are effective, but are typically influenced by aircraft attitude which makes interpreting results and online detection difficult.

Doc 8071, Volume 2 [3], states the following at Appendix 3 to Chapter 1, section 4.10:

> *Even with a flight inspection there is no full guarantee that all interference sources have been identified. For example, some sources may be intermittent transmitters or may come from mobile transmitters. Therefore it is recommended that aircraft be equipped with interference sensors (GNSS receivers with interference detection capability producing automatic reports).*

While this consideration is perhaps skewed towards primary GNSS receivers with some kind of alerting function, improved GNSS interference detection techniques have been developed on the basis of that presented at IFIS 2014 [1] and at ION GNSS Conference 2015 [2] and implemented in an AFIS.

The resulting Compensated C/No has proven to be a reliable measure of GPS interference and an online implementation of these techniques into a "C/No Monitor" aids real time detection and reporting of interference. This technology also provides the basis for routine monitoring of the GPS environment during periodic flight inspection tasks such as ILS or VOR inspection and "on opportunity" monitoring during ferry flights.

AFIS SUPPORTED ONLINE GNSS DETECTION

Given the identified problems with existing methods, consideration was given to how the AFIS could be used to better support the detection of GNSS interference online and in real time. The aim was to develop a set of tools available to the Flight Inspector to confidently assess if the GPS environment is free of interference, in flight, and without the need to conduct post-processing or analysis of the recorded data.

GPS antenna pattern correction

The concept of software correction or compensation of antenna pattern for field strength measurement effects has been around for some time. As presented at IFIS 2014 [1], similar techniques can be used to compensate for the influence of a GPS antenna reception pattern on the C/No as measured by a GPS receiver. The result is a Compensated GPS C/No, largely independent of influences from the antenna reception pattern and aircraft attitude, which makes detection of GPS inference easier.

A drawback of the described technique was that the analysis and correction was applied in post-processing, meaning a delay between observation of the interference (by the measurement equipment) and identification of the interference (by the engineer) was present. By this time the opportunity to complete further investigation was lost.

An online implementation of this GPS antenna pattern compensation method was considered to have several benefits:

1. Make real-time identification of GNSS interference easier
2. Use the Compensated C/No values in algorithms to automate GNSS interference detection and/or trigger specific actions when interference is detected
3. Potential to identify and investigate short-duration GNSS interference effects (which may otherwise go unnoticed)

With this in mind the AFIS software was developed to use an antenna model to calculate the Compensated C/No values and present these for visualization and further analysis.

Development of Antenna Pattern

The antenna pattern was derived empirically using the same methodology as presented in [1]. Specific flight profiles were not used to gather data, rather a collection of recordings from approximately 50 hours of routine flight inspection tasks were processed to calculate the pattern.

Processing required calculation of the relative position of each GPS SV with respect to the AFIS GPS antenna and subsequent calculation of a correction factor to give a normalized C/No of 50 dBHz. These correction factors were arranged into to 1x1 degree "bins" across the GPS antenna surface and further processing though averaging and smoothing provided a suitable 3D model for implementation in the software.

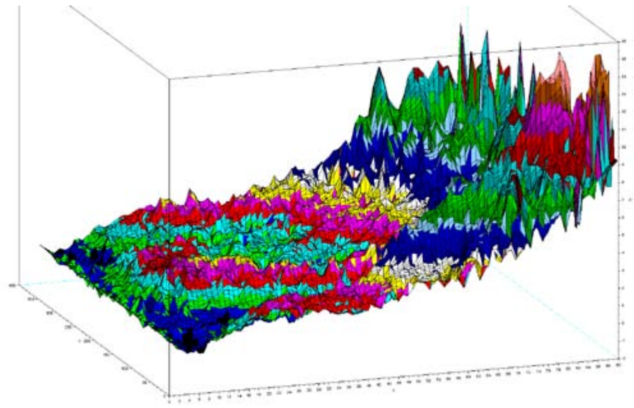

Figure 1 – GPS Antenna Pattern, X – Azimuth (0-360 degrees), Y – Zenith (0-90 degrees), Z – Correction (dBHz)

As a plausibility check the derived pattern was compared with that from the antenna manufacturer, correlation was considered to be acceptable noting that the manufacturer only provides information relating to the antenna gain in elevation and assumes no directionality in azimuth, an assumption that is not valid when considering installation on an aircraft.

For comparison purposes two antenna models were finally generated for software implementation, one being the manufacturer's with gain as presented on that datasheet and one model with derived gain in elevation and azimuth for the aircraft specific installation.

Implementation and Validation

The antenna models were packaged into an existing data format used in the AFIS software for 3D correction of antenna gain in field strength calculations. Data from flights free of GPS interference was "reprocessed" to see how the compensation algorithm performed and if the results were plausible, especially during periods where the aircraft was banked.

From the initial testing it became apparent that use of the empirically derived aircraft specific model provided better results. Azimuth dependent effects, typically affecting SVs at low elevation angles and in the region of the wing and tail structures, could not be considered negligible. Given this finding further use of the standard model was abandoned with focus shifting to refining the aircraft specific model.

The use of the model meant that the C/No of each SV was compensated to a normalized C/No of 50 dBHz, small variations and noise were filtered out through averaging to give an Averaged Compensated GPS C/No which was largely resilient to aircraft attitude while remaining sensitive to simultaneous C/No drops like those seen during periods of GPS interference.

Using this new parameter with a limit on minimum Average Compensated GPS C/No provides the basis for the C/No Monitor and thus the online detection of GPS interference.

False Positives

Reprocessing of previous ILS flight inspection data where no interference was observed showed some peaks and unexpected noise on the Averaged Compensated C/No parameter, however as these were all "positive" they did not trigger false alarms of the C/No Monitor.

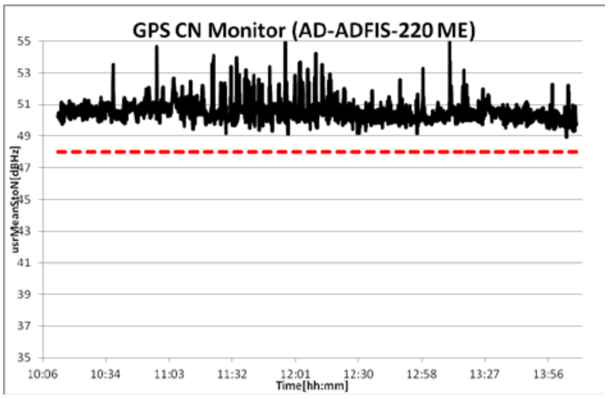

Figure 2 – Typical ILS Flight Inspection (4 hours) Without Observed GPS Interference

Missed Detections

Analysis into the possible rate of missed detections has not been completed, however if we consider the previous implementation as a baseline we can see that the C/No Monitor immediately reduces the probability of a missed detection.

<u>CASE STUDIES</u>

While these examples are from the past they clearly demonstrate the effectiveness of the newly implemented AFIS capabilities.

<u>#1 – HeliFIS: Intermittent short term interference</u>

During post flight evaluation of a helicopter RNAV procedure a C/No ratio irregularity in the region of the missed approach turning fix (MATF) was observed. However, as tracking was not lost on any of the onboard GPS receivers and the irregularity was only observed on one of the two approaches there was no "trigger" to consider further investigation in flight at the time.

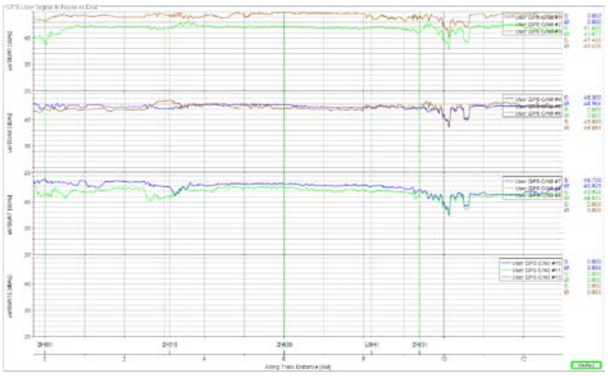

Figure 3 – Conventional C/No Graphic

As can be seen, the conventional graphic shows a drop in all C/No but not one that causes immediate concern. When using the C/No Monitor method the drop is much more obvious.

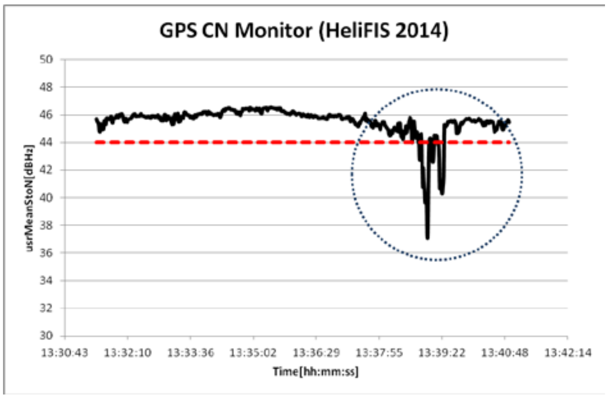

Figure 4 –C/No Monitor Graphic

In April 2016, some two years after the original occurrence and during a VFR departure, the C/No Monitor triggered in the same region.

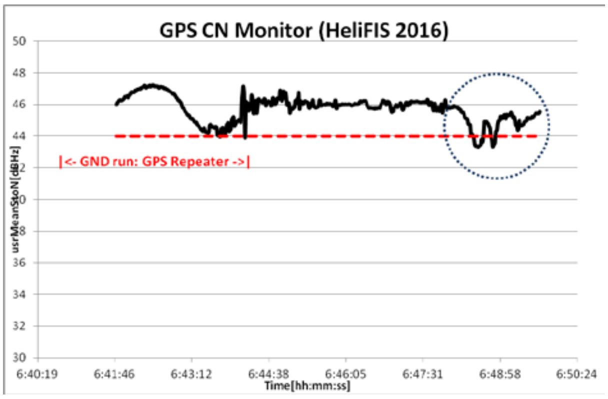

Figure 5– Similar Path, C/No Monitor Graphic

Given the points at which the inference was observed to begin and end, a general region where the interference source may be located can be deduced.

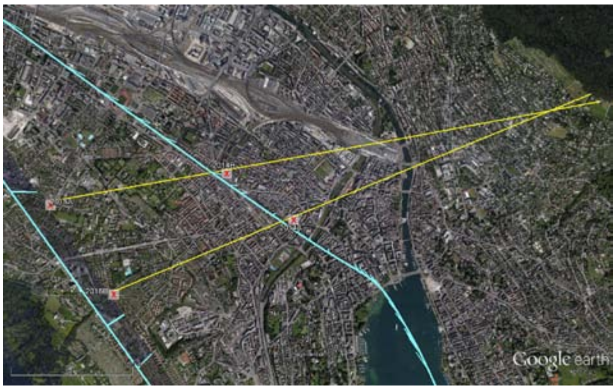

Figure 6 – Possible Location of Interference Source

The source of this interference is yet to be located, however the authorities have been provided with useful information to start their investigation.

#2 – ILS calibration: Short term interference

During routine flight inspection of the ILS at a military airfield a complete loss of GPS was observed on the AFIS receiver. Pilots reported seeing no loss of GPS, however later analysis revealed that Primary GPS was lost, but as the FMS reverted to DR mode for these 1-2 seconds it effectively went unnoticed.

GPS was lost at a point abeam the Precision Approach Radar (PAR) installation, approximately at the mid-point of the runway. Troubleshooting at the time, which included temporarily removing power to the PAR, was unable to positively identify the source of the interference.

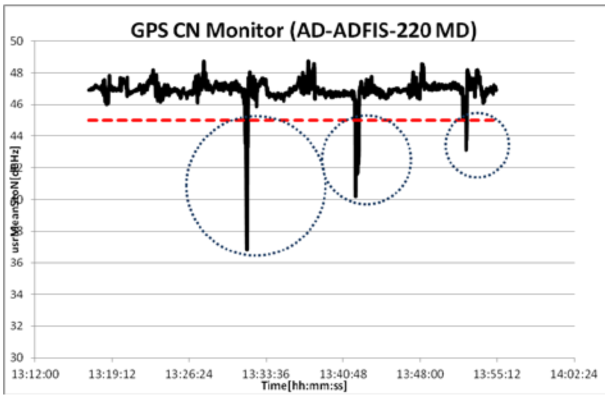

Figure 7 – Interference During Low Pass

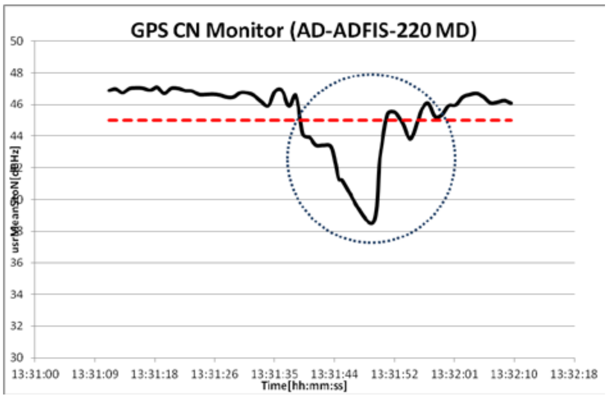

Figure 8 – Expansion of Interference (10 Sec / 80m)

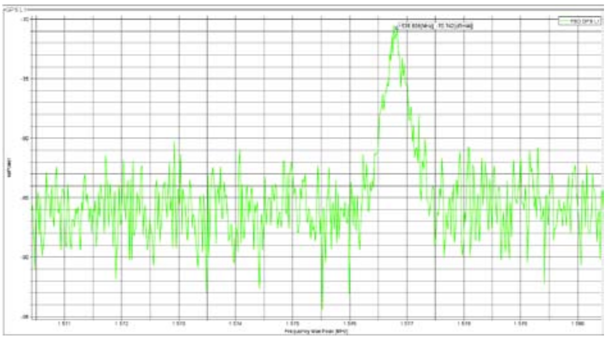

Figure 9 – Spectrum Plot

Figure 10 – Location of Interference

The source was traced to a faulty GPS antenna which was part of the PAR installation, which, due to an internal failure, was transmitting a CW signal near to the L1 frequency.

#3 – ILS calibration: Scattered interference

Crews reported several losses of GPS RTK during an ILS flight inspection in different locations around the airport. While post evaluation of the flight discovered suspicious C/No behavior during the entire flight, the source of the interference could not be detected and was not observed during subsequent ILS inspections at this location.

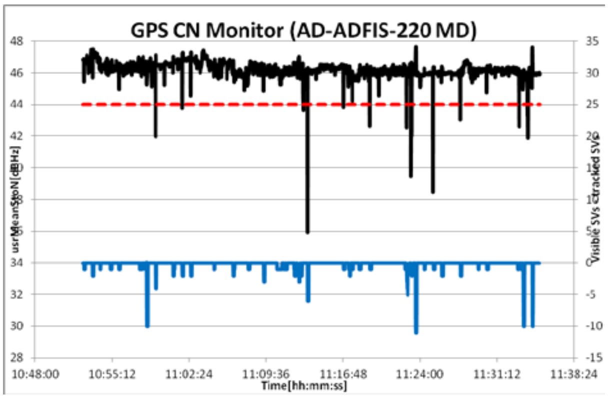

Figure 11 – Several Losses of RTK

As seen on the second trace, even though the C/No was clearly disturbed it was not sufficient for all satellite tracking to be lost.

AIRBORNE INVESTIGATION

Once interference is observed the primary objective is normally to positively identify the source so that it can be suppressed. However, a Flight Inspection aircraft is typically not equipped to complete this task and often the responsibility for this mission (and hence the necessary tools and experience) lies with Federal Radio or Spectrum Management Authorities.

In this case the aim of the Flight Inspection crew should be to quantify if/how the interference poses any threat to the procedures that rely on GNSS, and to gather as much information as possible on the characteristics of the interference to aid further investigation by the responsible authorities.

A spectrum analyzer (SPA) and suitable antennas for signal reception, are important tools for capturing the characteristics of the signal suspected of causing interference however the characteristics of the measurement system must be understood.

Spectrum Analyzer Settings

A balance must be found in the configuration as compromises between Span, Resolution/Video bandwidth and Sweep Time have an influence on the minimum detectable signal. In general, settings which improve sensitivity of the SPA increase the sweep time, however this can often be controlled independently at the expense of accuracy. Taking advantage of this to reduce the sweep time to 1 second, normally leads to the SPA operating in an un-calibrated state.

For our purposes this is of no consequence since the exact level of the interference signal is of little interest, however its presence and general characteristics are; and with a low sweep time we can take more samples in a short period of time. This not only increases the probability if detection for a short duration or highly localized interference source, but may also provide useful information for locating the source as relative changes in amplitude can be referenced to aircraft location to deduce a location.

GPS Antenna Frequency Response

The frequency response of the antenna also impacts on whether or not the signal is detectable with the SPA. By using a SPA with tracking generator and a suitable horn antenna as a transmitting source the frequency response of the GNSS antennas installed on a Flight Inspection aircraft were measured.

The results show that some antennas are better suited to the job of searching for interference signals than others.

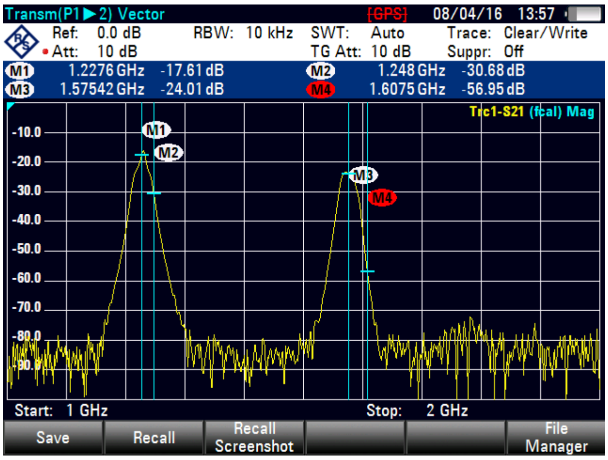

Figure 12 - Typical AFIS GPS Antenna (L1, L2)

This dual frequency antenna would strongly attenuate any signals outside of the L1 or L2 band, so would be suitable for searching for in band interference but not out of band interference.

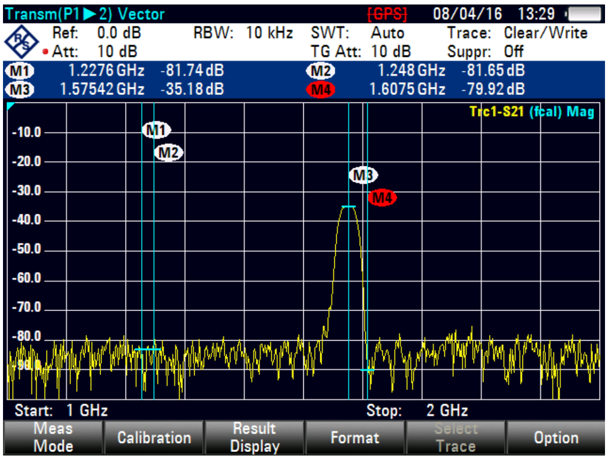

Figure 13 - Typical Primary GPS Antenna (L1)

Again, the strong filter effects most likely from the pre-amplifier, would make an antenna like this suitable for searching for in band interference but not out of band interference.

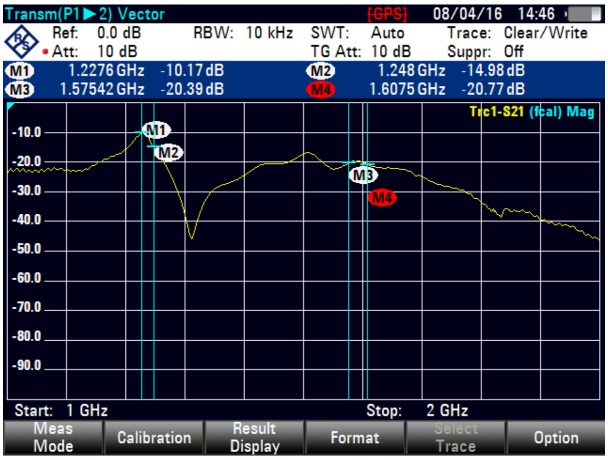

Figure 14 - Typical Multiband GNSS Antenna (L1, L2, L5, Omnistar, GLONASS)

This multiband GNSS antenna may provide little resilience to interference when connected to a GNSS receiver but provides a great frequency response for both in and out of band interference detection.

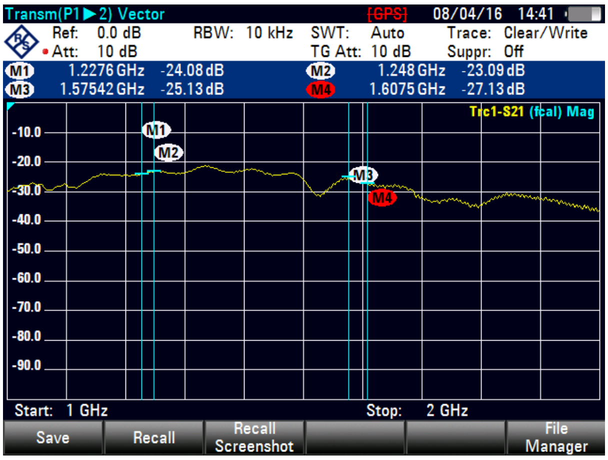

Figure 15 - Typical Passive L-Band Antenna

A standard, passive L-Band antenna provides a relatively flat frequency response as expected, however to measure this it was required to remove 40 dB of attenuation from the test setup. This means the antenna is 40-50 dB less sensitive than a standard GNSS antenna, limiting its usefulness for detecting low power interference sources such as personal privacy devices.

GNSS Antenna Location

GNSS antennas installed on top of the aircraft can have limited usefulness when localizing inference, which typically comes from below the aircraft. For this reason it has become typical to install the antenna intended for connection to a monitoring receiver, such as a SPA, on the bottom of the aircraft so that it is “downward facing”.

The antenna pattern data shows that GPS antenna performance is strongly affected by elevation angle. When mounted on the bottom of an aircraft this means that interference signals coming from the side will be attenuated and it may be difficult to capture a useful spectrum of the inference unless near to overhead the source. While this has a certain disadvantages, using a standard L-Band antenna with a more useful reception pattern, would mean losing at least 40dB of sensitivity.

Given these considerations, the benefits of using a dedicated GNSS antenna for this purpose outweigh the relative disadvantages of using the next best alternative. With further knowledge of the relative frequency responses we can also see that it is beneficial to use a Multiband GNSS antenna for this purpose as the wide frequency response allows for effective detection of out of band interference sources.

Search Patterns

It should be stressed that the primary focus of these search patterns is to improve the chances of characterizing the interfering signal, not necessarily to locate the source.

Two radials at 90° to each other and of length ± 5NM over the point where the interference is suspected is a simple yet effective search pattern. A distinct advantage of this pattern is that by describing the profile in terms of heading and distance it is normally easy to relay intentions to ATC, which can be important when the detection occurs in flight and warrants immediate investigation before further briefings are possible.

A pattern such as this can show the relation between C/No and location, which is important to know when assessing the potential impact of the disturbance. Additional radials can easily be flown parallel to the initial radial, and if sufficient radials are flown a grid pattern is eventually formed, which will likely provide the authorities with a very good starting point for locating the source so that it can be suppressed.

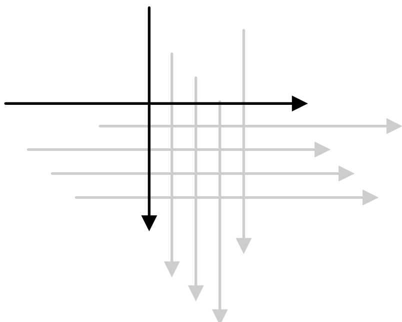

Figure 16 – Simple Search Pattern

Adaptation of Complex, Search and Rescue type search patterns, such as a Creeping Line or Expanding Square would also be useful in assessing the extent of an interference source's impact, however prior coordination with ATC for such "non-normal" maneuvers would be required.

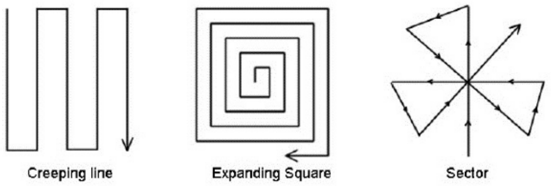

Figure 17 – Complex Search Patterns [4]

Rotary wing platforms offer significant advantages in this scenario, with reduced speed and tighter turns, not to mention the ability to hold over a defined position, all of which allow for increases in sample rate with respect to position.

PERIODIC INSPECTION OF GNSS ENVIRONMENT

During ILS, VOR or NDB periodic flight inspections the aircraft typically spends a lot of time at low altitude, normally less than 3000ft above ground. These low altitudes provide the best conditions for the detection of GNSS interference sources, and given the typical ILS flight inspection periodicity of 6 months, changes in the GNSS environment can be identified quickly.

GNSS based approaches at the airport will share similar final approach profiles to any ILS, VOR or NDB approach, and as such measurements completed in the background during these periodic inspections could constitute a periodic inspection of the GNSS environment without additional flying, important in busy airspace.

This periodic inspection should be seen as an important step towards ensuring the availability of published GNSS procedures.

Applicable Tolerances

From the performance of the C/No Monitor during cases of known interference the following tolerances can initially be derived for this specific configuration of GPS receiver, antenna, and normalization algorithm:

Average Compensated C/No	Interference
> 50 dBHz	Nil Observed
> 45, < 50 dBHz	Probable
< 45 dBHz	Present

Note that secondary effects, such as loss of RTK or primary GPS, should be used to confirm or quantify the impact of the interference.

Reporting

Consideration will need to be given to how the results from such a periodic investigation are documented. One possibility would be for the AFIS to generate a simple report, tabulating the time and location of instances where the C/No dropped below pre-defined limits.

The report could be generated when the monitoring makes any detection in the background and of course specifically included as part of the Flight Validation Report for GNSS based procedures.

FURTHER DEVELOPMENT

While implementation of the C/No Monitor provides a significant step forward in real time detection of GNSS interference, consideration has been given to further AFIS enhancements to build on this functionality.

Automation Based on C/No Limits

The C/No Monitor could be used to automatically trigger specific software actions when exceeding specified limits.

For example, if Average Compensated C/No dropped to a level indicating *probable* interference, the software could automatically make a spectrum analyzer measurement in the GPS L1 and GPS L2 bands, recording also the Latitude, Longitude and Altitude at the time of the measurement. An important requirement on the AFIS for this capability would also be a navigation solution based on multiple sensors (such as IRS, DME/DME) such that a temporary loss of GNSS can be compensated for and have minimal influence on the positional accuracy.

An automatically generated report would combine information relating to the detection (time, minimum value of Average Compensated C/No, aircraft, duration of detection) and the spectrum measurement for further distribution as required.

If the Average Compensated C/No dropped further, for example into the range where interference is considered certain, the software could additionally provide alerts to the Flight Inspector and generate a simply search pattern centered on the point of detection for the purposes of further investigation.

Continuous Monitoring

Currently the C/No Monitor is only active during calibration tasks, however it would be useful for it to be running at all times from AFIS start-up to shutdown.

While this will generate a lot of recording data the alert of possible interference will be available during ferry flights (in particular during take-off and landing) or in between calibration tasks.

This would provide the Flight Inspector the opportunity to conduct further investigation as warranted and could also lead to an AFIS generated "end of week GNSS interference" report, listing the locations where *probable* interference was detected along with information relating to each detection such as time, minimum observed Average Compensated C/No, duration and a spectrum measurement.

Predicted Vs. Observed Performance

Consideration may be given to further developing the capabilities to include alerts when achieved GNSS performance is not in-line with predicted performance. This would act as an additional indication of a potential interference.

An example would be for the software to detect when the observed constellation, including geometry and expected SVs, is different to one calculated from received almanac data. If for example there were to be 10 SVs in view and only 4 SVs are available, a further indication of GNSS interference or unexpected shielding is available without total loss of GNSS tracking.

Another possibility would be for the FIE to conduct a RAIM prediction for the expected duration of the next procedure, similar to that completed in an FMS before a GNSS approach. It is worth noting that a RAIM alert itself is not cause for concern, as this is simply the FMS stating that the GNSS conditions (number of SVs, geometry) are not suitable for application of RAIM algorithms. However if this RAIM alert is not expected through forward prediction it may be useful as an indicator of interference or shielding.

Interference Visualization

Consideration could also be given to exporting the flight track in Google Earth™ compatible KML format with traffic-light style color coding corresponding to the level of observed GPS interference, for example the following legend could be implemented:

Average Compensated C/No	Color
> 50 dBHz	Green
> 45, < 50 dBHz	Orange
< 45 dBHz	Red

This data, unlike the raw flight inspection data and associated plots, could be easily distributed to and interpreted by 3rd parties without the need for specialized training or tools.

Visualization of the data in this format could also provide clues as to the source of the interference and be useful in planning any follow up investigation activities.

Further Development of Antenna Pattern

In order to develop a more accurate antenna model, further consideration would need to be given to factors such as:

1. Varying power output from each GPS SV
2. Atmospheric effects

Specific flight profiles may also need to be developed and flown, where necessary by multiple aircraft in a close timeframe, to ensure a common baseline.

Initial experience shows that the compensation function works quite well but that there are some unexpected variations in Average Compensated C/No, in the order of 3-5 dB, during turns and subsequent changes in heading.

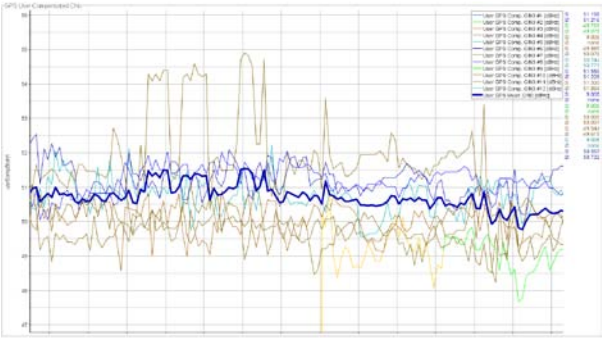

Figure 18 – Azimuth Induced Variations in Average Compensated C/No

While it will never be possible to completely eliminate these effects, it is suspected that some azimuth data in the model is causing overcompensation of the C/No value and that refining the model with additional data from dedicated flight profiles and smoothing processes will improve performance.

Experience gained through further and longer term use of software will drive development of the antenna pattern as warranted.

Important to note is that the goal of any further development will be to reduce the risk of false-positives from the C/No Monitor and not to measure GPS C/No with a specified accuracy.

CONCLUSIONS

From the development and implementation of the C/No Monitor we can make the following conclusions:

1. Implementation of a C/No Monitor provides a useful tool for online detection of GNSS interference such that an appropriate response (such as further investigation) can be considered and carried out in real time
2. Implementation of a C/No Monitor provides a suitable means of compliance with the recommendations of Doc 8071 Volume 2
3. A C/No Monitor provides the basis for Periodic Inspection of the GNSS environment, which can be completed "in the background" of normal Flight Inspection activities and without the need for additional flying
4. Similar techniques to those presented here for GPS could be used to monitor other GNSS signals, such as Galileo, GLONASS or BeiDou for evidence of interference in real time

RECOMMENDATIONS

Based on the experience with the C/No Monitor thus far the following recommendations are offered for consideration:

1. A GNSS C/No Monitor should be considered as "minimum equipment" for all AFIS designs
2. Requirements and guidance material relating to airborne GNSS interference detection, both from a technical capability and reporting perspective should be further defined

FUTURE WORK

The algorithms and functionalities presented in this paper will continue to be refined by FCS, skyguide and Aerodata as operational experience builds. An important future development will be derivation and implementation of the antenna model in preparation for civil use of L2 and L5 frequencies and adaptation of the C/No Monitor such that interference on these frequencies can be identified.

ACKNOWLEDGMENTS

Mr. Manfred Webers (FCS Technical Department) lead the analysis required to develop the GPS antenna models used in the on-line algorithms, and along with the programming efforts of Mr. Volker Logemann (FCS Flight Inspection Department) generated the necessary basis for this research. The AFIS OEM, Aerodata, were able to quickly develop the software in-line with FCS' specifications and implement this new technology.

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