01 Jul 2020

Adaptive Interference Mitigation Using Frequency-Selective Limiters Over GPS Band For Automotive Applications

Mahima Shukla

Marina Y. Koledintseva
Missouri University of Science and Technology, marinak@mst.edu

Michael Geiler

Scott Gillette

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/ele_comeng_facwork/5098

Recommended Citation

M. Shukla et al., "Adaptive Interference Mitigation Using Frequency-Selective Limiters Over GPS Band For Automotive Applications," *2020 IEEE International Symposium on Electromagnetic Compatibility and Signal/Power Integrity, EMCSI 2020*, pp. 614 - 618, article no. 9191469, Institute of Electrical and Electronics Engineers, Jul 2020.
The definitive version is available at https://doi.org/10.1109/EMCSI38923.2020.9191469

Adaptive Interference Mitigation Using Frequency-Selective Limiters over GPS Band for Automotive Applications

Mahima Shukla[1], Marina Y. Koledintseva[1], Michael Geiler[1], Scott Gillette[1], Michael Hunnewell[1], and Anton L. Geiler[1],
[1]Metamagnetics, Inc., Westborough, MA, USA

***Abstract*— In this work, we address the challenges associated with the necessity to protect Global Positioning system (GPS) receivers from various types of electromagnetic interference (EMI) generated by internal or external sources. We have developed a compact, lightweight, and passive frequency selective limiter (FSL) technology that automatically and adaptively protects vulnerable input circuits of a GPS receiver from unwanted emissions and prevents a GPS receiver from going into saturation. This technology is based on using magnetostatic surface waves in a magnetically biased ferrite film. The nonlinear processes in ferrite films enable discrimination of signals based on their power levels. In these devices, the frequency-selective transmission response adjusts rapidly and automatically, in real time, such that no portion of the output spectrum exceeds a designated power threshold. FSLs are capable of mitigating multiple interfering signals without prior knowledge of the timing or the frequency content of the interferers. A few examples of FSL design and measured characteristics are provided for GPS L1 band.**

Keywords—Receiver protection, communication radio, GPS, EMI, Frequency Selective Limiter (FSL), Magnetostatic surface waves (MSSW), frequency selective attenuation, sensitivity

I. Introduction

The biggest challenge faced by autonomous automobile industry is electromagnetic interference (EMI) from the internal and external interference sources [1]-[5]. Internal interference source could be any electronic integrated circuit (IC) within the system and this interference could be controlled to a certain extent by effective EMI shielding techniques. The main threat is external interference generated by intentional or unintentional EMI from some transmitter, in-band emissions, near-band emissions, as well as their harmonics. The power, frequency, and waveform of external interference are typically unknown in advance. Therefore, a new technology is required to protect navigation and communication links of autonomous (self-driving) vehicles.

EMI protection research for GPS receivers has primarily been focused on producing high-performance systems operating in highly stressed electronic environments [6]-[13]. However, GPS receivers used in automotive applications and portable handheld devices cannot implement such high-end EMI mitigation technologies due to stringent size, weight, power, and cost requirements. They require compact, lightweight, low-power, and inexpensive adaptive interference mitigation capability.

There is a technology called frequency selective limiters (FSLs) (Fig.1) that can solve these problems [14]-[19].

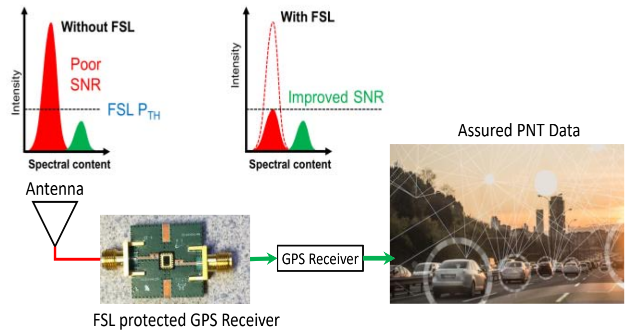

Fig. 1. FSLs protect the front-end of GPS from intense EMI and improve signal-to-noise ratio (SNR) while simultaneously enabling continuous reception of GPS signals for operation in denied environments. (Image of cars is taken from [5]).

Herein, ferrite FSLs that automatically adaptively attenuates RF interference are presented. The advantages of the ferrite FSL electronic components are small size, lightweight, and passivity – they do not need power for operation. The FSL technology utilizes advanced magnetic materials, in particular, thin ferrite films [15]. Such films, mostly Yttrium Iron Garnet (YIG) monocrystals, are from a few micrometers to a few dozen micrometers thick and are grown or deposited on dielectric substrates made of Gadolinium Gallium Garnet (GGG).

The non-linear microwave properties of ferrite films enable automatic filtering of signals based on power level [16]-[19]. FSLs discriminate input signals based on power level and automatically attenuate signals that exceed a designated power threshold. Below-threshold spectral content of desired GPS/communication signals passes through the FSL device unaffected, as illustrated in Fig. 2. This power threshold and the frequency range of limiting can be tailored to a specific application. FSLs can filter out multiple interference signals simultaneously without prior knowledge of the timing or the frequency content of the interferers, continuously adapting to the electromagnetic (EM) environment and enhancing signal reception. An FSL requires no software, analog to digital converters, or complex digital signal processing to operate.

A typical realizable FSLs at 1.5 GHz, have the quality factor of Q~1000 i.e., ~ 1.5 MHz wide notch at -3dB level.

978-1-7281-7430-3/20/$31.00 ©2020 IEEE

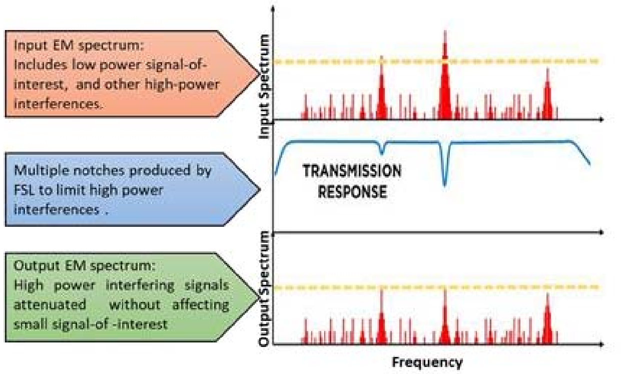

Fig. 2. Signals with a power level above a pre-designated threshold are automatically attenuated by FSL while, simultaneously, signals below threshold pass through the device with small insertion loss. Frequency adaptation occurs in less than a microsecond with a high degree of selectivity and multiple rejection notches are supported.

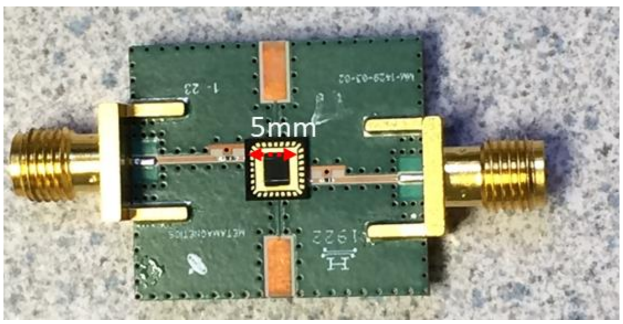

Fig. 3. (Top) FSL (5x5 mm QFN package) on a connectorized PCB for evaluation.

Its functions are dictated by the physics of a special magnetic (typically, ferrite) thin film material that interacts in a nonlinear and highly controlled manner with the electromagnetic energy. When EM energy is injected into a circuit formed on the surface of the thin film material, it is coupled to a purely magnetic domain where it manifests as magnetostatic and/or spin waves. Unlike most electronic devices that operate by propagating and manipulating charges, FSL devices operate by coupling RF electromagnetic energy to pure magnetic spin oscillations in a biased ferrite medium that result in magnetostatic and spinwaves. Strictly speaking, these are all spinwaves. Magnetostatic waves are a particular case of spinwaves with spinwave vector $|\boldsymbol{k}|\approx 0$, while spinwaves in the general have broad range of wave vectors with high $|\mathbf{k}|$ magnitudes, as well as so-called exchange energy between neighboring magnetic moments. The micromagnetic dynamics of interaction between electromagnetic field, static bias magnetic field, and spin magnetic moments of ferrite medium follow quantum physics rather than classical. However, for the design of our devices, classical phenomenological magnetization motion Landau-Lifshitz equation with dissipation represented in one of the existing forms, e.g., the most widely used Gilbert form [20], can be used. These spinwaves offer ability to provide analog signal processing functions in the magnetic domain, for example to provide high power interference suppression practically without affecting small signals (unless they exactly fall into the filter passband), and then recouple back into RF electromagnetic domain. An important feature of magnetostatic and spin waves excited in ferrite films is that they propagate at speeds much lower than speed of light, ~ 10^5 m/s [21]. Therefore, devices based on these waves could be miniature – see Fig. 3. The size could be as small as 5 mm^2 and even less.

There are two types of FSLs, and basic configurations are described in [16]-[19]. The first type is based on magnetostatic surface waves propagating between two metallic transducers ("antennas") directly placed on the ferrite film in, *e.g.*, a microstrip structure with ferrite as a substrate [16]. Coupling between electromagnetic and slow magnetostatic surface waves (MSSW) occurs through these transducers. When signal power is low, MSSWs propagate between the transducers in the magnetically biased (in-plane, parallel to transducers, and mainly perpendicular to RF H-field on the line – so-called perpendicular pumping) ferrite film with low loss. At the high-power levels above the threshold, MSSWs no longer propagate, since they transform to the multitude of parametrically excited spinwaves with broad range of spin wave numbers. This is the so-called spinwave instability [22]-[24]. This interrupts linear MSSW propagation between the transducers. As a result, electromagnetic signal is reflected. Since this happens in the limited frequency range where power exceeds threshold, this causes frequency-selective limiting. Overall, operational frequency range is determined by the ferrite type, magnetic bias field, and thickness of the film.

The second type is an absorptive FSL [15], [16], [19]. Absorptive FSLs operate in a different way. They contain a regular planar transmission line (microstrip, stripline, co-planar waveguide, slot-line, etc.) on a magnetically biased ferrite substrate. Typically, d.c. bias magnetic field is transverse to the direction of propagation along the line. This provides mostly parallel RF pumping. However, in reality pumping is always hybrid with both components – along bias (parallel pumping) and perpendicular to it (perpendicular pumping due to the structure of the field in a particular transmission line).

There are input and output ports on this waveguide. When low-power signal propagates along this line, it does not experience significant loss or distortion. However, if power is higher than the threshold, first, electromagnetic power effectively couples to uniform magnetostatic modes [20], and then these modes fall apart into a multitude of spinwave vectors due to spinwave instability generated in the ferrite substrate [19]-[25]. These chaotic spinwaves eventually dissipate, and thus EM energy is absorbed. The longer the line, the higher is the dissipation. However, at some very high-power level, the system becomes saturated, and electromagnetic energy can no longer be absorbed by spinwaves. This is related to effects that could be explained by quantum approach only (3-magnon splitting results in recombination, and 4-magnon processes start taking place). In the "classical" language this means that any spin magnetic system has some “capacity” to accumulate magnetic energy from EM signal, and when this “capacity” is reached, limiting no longer is possible with the same rate and can even be stopped. This determines the upper limit of the limiting dynamic range of an FSL.

For applications over the GPS band, the reflective-type FSLs operating on MSSWs appear to be more suitable that absorptive-type FSLs. The absorptive FSLs are usually designed for more high-frequency applications than their MSSW counterparts. In this work, it is shown that the FSLs can be designed for operation at L1 band (~1575.42 GHz), and interference mitigation for this GPS band is evaluated on a commercial (u-Blox) GPS receiver.

II. Charecteristics of FSL

An FSL device is characterized by insertion loss, power threshold, frequency selectivity and dynamic range parameters. The power characteristic of an ideal FSL device is schematically shown in Fig. 4. The horizontal axis represents input power and vertical axis is output power of FSL. Power threshold is the minimum input RF power level, at which the nonlinear limiting process in the FSL starts. A good FSL design should have flat power limiting within the given dynamic range. An FSL frequency-selectively limits any spectral component that exceeds the pre-defined threshold level, and in this sense, it operates with integrated power of the input signals within the typical FSL absorption band, which is close to the power spectral density, but not quite the same. Note that all the measured data in this work is obtained for continuous wave (CW) signals. In this case, if interference signal has bandwidth BW< 1 MHz, then power threshold will be the same as for CW signal. If EMI signal BW>1 MHz, then power threshold should be the same as for the CW signal plus 10 dB. Modulation type (FM, AM, or PM) makes a difference, and the power threshold becomes dependent on the modulation type, rate (depth), and bandwidth.

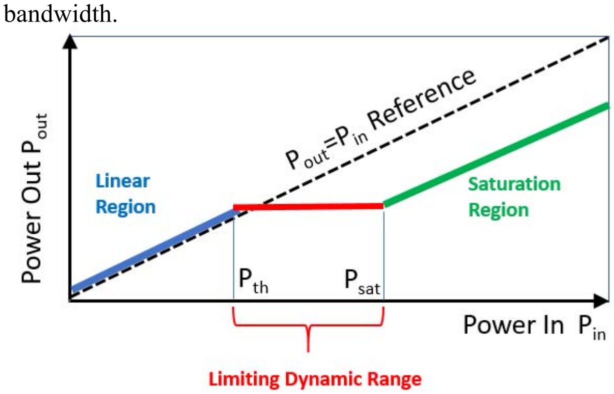

Fig. 4. An ideal FSL device characteristic has flat limiting over the limiting dynamic range and should be nondispersive, means it should have same response for all the frequencies in the operating band.

The MSSW FSLs have insertion loss typically on the order of a few decibels. Loss can be approximated to a first order as follows: for a monocrystal YIG ferrite with FMR linewidth of ΔH= 1 Oe, the typical insertion loss (IL) in an FSL is on the order of 5±2 dB. However, IL of MSSW FSL is a function of the power threshold. Very low-power threshold devices (~ -40 dBm) may have IL ~ -10 dB. Fig. 5 shows the measured power characteristics of an MSSW FSL operating over the L-band (1-2 GHz). For input power less than -17 dBm, FSL output power varies linearly with the input power, and FSL is operating in linear regime. For input power higher than -17 dBm, FSL output is held constant at -20 dBm. There is seen flat limiting over the wide dynamic range of input power. This measurement has been done up to 6 dBm input power.

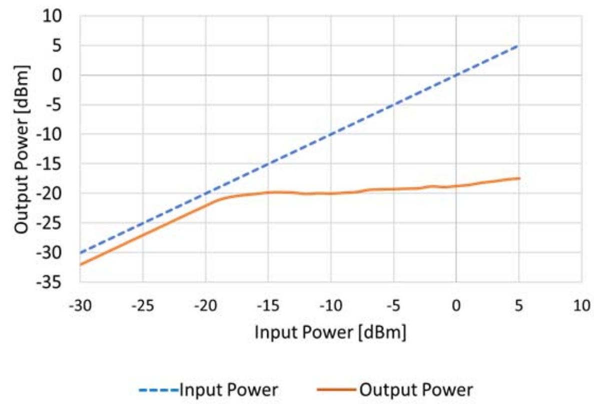

Fig.5. Measured power characteristics of MSSW FSL in L band (1.5 GHz). This FSL has power threshold of -17 dBm.

Frequency selectivity of an FSL, as is shown in Fig. 6, is measured by inserting a high-power signal along with signal of interest at the input of FSL. At the output of the FSL, insertion loss plots (transmission responses) are collected for different input power of high-power signal. As is shown in Fig. 6, an EMI at 1.5 GHz creates a notch in the insertion loss plot of the FSL. It is seen that the FSL due to its frequency selectively removes interfering frequency at 1.5 GHz with selectivity bandwidth of FSL is < ± 5 MHz. This means that the frequency component at 1.51 GHz will pass with linear insertion loss.

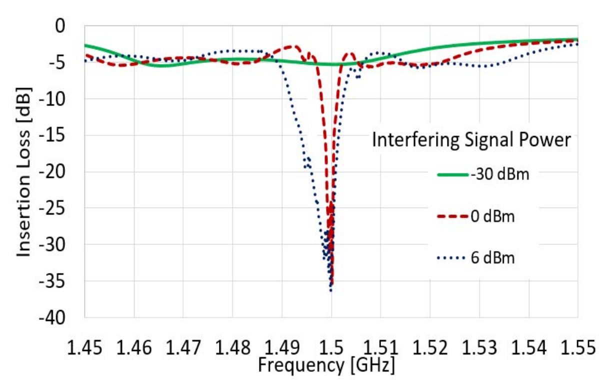

Fig.6. Selectivity plot of an FSL in L band with interfering signal at 1.5 GHz. FSL removes this interfering signal by attenuating it to -35 dB without affecting small signal of interest outside the notch.

In linear regime (when power spectral density at the input is below threshold), FSL functionality has no intermodulation distortion. This is because FSL is a passive component that is in this case works as a passive filter. However, in nonlinear regime (at power higher than threshold), intermodulation distortion may take place. It depends on the frequency difference between interfering signal and signal of interest and the amplitude of interfering signal. Though intermodulation products that may appear due to the pulsed interference signals and their harmonics are an inherent problem with any type of nonlinear devices, this aspect is beyond the scope of the present paper.

III. GPS Protection with FSL

High power interference mitigation for a GPS receiver can be demonstrated using an MSSW FSL device. The test is created by adding interfering signals to the GPS transmitted signal, which is the signal of interest (SOI). A test setup consists of a commercial off-the-shelf GPS simulator, GPS receiver, and an RF interference network. The block-diagram of the test setup is shown in Fig. 7. The combined SOI and interfering signal are applied at the input of the GPS receiver using a switched path. One path is direct, and second path is through FSL. Received data from the GPS receiver is collected for both the paths.

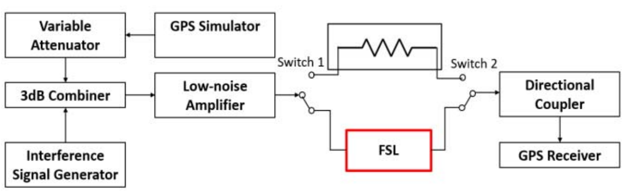

Fig. 7. GPS-FSL test setup

he results of the test simulations are shown in Fig. 8. On the left of Fig. 8, it is demonstrated that at the absence of the FSL protection at the input of the GPS receiver, it is not able to see any satellite data due to interference by high power interfering signal. However, on the right-hand part of Fig. 8, when U-Blox receiver is protected by our FSL, it is able to lock with more than three satellites.

With the signal level of -130 dBm, which is typical for L1 band Coarse/Acquisition (C/A) code GPS, the signal-to-noise (S/N) ratio has been improved by more than 10 dB for a 50-dB continuous wave noise-to-signal ratio that was only 5 MHz away from the L1 (1.57542 GHz) frequency. This is illustrated by Fig. 8. The receiver data is measured when the GPS input signal is coupled with an interfering signal at below -70 dBm power level. Without the FSL the receiver is desensitized significantly, and the GPS signal is lost. The FSL provides significant attenuation to the interfering signal, reducing its power so that the receiver is no longer desensitized and can continue receiving GPS data. Though FSLs have shown frequency-selective limiting ability with CW signals, the similar performance is expected for pulse interference.

IV. Conclusions

Herein, it is shown that ferrite FSLs based on magnetostatic surface waves and non-linear phenomena in ferrite films can be used to protect sensitive receivers from high power interfering signals. Since FSL limits signal levels based on their power, it is capable of operating at any frequency and type of waveform. FSL also allow for increasing the effective dynamic range by selectively attenuating only the interfering signal. FSL does not require a prior knowledge of interfering signal, hence it is best suitable solution for the systems which are exposed to wide open spectrum. The FSL can be designed to meet the requirements of any size for a moving vehicle. Due to its small size and passive nature, it can be a part of existing predesigned system as well.

In this work, we studied only interference near the GPS band. However, it may happen that an unintentional interference may fall into the band of the signal of interest. This scenario could be treated using a so-called frequency-selective canceller [26]. However, this is beyond the scope of the present paper.

References

1. T. Hubing, "Autonomous vehicles will transform the field of automotive EMC", *IEEE Symp. EMC+SIPI*, 30 Jul- 3 Aug. 2018, Long Beach, CA, USA, DOI 10.1109/EMCSI.2018.8495279.
2. R. Frank, "Avoiding EMC problems in automotive systems", *Electronic Design*, Apr. 2010, https://www.electronicdesign.com/markets/automotive/article/21796735/avoiding-emc-problems-in-automotive-systems.
3. J. Fischer, "The role of GNSS in driverless cars", *GPS World*, Aug. 2018, https://www.gpsworld.com/the-role-of-gnss-in-driverless-cars/
4. "Robust GPS/GNSS: driving the future of autonomous cars", *CAST Navigation,* https://castnav.com/robust-gps-gnss-driving-future-autonomous-vehicles/
5. "A survey of the existence of GPS interference in Europe", *Electronic Environment*, Mar. 2018, https://www.electronic.nu/2018/03/15/a-survey-of-the-existence-of-gps-interference-in-europe/
6. R.S. Littlepage, "The impact of interference on civil GPS", *Proc. 55th Annual Meeting of The Institute of Navigation,* Cambridge, MA, USA, Jun. 1999, pp. 821-828.
7. W. A. Radasky, C. E. Baum, and W. W. Manuel, "Introduction to the special issue on high-power electromagnetics (HPEM) and intentional electromagnetic interference (IEMI)", *IEEE Trans. Electromag. Compat.,* vol. 46, no. 3, pp.314- 321, Aug. 2004.
8. J. Gavan and E. Joffe, "Nonlinear radio mutual interference main effect analysis and mitigation methods", *IEEE Int. Symp. Electromag. Compat.*, vol. 1, Denver, CO, Aug. 1998, pp. 74-79.
9. Y. Zhang and M.G. Amin, "Array processing for nonstationary interference suppression in DS/SS communications using subspace projection techniques", *IEEE Trans. Signal Processing*, vol. 49, no. 12, pp. 3005-3014, Dec. 2001.
10. L. Zhao, M.G. Amin, and A.R. Lindsey, "Subspace array processing for the suppression of FM jamming in GPS receivers", *Proc. Asilomar Conf. Signals, Systems, and Computers*, Monterey, CA, Oct. 2000.
11. I. Sisman and K. Yegin, "Reconfigurable antenna for jamming mitigation of legacy GPS receivers", *Int. J. Ant. Prop.*, vol. 2017, art. ID 4563571, Apr. 2017.
12. H. Steyskal, R. Shore, and R. Haupt, "Methods for null control and their effects on the radiation pattern", *IEEE Trans. Ant. Prop.*, vol. 34, no. 3, pp. 404-409, Mar. 1986.
13. F. Leveau, S. Boucher, E. Goron, and H. Lattard, "Anti-jam protection by antenna", *GPS World*, Feb. 1, 2013, available at https://www.gpsworld.com/anti-jam-protection-by-antenna/

GPS RECEIVER IN THE PRESENCE OF HIGH-POWER INTERFERING SIGNAL

GPS RECEIVER PROTECTED BY FSL IS ABLE TO LOCK WITH THE SATELLITES AND OPERATE IN THE PRESENCE OF HIGH-POWER INTERFERING SIGNAL

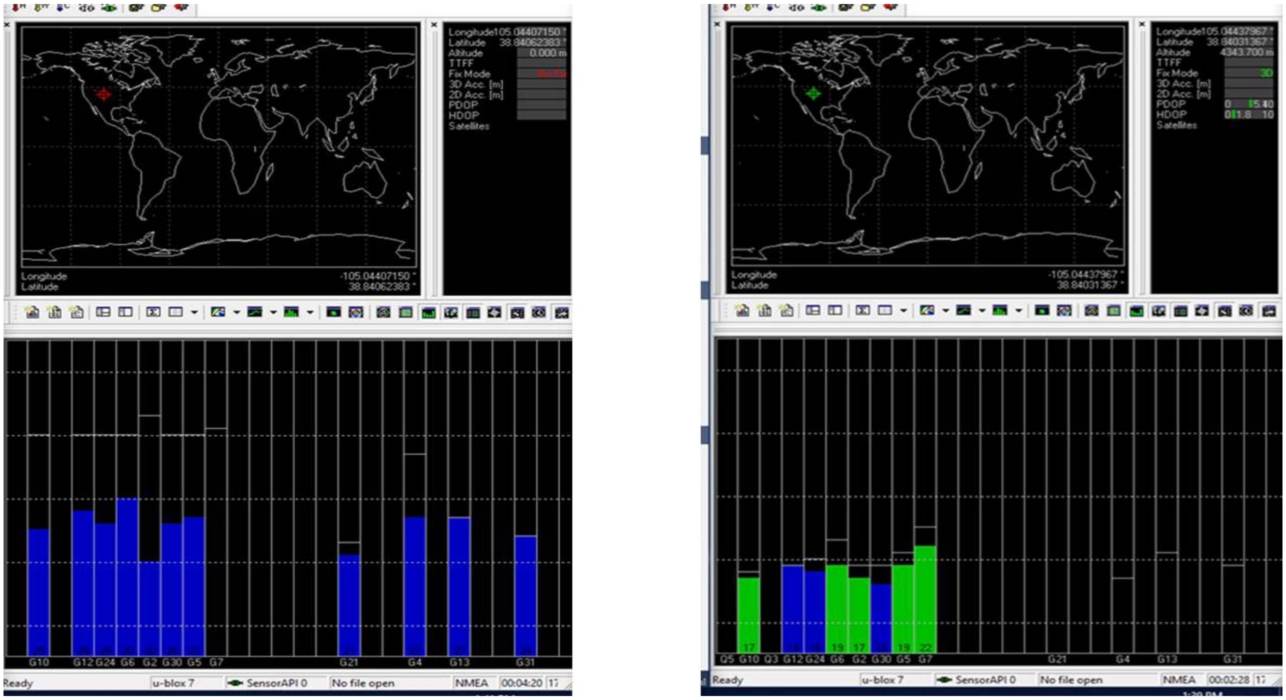

Fig. 8. U-Blox GPS receiver data. (Left) GPS receiver is not able to see any satellite data due to interference by high power interfering signal. (Right) When U-Blox receiver is protected by an FSL, it is able to lock with more than three satellites.

14. R.W. Orth, "Frequency-selective limiters and their application", *IEEE Trans. Electromag. Compat*., vol. 10, no. 2, pp. 273-283, 1968.
15. V. G. Harris, "Advances in magnetics: modern microwave ferrites", *IEEE Trans. Magn.*, vol. 48, no. 3, pp. 1075-1104, 2012.
16. J.D. Adam, "Mitigate the interference: nonlinear frequency selective ferrite devices," *IEEE Microw. Mag.*, vol. 15, no. 6, pp. 45-56, Sept.-Oct. 2014.
17. J.D. Adams and F. Winter, "Magnetostatic wave frequency selective limiters, *IEEE Trans. Magn.*, vol. 49, no. 3, Mar. 2013, pp 956-962.
18. S. Gillette, M. Geiler, J. D. Adam, and A.L. Geiler, "Ferrite-based reflective-type frequency-selective limiters", *IEEE MTT-S Int. Microw. Workshop on Advanced Materials and Processes for RF and THz Applications,* Jul. 16-18, 2018, Ann Arbor, MI, USA, pp. 1-3.
19. J.D. Adam and S.N. Stitzer. "Frequency selective limiters for high dynamic range microwave receivers", *IEEE Trans. Microw. Theory Techn.*, vol. 41, no. 12, pp. 2227-2231, Dec. 1993.
20. A.G. Gurevich and G.A. Melkov, *Magnetic Oscillations and Waves*, 1st ed., CRC Press, Boca Raton, FL, USA, Sep. 1996.
21. L.K. Brundle and N.J. Freedman, "Magnetostatic surface waves on a YIG slab", *Electronics Lett.*, vol. 4, no. 7, Apr. 1968, pp. 132-134.
22. H. Suhl, "The nonlinear behavior of ferrites at high microwave signal levels", *Proc. IRE*, pp. 1270-1284, Oct. 1956.
23. M. Chen and C.E. Patton, "Spin-wave instability processes in ferrites", in *Nonlinear Phenomena and Chaos in Magnetic Materials*, ed. P.E. Wigen, World Scientific, 1993, Chapter 3, pp. 33-82.
24. M. Geiler, *Detection of Spinwave Instability Threshold in Partially Magnetized Ferrites Using Dielectric Resonators*, MS Thesis, Northeastern University, Boston, MA, USA, 2016.
25. A. Boryssenko, S. Gillette, and M. Koledintseva, "Non-linear loss model in absorptive-type ferrite frequency-selective limiters", *IEEE Trans. Microw. Theory Techn.,* vol. 67, no. 12, pp. 4871-4880, Dec. 2019.
26. S.M. Gillette, "Frequency-selective canceller", 16/223,960 U.S. Patent Appl. Publ. US 2019/0267960 A1, Aug. 29, 2019.