Theory and Practice of the Interference Mitigation Technology (AIM+) in Septentrio Receivers

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BIOGRAPHIES

Tom Willems works as a senior GNSS engineer at Septentrio. He has been involved in GNSS research since 1998. In 2006, he received a Ph.D. degree from the University of Ghent, Belgium. At Septentrio, he is responsible for the development of embedded software for GNSS signal processing in multi-constellation GNSS receivers. He is also involved in the development of Galileo Test User Segment receivers for ESA.

Wim De Wilde received a M.Sc. in electrical engineering from the University of Ghent, Belgium. Upon graduation, he joined the research team at Alcatel Bell. Since 2002 he has worked as a senior R&D engineer at Septentrio. His area of research includes digital signal processing, interference and multipath mitigation and receiver design.

ABSTRACT

Because GPS and other satellite navigation signals as received on ground are of very low power, they are vulnerable to radio-frequency interference. In addition, the radio-frequency spectrum is crowded, and getting more crowded every day. In some cases, the effect of interfering signals is becoming noticeable, particularly in the GLONASS L2 band and the L5 band. Accidental and intentional jamming is also on the rise.

GNSS positioning accuracy ultimately depends on the availability and the accuracy of satellite measurements. When one individual measurement is adversely affected or becomes unavailable due to interference, the advanced positioning engine implemented in most high-end receivers is able to limit the effect on final positioning accuracy. However, a source of interference is likely to affect multiple signals in the same GNSS band and can block reception of a whole GNSS band. In such cases, the effect at the positioning level can be more severe.

Although it depends on the user's application and the employed GNSS receiver (single or multi-frequency, GPS-only or multi-constellation, etc.), it is clear that interference has become a real threat to positioning accuracy and availability. As a result, interference countermeasures form a crucial part of professional GNSS receivers. Septentrio has implemented unique receiver interference mitigation techniques. These countermeasures include: adaptive notch filtering, pulse blanking and GLONASS L2 band remapping. Working in concert, these countermeasures as well as other analog and digital countermeasures form what is known as Septentrio's AIM+ (Advanced Interference Mitigation) technology.

This paper discusses the different categories of interference sources which have been encountered in the field and the methods used by Septentrio in the design of their receivers to alleviate effects for the user. This includes dedicated hardware and software to mitigate continuous wave, narrowband, pulsed and other types of interference. In addition to a description of different mitigation techniques (adaptive notch filtering, pulse blanking and GLONASS L2 band remapping), we provide specific case studies of how each technique has worked in the field. This demonstrates the effectiveness of AIM+ in real world applications. We conclude that, in many cases, positioning accuracy and availability can be maintained by appropriate countermeasures in the analog and digital domain.

INTRODUCTION

Because GPS and other satellite navigation signals as received on ground are about 15 to 20 dB below the thermal noise floor, they are vulnerable to radio-frequency interference. In addition, the radio-frequency spectrum is getting more crowded every day. GNSS receivers have to operate in an increasingly challenging spectral environment, with many extraneous signals present in bands adjacent to or falling within the GNSS bands.

For instance, some aeronautical radio-navigation aids share the radio spectrum with the GNSS L5 band (1176.45 MHz center frequency). DME (Distance Measuring Equipment) and TACAN (Tactical Air Navigation) radio beacons are deployed in the neighborhood of many airfields, and emit high-power pulses which can disturb GNSS receivers using the (new) GPS and Galileo signals in the L5 band. Similarly, part of the GLONASS L2 band overlaps with amateur radio bands in certain countries, potentially causing local loss of signal reception of GNSS receivers – typically high-precision receivers – using this part of the spectrum.

People also disturb GNSS signals unintentionally, or even on purpose. For example, there have been reports of some active maritime television antennas which, due to a flaw in their design, inadvertently turned into GPS jammers [3]. With the proliferation of vehicle tracking systems based on GNSS, and the future expansion of road toll collection systems based on GNSS, it is also likely that the use of illegal GPS jammers will become an increased nuisance in the future.

It is clear that GNSS equipment manufacturers need to develop countermeasures to monitor and eliminate the effects of harmful interference.

EFFECT OF INTERFERENCE ON POSITIONING ACCURACY AND AVAILABILITY

GNSS positioning accuracy ultimately depends on the availability and the accuracy of satellite measurements. When one individual measurement is adversely affected or becomes unavailable due to interference, the advanced positioning engine implemented in high-end receivers is able to limit the effect (if any) on final positioning accuracy. This is facilitated by the large redundancy of measurements, particularly in multi-frequency receivers.

However, a source of interference is likely to affect multiple signals in the same GNSS band and can block reception of a whole GNSS band. In such case, the effect at the positioning level can be more severe. When GLONASS L2 reception would be completely lost, for example, a receiver in GPS+GLONASS dual-frequency RTK mode would have to switch to GPS-only dual-frequency RTK mode, with potentially reduced accuracy as a result. When L2 reception would be completely lost, same receiver would have to fall back to another position mode such as L1-only RTK, DGNSS or even stand-alone mode. For applications requiring an RTK solution, a fallback to a non-RTK mode is equivalent to positioning unavailability.

Although it depends on the user's application and the employed GNSS receiver (single or multi-frequency, GPS-only or multi-constellation, etc.), it is clear that interference is a threat to positioning accuracy and availability. As a result, interference countermeasures form a crucial part of professional GNSS receivers.

CATEGORIES OF INTERFERING SIGNALS

Depending on the signal's bandwidth, an interfering signal may be categorized as being of the continuous wave (CW) type, narrowband or, when its bandwidth is greater than 1 MHz, wideband. Looking at its characteristics in the time domain, an interfering signal may be either non-pulsed (continuous) or pulsed.

A signal may be either in band, partially in band or out of band with respect to the radio-frequency spectrum occupied by GNSS signals. It is important to note that radio-frequency filters in GNSS receivers cannot practically be made to be infinitely selective, so strong "out-of-band" signals adjacent to a GNSS band may still cause concern. A case in point is the controversy surrounding the LightSquared communications provider in the U.S., which proposed to deploy terrestrial base stations transmitting just below the GPS L1 band. While the LightSquared plans ultimately have been barred by regulatory authorities, this example goes to show that spectrum is an increasingly rare commodity.

CATEGORIES OF INTERFERENCE COUNTER-MEASURES

Throughout the whole design of GNSS equipment, possible sources of interference should be taken into account. In the analog domain, interference robustness should be considered in the antenna and receiver radio-frequency design. This includes aspects such as out-of-band rejection performance of filters and saturation avoidance of amplifiers. Careful design at analog level must be followed by countermeasures at digital level. Working in concert, these analog and digital countermeasures should protect against degradation of positioning accuracy and availability due to interference.

In Septentrio equipment, these countermeasures are collectively known as AIM+ (Advanced Interference Mitigation). Below, we describe three techniques which form part of Septentrio's AIM+ technology:

- Adaptive Notch Filtering,
- Pulse Blanking,
- GLONASS L2 Band Remapping.

In addition, diagnostic tools are made available to the user, notably time domain analysis using the ADC sample logging feature and frequency domain analysis using the spectrum analyzer feature.

ADAPTIVE NOTCH FILTERING

The AIM+ adaptive notch filtering feature minimizes the impact of CW and narrowband interference on receiver performance.

A conceptual diagram of the adaptive notch filter is shown in Figure 1. Note that AIM+ can incorporate one or several adaptive notch filters, depending on receiver type. The core of the adaptive notch filter is a digital bandpass filter with adjustable center frequency. The output of the bandpass filter is subtracted from the input signal to obtain a filtered signal. A continuous scan in the frequency domain is performed by software control. The presence of an interferer is detected by comparing the magnitudes of the input signal and the filtered signal (identification stage).

When an interferer is detected, a software-controlled switch (see Figure 1) routes the filtered signal to the remainder of the signal processing engine (suppression stage) instead of the input signal. During the suppression stage, the filter bandwidth is narrowed down and its center frequency is fine-tuned. The magnitude of the original vs. filtered signal is monitored to detect disappearance of the interference at the input. The installation process of the notch filter, including the fine-tuning of its bandwidth and center frequency, is fully automated. If required, user controlled manual operation is also possible.

We now present two case studies which show the effectiveness of adaptive notch filtering for minimizing the impact of CW and narrowband interference on receiver performance.

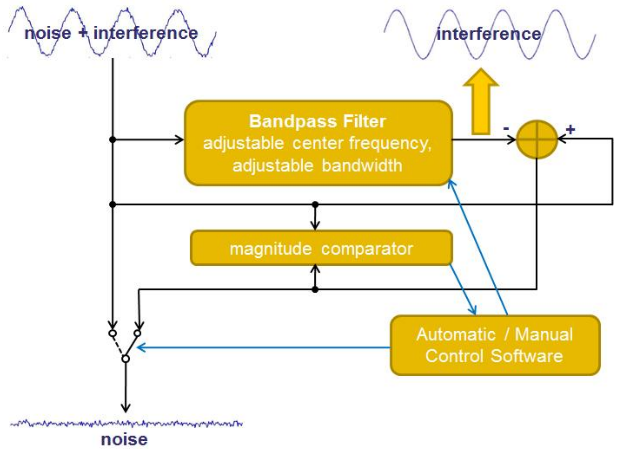


Figure 1. Adaptive notch filtering concept

ADAPTIVE NOTCH FILTERING EXAMPLE: HILVERSUM RADIO TOWER

Following reports that GNSS receivers had trouble maintaining an RTK fix in the region of Hilversum (The Netherlands), Septentrio visited the location to investigate the issue. The problem was traced to a radio tower (see Figure 2) which houses, among others, an amateur radio digipeater with a center frequency of 1240.4 MHz, i.e. a narrowband interferer in the GLONASS L2 band.

Figure 5 shows the L2 radio-frequency spectrum, captured using the receiver's spectrum analyzer feature. The digipeater's signal is clearly visible. With adaptive notch filtering intentionally disabled, Figure 3 shows that the C/N0 of the L2 signal is severely degraded. Figure 8 shows the spectral plot after enabling adaptive notch filtering. It is clear that the adaptive notch filter is able to identify and is actively suppressing the extraneous signal. More importantly, Figure 4 shows that the C/N0 of the L2 signal is much less affected. The residual power drops are due to the very close proximity to the radio tower during the test (less than 100 m) which sporadically caused some saturation of the analog signal chain.

Figure 2. Radio tower in Hilversum (The Netherlands)

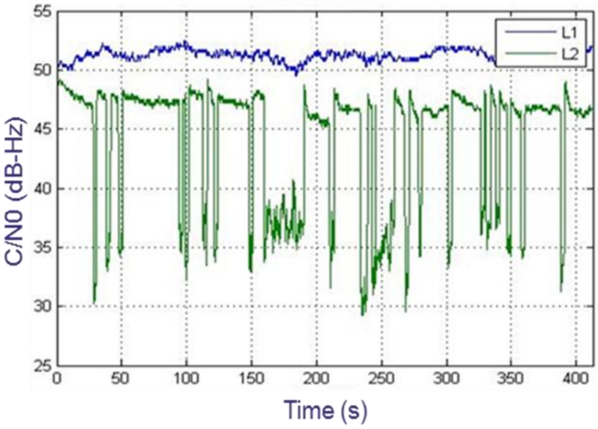


Figure 3. Observed L1 and L2 C/N0 (dB-Hz) (Hilversum, The Netherlands) before enabling adaptive notch filtering, showing significant impairment of L2 C/N0 (shown in green)

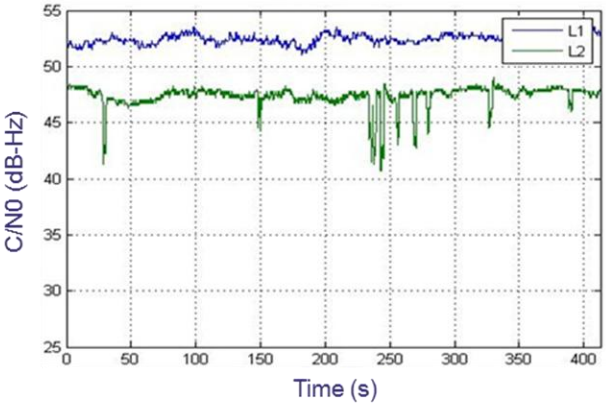
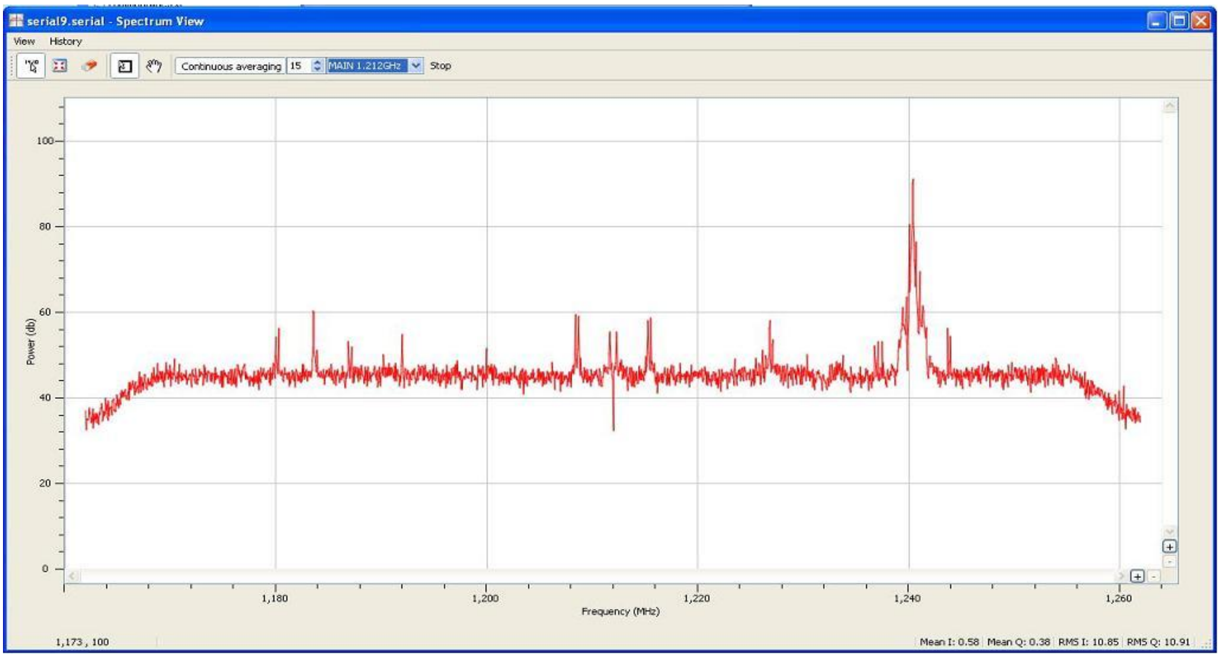


Figure 4. Observed L1 and L2 C/N0 (dB-Hz) (Hilversum, The Netherlands) after enabling adaptive notch filtering



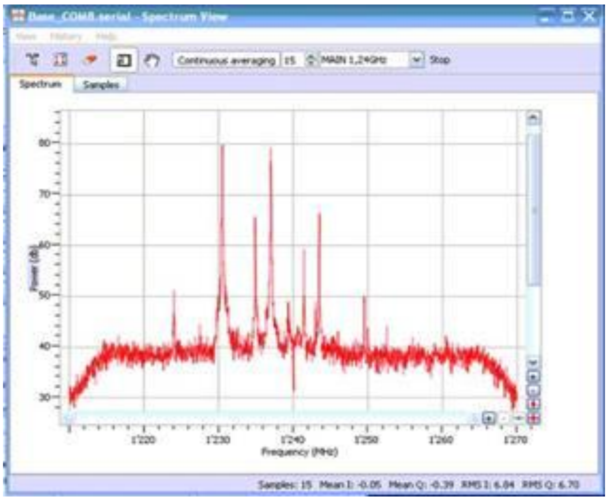
1,173 , 100

Mean I: 0.58 Mean Q: 0.38 RMS I: 10.85 RMS Q: 10.91

Figure 5. Observed L2 spectrum (Hilversum, The Netherlands) before enabling adaptive notch filtering with an extraneous signal clearly visible around 1204 MHz

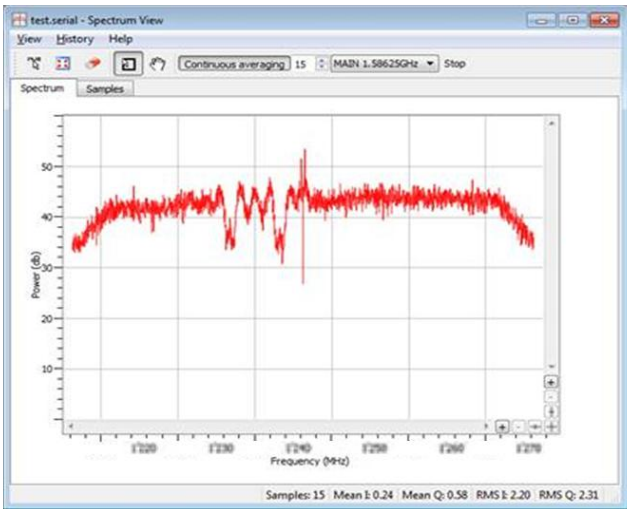
ADAPTIVE NOTCH FILTERING EXAMPLE: PRECISION AGRICULTURE IN RUSSIA

Near Tuymen in Russia, a local farming community was equipping their equipment with high precision (RTK) GPS systems for auto steer and precision farming applications. To that end, they had also set up a local base station. However, when they were trying to bring up the service, rovers receiving data from this base station were unable to obtain an RTK position. When activating adaptive notch filtering, cm-accurate positioning became possible. Figure 6 shows that strong interference sources were present which, as shown in Figure 7, were largely suppressed by multiple adaptive notch filters.



Samples: 15 Mean I: -0.05 Mean Q: -0.39 RMS I: 6.84 RMS Q: 6.70

Figure 6. Spectral plot captured in Tuymen (Russia) before applying adaptive notch filtering

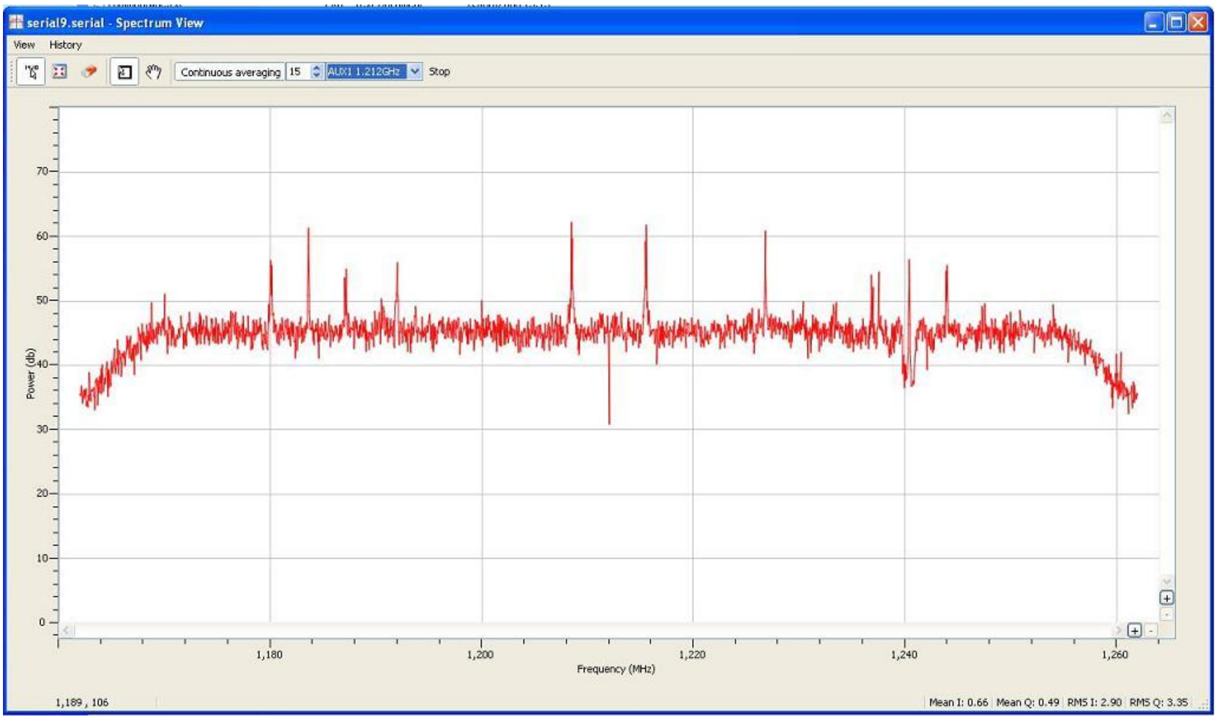


Samples: 15 Mean I: 0.24 Mean Q: 0.58 RMS I: 2.20 RMS Q: 2.31

Figure 7. Spectral plot captured in Tuymen (Russia) after applying adaptive notch filtering, showing strong attenuation of the extraneous signals

PULSE BLANKING

The AIM+ pulse blanking unit minimizes the impact of pulsed interference on receiver performance. The pulse blanking unit triggers whenever a pulsed signal arrives at the receiver's input and prevents it from passing into the tracking/measurement engine of the receiver. The pulse blanking unit is highly responsive by design and tuned such that the input signal is inhibited for the duration of the pulse only, as detailed below.



Continuous averaging 15 AUX1 1.212GHz

1,189 , 106

Mean I: 0.66 Mean Q: 0.49 RMS I: 2.90 RMS Q: 3.35

Figure 8. Observed L2 spectrum (Hilversum, The Netherlands) after enabling adaptive notch filtering, showing strong attenuation of the extraneous signal

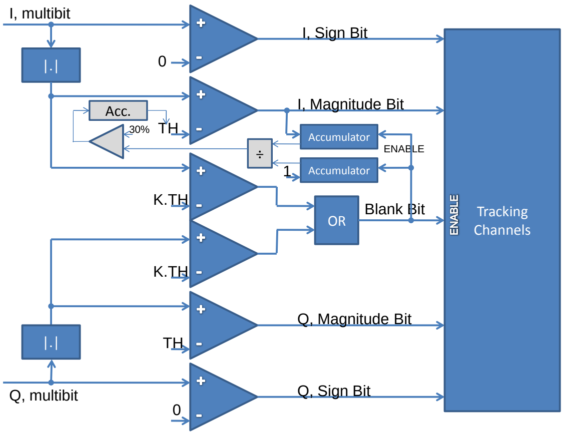


Figure 9. Pulse blanking circuit

Figure 9 shows the pulse blanking circuit. The pulse blanking unit works on a sample-by-sample basis: individual samples are compared against a specific threshold and discarded when the threshold is exceeded. The pulse-blanking circuit uses the multi-bit signal before its conversion into 2-bit sign/magnitude data streams. This conversion of a multi-bit value to a magnitude bit is done through comparing the signal against a threshold TH. The threshold TH is automatically adjusted to keep the duty cycle of the magnitude bit during the interference-free periods at a level of 30% [1]. The interference detection is triggered if a multi-bit value exceeds K·TH. If that occurs, the pulse blanking is activated and the correlators are disabled to avoid the integration of noise. The value of K can be set to either 2 or 4. It has been shown in [4] that the value of 2 is preferred because the functioning of the quantization scheme as a whole is more reliable, although this results in a minor loss of signal power (about 0.2 dB; see [4]) due to greater probability of false alarm.

The pulse blanking unit mitigates pulsed interference in an effective and robust way. We now present results from a field test of the pulse blanking unit in the presence of DME signals near airports.

PULSE BLANKING EXAMPLE: DME INTERFERENCE NEAR AIRPORTS

The GNSS L5 band (1176.45 MHz center frequency) belongs to a wider band allocated to aeronautical radio-navigation services. Aeronautical DME beacons (Distance Measuring Equipment) and TACAN beacons (Tactical Air Navigation) also operate in the same band. These ground-based transponders, which are installed at nearly all major airports worldwide, transmit high-power pulses to airborne equipment.

Figure 10 shows DME pulses observed in close vicinity of the “BUB” beacon at Brussels Airport (Belgium) as captured using the receiver’s ADC sample logging feature. Figure 11 shows that the observed pulses fall directly inside the GNSS L5 band. The DME pulse pair shown in Figure 10 has a pulse width of 3.5 µs and pulse separation of 12 µs. These pulse pairs are typically repeated at a rate of 2700 pulse pairs per second.

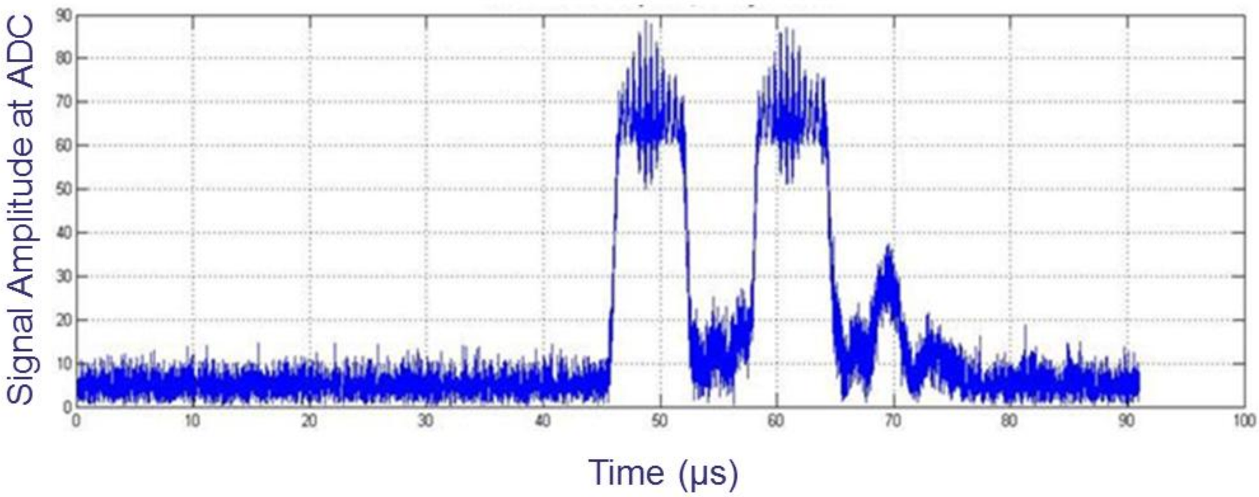
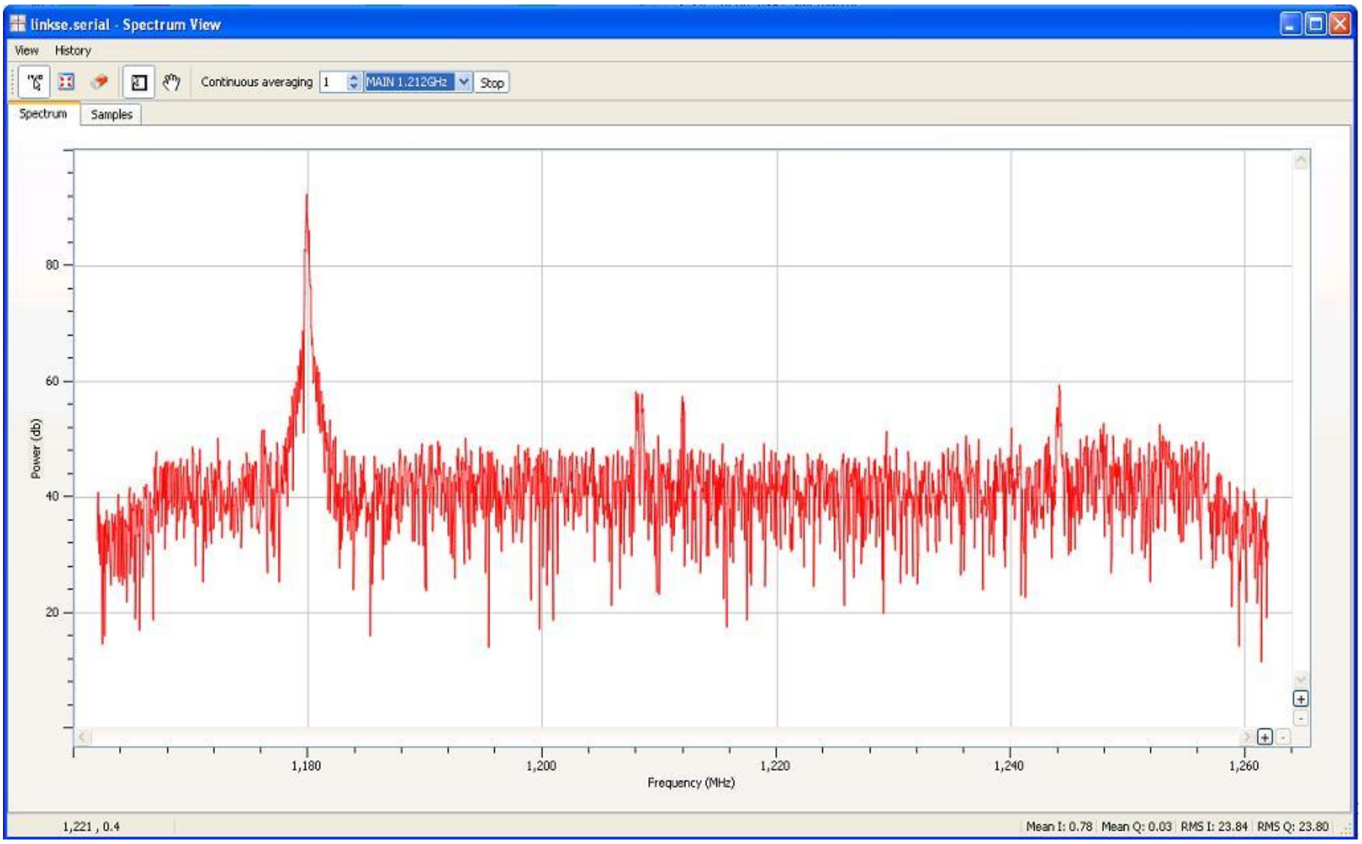


Figure 10. Time domain plot of a pulse pair observed near DME beacon BUB (Brussels Airport)



Continuous averaging 1 MAIN 1.212GHz

1,221 , 0.4

Mean I: 0.78 | Mean Q: 0.03 | RMS I: 23.84 | RMS Q: 23.80

Figure 11. Spectral plot captured near DME beacon BUB (Brussels Airport)

The pulse blanking unit, once enabled during the test, reported a blanking percentage of about 3%, as expected. While such a low jamming percentage would not significantly degrade receiver operation, it does show that the pulse blanking unit is operational. Similar results were obtained during a field test near the “HUL” DME beacon (Huldenberg, Belgium).

Although not observed during the field tests, a batch of synchronized responses to different airplanes can be transmitted, increasing the jamming percentage. The situation is even worse for airborne receivers due to a much greater number of visible beacons. On board an airplane cruising at an altitude of 10 km, DME transmissions can be received from beacons at distances up to 400 km. With aircraft flying over densely populated regions, the interference might reach unacceptable levels [2]. Hence, in an airborne environment, the use of pulse blanking is vital for the operation of L5 GNSS receivers. In general, the pulse blanking unit is considered indispensible to ensure undisturbed receiver operation in the vicinity of DME/TACAN beacons.

GLONASS L2 BAND REMAPPING

GNSS receivers supporting GPS+GLONASS L2 usually cover both bands with a single analog L2 reception chain. However, the GLONASS L2 band is more prone to interference than the GPS L2 band. This is particularly the case in the frequency range above 1240 MHz which is shared with, among others, the amateur radio service.

In case of severe GLONASS L2 interference (for example, multiple high-power wideband signals), the entire L2 reception chain may become unusable. To prevent the loss of GPS L2 in case of severe GLONASS L2 interference, a special feature which remaps the L2 reception chain was developed. When this GLONASS L2 band remapping feature is enabled, the center frequency of the receiver's GPS+GLONASS L2 digital filter is decreased such that GPS L2 remains fully usable while the GLONASS L2 band is blocked. See Figure 12 for a graphical depiction.

This feature, while considered an option of last resort, can be very useful because the availability of L2 measurements is of crucial importance to many users. When severe GLONASS L2 interference is present, the GLONASS L2 band remapping feature in many cases is able to restore L1+L2 RTK, albeit in GPS-only mode.

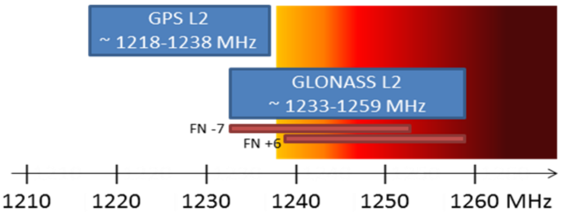


Figure 12. Frequency range of GPS and GLONASS L2 bands; when GLONASS L2 band remapping is enabled, signals in the frequency range indicated by the gradient are attenuated

GLONASS L2 BAND REMAPPING EXAMPLE: WIDEBAND INTERFERENCE IN OSTEND

Several times a week, construction and piling work on the dyke in Ostend (Belgium) had to be interrupted, as all GNSS signals were heavily disturbed. Investigation of the type and source of interference revealed wideband interference in the 1250 MHz region (see Figure 13), originating from radio/TV amateur equipment nearby. This interference in the GLONASS L2 band was so significant, that it spilled over into the GPS L2 band as well, and rendered all precision work requiring dual-frequency measurements impossible.

The GLONASS L2 band remapping feature effectively filtered out all harmful signals. While this also eliminates all GLONASS L2 signals, the resulting behavior makes dual-frequency GPS signals available again, and normal operation can resume. Figure 14 shows that dual-frequency L2 GPS signals are available (blue and red bars in the top panel of Figure 14), while for GLONASS only L1 signals are available (green bars in the bottom panel of Figure 14).

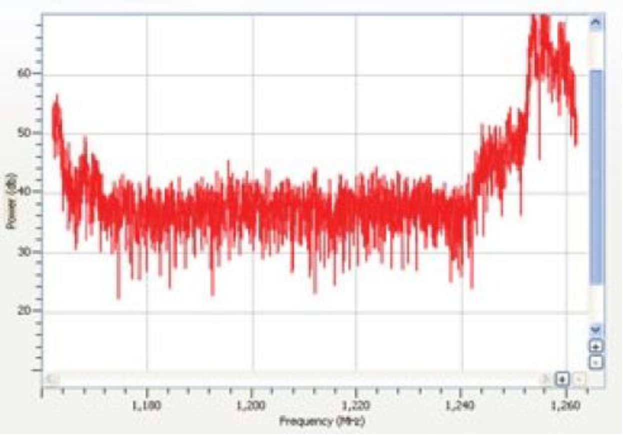


Figure 13. Spectral plot captured in Ostend (Belgium)

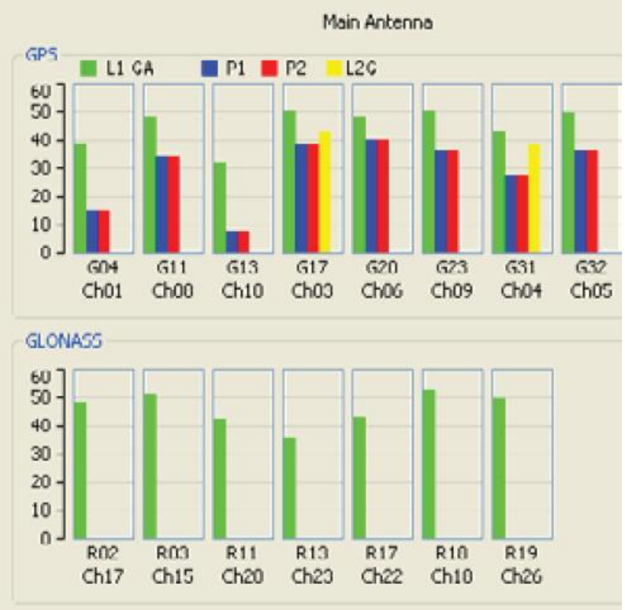


Figure 14. GPS and GLONASS C/N0 (dB-Hz) observed in Ostend (Belgium) after enabling the GLONASS L2 band remapping feature

COMPLEX INTERFERENCE SCENARIOS

Reviewing the categories of interfering signals and interference countermeasures described above, continuous wideband interference covering a whole GNSS band remains a concern. In case the GLONASS L2 band is jammed, the GLONASS L2 band remapping feature can be activated.

The increasing diversity of frequency bands employed by existing and upcoming GNSS constellations helps to mitigate the effects of interference on positioning accuracy and availability. Multi-frequency multi-constellation receivers tracking signals in a multitude of bands (L1, L2, L3, E5a, E5b, E6, etc.) can continue to operate, possibly with reduced performance, when one of the bands is jammed.

Another evolution which contributes to interference resistance is the fact that an increasing number of GPS satellites transmit the L2C signal which, in contrast to L2P, can be tracked independently. While loss of GPS L1P implies loss of GPS L2P reception (and vice versa), L2C can continue to be tracked in case the L1 band is jammed. As additional GPS satellites with L2C capability become available in the future, the availability of GPS L2 measurements will increase in case of L1 interference.

Continuous wideband interference over all GNSS bands (500 MHz wide) is rather unlikely. However, to further increase interference robustness, there is a clear industry trend towards hybridization with other sensors. The Septentrio AsteRxi receiver, for example, processes GNSS measurements with IMU measurements to generate an enhanced integrated position.

CONCLUSION

Maintaining positioning accuracy and availability in the presence of radio-frequency interference constitutes a serious challenge. Septentrio’s AIM+ technology addresses this challenge by a range of countermeasures in the analog and digital domain. Three techniques which form part of AIM+ have been described: adaptive notch filtering, pulse blanking and GLONASS L2 band remapping. The case studies presented above demonstrate the effectiveness of these techniques in real-world conditions. In many cases, thanks to the dedicated AIM+ hardware and software, positioning accuracy and availability can be maintained in the presence of interference.

REFERENCES

[1] Van Dierendonck, A.J. (1996). GPS Receivers. In *Global Positioning System: Theory and Applications*, Vol. 1, Ch. 8, pp. 352-355. American Institute of Aeronautics and Astronautics.

[2] Hegarty, C., Kim, T., Ericson, S., Reddan, P., Morrissey, T. & Van Dierendonck, A.J. (1999). Methodology for Determining Compatibility of GPS L5 with Existing Systems and Preliminary Results. In *Proc. 55th Annual Meeting of the Institute of Navigation*, pp. 635-644.

[3] Clynch, J.R., Parker, A.A., Adler, R.W., Vincent, W.R., McGill, P. & Badger, G. (2002). Multiple GPS RFI Sources in a Small California Harbor. In *Proc. 15th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 2002)*, pp. 605-612.

[4] Simsky, A., De Wilde, W., Willems, T., Mertens, D., Koitsalu, E. & Sleewaegen, J.-M. (2009). First Field Experience with L5 signals: DME Interference Reality Check. In *Proc. 22nd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2009)*, pp. 29-37.