

Demonstrated Interference Detection and Mitigation with a Multi-frequency High Precision Receiver

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BIOGRAPHY

Feng Gao is the Principal Systems Engineer for core receiver cards at NovAtel Inc. She received the B. Sc. and M. Sc. degrees in Electronic Engineering from Tianjin University, and her second M. Sc. degree in Electrical Engineering from the University of Saskatchewan. Her current work involves GNSS receiver RF architecture, systems analysis and design, systems engineering and integration. In the past, she has worked for over 15 years on 2G, 3G and 4G radio systems in the wireless communication industry.

Sandra Kennedy is the Chief Engineer for core receiver cards at NovAtel Inc. She received her B.Sc. and M.Sc. in Geomatics Engineering from the University of Calgary, in 2000 and 2002 respectively. She has been employed by NovAtel since 2004, working in the research and GNSS/INS product groups prior to leading the core card team. Her focus has primarily been on high precision positioning under difficult GNSS conditions.

ABSTRACT

GNSS interferers come in many forms and classifications. Some are intentional, purpose built in-band jammers, but many are unintentional, originating from sources such as radio, TV, wireless communication and radars. Unquestionably, interference to GNSS is increasing in an increasingly wireless world and as GNSS is built into more systems there is more opportunity for self-generated interference. At the same time, there are many more signals beyond GPS L1 to utilize, from receiving satellite broadcast correction data below 1559 MHz to receiving E6 signals from Galileo. The pass bands of GNSS receivers must expand to support all the frequencies of navigation interest, which inherently exposes them to more risk of interference. Receiver designs must become more sophisticated to offer the full set of signals while also mitigating interference impacts.

Using real data produced from NovAtel receivers, the effect of the various interference types is shown, both in controlled laboratory test setups and in real life examples

of typically encountered interference issues. Methods to detect the interference are also demonstrated in those examples. Finally, the efficacy of the mitigation methods is presented. It is shown that the characteristics of a high precision receiver can be maintained while functioning in the presence of interference with mitigation measures running.

INTRODUCTION

While the methods to mitigate interference are well known from a theoretical perspective, implementing them in a practical receiver design requires careful consideration of how much the detection and mitigation methods drive the overall system design in terms of power consumption, CPU usage, and increased size to accommodate additional components. A practical high precision GNSS receiver must be able to mitigate interference while still providing all the functionality it normally does, such as centimetre level RTK positioning with multiple frequencies at high rates, all while staying within reasonable power and size budgets.

This paper illustrates that setting the receiver to an optimal condition and redistributing the receiver gain via an enhanced system gain control mechanism reduces the generation of in-band intermodulation products when interference is present, resulting in higher interference tolerability. It will be demonstrated that the additional bits from higher resolution analog to digital conversion (ADC) allows the receiver to handle both strong interference and a weak signal (below thermal noise for GNSS) at the same time, improving the receiver dynamic range in the presence of interference. This allows for the effective application of digital filters to further mitigate in-band and out-of-band interference.

RECEIVER ARCHITECTURE

We begin with a high level review of the architecture of a high precision GNSS receiver [1]. A simplified GNSS receiver block diagram is shown in the following figure.

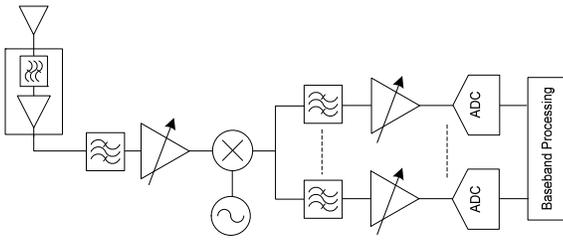


Figure 1 Simplified GNSS Receiver System Block Diagram

A good quality active antenna (with built-in low noise amplifier LNA) is typically paired with a high precision GNSS receiver, which sets the receiver system noise floor; the received analog signal is filtered, amplified, down converted, and digitized into digital domain for further processing. The receiver front end gain is controlled automatically via a feedback control loop (automatic gain control AGC) to maintain the optimum input signal level into the analog to digital converter. Then the signal is decimated, and the opportunity for further digital filtering exists prior to the GNSS processing, where the raw signal becomes a measurement.

The receiver replicates the satellite PRN codes and correlation process identifies the SV PRN in the incoming signals and keeps tracking of the code for every satellite; at the same time, the receiver also replicates the satellite carrier frequency and Doppler to acquire and maintain the carrier phase lock with the incoming carrier. Both code and phase acquisition and tracking produce the pseudorange and carrier phase measurements which are used to generate position, velocity and time solutions within GNSS receivers.

Typically, a single antenna receives all signals supported, the output of which feeds a multi-frequency GNSS receiver where the analog signal is split into radio frequency (RF) and intermediate frequency (IF) paths that are filtered to contain just the frequency bandwidth of a specific GNSS signal or a set of GNSS signals. The ADC sampling rate must be at least twice that of the final IF bandwidth to prevent aliasing as per Nyquist's theory. In practice, the sampling rate should be higher than the minimum to provide some transition band for analog anti-aliasing filtering. One of the first considerations when choosing the number of RF/IF paths needed in a receiver design is what rate the ADCs can run at and how much power is consumed. Other considerations include the cost of components in each path, as well as the amount of space each one requires.

The ideal frequency response of the receiver is a step function: a perfectly flat pass band with unity gain, no transition band, and a perfectly flat stop band with zero gain. This ideal can never actually be realized. It is an engineering challenge to get as close to the ideal as

possible, with constrained cost, size and power consumption.

To deal with interference, filtering is an excellent mitigation method. The usual use of filtering is in the analog domain, selecting hardware (HW) components that make the roll of the pass band as sharp as possible. There are filters at the antenna, at the RF path of the receiver, and within the IF path as well. These HW filters prevent out of band effects from sneaking through the receiver, but they cannot prevent in band interferences. When the interference becomes close to the pass band, filtering to provide a very sharp roll off becomes large, lossy and impractical, as well as introducing longer delays.

The other type of filtering that can be used is digital filtering to deal with unwanted signals within the passband. Some digital filtering can produce closer to ideal frequency response with sharper roll off and smaller transition band. Again, there are limitations here. Firstly, you can't filter out an unwanted signal that lies directly on top of your signal of interest. You can tolerate losing some of the GNSS signal bandwidth, but not the majority of it. Secondly, the linearity (i.e. the receiver's ability of keeping a clean, flat pass band from non-linear distortion products) must be maintained so that the digital filters have a predictable and desired effect. Finally, the in band interference level must be at a low enough strength that it has not overwhelmed the signal of interest.

The presence of interference (strong signal) requires that additional bits from higher resolution ADCs such that a strong interference and a weak GNSS signal (typically below thermal noise) can be handled at the same time. Receiver dynamic range is the measure of a receiver's ability to handle a range of signal strengths from the weakest to the strongest. The receiver dynamic range (DR) can be extended by utilizing a high dynamic range ADC. A high precision GNSS receiver is a special type of digital communication receiver with a focus on measuring carrier phase rather than recovering high rate data. It follows similar interference blocking phenomena as in digital communication, perhaps more sensitive due to the traditional nature of recovering the weaker GNSS signals below thermal noise.

While the lower end of the dynamic range is determined by the sensitivity of the receiver, the higher end of the dynamic range drives the higher receiver linearity. This allows the receiver to handle the increased interference power going through the receiver stages such that distortion products due to components nonlinearity are minimized or reduced and the interference can be processed in digital domain.

However, both higher linearity front end and higher dynamic range data converters drives higher power

consumption in the system, which is contradictory to the general trend towards lower power consumption in GNSS receivers.

In the absence of interference, the thermal noise and receiver internal noise is the dominant signal so that the ADC output probability density function is of a Gaussian shape. Past study [2] has shown that the ADC number of bits can be 1, 1.5, or 3, where the maximum quantization gain from 1-bit ADC to 3-bit ADC is about 2.5dB; further increasing ADC bit does not significantly improve the performance of GPS signals tracking and acquisition. While increasing the number of bits used does not improve GNSS performance in noise only environment, having a wide range of bits to choose from can enhance GNSS receiver performance under interference environment, especially when the gain is being adjusted to accommodate incoming signal levels.

If a strong interferer falls inside the analog IF bandwidth, it can overload or saturate the last stage amplifier or ADC. This results in the generation of in-band intermodulation products and can result in significant degradation of the desired signal. Similarly, a strong interferer falling outside of the analog IF bandwidth could push the receiver RF front end into saturation or generate intermodulation distortion products (especially when interference is wideband) falling inside the analog IF passband, and potentially landing in the passband after decimation, which will be difficult to remove.

In these scenarios, large signal levels are detected at the ADC and the receiver gain can be re-distributed by reducing the pre-conversion analog gain and increasing the digital gain to maintain the desired signal output level.

Since the mixer and the last stage IF amplifier is the weakest link for the receiver frontend under strong interference conditions, it's important to improve the device linearity and protect the device from being overdriven. In strong interference conditions, gain control at the RF stages will provide more protection for the receivers from being driven into non-linear state. From the RF LNAs, to the IF amplifier, to the ADCs, the goal is to keep the signal levels in the middle of the operational range of each device, where there is the least distortion/loss.

For a practical system design, it's important to balance the supported signals and the potential interference presence and to distribute the filtering protection throughout the receiver system to get the best trade-off between size, power, and performance. NovAtel's OEM7 generation of GNSS receivers realizes such a design that can operate in low power mode when in benign conditions, and then be software (SW) re-configured to operate under interference conditions by increasing the front end linearity, realigning

the system gain at different stages to correctly capture the incoming GNSS signals, and selectively applying digital filters. This combination of mitigation methods is referred to as High Dynamic Range (HDR) mode throughout this paper.

INTERFERENCE EFFECTS

A traditional GNSS receiver is designed to be very sensitive to recover GNSS signals below the thermal noise. GPS L1 CA signal power on earth ranges from -120dBm to -130dBm, 10^{-15} to 10^{-16} W. It does not take much interference power to impact the receiver noise floor within its pass band, causing receiver desensitization. Considering a frequency source with a transmit EIRP (Effective Isotropic Radiated Power) of 200mW, like a typical mobile handset power level from 3G/4G wireless network, located one kilometer away from a GNSS receiver system, the power at the GNSS system antenna will be attenuated by ~100dB (assuming free space propagation path loss), leaving the power level seen at the GNSS antenna to be 4×10^{-11} W, which is still ~10000 times higher than GNSS signal level.

If the interference power is strong enough, the receiver tracking loops will have cycle slips, lock breaks and lock loss, which will have direct impact to positioning domain, particularly carrier phase based positioning methods. A user will observe changes in the C/No reported, such as overall reduction in C/No levels and/or rapidly fluctuating C/No values. The user will also observe many lock breaks and have difficulties acquiring GNSS signals. Close examination will also reveal an increase in carrier phase standard deviation as well. Cycle slips and frequent lock breaks will prevent a precise carrier phase based positioning solution (RTK or PPP) from being achieved.

Different types of interference will have similar observed effects on the receiver, in terms of tracking behavior. This makes it very difficult to diagnose what type of interference is present, and choosing a mitigation method can often be a trial and error process.

INTERFERENCE TYPES

Regardless of the source, interference can be categorized into three main types. From frequency location, some are located inside the receiver pass band (in-band), some are outside of the receiver pass band (out of band); from spectrum domain, some are continuous wave (CW), some are narrow band (NB), some are wide band (WB); in time domain, some interference can be pulsed. Pulsed interference impact is not as severe due to the integration nature of the GNSS receivers. NovAtel OEM receivers can handle larger pulsed interference by default, and additional capability can be enabled by a digital pulse

blanking technique in digital signal processing and is not covered in this paper.

DETECTION METHODS

Being able to view the frequency spectrum as the receiver experiences it is a very powerful tool to diagnose what type of interference is present. The spectral analysis tool onboard the OEM7 provides the power spectrum computed via FFT (Fast Fourier Transform) at different stages of the signal processing chain; pre-decimation; post decimation; and post digital filter if one is enabled, as shown in Figure 2.

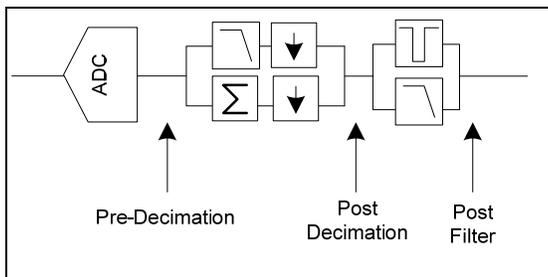


Figure 2 Spectral Analysis Tool Output Points

The spectrum analysis runs continuously on OEM7 receivers to monitor the environment.

A human can examine frequency spectrum plots and discern interference effects fairly easily, which is why the spectral analysis tool and visualization program are provided to the user. For the receiver to be able to detect interference autonomously, the shape recognition done so easily by a human must be distilled into machine logic, with sufficient checks to confirm that the detection is accurate.

A reference spectrum and an adjustable threshold are used for interference detection. The FFT method can be quite sensitive to the presence of narrow band and some wideband interference. However, it's not sensitive to the out-band interferences located far away from receiver pass band or any broadband noise interferences that generally raise receiver noise floor. Using a proprietary mechanism on OEM7, the receiver input power level is monitored via a factory receiver calibration; and the input power level beyond the receiver expected operating conditions is raised as warning for user attention including the potential presence of interferences.

Other artifacts in the signal processing chain can give an indication of interference presence as well. Under normal/healthy conditions, the probability density distribution after ADC should be approximately Gaussian. Under interference conditions, this is no longer true and with a high number of bins, a non-Gaussian distribution is

detectable and can be used to further confirm harmful interference levels.

MITIGATION METHODS

With the presence of interference confirmed, appropriate mitigation methods must be applied. As part of Interference Tool Kit, programmable filters are available to sharpen the roll-off beyond the GNSS signal pass bands. The best interference mitigation is achieved with NovAtel's high dynamic range mode, which is a combination high dynamic range ADCs, higher linearity of the receiver frontend, and a low pass filter with sharp roll off applied after decimation. Depending on the type of interference encountered, some or all of the mitigation methods are required.

TEST SETUP AND RESULTS

To illustrate the efficacy of the mitigation methods, three practical examples of interference are presented: in-band continuous wave, out of band narrow band, and out of band wide band. Since GPS L1 is the most familiar signal to most users, the frequency band around 1575.42 MHz is examined in all three examples. The mitigation methods can be applied to all GNSS signals tracked by OEM7 receivers.

The general test setup is shown in Figure 3. Receivers in each test track live GPS signals from NovAtel standard pin wheel antennas (GPS-703-GGG) mounted on stationary posts with known coordinates on NovAtel's roof in Calgary, Alberta. The GPS-703-GGG is a wideband antenna supporting triple frequency GPS (L1, L2, L5) and GLONASS (L1, L2, L3), and dual frequency Galileo (E1, E5a/b) and BeiDou (B1, B2). Interference signals are produced by a Keysight Vector signal generator and introduced into the system at the receiver RF input. The unit under test is the OEM719, which supports GPS (L1 C/A, L1C, L2C, L2P, L5), GLONASS (L1 C/A, L2C, L2P, L3), BeiDou (B1, B2, B3), Galileo (E1, E5 AltBOC, E5a, E5b, E6), and QZSS (L1 C/A, L1C, L2C, L5, L6), in addition to L-band for the receipt of correction services.

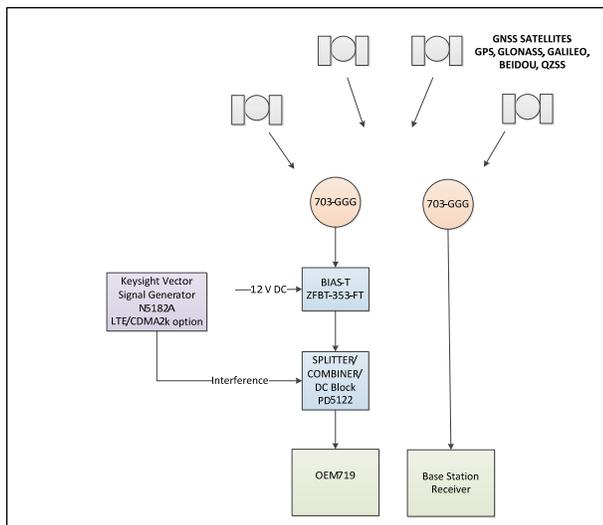


Figure 3 Test Setup

For each test case, the type of interference is described and the receiver performance in the presence of the interference with and without mitigation measures is presented.

Receiver performance is characterized by the reported C/No, the number of satellites tracked, and positioning error from both differential carrier phase and standalone pseudorange positioning modes. The average C/No for all GPS L1 signals tracked at each second is presented, along with the number of GPS L1 measurements that are phase locked and have known parity. A short baseline (5 m) differential carrier phase real-time kinematic (RTK) solution is estimated using GPS L1 and semi-codeless L2P measurements from the base station receiver (free of interference) and the OEM719 (with interference injected at receiver input). The 3D position errors of the RTK solution are computed with respect to the known coordinate of the antenna location. The single point, or autonomous, pseudorange position of the OEM719 under test is also computed, with the 3D position error computed and presented in the same way the RTK position solution.

For reference, a normal C/No for a GPS L1 measurement ranges from about 45-55 dB-Hz at elevation angles of more than 40 degrees and varies by fractional dB-Hz from epoch to epoch. GPS L1/L2 RTK 3D accuracy over a 5 meter baseline should be less than 1 cm, 1 sigma. The typical accuracy of GPS L1/L2 single point solution is governed by atmospheric conditions, but is generally less than 3m varying over time by on the order of decimeters, notwithstanding constellation changes and high multipath conditions.

The frequency spectrum as measured by the OEM719 receiver is also shown, to verify the presence of the

interferer and to show the impact of the mitigation measures.

IN-BAND CW INTERFERER

An in-band CW interferer is often unintentionally created when a GNSS receiver is integrated with other electronics that produce frequencies of their own. For example, the CPU clock of a processor within the same enclosure as the GNSS receiver could be running at a frequency that is in band, either directly or through a harmonic. Another potential of sources of in-band interference comes from harmonics of communication signals, e.g. 12th harmonics of 230 VHF communication channels or second harmonics from 3GPP E-UTRA band class 14, whose uplink (UL) is designated between 788 to 798MHz.

At GPS time of week 22046 seconds, an in-band CW interferer located at 1582.5 MHz with -44 dBm strength is injected at the receiver input. Viewing the power spectrum output by the receiver in Figure 4, one can see the expected spike on the right hand side of the GPS L1 signal.

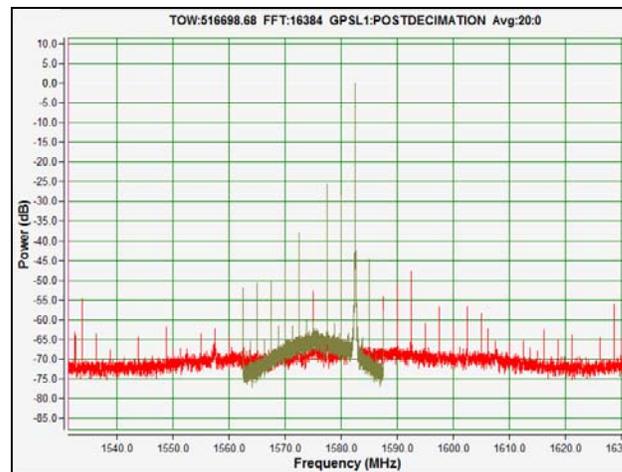


Figure 4 Power Spectrum at Pre-Decimation (red) and Post Decimation (green) with -44dBm CW Interference

The average GPS L1 C/No drops by more than 10 dB-Hz to the low 30s, and fluctuates by about 2 dB-Hz, as shown in Figure 5 below.

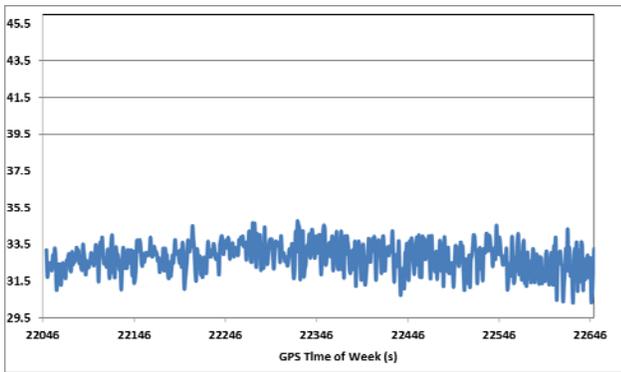


Figure 5 Average GPS L1 C/No (dB-Hz) With In-band CW Interference

The number of satellites tracked with known parity and phase lock achieved is shown in Figure 6.

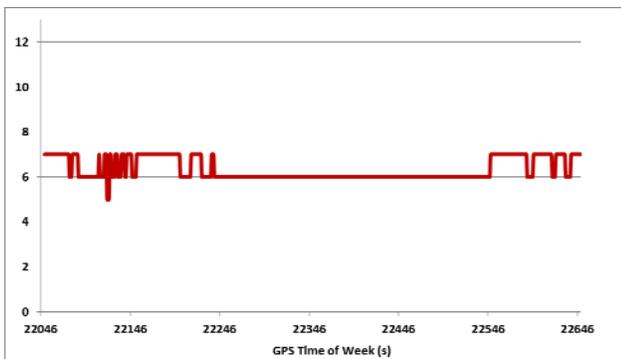


Figure 6 Number of GPS Satellites Tracked with In-band CW Interference

An RTK position solution is achieved, but the accuracy is impacted, with the 3D errors well above 1 cm, as can be seen in Figure 7, when they are expected to be under 1 cm. The 1-sigma standard deviation reported by the receiver (shown in red), accurately reflects the positioning error. The pseudorange position errors and reported standard deviation are also increased, as shown in Figure 8.

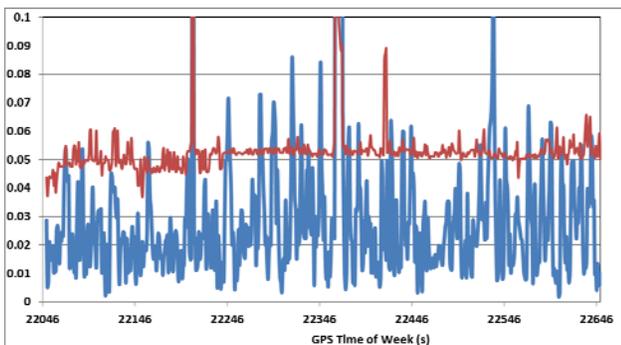


Figure 7 3D RTK Position Error (m, blue) and Reported Standard Deviation (m, red) with In-band CW Interference

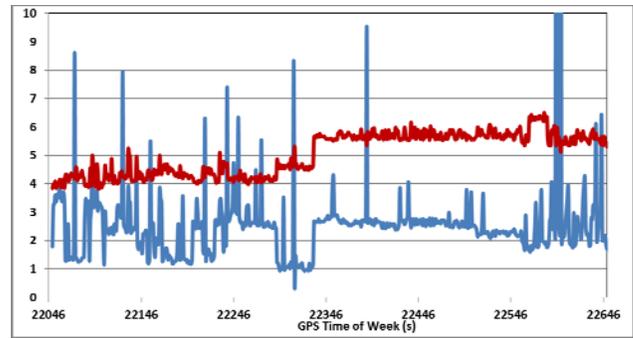


Figure 8 3D Pseudorange Position Error (m, blue) and Reported Standard Deviation (m, red) with In-band CW Interference

The receiver is then configured to use HDR mode, and to apply a notch filter 1 MHz wide, centered at 1582.5 MHz. Figure 10 shows the pre-decimation and post-filter spectrum with the new configuration active. The CW interferer is still present in the pre-decimation but it is suppressed in the post-filter view. Due to their design, the notch filters are symmetric about the central frequency of the signal path, which is GPS L1 at 1575.42 in this case. Also note the improved linearity (i.e. flatness) of the L1 signal in Figure 9 as compared to Figure 4.

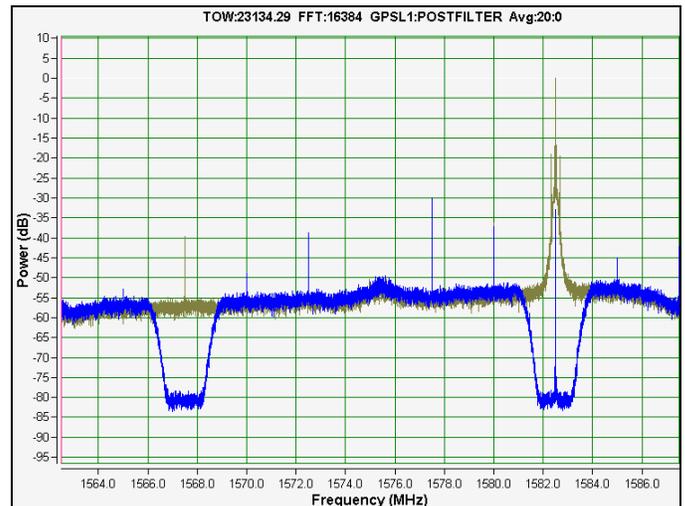


Figure 9 Power Spectrum at Post Decimation (green) and Post Filter (blue) with -44dBm CW Interference Mitigated with HDR Mode and Notch Filter

Applying the notch filter and using HDR mode for the L1 and L2 signals increased the power consumption of the receiver by 0.23 W. The average C/No recovers to the mid-40 dB-Hz range, as does the number of satellites tracked, rising from 6 to 12.

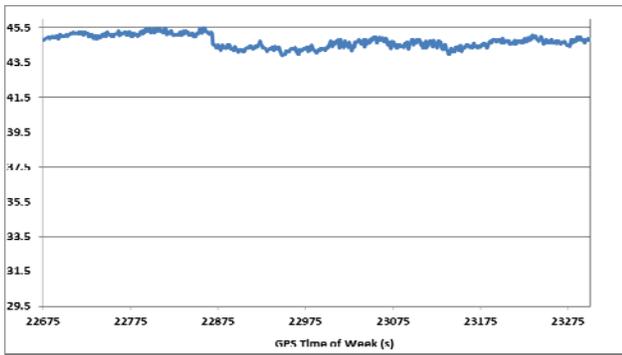


Figure 10 Average GPS L1 C/No (dB-Hz) With Mitigated In-band CW Interference

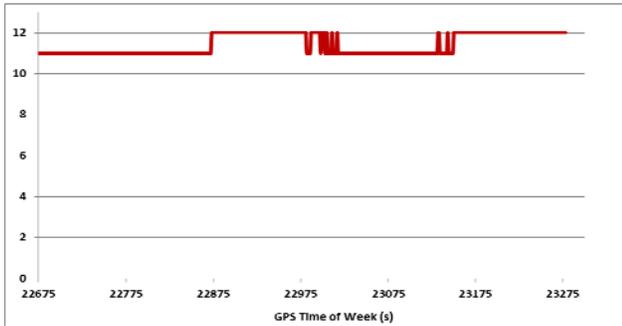


Figure 11 Number of GPS Satellites Tracked with Mitigated In-band CW Interference

With the signal quality restored on the full complement of available satellites, the positioning performance also recovers to the expected level, shown in Figure 12 and 13 for an open sky environment for both RTK and autonomous pseudorange solutions.

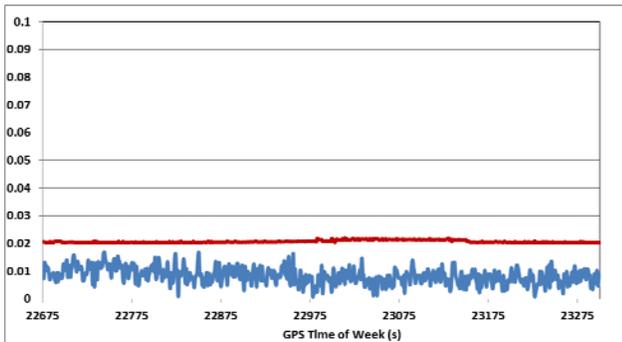


Figure 12 3D RTK Position Error (m, blue) and Reported Standard Deviation (m, red) with Mitigated In-band CW Interference

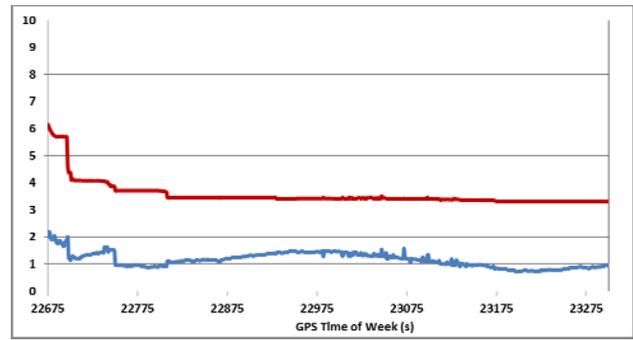


Figure 13 3D Pseudorange Position Error (m, blue) and Reported Standard Deviation (m, red) with In-band CW Interference

OUT OF BAND NARROWBAND INTERFERER

A narrow band interferer just outside the pass band of GPS L1 can leak into the pass band and degrade signal tracking performance to the point that precise positioning is not possible. A potential source of this type of interference is the Globalstar satellite communication service. Globalstar uses Qualcomm CDMA2000 technology to offer low rate data and voice communication using a network of LEO satellites. The telephone service is useful for remote locations without cellular service, while the two way data service is widely used for commercial facility control and remote data transmission. Systems requiring this type of communication service often employ GNSS receivers as well, and the simplest mitigation method is to separate the antennae by 10m or more, but this not always possible.

In this test setup, 1.2288MHz BW CDMA2000 signal at 1625MHz is used, which closely resembles the real world Globalstar interference, and a 1-3 meter separation between the GNSS and Globalstar antenna was emulated.

The -14dBm interference power is applied at OEM719 input at GPS time 359072 second. Viewing the spectrum as experienced by the receiver in Figure 14, the effect of the Globalstar signal is evident in the pre-decimation view of the IF path. The large bump at 1625 MHz is the power of the CDMA2000 signal. The rest of the pre-decimation spectrum shows the distortion from this strong signal, slanting upwards towards the interferer. The GPS L1 signal power spectrum is dished downwards.



Figure 14 Power Spectrum Pre-Decimation (red) and Post Decimation (green) View with Out of Band Narrowband Interference

As in the CW interferer test case, the average GPS L1 C/N₀ is depressed to values in the low 30s.

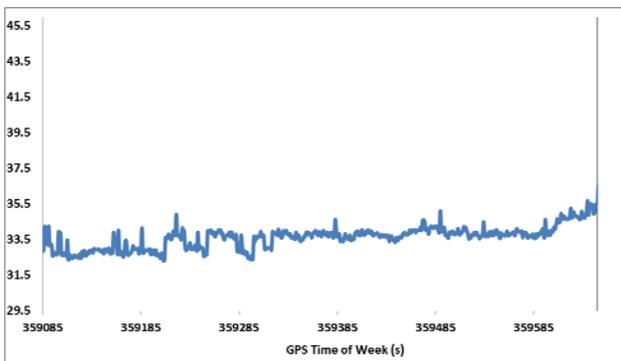


Figure 15 Average GPS L1 C/N₀ (dB-Hz) With Out of Band Narrowband Interference

Viewing the time series of number of satellites tracked under the out of band narrowband interference shown in Figure 15, one can see the receiver is struggling to acquire satellites but cannot maintain them, moving from 4 to 6 satellites at a given epoch.

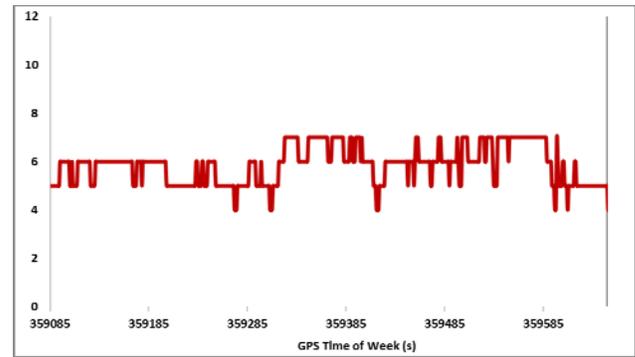


Figure 16 Number of GPS Satellites Tracked with Out of Band Narrowband Interference

Recall that measurements from a minimum of five satellites are required to resolve ambiguities. An RTK position is achieved, but its errors are unacceptably high, as shown in Figure 17. This poor quality RTK solution is due to poor positioning geometry, as evidenced by the reported standard deviation accurately following the error. An incorrect ambiguity fix would not show in the reported standard deviation, but would show in the actual measured errors. The RTK solution is still possible at the epochs with only 4 satellites tracked because previously solved ambiguities will continue to be used with the remaining satellites. When the number of satellites tracked increased to six for a sustained period of time near the end of the period of unmitigated interference, the RTK solution re-initializes to a solution with improved quality but it is still not meeting typical performance specifications.

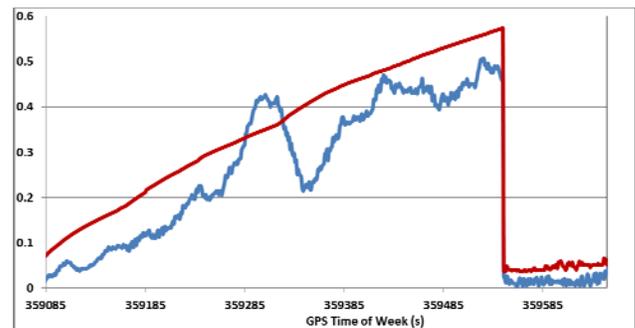


Figure 17 3D RTK Position Error (m, blue) and Reported Standard Deviation (m, red) with Out of Band Narrowband Interference

The pseudorange solution shows similar behavior in Figure 18, with the standard deviations spiking and stepping with constellation changes.

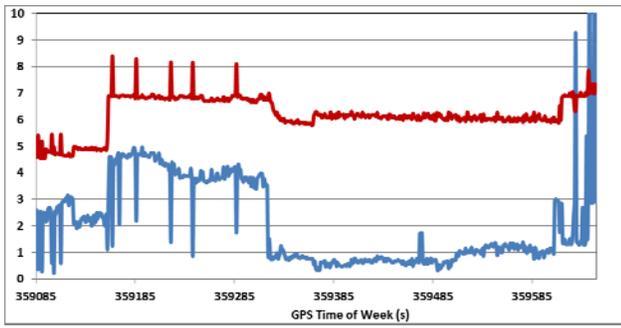


Figure 18 3D Pseudorange Position Error (m, blue) and Reported Standard Deviation (m, red) with Out of Band Narrowband Interference

At GPS time 359700 s, the receiver was configured to use HDR mode. Applying HDR mode to the L1 (and L2) signals increased the power consumption of the receiver by 0.2W.

The power spectrum with HDR mode on shows the interference suppression in the frequency domain in Figure 19. The distortion in the pre-decimation output of the full IF path (in red) is greatly reduced, as compared to Figure 14. The GPS L1 power spectrum (in green) also shows much less distortion.

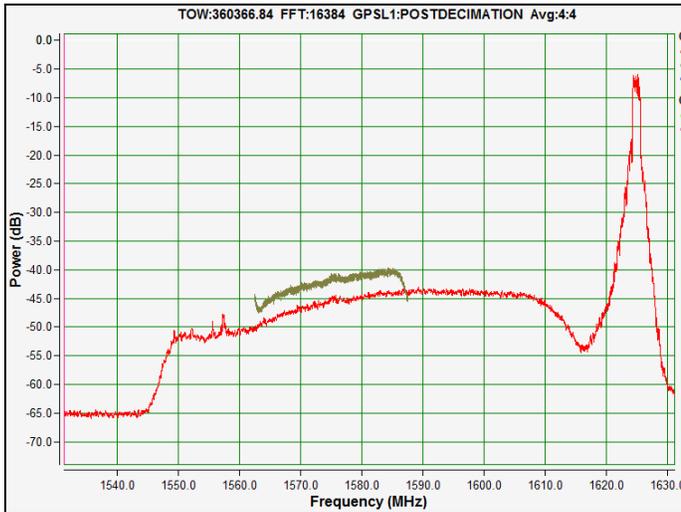


Figure 19 Power Spectrum Pre-Decimation (red) and Post Decimation (green) View during Out of Band Narrow Band Interference with HDR Mode Enabled

With HDR mode on, the average C/No in Figure 20 is still below the expectation of high 40s for this test setup without interference present; however, the increase of approximately 4 dB-Hz is significant. Most importantly Figure 21 shows the number of satellites tracked has recovered to 10, from just 4-6 when the interference was un-mitigated.

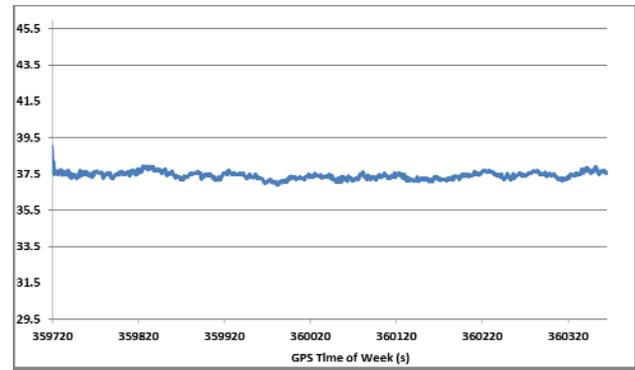


Figure 20 Average GPS L1 C/No (dB-Hz) with Mitigated Out of Band Narrowband Interference

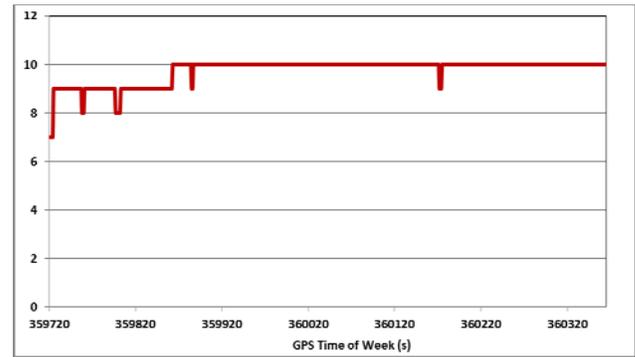


Figure 21 Number of GPS Satellites Tracked with Mitigated Out of Band Narrowband Interference

The positioning view confirms that the mitigation has been effective. Figure 22 shows the RTK 3D position errors are at the centimetre level with strong geometry reflected in the low reported standard deviation. In Figure 23, the pseudorange positioning errors are also as expected for an open sky environment.

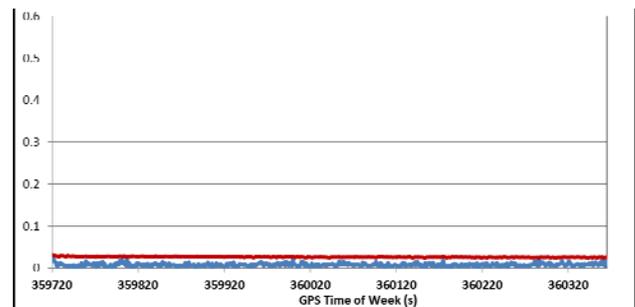


Figure 22 3D RTK Position Error (m, blue) and Reported Standard Deviation (m, red) with Mitigated Out of Band Narrowband Interference

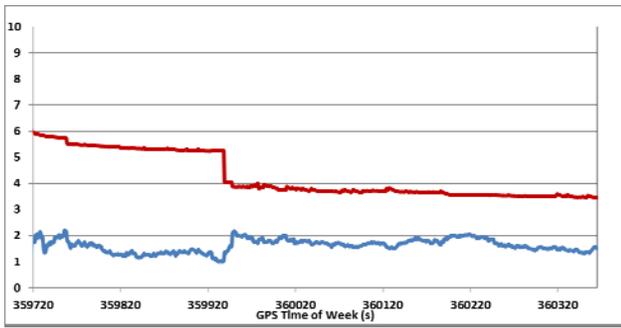


Figure 23 3D Pseudorange Position Error (m, blue) and Reported Standard Deviation (m, red) with Mitigated Out of Band Narrowband Interference

OUT OF BAND WIDEBAND INTERFERER

A 10MHz LTE signal was generated using Agilent signal generator with LTE Option, centered at 1625 MHz to emulate the potential interference from 4G wireless communication handsets. The interference was injected at the receiver input at strength of -28dBm at GPS time 414,415 s.

In this case, the power spectrum plot in Figure 24 shows the severe effect the out of band wideband interference receiver. The pre-decimation view shows the full IF and how this wide band OOB interferer is manifesting within the pass band, with interfering power spread across the pass band. The post-decimation view shows that the GPS L1 signal is no longer discernible, with the small bump of the main signal lobe completely obliterated by the interferer power.

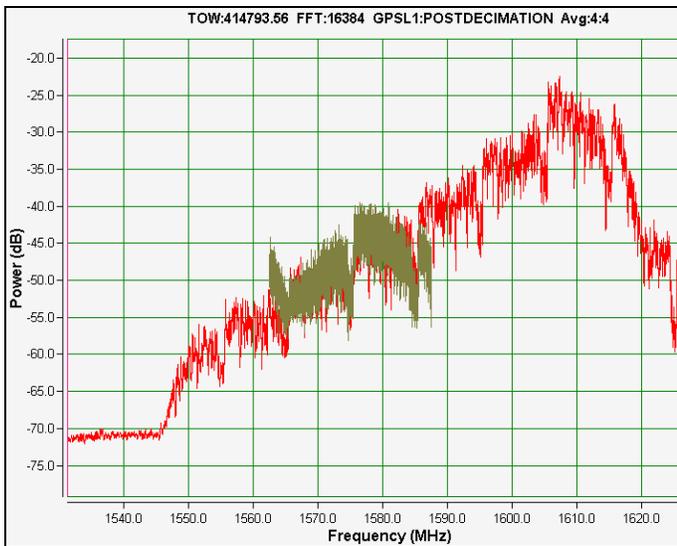


Figure 24 Spectrum at Pre-Decimation and Post Decimation with -28dBm 10MHz LTE Interference

Not surprisingly, the average C/No in Figure 25 is also low and computed over just 3 satellites tracked as shown in Figure 26.

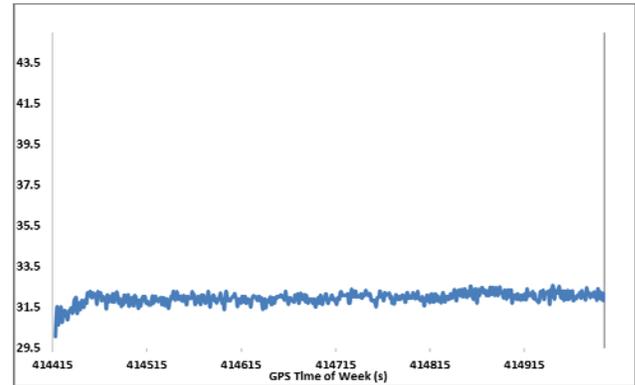


Figure 25 Average GPS L1 C/No (dB-Hz) with Out of Band Wideband Interference

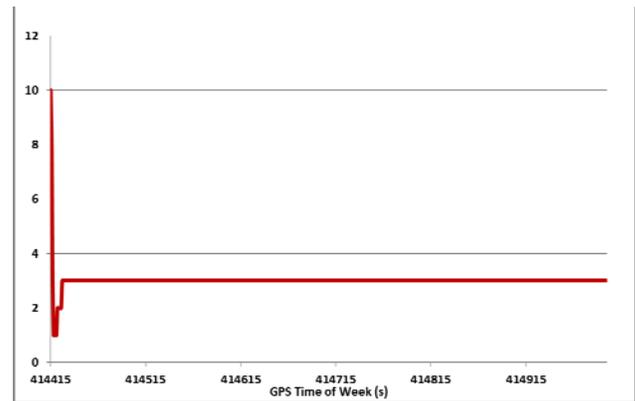


Figure 26 Number of GPS Satellites Tracked with Out of Band Wideband Interference

With only 3 satellites tracked, the receiver cannot provide any type of 3D positioning solution, neither RTK nor pseudorange based.

To combat this severe interference, the receiver is configured to use HDR mode at GPS time 415033 second. The power spectral analysis in Figure 27 shows the dramatic improvement in receiver performance, particularly in the post-decimation view that is processed to become the GPS L1 measurements. The GPS L1 main lobe signal power is evident again in the small bump at 1575.42 MHz, and the linearity is vastly improved.

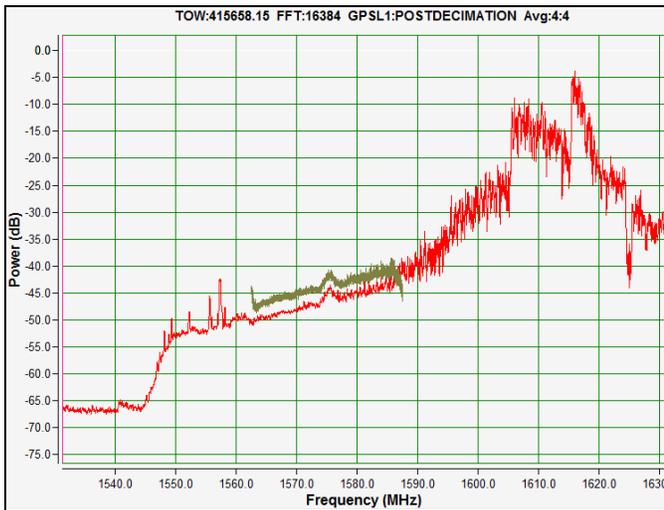


Figure 27 Spectrum at Pre-Decimation (red) and Post-Decimation (green) with -28dBm 10MHz LTE Interference when HDR Mode is Enabled

Returning to the measurement domain, the C/No has rebounded to the expected healthy range (in Figure 28), and the number of satellites tracked is normal again as shown in Figure 29.

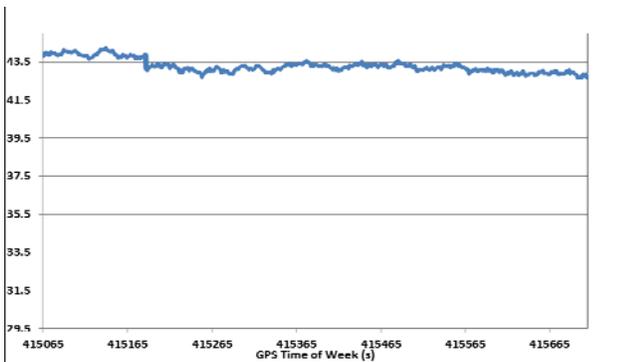


Figure 28 Average GPS L1 C/No (dB-Hz) with Mitigated Out of Band Wideband Interference

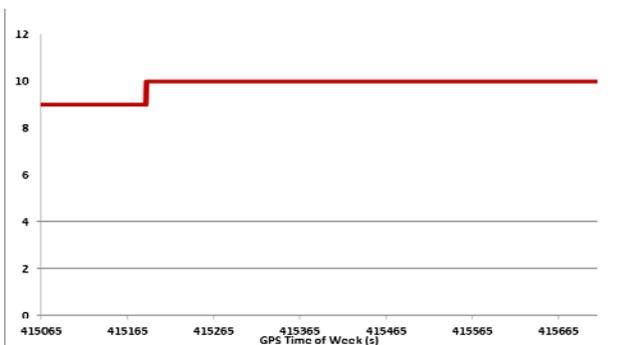


Figure 29 Number of GPS Satellites Tracked with Mitigated Out of Band Wideband Interference

Enabling HDR mode increased the power consumption of the receiver by 0.2W for GPS L1 and L2 signals.

With 10 satellites tracked, a centimeter level RTK solution is achieved, as shown in Figure 30 below. Figure 31 shows the pseudorange positioning error which is also healthy and as one would expect for an open sky, low multipath environment.

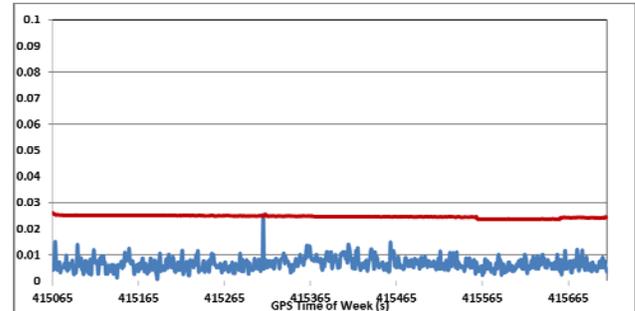


Figure 30 3D RTK Position Error (m, blue) and Reported Standard Deviation (m, red) with Mitigated Out of Band Wideband Interference

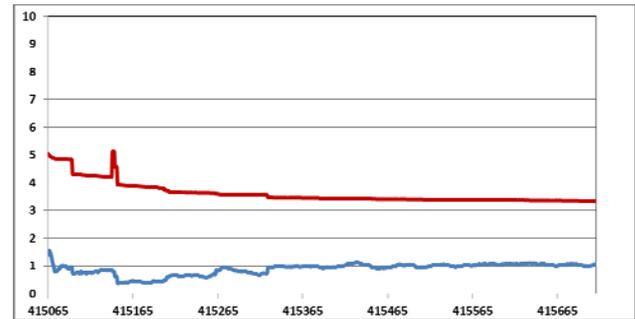


Figure 31 3D Pseudorange Position Error (m, blue) and Reported Standard Deviation (m, red) with Mitigated Out of Band Wideband Interference

DISCUSSION AND CONCLUSIONS

The receiver performance illustrated in the plots in the previous section are summarized in Table 1 through 3 for each of the interference test cases.

Table 1 Summary of Receiver Performance Before and After Mitigation with In-band CW Interference

| | | Before | After |
|-----------------------------------|-----------|--------|-------|
| SV Tracked | Avg. | 6.3 | 11.5 |
| | Std. Dev. | 0.8 | 0.4 |
| C/No (dB-Hz) | Avg. | 32.8 | 44.7 |
| | Std. Dev. | 0.8 | 0.4 |
| | Max. | 0.235 | 0.017 |
| RTK 3D Position Error (m) | Avg. | 0.029 | 0.008 |
| | Std. Dev. | 0.028 | 0.003 |
| | Max. | 0.235 | 0.017 |
| Pseudorange 3D Position Error (m) | Avg. | 2.52 | 1.16 |
| | Std. Dev. | 1.35 | 0.27 |
| | Max. | 20.46 | 2.19 |

Table 2 Summary of Receiver Performance Before and After Mitigation with Out of Band Narrowband Interference

| | | Before | After |
|--|------------------|--------|-------|
| SV Tracked | Avg. | 5.7 | 9.7 |
| C/No (dB-Hz) | Avg. | 33.7 | 37.4 |
| | Std. Dev. | 0.8 | 0.3 |
| RTK 3D Position Error (m) | Avg. | 0.221 | 0.008 |
| | Std. Dev. | 0.171 | 0.004 |
| | Max. | 0.508 | 0.025 |
| Pseudorange 3D Position Error (m) | Avg. | 2.24 | 1.62 |
| | Std. Dev. | 2.92 | 0.24 |
| | Max. | 60.93 | 2.19 |

Table 3 Summary of Receiver Performance Before and After Mitigation with Out of Band Wideband Interference

| | | Before | After |
|--|------------------|--------|-------|
| SV Tracked | Avg. | 3.0 | 9.8 |
| C/No (dB-Hz) | Avg. | 32.0 | 43.3 |
| | Std. Dev. | 0.8 | 0.4 |
| RTK 3D Position Error (m) | Avg. | N/A | 0.007 |
| | Std. Dev. | N/A | 0.002 |
| | Max. | N/A | 0.025 |
| Pseudorange 3D Position Error (m) | Avg. | N/A | 0.89 |
| | Std. Dev. | N/A | 0.20 |
| | Max. | N/A | 1.56 |

Table 4 shows the power consumption for the OEM719 in default and HDR modes of operation, in two tracking configurations: the GPS L1/L2 configuration used in the test cases, and a general configuration tracking all signal types supported. The in-band CW mitigation also employed a notch filter, which consumed an additional 0.025 W.

Table 4 OEM719 Power Consumption

| | Default | HDR Mode |
|--------------------|---------|----------|
| GPS L1/L2 | 1.3 W | 1.5 W |
| All Signals | 1.8 W | 2.4 W |

In all three test cases, the indicator to the user that interference was present was reduced tracking capability, in both the number of satellites tracked and the quality of the signals tracked as indicated by the reduced C/No, which ultimately manifested in a poor quality or unavailable position solution. The power spectrums computed and output in each test case showed how the interferer affected the spectrum sensed by the receiver, and the effect is quite different depending on the type of

interferer. For a system integrator, this is valuable information to determine if the problem is self-generated and what the likely interference source is.

HDR mode is a powerful mitigation tool, allowing the receiver to perform equivalently under interference as it does when no interference is present. At a cost of 0.2 W in power consumption to apply to GPS L1 and L2, a centrimetre level RTK solution is available, when no solution at all was possible in the case of the out of band wideband interferer without enabling HDR mode.

In the in-band CW interference case, the combination of the notch and HDR mode was necessary to achieve high performance levels. The notch filter alone is useful when the CW interferer is weak, but when the interferer is strong enough to cause distortion across the pass band, the increased linearity provided by HDR mode is key for the notch filter to be able to cleanly suppress the CW interferer.

REFERENCES

- [1] E. D. Kaplan and C. Hegarty, Understanding GPS: Principles and Applications, Artech House Publishers, 2nd edition, 2005
- [2] H. Chang 'Pre-sampling, Filtering, Sampling and Quantization Effects on the Digital Matched Filter Performance', Proceedings of the International Telemetry Conference, 1982, pp. 889-915