Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
	)	
Office of Engineering and Technology	)	ET Docket No. 17-340
Seeks Comment on Technological Advisory	)	
Council Spectrum Policy Recommendations	)	
	)	

REPLY COMMENTS OF LIGADO NETWORKS

Ligado Networks LLC ("Ligado") takes this opportunity to once again commend the Commission for considering the spectrum management guidance and principles that the Technological Advisory Council ("TAC") has recommended. Ligado submits these Reply Comments to respond to the statements by one commenter that the Commission should not apply the core TAC spectrum management principles to GNSS receivers, and that such receivers should not be required to tolerate signals that cause a greater than 1dB decrease in C/N_0.[1]

The suggestion that the Commission should in essence exempt certain devices from rigorous and scientific-based spectrum management analysis runs directly counter to the TAC Principles, which emphasize that effective spectrum usage requires effective spectrum management, that spectrum management determinations should be grounded in empirical analysis, and that spectrum management metrics should be robust and reliable. More specifically, as explained below, application of a 1dB decrease in C/N_0 as a measure of harmful interference is entirely inconsistent with these tenets.

One of the primary problems with the 1dB decrease in C/N_0 metric is that it does not correlate with the purpose of a GPS device: to report position, velocity, and time outputs. The

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[1] *See* Comments of GPS Innovation Alliance, ET Docket No. 17-340 (filed Jan. 10, 2017).

supposed "shortcut" of looking for a 1dB decrease in C/N_0 may have been understandable in the 20th Century, but today's metrics and technology are much more sophisticated and can examine what users actually care about: is the device working as intended and providing me with the information I need? Recognizing the rapid pace of innovation and technologic advancement, Ligado has repeatedly advised policymakers to examine how a GNSS device reports position error in the presence of adjacent band utilization as the metric for evaluating device response.[2]

The scientific evidence is clear: a small change in the noise floor (or 1dB decrease in C/N_0) does *not* correlate with a change in the ability of a GPS device to report accurately its position or timing information.[3] In the ordinary course of their operation, GPS devices experience changes in the noise floor significantly greater than 1 dB and yet still function smoothly.[4] These changes in C/N_0 values may be caused by any number of sources, including antenna gain, trees, ionospheric scintillation, and/or urban canyons. More fundamentally, the testing evidence available to the Commission shows there is a stochastic (*i.e.*, random) relationship between reports of position error and a 1 dB change in the noise floor.[5]

[2] *See* Letter from Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 12-340 (Oct. 13, 2015) (responding to Garmin's 1 dB proposal); Letter from Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 12-340 (Oct. 26, 2013) (incorporating comments on Department of Transportation ("DOT") draft test plan contesting 1 dB proposal). *See also* Letter from Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 11-109 (June 5, 2017) at 14, 21-27 (discussing use of 1 dB in DOT testing).

[3] *See e.g.*, William F. Young et al., *LTE Impacts on GPS Final Report, National Advanced Spectrum and Communications Test Network* (Feb. 15, 2017), http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1952.pdf ("NASCTN Test Results"); Roberson and Associates, LLC, *Results of GPS and Adjacent Band Co-Existence Study*, IB Docket No. 11-109 (May 11, 2016), *available at* https://ecfsapi.fcc.gov/file/60001841466.pdf ("RAA Test Results"); Reply Comments of Ligado Networks LLC, IB Docket No. 11-109 (filed June 6, 2016), at 11-14, Attachment B ("Ligado Reply Comments"). The NASCTN Test Results, RAA Test Results, and Ligado Reply Comments are incorporated herein by reference.

[4] *See* Ligado Reply Comments, *id.* at Attachment B, at 3-6.

[5] *See* NASCTN Test Results, RAA Test Results, *supra* note 3.

In fact, most of the errors in commercial GPS devices are caused predominantly by elements completely independent of C/N_0. Significant factors affecting position, velocity, and time inaccuracy include the GPS device's local environment and the atmosphere on any particular day. For example, inaccuracies could result from GPS satellites and the GPS ground control system; multipath fading; and delay in the signal's path from satellite to receiver caused by changes in the troposphere, including temperature, pressure, and humidity. These components are independent of changes in C/N_0, and in typical operating conditions, play a much greater role in GPS error than do changes in C/N_0.

Furthermore, changes in C/N_0 are not how GPS manufacturers speak to their customers in their product warranties and not how consumers purchase and use the products.[6] The GPS manufacturers' own commitments to their customers offer powerful evidence of consumer expectations with respect to the accuracy of GPS devices. GPS companies do *not* warrant to their customers they will not experience a 1 dB change in C/N_0. Instead, they focus on the metric of harm that matters: the positional accuracy of their devices. Accordingly, the notion that GNSS devices should be required to tolerate only a 1dB change in the noise floor is contrary to sound useful spectrum management guidelines.

Indeed, the evidence shows that GPS device manufacturers are confident in the resiliency of their devices. Consistent with the TAC Principles' point that transmitters and receivers must share responsibility for interference mitigation, GPS device manufacturers have recognized the

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[6] *See e.g.*, Garmin GPSMAP 76 CSx Owner's Manual, *available at* http://static.garmincdn.com/pumac/GPSMAP76CSx_OwnersManual.pdf (last visited Feb. 14, 2018); Lassen IQ GPS Module Product Brochure, *available at* ftp://ftp.trimble.com/pub/sct/misc/bin/Exact%20Imaging%20Folder%2010_07/LasseniQ/022542-006A_LasseniQ_DS_0907%20US_hr.pdf (last visited Feb. 14, 2018); Deere RTK Radio 450 Key Features, *available at* https://www.deere.com/en_US/products/equipment/ag_management_solutions/displays_and_rec.

increasingly dense spectrum environment and have chosen to improve their devices to mitigate interference and other threats. As one such manufacturer has stated:

> Radio interference is everywhere. GSM, LTE, FM broadcast radio, VHF/UHF communications, Wi-Fi, satellite phones and GNSS signals are all competing for a finite space on an already heavy populated radio spectrum…. At Septentrio, we devote considerable attention to interference throughout the design of our equipment. Working with customers over many years to solve real problems, we have developed Advanced Interference Mitigation (AIM+). These algorithms counteract the effects of interference.[7]

Innovations such as these have resulted in smaller, less expensive, and more resilient receivers that are capable of both tolerating adjacent band operations and resisting intentional interference from jammers and similar devices.[8]

Given this forward progress in technology, a suggestion that GPS receivers should be entitled to a special type of protection against more than a 1 dB decrease in the noise floor seems very backward-looking. Not only does that metric have no correlation with position accuracy, but it also has no standard method of measurement. As testing by the federal government's scientists at NASCTN observed, GNSS devices not only report different changes in C/N_0 when faced with the *identical* spectrum environment, but different devices ***by the same manufacturer*** report different changes in C/N_0.[9] It is wholly inconsistent with the focus of the TAC's

[7] Septentrio, *Targeting Interference with AIM+* (Dec. 15, 2015), http://www.septentrio.com/insights/targeting-interference-aim (last visited Feb. 14, 2018).

[8] *See, e.g.*, Ian T. McMichael, Erik Lundberg, Drayton Hanna, and Steven Best, MITRE Corporation, *Horizon Nulling Helix Antennas for GPS Timing* (2017) (describing a "helix" antenna system for GPS timing devices capable of resisting interference from both unintentional and intentional sources of interference) (Attachment A hereto). *See also* Septentrio, *Data Quality: from Tracking to Archiving with no Gaps*, IGS Workshop 2017 at 11 (graphic demonstrating that Septentrio GNSS receivers can coexist with GNSS-adjacent operations without the need for filters that could affect device performance) (Attachment B hereto).

[9] *See* NASCTN Test Results, *supra* note 3, at 271-275.

Principles on data-driven analysis and transparency that a party would propose the Commission adopt a yardstick when there is no industry agreement on the length of that yardstick.

In sum, these issues demonstrate that relying on the 1 dB change in C/N_0 metric would effectively block any meaningful spectrum usage because that metric is based wholly on theoretical concerns rather than real-world performance and is wholly unpredictable and unreliable. Accordingly, the Commission should adopt the TAC Principles as proposed in our initial comments and reject attempts to dilute the impact of these important spectrum management concepts.

Respectfully submitted,

/s/ Gerard J. Waldron
Gerard J. Waldron
Ani Gevorkian
Counsel to Ligado Networks LLC

February 15, 2017

<u>Attachment A</u>

Horizon Nulling Helix Antennas for GPS Timing

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***Abstract*— Global Positioning System (GPS) antennas installed at fixed site infrastructure are susceptible to interference incident along the direction of the horizon. In this paper, a series of quadrifilar helical antennas are presented for the application of GPS timing. The first antenna employs a novel method of reactive loading along the length of the multi-turn helix. The phase distribution along the helix creates a deep null in the gain pattern at the horizon while maintaining sufficient beam width in the zenith direction. The horizon null minimizes ground based interference. The second antenna achieves similar performance by varying the pitch of the helix arms along the length of the antenna. The third antenna operates over L1 and L2 frequencies using concentric helices. A novel method is presented to decouple the concentric helices based on distributed trap circuits along the length of the helix arms, which preserves the horizon nulling patterns at both frequencies. The proposed antennas offer improved performance over previous horizon-nulling designs. Additionally, the proposed antennas can be manufactured at a lower cost compared to other interference mitigating antennas based on the simple architecture.**

Keywords—helical antenna; GPS; interference suppression

I. Introduction

Global Positioning System (GPS) antennas are frequently used for accurate timing reception from satellite constellations for a variety of applications where synchronization and timing is required. Example applications include wireless telephone and data networks, digital broadcast radio, time-stamped business transactions, distributed instrument networks, and power grids [1]. GPS timing antennas at fixed site infrastructures are susceptible to unintentional inference, such as out-of-band and multipath signals, as well as intentional interference from ground based sources [2].

In this paper, multiple quadrifilar helix antennas are presented for the application of GPS timing. The significant feature of these antennas is a null in the gain pattern at the horizon and around all azimuth angles to mitigate ground based interference. The half power beamwidth (HPBW) of these antennas is between 60° and 100°. While this beamwidth may not be sufficient for reliable positioning, it is sufficient to have access to the required number of satellites for timing applications at least 95% of the time [3].

Other types of GPS antennas have been developed to minimize interference, like adaptive antennas, which steer a null in the direction of the high power interference using active circuitry [2]. While adaptive antennas can achieve exceptional nulling in a particular direction, they can be large due to the multiple antenna elements necessary for null steering, are typically expensive due to the active electronics, and can only null a finite number of interferers. Another previously developed alternative is the horizon ring nulling (HRN) antenna that achieves an exceptional RHCP horizon null around all azimuth in a compact form at the expense of higher LHCP at the horizon [5], [6]. The HRN achieves a null using a coplanar array consisting of an annular ring antenna around a center patch antenna. Complex weights are applied in a combiner network to null the energy at the horizon. While the combiner network functions well, the associated electronics increase the cost compared to a passive antenna.

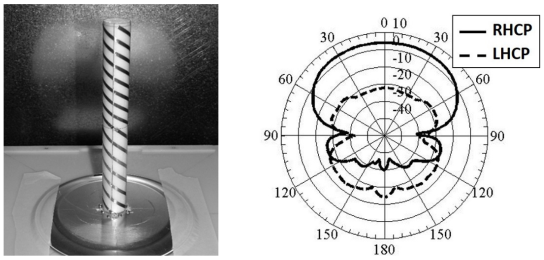
II. Inductively Loaded Quadrifilar Helix

Array theory tells us that two radiating elements spaced a half wavelength apart and fed 180° out of phase will have a null in the broadside direction and main beam lobes along the axis of the array. The initial concept for the designs described in this paper was to create a vertical phased array of two elements, each with a hemispherical radiation pattern, to create a null at the horizon while minimizing back lobe radiation. The helix antenna is one such antenna element with a small back lobe.

Low cost manufacturing is of primary importance for the application of GPS timing due to the large number of sites that would benefit from these antennas. Therefore, a feed structure for the collinear helix array was investigated without using separate feeds for each element. The design for the collinear helix antenna employs a reactive section between the elements that causes them to be out of phase with one another. This phasing creates a null in the direction of the horizon and a main beam in the zenith direction. Quadrifilar helix elements were simulated, tuned to the L1 GPS frequency and fed in series with a ground plane under the bottom element. The helix elements were connected with a series inductor on each helix arm. The inductor value was optimized to create a deep null at the horizon for ground based interference suppression.

The inductively loaded collinear helix antenna, operating at the GPS L1 (1.575 GHz), was prototyped using 7.5 inch tall foam cylinder with copper tape wrapped around it, which comprised the quadrifilar helix arms, as shown in Fig. 1(a). Surface mount inductors were placed in series between the top and bottom helix sections. The antenna was fed using commercial hybrid combiners for quadrature phasing. Gain pattern measurements, shown in Fig. 1 (b), exhibited a 4.0 dBiC zenith gain, a 100° HPBW, and a zenith-to-horizon gain ratio (i.e. null depth) of 29 dB for RHCP and 34 dB for LHCP.

Direct-contract funded by Office of the Secretary of Defense, contract W56KGU-14-0010; does not constitute an express or implied endorsement of the results or conclusions by OSD or U.S. Dept. of Defense. Approved for public release, distribution unlimited.



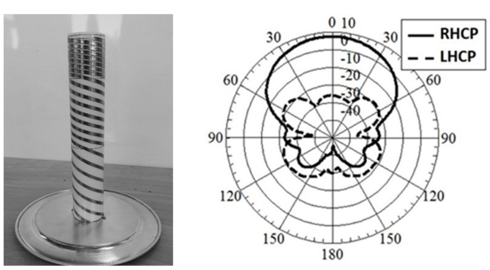
(a) (b)

Fig. 1 (a) Inductively loaded quadrifilar helix antenna and (b) measured gain pattern.

III. Variable Pitch Quadrifilar Helix Antenna

A logical next step to simplify the inductively loaded helix antenna was to investigate alternative methods of controlling the phase between the helix sections. It was theorized that the surface mount inductors could possibly be replaced by a tightly wound, non-radiating section of helix to provide a phase delay between the bottom and top helix sections. Attempts at optimizing the tightly wound helix section while keeping the top and bottom helix parameters constant were not successful. However, the optimization process led to a functioning design after the helix parameters for all three sections (i.e. bottom, center, and top) were allowed to vary. That is, the number of turns, helix pitch, and section height were allowed to vary in an iterative process. This multi-section helix concept is similar to the multi-step helix design shown in [7]. Compared to the antenna in [7], the design presented here exhibits a deeper null depth at the horizon and is simpler to construct due to the constant helix diameter. Additionally, the current design is 5 times smaller in height than the antenna in [7].

The multi-section helix antenna in Fig. 2 (a) was prototyped with copper tape on a 7.8 inch tall foam cylinder. The antenna was fed using commercial hybrid combiners for quadrature phasing. Gain pattern measurements, shown in Figure 1 (b), exhibit a 7.5 dBiC zenith gain, a 60° HPBW, and a 30 dB zenith-to-horizon ratio (i.e. null depth) for both RHCP and LHCP.



(a) (b)

Fig. 2 (a) Variable pitch quadrifilar helix antenna and (b) measured gain pattern.

IV. Dual Band, Concentric Helix Antenna with Decoupling Method to Preserve Horizon Null

Dual band, L1 and L2, GPS timing antennas are desirable for some applications. Helix antennas can be nested concentrically for dual band operation in a compact form, where the outer helix typically radiates at a lower frequency than the inner helix due to its larger diameter. However, if the helices are more than a half turn each, the coupling between the antennas can affect the patterns of the individual elements.

Decoupling of the concentric helices was achieved by placing several trap circuits along the entire length of the arms of the outer helix. When the trap circuit high impedance resonance is designed to coincide with the resonant frequency of the inner helix, i.e. L1, the outer helix is open circuited at each trap circuit location. Open circuiting the outer helix arms at multiple locations breaks up the helix into multiple short sections, which significantly reduces coupling to the inner helix. While the short sections of the outer helix scatter a small amount of energy, the horizon nulling pattern created by the inner helix is minimally distorted. At the resonant frequency of the outer helix, i.e. L2, the trap circuits have a low impedance and the L2 antenna pattern with a horizon null is preserved. In this way, the helix antennas described in the previous sections are able to be nested concentrically for dual band operation without degrading the horizon null for either band.

The dual band concentric quadrifilar helix antenna was simulated in HFSS. The number and locations of the trap circuits necessary for sufficient decoupling were determined by iterative simulations. It was found that four trap circuits strategically placed along each helix arm were sufficient. The locations were determined by analyzing the magnitude of the current distribution without the trap circuits in place. The four trap circuits were then placed near the locations of maximum current in order to break up that current. The simulated L1 zenith-to-horizon gain ratio was approximately 35 dB and the simulated L2 zenith-to-horizon gain ratio was approximately 36 dB. Future work will include prototyping and measuring the dual band helix antenna.

Acknowledgment

The authors would like to acknowledge Eddie Rosario at the MITRE Corporation for assistance with antenna construction and measurements. This effort was direct-contract funded by the Office of the Secretary of Defense, contract W56KGU-14-0010.

References

[1] *Timing*. http://www.gps.gov/applications/timing

[2] E. Kaplan, "Understanding GPS Principles and Applications," Artech House, 1996.

[3] E. Lundberg, "Assessing the Minimum Antenna Beam Width to Ensure Globally Available GPS Time," unpublished, 2016.

[4] A. Lopez, "GPS Landing System Reference Antenna," *IEEE Ant. Prop. Magazine*, Vol. 52, No. 1, Feb. 2010.

[5] B. Rao, E. Rosario, "Spatial Null Steering Microstrip Antenna Array," U.S. Patent 6,597,316, July 22, 2003.

[6] B. Rao, E. Rosario, R. Davis, "GPS Dual-Band Horizon Ring-Nulling Antenna Design," MITRE Corp., Bedford, MA, Tech. Rep. MTP070057, Apr. 2007.

[7] S. Best, "A 7-Turn Multi-Step Quadrifilar Helix Antenna Providing High Phase Center Stability and Low Angle Multipath Rejection for GPS Applications," *IEEE Antennas and Propagation Society Symposium (APS/URSI)*, June, 2004, Monterey, CA.

Attachment B

Official sponsor IGS Workshop 2017

septentrio

designs, manufactures and sells

highly accurate GNSS receivers

for demanding applications

MADE IN BELGIUM

septentrio

Data Quality: from Tracking to Archiving with no Gaps

F. Clemente, S. Dean, J.M. Sleewaegen, W. De Wilde

IGSWORKSHOP2017 PARIS

GNSS RFI vulnerability: interference is everywhere

GNSS signals as received on the ground : very low power

Sharing of radio spectrum with other services, some operating at high power (Ligado/Docomo LTE , DME, Iridium, Inmarsat)

Narrowband
Wideband

Pulsed
Continuous

Unintentional
Intentional (jamming)

In-band
Out of band

septentrio

Interference impact on applications

Depends on frequency and duration of the offending transmissions

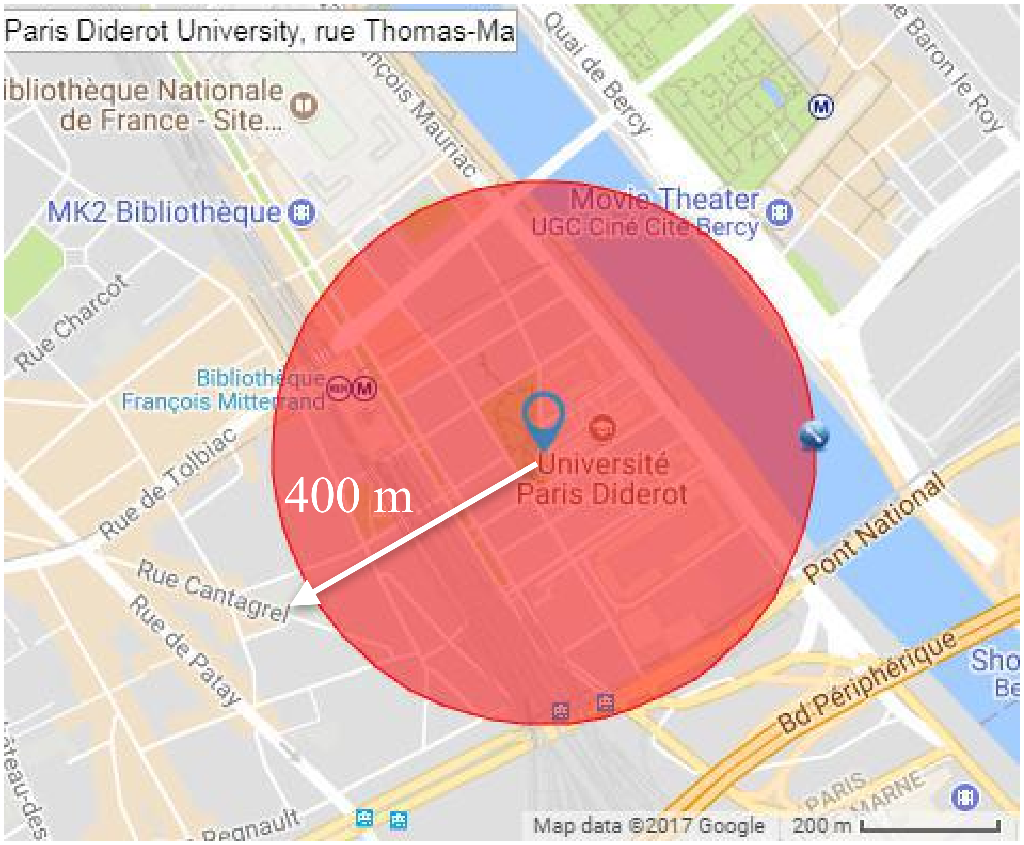
Daily processing: data editing → remove arcs with less than a specified amount of continuous slip free observations.

Accuracy effected.

Kinematic processing: most impacted is real-time PPP (re-convergence), risk of missing out on events.

Ambiguity resolutions difficult to impossible depending on interruptions.

What if a 10mW jammer was on the roof of the this building?



With no mitigation

Reference station → no supply of differential corrections
→ Gaps in RINEX files

Rover → No RTK in a radius of 400 m from the emitter

Old school troubleshooting

Specialized personnel & dedicated hardware (spectrum analyzer)

Long field campaign

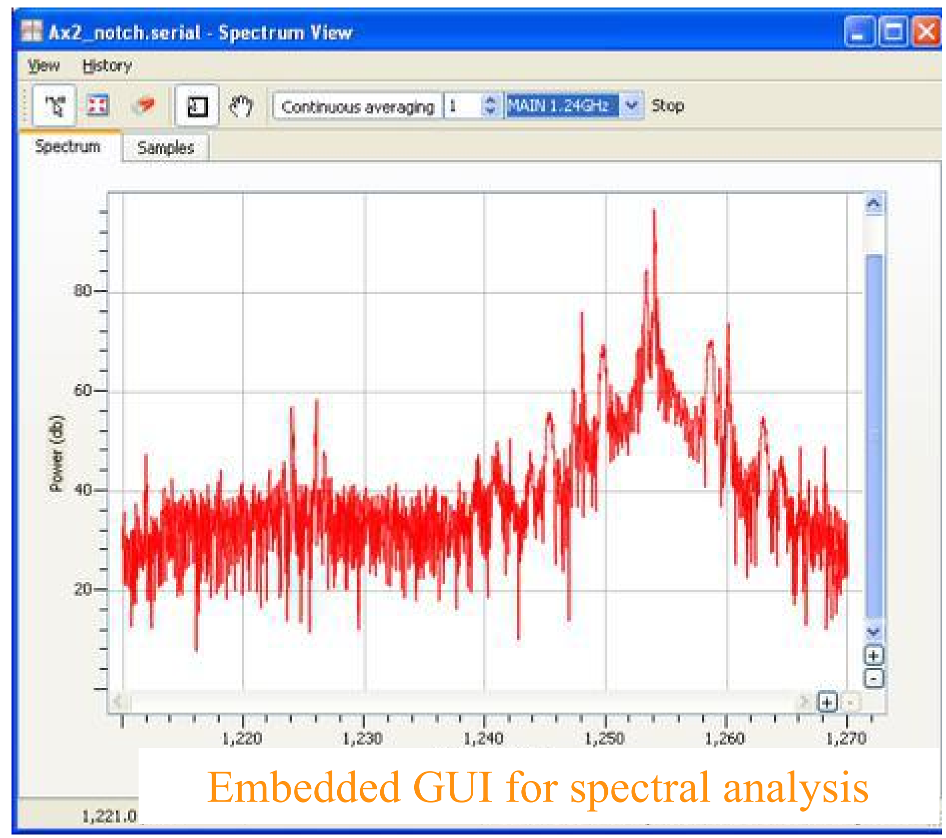
Intermittent interference hardest to detect

septentrio

Analog Video Transmission @ 1254 MHz

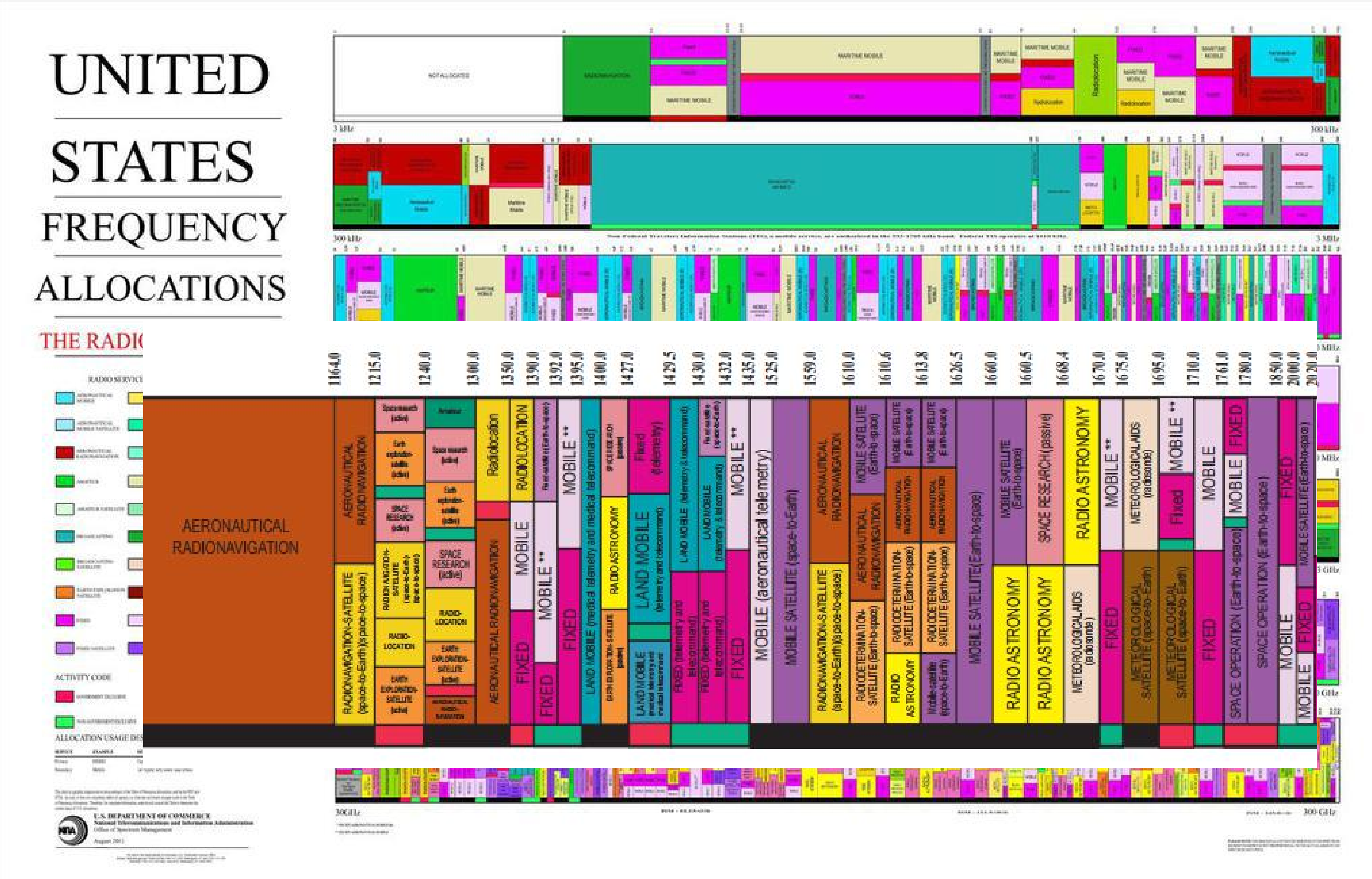
Septentrio GNSS receiver

SBF Protocol



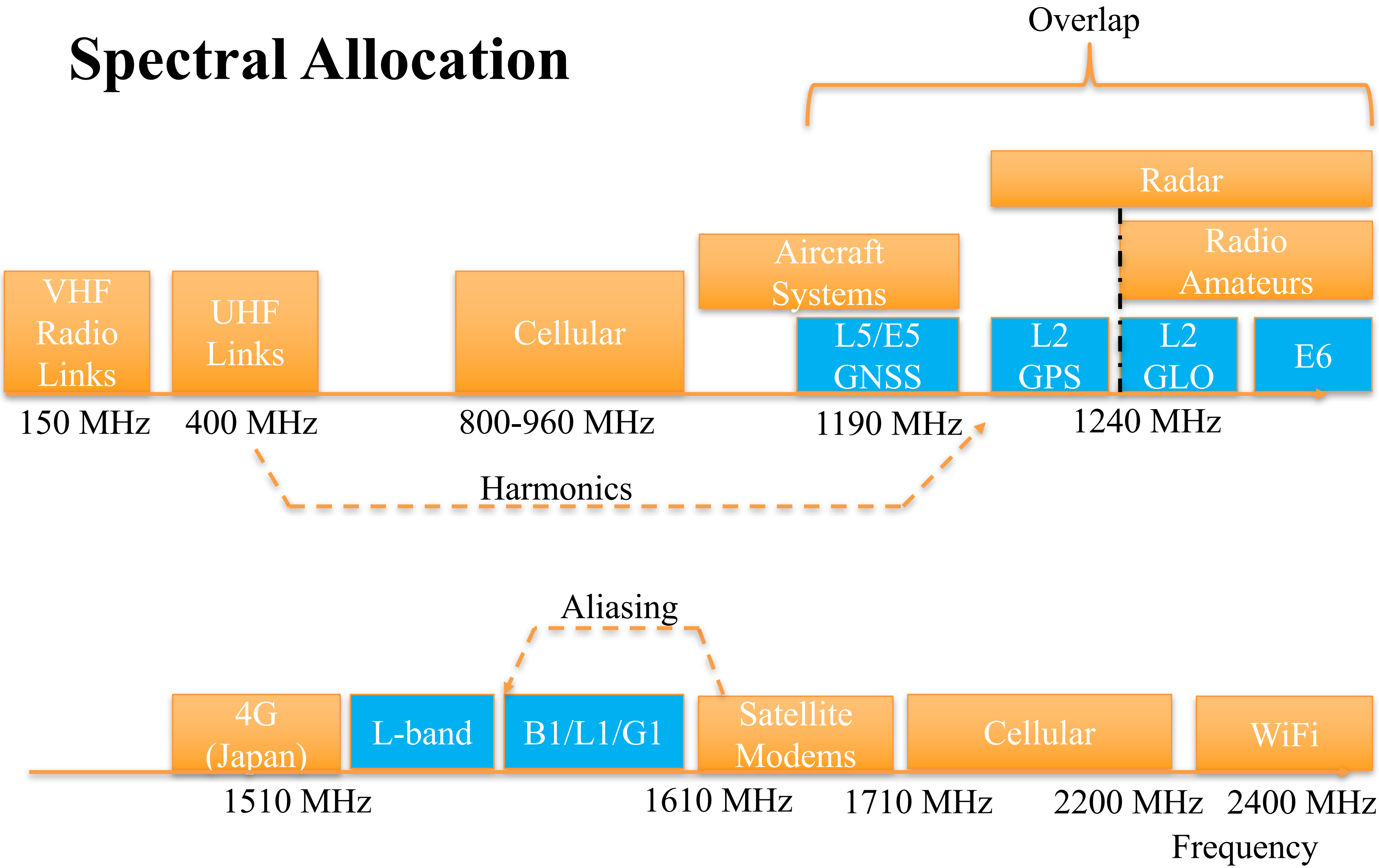
Much more than detection

AIM+ @ interference

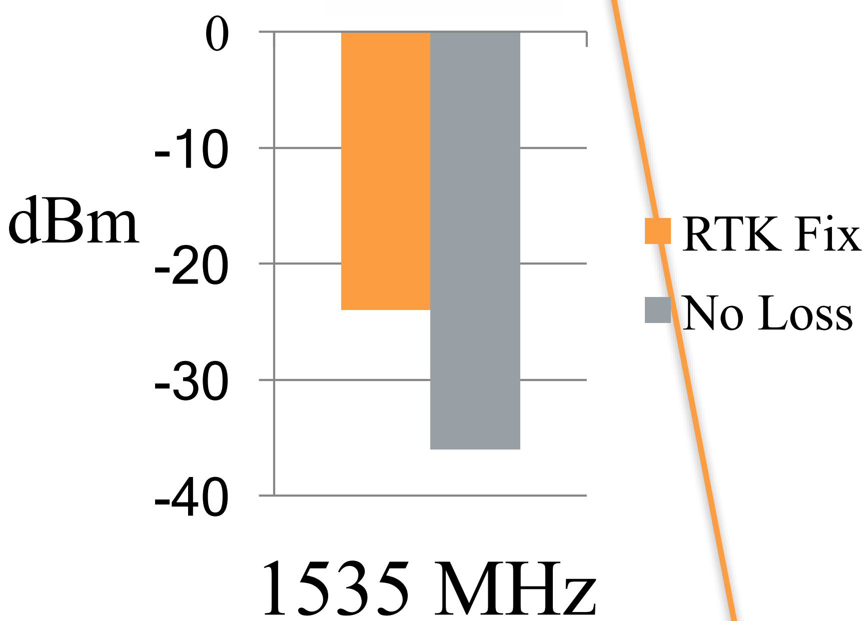


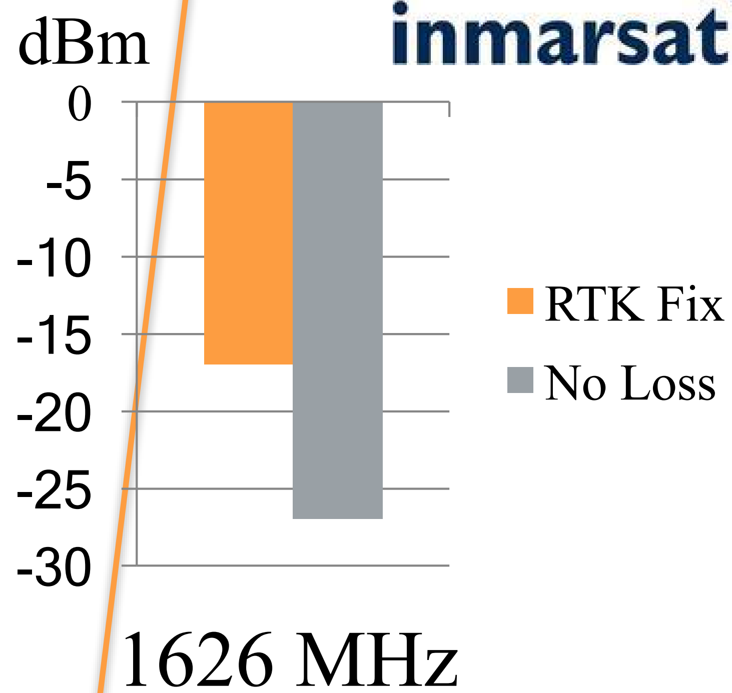
Septentrio in Confidence

Spectral Allocation



Out of band and adjecent bands rejection





GNSS
L1

No Need Sharp
Antenna Filters

AIM+ Interference Mitigation

Out-of-band

4 demodulators

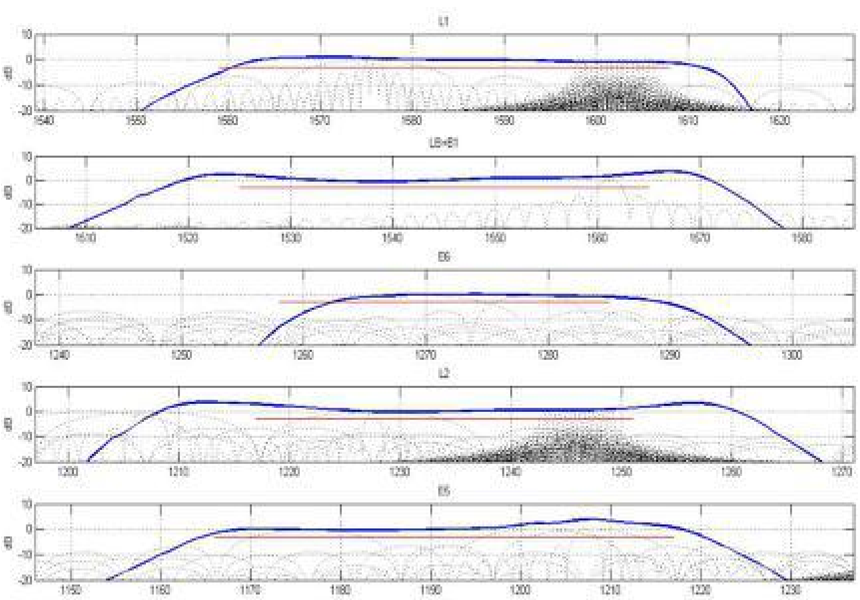
Separated filtering for all bands

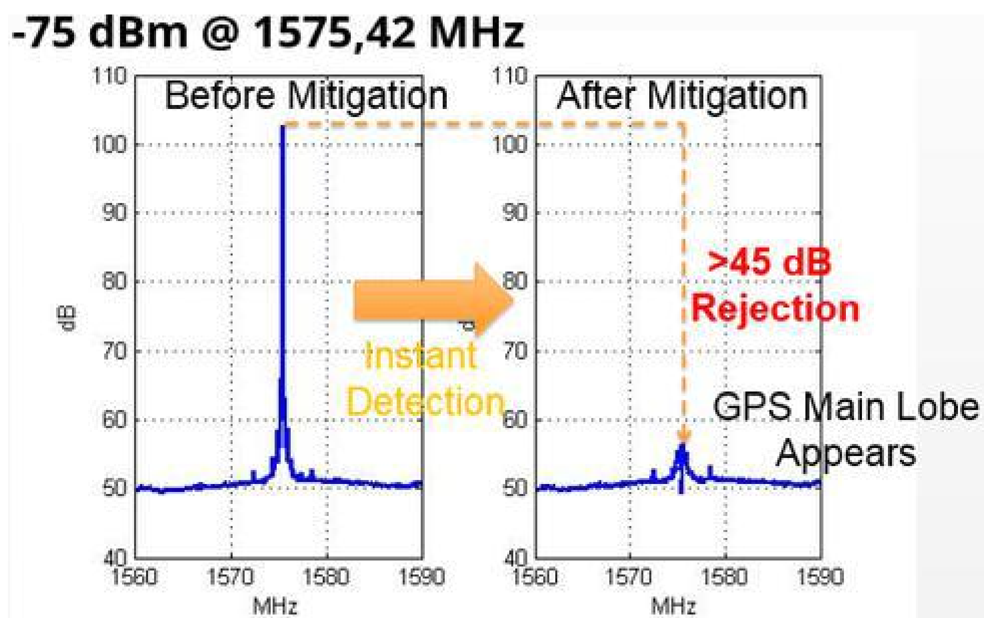
In-band

3 notch filters

Wide band mitigation unit

Pulse-blanking





Hilversum, The Netherlands

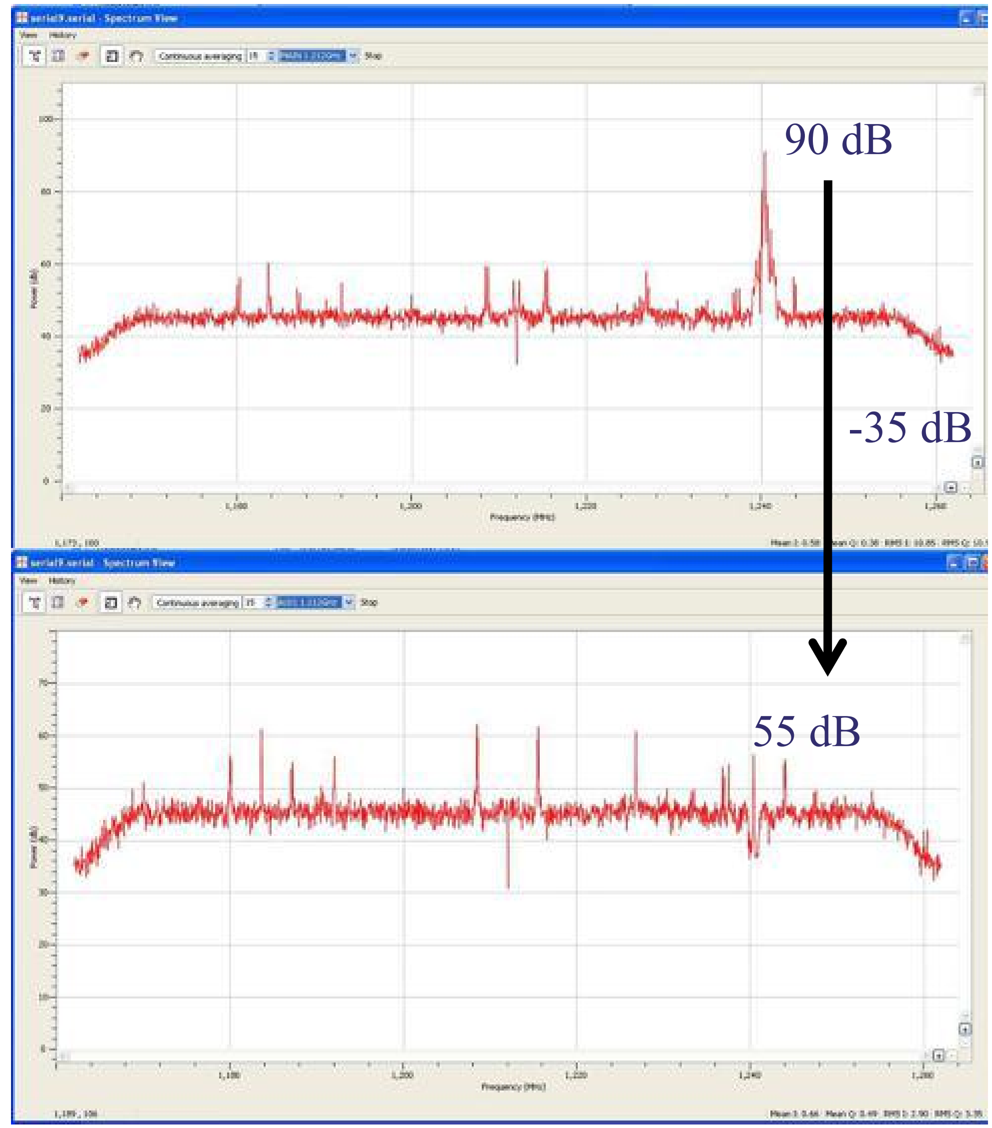
Radio Amateur digipeater

1240.4 MHz (GLO L2)

Narrowband interference

Transmits in bursts

2 second on / 8 seconds off



Mitigated with notch filter

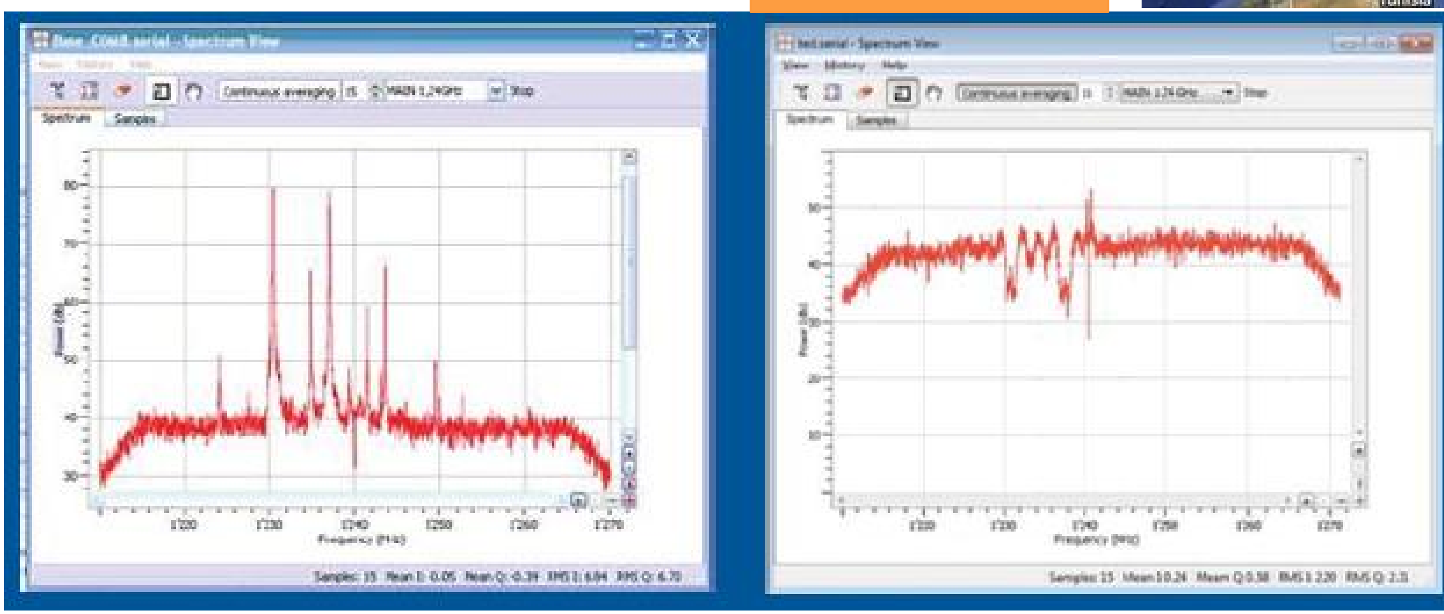
Tuymen, Russia

In-Band interference

Unknown source

GPS & GLO L2-Band

Mitigated with notch filter

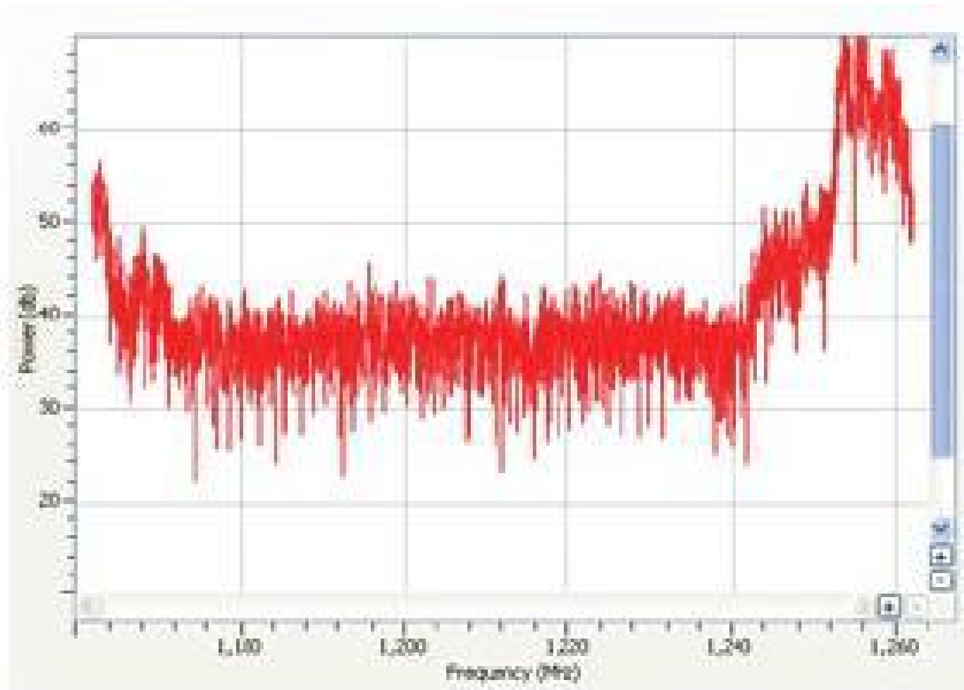


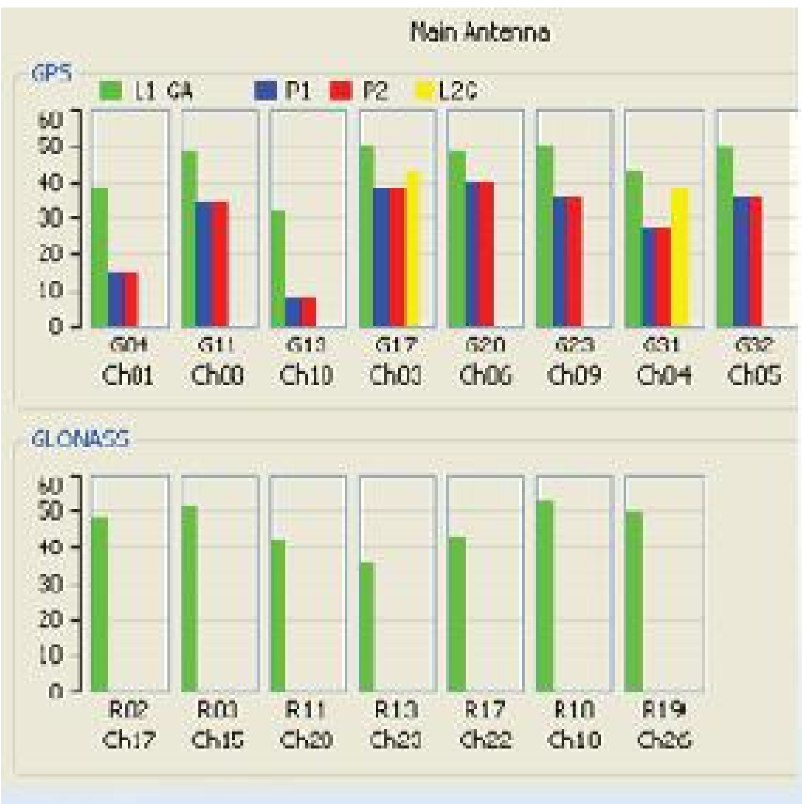
Ostende, Belgium

Broadband Amateur TV

1250MHz GLO L2

Spill over in GPS L2

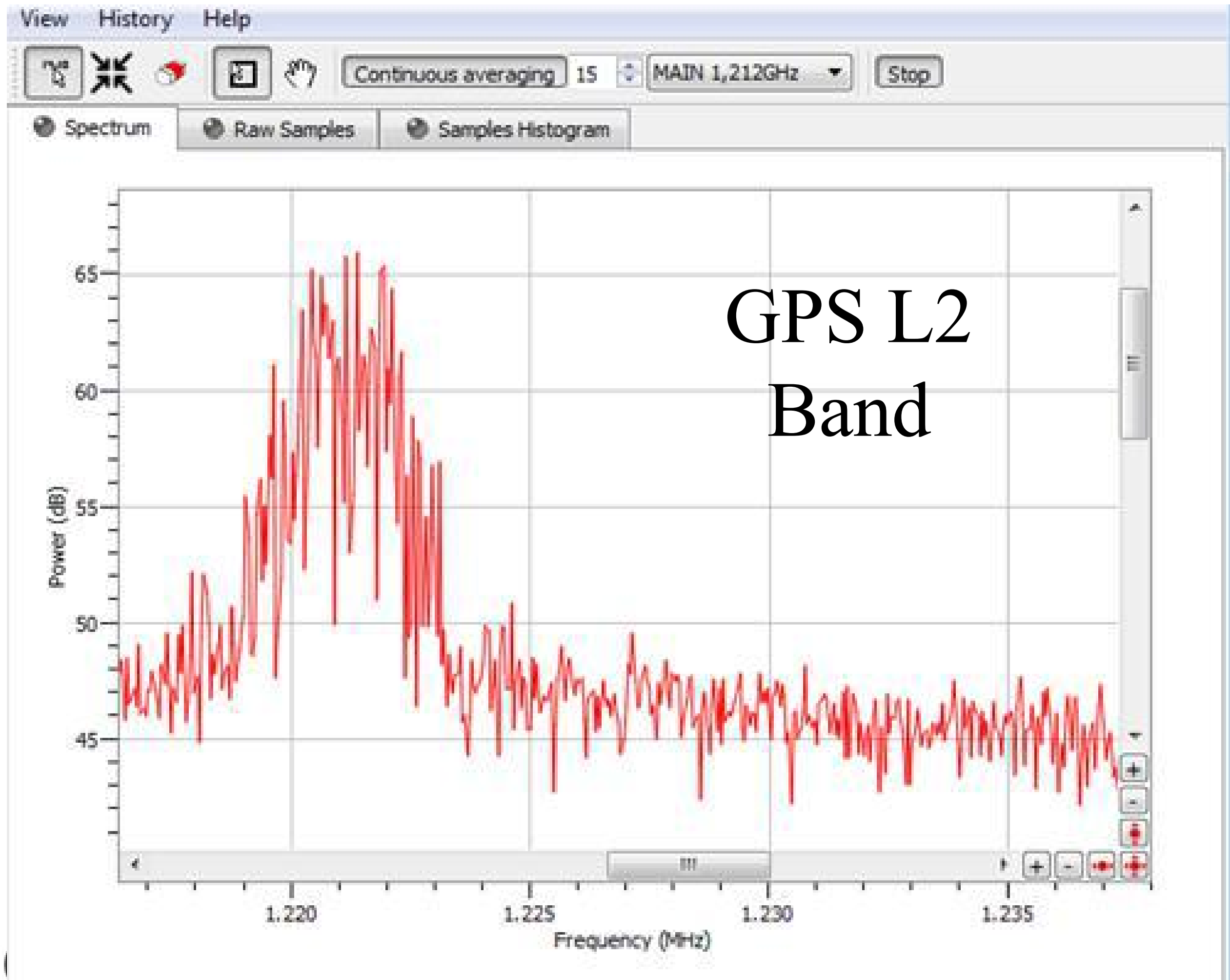




L2: Radiolocation Devices

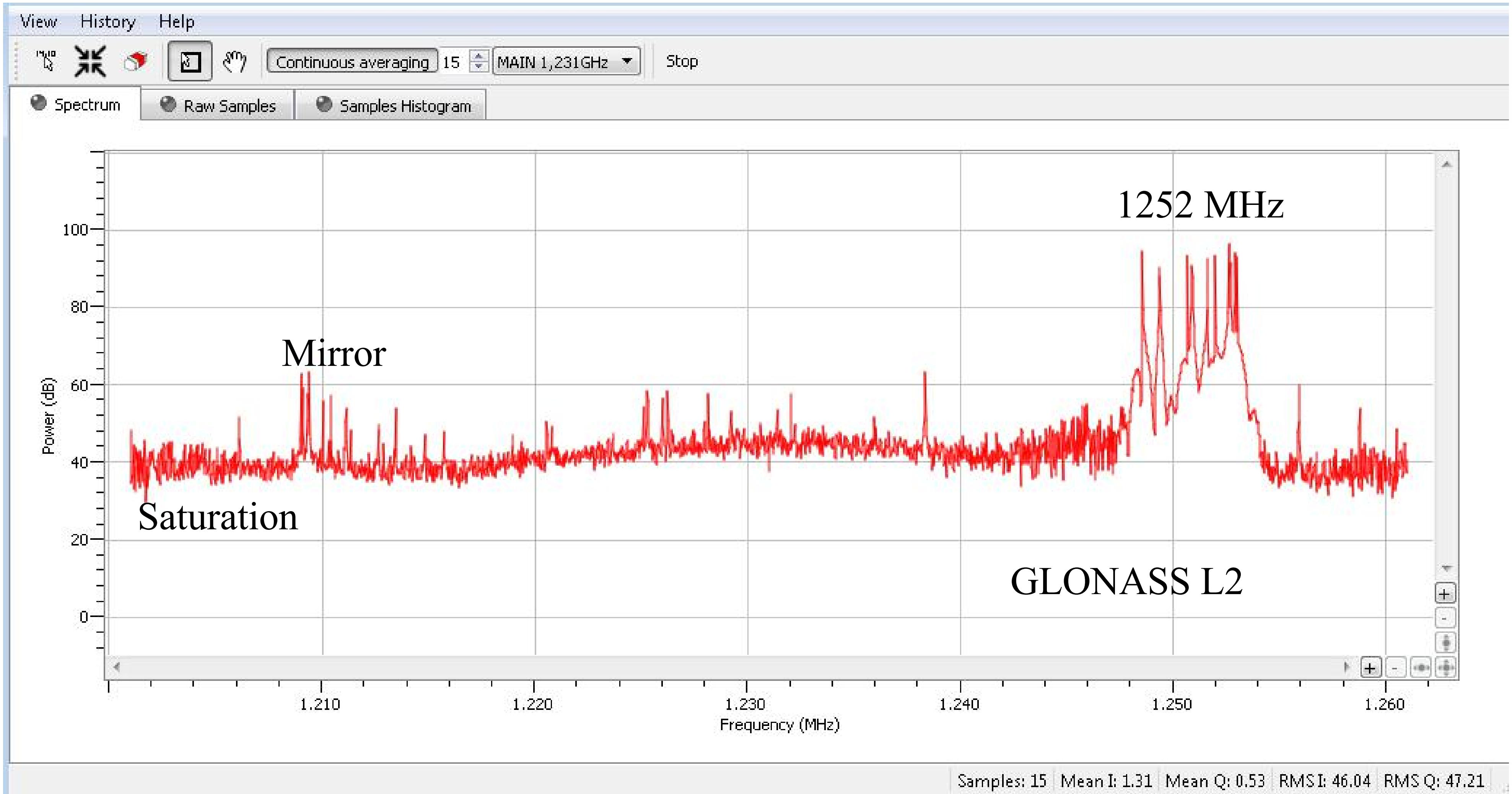
- **Sharing L2 band with GPS**

Singapore



septentrio

Amateur Radio



In-Band interference – DME

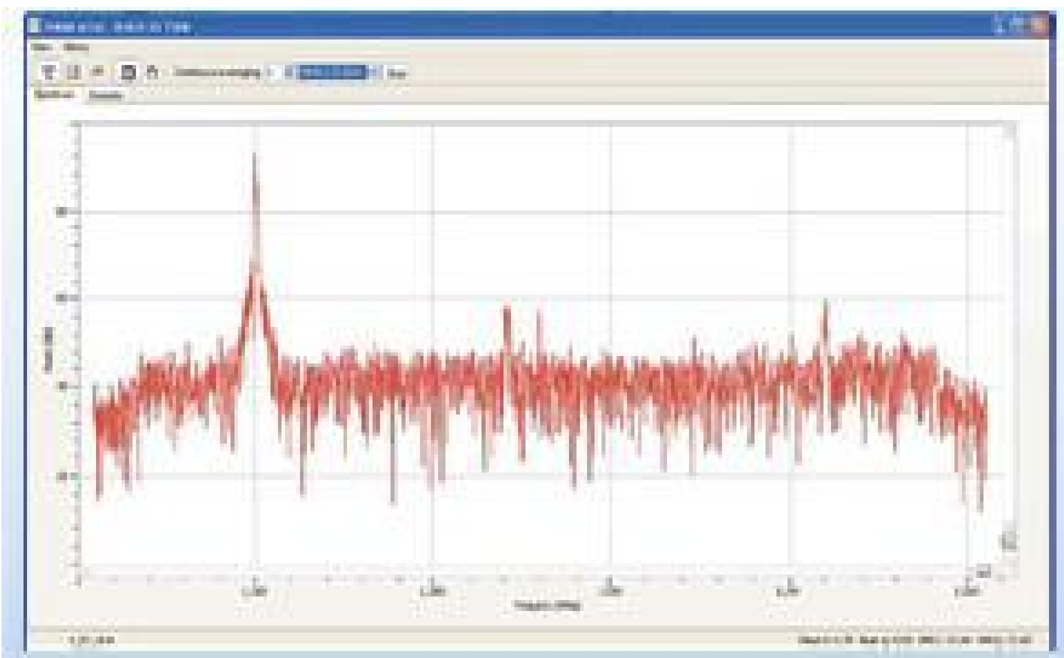
Distance Measurment Equipment (DME)

Tactical Air Navigation (TACAN)

Share band with GPS L5 and GALILEO E5

2700 high-power pulse pairs sent per second

Mitigated with notch filter
&
Pulse blanking



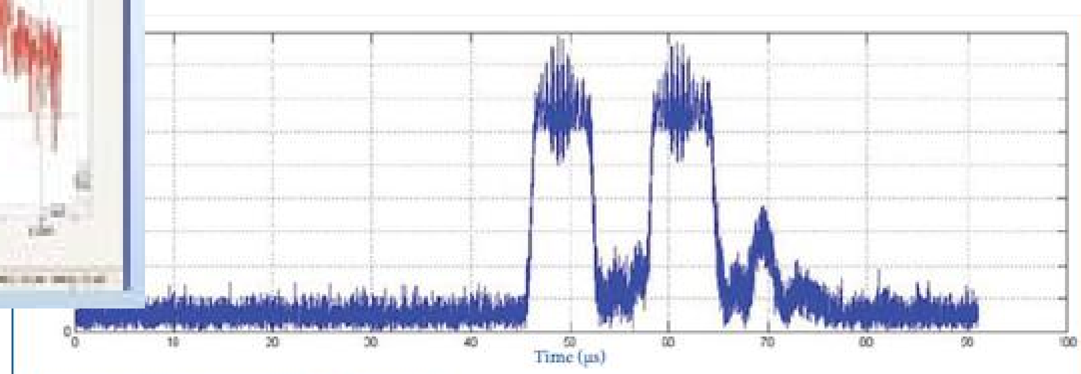


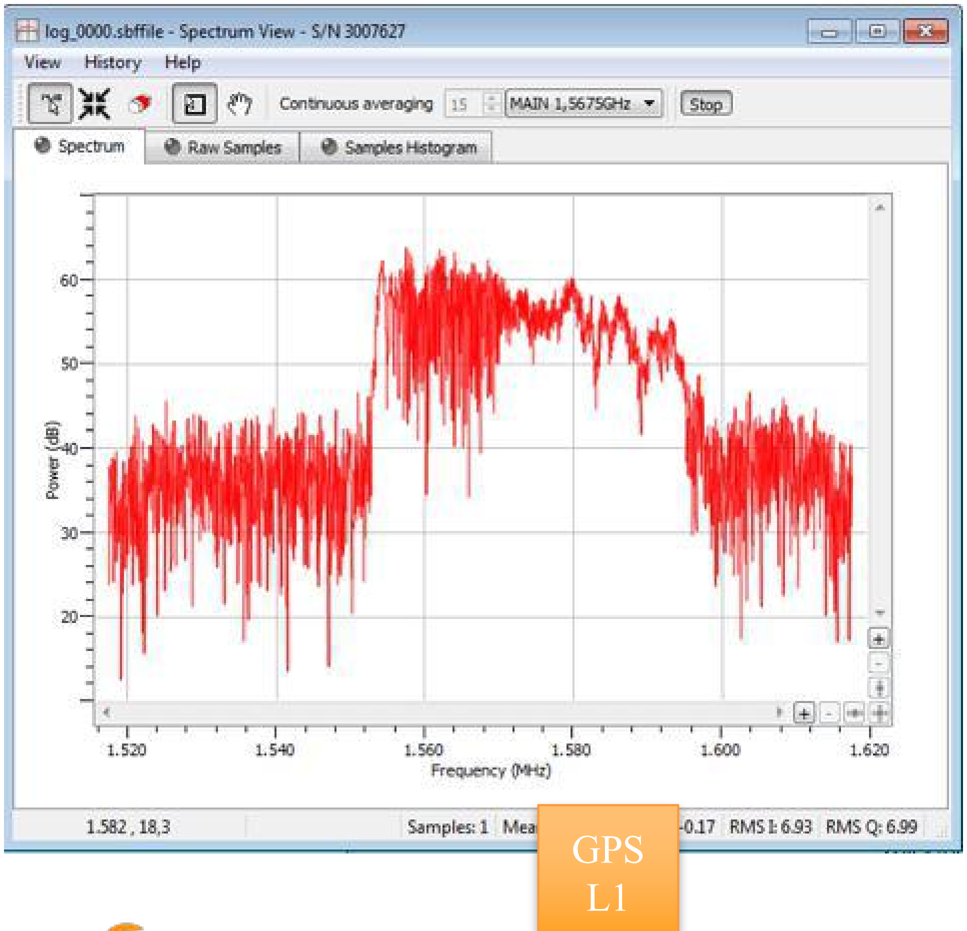
Figure 6. Pulse pair observed near DME beacon "BUB"

August 8, 2017

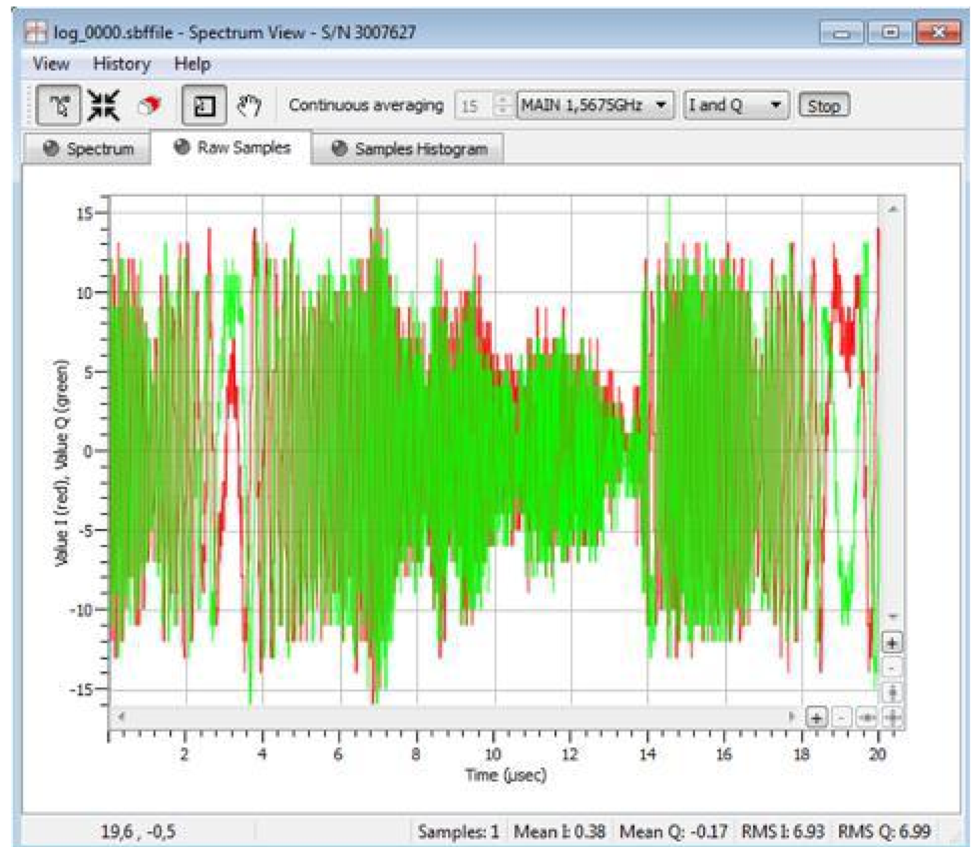
Chirp Jammers

4x 300 mW

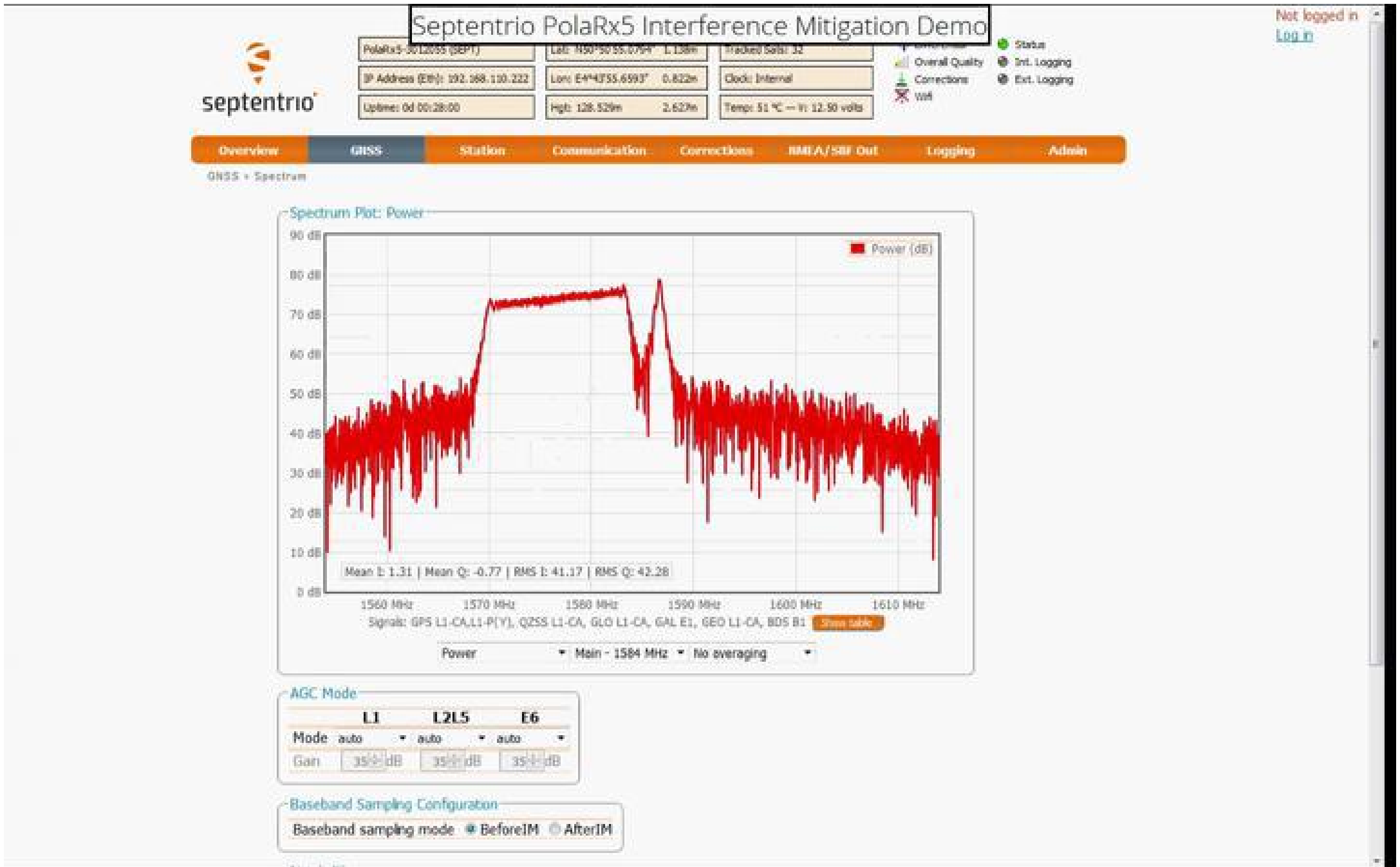
Spectrum:



Time:



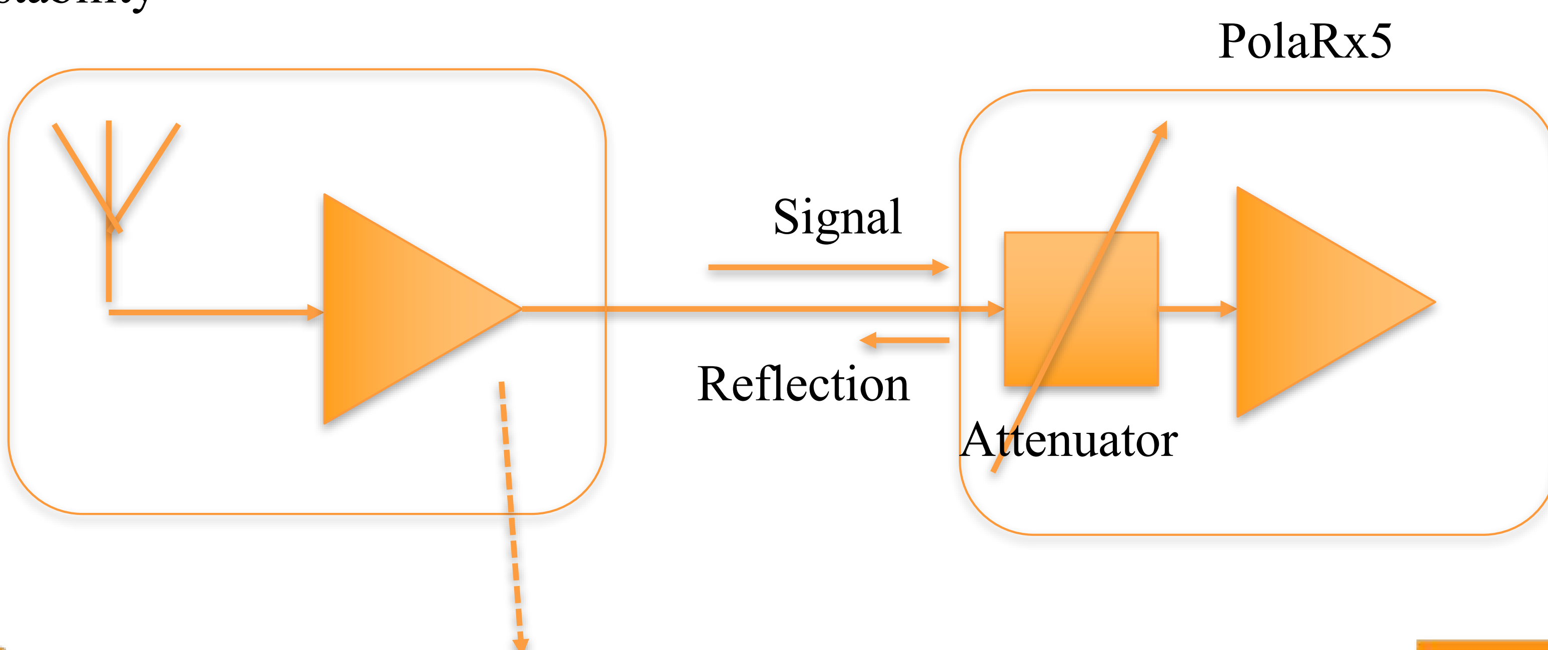
septentrio


Septentrio PolaRx5 Interference Mitigation Demo
septentrio
Not logged in
Log in
IP Address (Eth): 192.168.110.222
Uptime: 0d 00:28:00
Clock: Internal
Hgt: 128.529m
Overall Quality
Corrections
Status
Int. Logging
Ext. Logging
Overview
GNSS
Station
Communication
Corrections
NMEA/SBF Out
Logging
Admin
GNSS › Spectrum
Spectrum Plot: Power
Power (dB)
90 dB
80 dB
70 dB
60 dB
50 dB
40 dB
30 dB
20 dB
10 dB
0 dB
Mean I: 1.31 | Mean Q: -0.77 | RMS I: 41.17 | RMS Q: 42.28
1560 MHz
1570 MHz
1580 MHz
1590 MHz
1600 MHz
1610 MHz
Signals: GPS L1-CA,L1-P(Y), QZSS L1-CA, GLO L1-CA, GAL E1, GEO L1-CA, BDS B1
Show table
Power
Main - 1584 MHz
No averaging
AGC Mode
L1
L2L5
E6
Mode
auto
auto
auto
Gain
35 dB
35 dB
35 dB
Baseband Sampling Configuration
Baseband sampling mode
BeforeIM
AfterIM

When it looks like Interference…but it is a broken LNA…

- Change in amplitude – T dependent
- Gradual and very significant frequency drift
- From one modus to another
- Loss on other frequency bands

Conditional stability



Oscillates Depending on Reflection
(Bad Amplifier)

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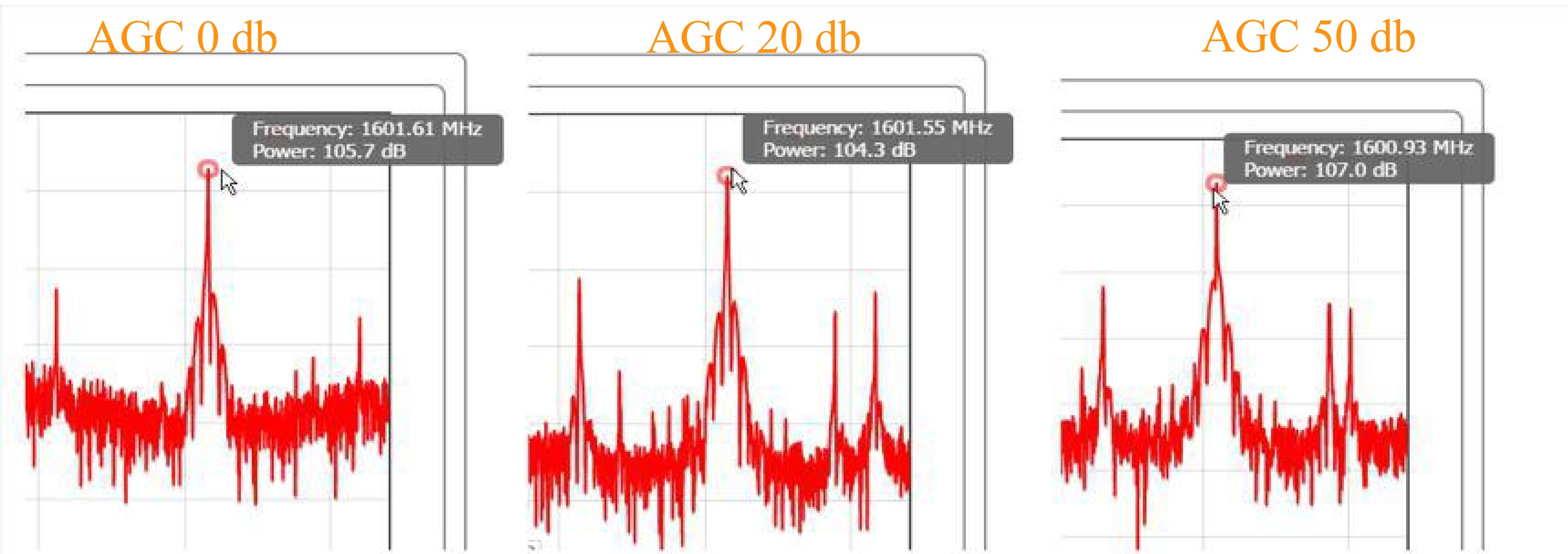
Explanation on the impedance

If the interference is external/environmental → changing AGC = no impact on IF

Resonating antenna LNA → change AGC = IF frequency shift.



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Data storage integrity

Storage integrity

Data collected by GNSS receivers are typically either streamed or FTP pushed to a server.

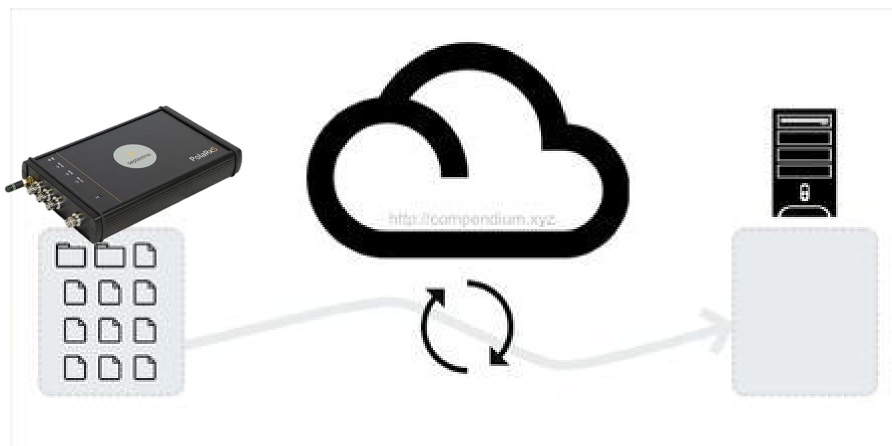
During telemetry it can happen that data packages are lost and that the files at the server side differ from what logged on the receiver.

So far, to recover the missing information, retransmitting the complete file was required.

Transmitting data can be expensive, especially when using Iridium telemetry and creates an unnecessary overhead.

Storage integrity

Fast differencing algorithm → delta encoding to minimize network usage



Only transfer the deltas
Reduce number of bytes
Lower the bill

Errors during transmission could be present →
Data gap in any part of the file

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Workflow

- Users configure data recording on an external computer
- Users configure the exact same recording on the internal disk of the receiver
- Synchronization scheduled on regular basis on the external computer to fetch data which would have been lost in the communication
- File names must be the same on both sides

3 take away

Septentrio is a Belgian manufacturer of high end GNSS receiver

Interference is a real threat and is widely diffused.

Septentrio has effective ways to monitor and mitigate it.

Optimize synchronization achieving data integrity by only transferring the deltas

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Much more @ the booth

Laurent, Bruno and I will be happy

to answer more questions offline and talk further about Septentrio technology

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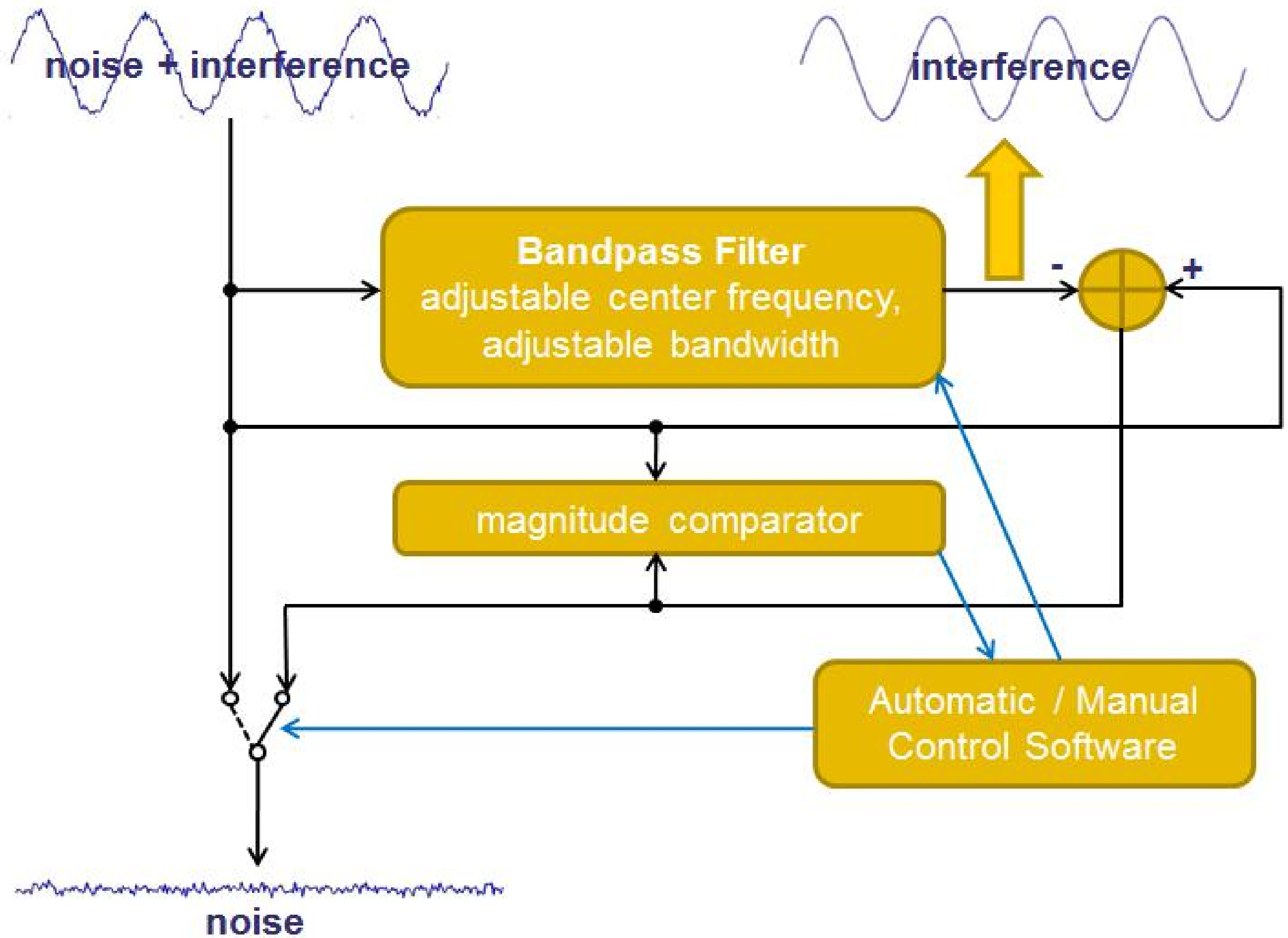
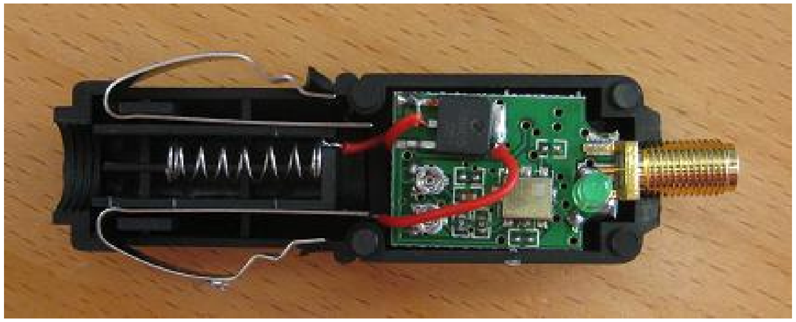
Back-up slides

Interference



Jammer Operating Principles

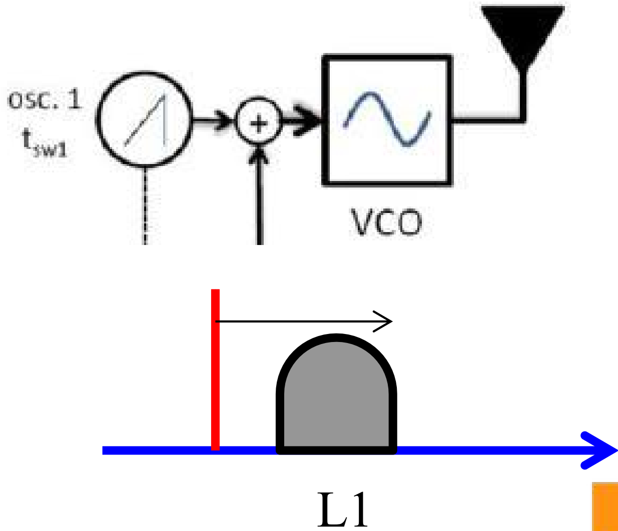


Cheap circuit

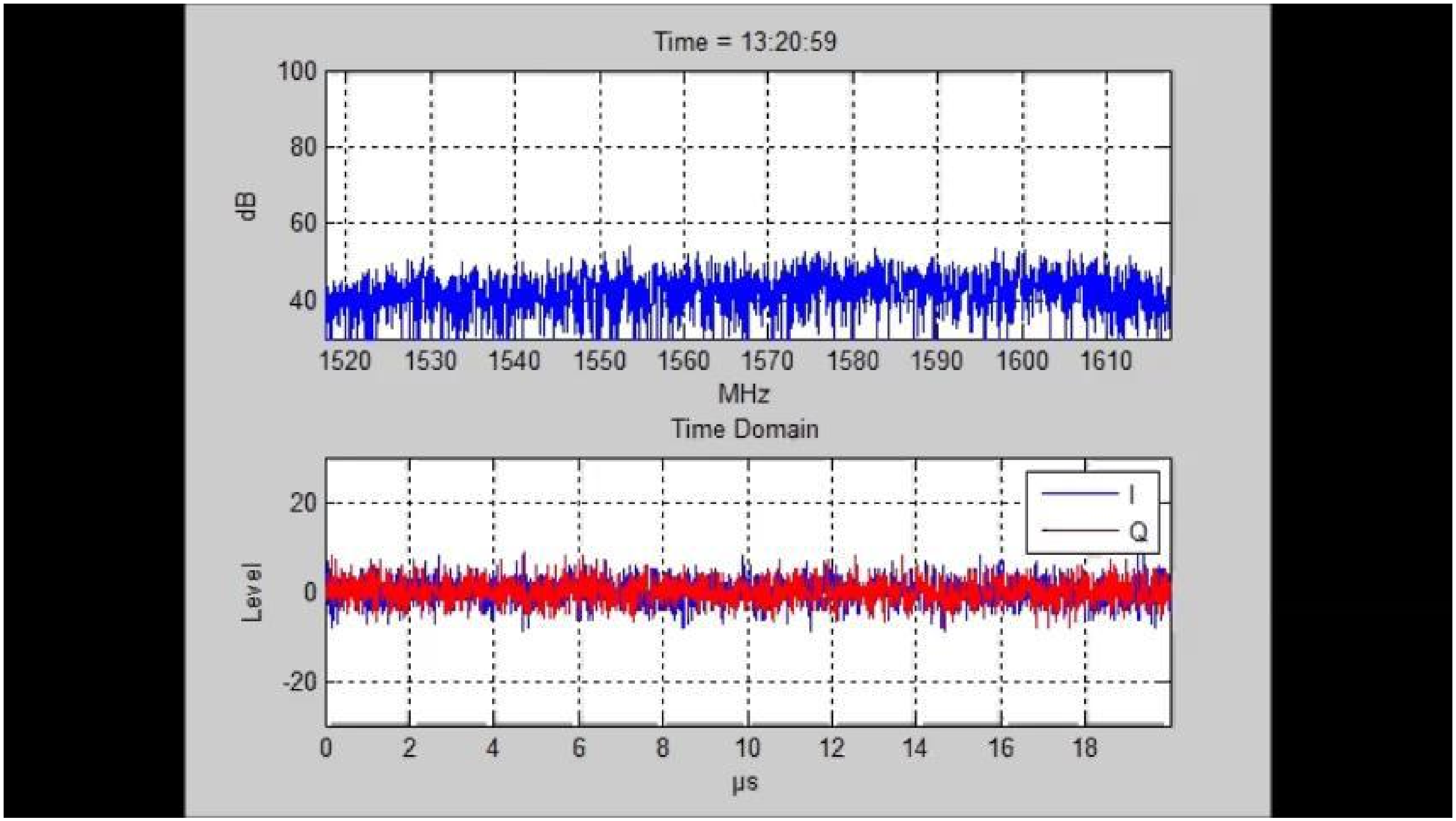
Two types:

- Pure sine-wave (CW)
  - VCO + manual tuning
  - Significant drift over temperature
  - Effective for narrowband
  - Can be mitigated by AIM+

- Chirp type
  - Frequency sweep sine wave
  - Sweep makes sure to hit L1
  - Less impact on narrowband
  - Septentrio has technology available to mitigate



Chirp jammer in action



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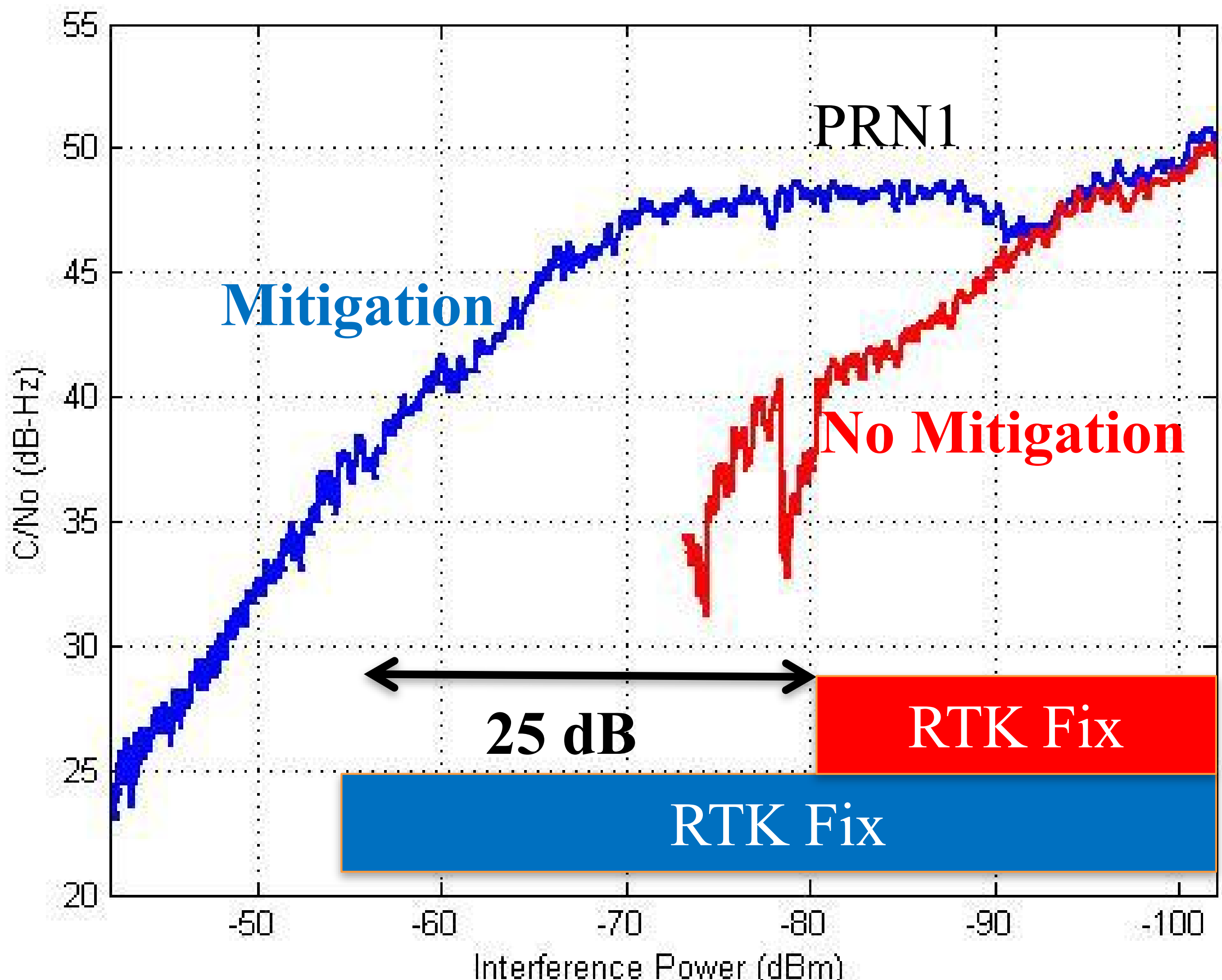
With AIM...Rejection



Decreasing Power

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Jammer Detection

C/No

- One band much worse than others

Histogram

- Normal signal (noise): Gaussian distribution
- Jammer: sine-wave distribution