The Impact and Sources of Radio Frequency Interference on GNSS Signals

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***Abstract*:** The utilization of the global navigation satellite systems (GNSS) services in both military and civilian applications as well as for scientific investigation has grown exponentially. However, the increasing reliance on GNSS applications has raised concerns about potential risks from intentional radio frequency interference (RFI) transmitters. RFI significantly affects GNSS's environmental monitoring capabilities by inflating the scintillation index and misleading the scientific community with scintillation indices not attributable to ionospheric dynamic events. Consequently, the existing climatological distribution of GNSS scintillations may require careful reevaluation, as it may not adequately filter out RFI induced scintillations. Thus, characterizing the global RFI occurrence regions and developing real-time detection capabilities to mitigate its effects is critically important. Leveraging GNSS measurements from ground stations and six COSMIC-2 satellite constellations, we have developed a technique to detect RFI events and identify RFI active regions. Additionally, for the first time, we have implemented techniques that differentiate RFI associated scintillations from scintillations caused by ionospheric turbulence.

Plain Language Summary

The global navigation satellite systems (GNSS) signals, transmitted by different navigation satellite constellations, are utilized by both military and civilian users for positioning, navigation, and timing (PNT) purposes. The GNSS services are also critically important for a wide range of modern economies, such as for surveying, geodesy, infrastructure, and farming applications. However, the performance of such services can be impacted by unauthorized radio frequency interference (RFI) transmitters that emit artificial noise (jamming) or false/modified pseudorandom noise (PRN) codes to deceive a receiver into calculating a false position (spoofing). We developed a technique that allow us to identify RFI events from GNSS observations and to pinpoint distinct regions where RFI is more active and intense. We also demonstrate that RFI can induce scintillation – referred to as "*fake scintillation*" – which is distinct from the scintillation caused by ionospheric irregularities, potentially sending false alarm to users of scintillation all-clear zone map. Our result clearly shows that RFI is often present in the vicinity of conflict zones and affect GNSS signals similarly to how signal blockage, foliage attenuation, ionospheric scintillation, and multipath do. Intentionally generated L-band (GNSS frequency band) RFI transmitters can be ground-based or space-based (orbital transmitters) and are frequently deployed for military purposes by governments and independent groups to deny regional access to GNSS capabilities, and more recently, to prevent the use of unmanned aerial vehicles (drones). However, such unintended RFI transmitters have the potential to disrupt GNSS applications or halt service operations (navigation blackout), thereby endangering human safety by providing false information to the users.

1. Introduction

The demand for precise Global navigation satellite systems (GNSS) signals is rapidly growing in both military and civilian applications, such as for positioning, navigation, and timing (PNT) as well as being integral to modern economies [*e.g., Cantelmo et al.*, 2009; *Perez-Ruiz et al.*, 2021; *Filjar et al.*, 2021; *Egea-Roca et al.*, 2022]. However, radio frequency interference (RFI), whether intentional or unintentional, poses a significant challenge to this increased reliance on GNSS applications [*Borio et al.*, 2013; *Jones*, 2011]. Despite restrictions on unauthorized L-band frequency transmission, unintentional RFIs from various sources such as satellite communication [*Berglund et al.*, 2011], television broadcasting [*Johannessen et al.*, 1989], radar [*Parkinson and Spilker*, 1996], ultra-wideband communication [*Aiello et al.*, 2000], and solar radio emission [*Marqué et al.*, 2018] can disrupt GNSS frequency bands. Intentional RFIs emit strong signals that can override or overwhelm the targeted signal [*Alexander,* 2009], potentially impacting GNSS application performance or even denying signal use, thereby affecting modern technological systems. High-power RFI signals not only hinder GNSS in close proximity but also disable its usage over larger areas, and such RFI issue has gained critical attention due to its growing severity for GNSS users, particularly the aviation industry. Recently, major media outlets such as Reuters [*Plucinska et al.*, 2024] and Forbes [*Tegler,* 2024] have highlighted how the aviation industry is urging regulators bodies like the International Air Transport Association (IATA) and European Union Aviation Safety Agency (EASA) to take urgent actions against RFI affecting GNSS signals. For example, the surge in RFI activity has led to commercial airliners being diverted off-course, especially in regions like Ukraine and the Middle East. Therefore, it's crucial to characterize RFI, including its occurrence rate and spatial distributions around the world, to take advance precaution and mitigating for operation.

The RFI transmitters send out artificial noise (jamming) [*e.g., Axell et al.,* 2015] or false/modified pseudorandom noise (PRN) codes to interfere and deceive a receiver into calculating a false position (spoofing) [*e.g., Hu et al.*, 2028]. Since the signal-to-noise ratio (SNR) is the fundamental parameter for defining signal quality at the receiver [*Hofmann-Wellenhof et al.,* 2007], it serves as a key indicator of RFI. RFI weakens SNR, thereby hindering ranging measurements and position solution computation. SNR is the ratio of received signal power to the power of noise, which could originate from the receiver itself due to random motion in its circuitry (thermal noise) or natural emissions (e.g., ground, and atmospheric radiations picked up by the antenna). The 'thermal noise' refers to a type of electronic noise that can affect GNSS receivers and is clearly visible on SNR data. Consequently, the contribution of artificial noise from RFI transmitter to the total noise causes a strong noise power density, leading to a decrease of SNR value. If the power of RFI artificial noise is less than that of thermal noise, RFI does not cause an amplitude reduction in SNR. However, when artificial noise equals thermal noise power, RFI leads to a 3dB SNR amplitude decrease, indicating reduced precision in pseudorange and carrier phase measurements by a factor of $\sqrt{2}$ [*Glomsvoll and Bonenberg,* 2017]. If RFI transmits noise with strong power greater than that of the thermal noise, a 1dB decrease in SNR amplitude will be recorded for every 1dB additional increase of RFI noise power. Thus, whenever a GNSS receiver suddenly loses satellite tracking or displays unexpectedly low SNR at a certain location, one should suspect RFI. SNR is typically expressed in decibels (dB) or in Volt (V/V) for linear scale SNR. SNR is also defined as the bandwidth-independent index number, relating the carrier power to noise per 1 Hz bandwidth, which is expressed in dB-Hz. The higher the SNR, the more accurate a GPS range measurement will be.

Since *Volpe* [2001] reported the vulnerability of GNSS signals to RFI sources, several studies have investigated GNSS RFI incidents that could jeopardize GNSS applications. These incidents range from In-Car Jammers blocking GNSS signals near vehicles, which can degrade GNSS performance [*Bauernfeind et al.,* 2011], to RFI associated navigational and situational awareness failures for mariners [*Grant et al.,* 2009]. Similarly, *Glomsvoll and Bonenberg* [2017] conducted authorized GNSS jamming along the Norwegian coast and discovered that the GLONASS constellation exhibited better jamming resilience than GPS. Recent studies [*e.g., Murrian et al.*, 2021; *Roberts et al.*, 2022; and *Chew et al.,* 2023] have utilized GNSS data onboard Low-Earth-Orbit (LEO) satellites to characterize the scope and structure of RFI, as well as to identify RFI regions. However, previous studies did not assess whether these RFIs occur consistently throughout the year or if they are random. Most importantly, they did not report how RFI affects GNSS's environmental monitoring capabilities, such as by inflating the scintillation index - in the same way that ionospheric irregularity inflates the scintillation index - and misleading not only

GNSS users for operation but also the scientific community by yielding "*fake scintillation*", even in regions of steady state ionospheric conditions – almost no disturbance that causes plasma irregularities. Although Roberts et al. [2022] also utilize LEO satellite data to identify RFI regions, this paper employs a different technique to locate RFI regions and addresses additional problems, mentioned below, not included in Roberts et al. Hence, this paper, for the first time, presents: (1) unlike the method used in *Roberts et al.* [2022], which was cross correlation technique, this paper employs a detrending technique to estimate the RFI index, (2) RFI associated scintillation index and how it can be differentiated from the scintillation activities due to ionospheric irregularities and onboard COSMIC-2 LEO satellites, and (3) how RFI associated periodic signal fading occurs in signals observed by GNSS receivers on the ground and onboard LEO satellite, and significantly inflates the scintillation index in the same way it gets inflated by the presence of ionospheric irregularities in the regions where the GNSS signals traverse. The paper also identifies regions where RFI events occur frequently or randomly throughout the year.

2. RFI Detection

2.1. RFI on COSMIC-2 Data

One of the scientific instruments onboard each COSMIC-2 satellite - six equatorial orbiting satellite constellations with a 24° inclination [*Schreiner et al.*, 2020] - is the Blackjack/TriG GNSS receiver. This instrument serves for precise-orbit determination (POD) and radio occultation (RO) measurements, vital for ionosphere and neutral atmosphere studies. SNR observations from this instrument are reported in a linear scale, expressed in volt/volt unit [*Thomas*, 1995], and can be affected by different factors, including antenna gain patterns, transmitter power, and internal and external noise contributions to receivers. Since SNR is a crucial parameter to indicate RFI presence, we developed RFI index (also known as AERO (Aerospace) RFI index) using SNR data from COSMIC-2 satellite mission to characterize the level of interference and to identify regions where RFI is most frequent. Unlike the RFI index in *Roberts et al.* [2022], which is estimated using cross correlation technique, the AERO RFI index is computed from low-rate (1Hz) SNR data by applying the following detrending technique. A 10-sec running average is subtracted from the 1Hz SNR data to obtained δSNR. The AERO RFI index is then equal to the square root of the absolute value of δSNR.

$$AERO\ RFI\ index(i) = \sqrt{|\delta SNR(i)|}$$

RFI is considered as strong and becomes an issue for GNSS applications when the AERO RFI index is greater than 3.0, a threshold value identified through extensive statistical analysis. While the signal is unaffected when RFI index is less than 2, the signal become obstructed and positional or timing information may not be obtained when RFI index greater than 4.5. These values are obtained through various case studies and years of statistical data analysis. The COSMIC-2 mission has an onboard trigger algorithm that assesses the presence of F-region scintillation. When the algorithm detects scintillation, it triggers the download of high-rate data. Consequently, high-rate data availability is limited to occultation tracks experiencing F-region scintillation. In contrast, low-rate (1Hz) data are downloaded from all COSMIC-2 passes and are available at all times and locations. This is the primary reason for using low-rate data for RFI detection, particularly for performing statistical analyses of RFI occurrence rates.

In addition to RFI, GNSS RO signals are also impacted by ionospheric F-region density irregularities. Random variations in SNR observations can occur from constructive/destructive interference of signals passing through plasma irregularity regions, causing radio frequency scintillation. *Figures 1a-1d* show randomly selected COSMIC-2 RO antenna tracks observed on different days, depicting different SNR characteristics (50Hz for GPS and 100Hz for GLONASS) due to ionospheric irregularity, jamming, and spoofing - depicted between solid and dashed vertical lines in each panel. As illustrated in the figures, ionospheric irregularities cause SNR to experience high-rate fluctuation without weakening the background SNR power (panel a). However, RFI incidents cause the total background SNR power to weaken (panel b & c) or to be periodically oscillate (panel d), typically every 10–50 seconds. Calculating the ratio of the standard deviation of the fluctuating SNR (due to RFI or ionospheric irregularity) to the mean SNR computed over a 60s period provides strong S4 index - a metric value that quantifies the strength of amplitude scintillations [*Groves et al.*, 1997].

RFI incident is evident on space-based GNSS data when SNR drops on both ram and anti-ram pointing antennas onboard COSMIC-2 satellites. In *Figure 1e*, the locations of two COSMIC-2 satellites (FM04 & FM06) with occultation links to GPS PRN 10 and 16, respectively, are displayed. The occultation raypaths traverse between GNSS and LEO satellite by piercing the atmosphere at different altitudes, and their ground projections are color coded according to the piercing point altitudes. While ionospheric disturbance is detected on both L1 and L2 frequencies along the FM04 occultation track (*Figure 1f & 1h*), in the present case RFI is only detected at the L1 frequency (*Figure 1g*), not at the L2 frequency (*Figure 1i*) along the FM05 occultation track. This may indicate that for this specific event, RFI transmitter was primarily targets the L1 frequency. From our extended several years of GNSS data assessment, RFI transmitters mostly target the L1 frequency compared to the L2 frequency. However, sometimes RFI affects both frequencies simultaneously, which may occur when the sources transmit broadband RFI. The drop in L2 SNR values for the entire track (*Figure 1i*) may not be due to RFI, as there is neither a sharp drop nor signal modulation in SNR. Instead, it indicates that the L2 signal maintains a consistently low SNR for the entire pass, including before and after the RFI event. The continuous low SNR values over the entire RO track could be attributed to an antenna gain pattern issue for the given channel rather than RFI. Such cases have often been observed even in the absence of an RFI event. The corresponding amplitude (*Figure 1j & 1k*) and phase (*Figure 1l & 1m*) scintillations reveal intriguing characteristics. It is evident that RFI triggers rapid GNSS fluctuations (embedded within the periodic signal fading) and produces significantly strong amplitude (S4-index) scintillation comparable to that associated with ionospheric irregularities. However, RFI does not cause phase scintillation (in radian) enhancement (*Figure 1m*).

The question is – where do these RFIs occur and how often? Utilizing the location of COSMIC-2 satellite when its GNSS receiver experiences RFI, the geographic regions where strong RFI is most frequent can be identified. However, this does not necessarily mean that the satellite passed directly over the RFI source; rather, the RFI transmitter had a line of sight to one of the GNSS antennas when the satellite passed through the region. Depending on its power, an RFI transmitter can achieve jamming or spoofing within a minimum of a few meters to a maximum of over 160 km radius [*Westbrook*, 2019], and a GNSS receiver onboard a LEO satellite that orbits within this proximity can experience RFI impact and record SNR drop. *Figure 2* illustrates the location of RFI along two randomly selected LEO passes, identified from low-rate (1Hz) SNR data - averaged from COSMIC-2 high-rate SNR data - on 18 April and 13 August 2020. The top two panels present the characteristics of GNSS signals, color coded with elevation angles, when the RFI source transmits artificial noise (jamming) or false/modified PRN codes (spoofing). This is evidenced on multiple GNSS satellite tracks shown in *Figure 2a & 2b,* where the PRNs of GNSS satellites that experienced RFI are listed. The corresponding RFI indices, also color coded with elevation angles, are shown in *Figure 2c & 2d*. The horizontal dashed lines in these figures indicate the threshold value of RFI index. The RFI durations on each case are depicted between solid vertical back lines

(*Figure 2a-2d*) as well as between dashed vertical blue lines (see *Figure 2b & 2d*). While jamming causes strong signal fading by more than 200V/V SNR power, spoofing does not cause significant signal fading (less than 50V/V SNR power) but instead triggers signal decoding. The two isolated RFI (spoofing) zones (*Figure 2b & 2d*) detected along a single satellite track (see *Figure 2e*) indicate that both forward and backward looking GNSS antennas experienced RFI in the Philippines Sea. The durations of RFI on each antenna are depicted between solid vertical back lines and dashed vertical blue lines, respectively. The bottom panel (*Figure 2e*) clearly indicates the locations of RFI (jamming and spoofing) zones, highlighted by red curves along the ground track of the two COSMIC-2 satellites.

2.2. RFI on Ground-Based GNSS Data

RFI incidents on ground-based antennas also manifest as periodic oscillations or overall depressions in SNR observations across different regions. Recently, observations by high-rate ground-based GNSS receivers, operated by UNAVCO [*Stein et al.*, 2000], have revealed that ground-based GNSS antennas are also highly susceptible to RFI. This requires a great deal of attention for scientific investigations using ground-based GNSS receivers. In *Figure 3*, a typical example illustrates RFI impacts, manifesting as periodic signal fading observed by a ground-based GNSS receiver located in the Caribbean region 96.93ºW, 19.52ºN). In *Figures 3a and 3b*, SNR data at L1 and L2 frequencies are color-coded with raypath elevation angles. While the L1 frequency exhibits periodic signal fading exceeding 5dB, almost no fading is observed in the L2 frequency at higher elevation angles. The periodic fading shown in both frequencies at lower elevation angles (~ < 30°) is most likely due to multipath effects. RFI also induces rapid SNR fluctuations, which are embedded within the periodic signal fading. These fluctuations can provide an enhanced scintillation index (*Figure 3c*) that is not related to environmental factors, such as the presence of ionospheric irregularities. Typically, environmental factors, such as those due to ionospheric irregularities, cause SNR to fluctuate up and down without weakening the background SNR power. However, if the entire signal power drops periodically when the elevation angles are high (~ > 30°), similar to what some GNSS antennas experience from multipath at low elevation angles, then it is due to RFI rather than environmental factors. If the inflated S4 index estimated from L1 frequency was due to environmental factors, it would also have been evident on L2 frequency. However, the scintillation index estimated from L2 frequency SNR fluctuation (black curve in *Figure 3c*) remains below the threshold value (horizontal dashed line). This implies that during this specific event, the rapid SNR fluctuations along with the periodic signal fading was due to RFI source that was targeting only L1 frequency. In GNSS navigation systems, amplitude scintillation (with S4 > 0.18) may cause data loss and cycle slip [*Groves et al.,* 1997]. *Figure 3d and 3e* show SNR data at L1 and L2 frequencies, respectively, for multiple GNSS satellite tracks, with different colors representing different PRNS listed in *Figure 3d*. The corresponding scintillation indices (sloid curves) and elevation angles (dashed curves) are shown in *Figure 3f*. The horizontal dashed line in *Figure 3d* indicates the threshold value of the scintillation index. While RFI induced SNR fading happens at the L1 frequency on multiple GNSS segments/satellites (*Figure 3d*) and significantly inflates the scintillation index (*Figure 3f*) at nearly the same time, almost no SNR fading occurs at the L2 frequency (*Figure 3e*). *Figure 3g* shows the 2D (longitude/latitude) maps of scintillation indices estimated from RFI associated GNSS signal fading observed in the Caribbean and African sectors for the duration of 8hrs (16:00 – 24:00 UT) on February 1, 2022. The geographic locations of the ground GNSS stations used to produce the RFI events map are provided in *Table 1*. These RFI associated scintillations are significantly strong (S4 > 0.4), potentially leading to GNSS application blackouts in the region as well as providing wrong information – "*fake Scintillation*" - to the scientific investigations. Just to confirm that RFI can degrade GNSS measurements both on the ground and in space at the same time, *Figures 3h* and *3i* depict RFI detected by GNSS receiver onboard COSMIC-2 satellite when it passes over the vicinity of the ground GNSS receiver that also detected RFI. The space-based SNR fading occurs (between the two vertical solid lines in *Figure 3i*) on four GNSS satellites – listed in *Figure 3i* - tracks during the same timeframe as ground-based RFI detection (see *Figure 3f*). During such events, SNR fading exceeds 5dB, potentially causing GNSS users to lose signals and be unable to track or locate their locations. This confirms that RFI can endanger the safety of human life by preventing the use of GNSS signals or misleading users to calculate wrong locations.

3. Discussion and Summary

RFI affects GNSS signals in the same way GNSS application gets affected by signal blockage, foliage attenuation, ionospheric scintillation and multipath. Thus, by analyzing the locations of COSMIC-2 satellites when they encounter RFI, the regions where strong RFI is most frequent can be identified. *Figure 4* presents an example of global RFI occurrence over a period of four months (August - November 2022), as identified from GNSS measurements onboard COSMIC-2 mission and from ground observations. The RFI impacts on GNSS receivers onboard COSMIC-2 mission are arranged for different local time sectors to understand the similarity and differences between dayside (*Figure 4a*) and nightside (*Figure 4b*) RFI occurrence, within the lower latitude band confined by the COSMIC-2 orbits (24° inclination). The ground tracks of all COSMIC-2 satellites are color-coded with RFI index values, distinctly highlighting regions where RFI impacts are active at all local time sectors. As depicted in *Figure 4a & 4b*, RFI occurrence on the nightside is more frequent and creates larger active zones compared to the dayside during the given statistical periods. The first RFI active zones encompass Yemen, north Ethiopia and Eritrea, Sudan, and Libya. The second active zone stretches along Mali, Nigeria, Cameroon, and the Central African Republic (CAR) region. The third region includes Eastern China and the Philippines Sea area (*90ºE – 150ºE*), while the fourth RFI active zone is in the Caribbean and Mexico peninsula region (*60ºW – 120ºW*). Similarly, the statistical RFI occurrence from ground observations is assessed. Available high-rate GNSS data from two stations, located in the vicinity of two RFI active zones – in the Caribbean (*Figure 4c & 4e*) and African (*Figure 4d & 4f*) - are used. The geographic locations of the stations are shown at the top of each panel. Only RFI events from ground GNSS observations with elevation angles above 40° are considered to avoid potential confusion with multipath effects. The similarities and differences between dayside (*Figure 4c & 4d*) and nightside (*Figure 4e & 4f*) RFI impact on ground GNSS observations are also investigated. It is evident that RFI impacts on ground GNSS signals are prominent and frequent across all local time sectors during the given statistical periods, resulting in strong scintillation index even during local dayside. This clearly indicates that RFI can induce scintillation – referred to as "*fake scintillation*" – which is distinct from the scintillation caused by ionospheric irregularities.

It is important to note that when analyzed as a function of sidereal time (not shown here), the RFI effect exhibits distinct patterns – different from its pattern as a function of local time - particularly in the Caribbean sector. In this region, the RFI impact occurs at nearly the same sidereal time on different days, without significant shifts from one day to the next. However, the RFI pattern as a function of sidereal time varies between regions. For example, in the African sector, the RFI pattern does not occur at a nearly fixed sidereal time across all days. This suggests that the RFI effects are not related to stars, as such signatures would be expected at different locations or longitudes if that were the case. Our ground based GNSS data analysis, however, did not show the same SNR depletion in areas where RFI is not present. The reasons behind these regional differences in RFI distribution, when plotted as a function of sidereal time, are beyond the scope of this paper but could be explored in future studies.

The question is – how frequently do these RFI incidents occur in the region mentioned above? Is it a random event, or does it persistently and consistently occur in these isolated RFI active regions? *Figure 5* shows global RFI occurrences over nearly five years (2019 – 2024) within the lower latitude regions (within ±24° latitudes due to COSMIC-2 orbit inclination). It clearly demonstrates that RFI is not a randomly occurring event in the African sector; rather, it consistently occurs throughout the observation periods. The figure also highlights four distinct meridians where RFI events are prominent almost continuously throughout the year: Nigeria (*10ºW – 3ºE*), Libya (*10ºE – 25ºE*), Ethiopia/Eritrea (*30ºE – 40ºE*), and Yemen (*50ºE – 60ºE*) meridians. These meridians are delineated between solid and dashed vertical white lines in *Figure 5*. While RFI event in the Nigeria meridian disappeared after October 2022, they remain highly active in the Libya meridian with no breaks throughout the observation periods. RFI events in the Ethiopia/Eritrea meridian were sporadic until June 2020 but became stronger and nearly consistent through the end of the observation periods. Just like the Libya meridian, the RFI events along the Yemen meridian were almost a day-to-day occurrence. All these patterns might be attributed to the ongoing regional conflicts and other geopolitical activity/events in the region mentioned above. Since conflict zones has an increased use of militarized commercial drones and GNSS-guided munitions, the correlation between RFI active regions and conflict zones is evident. Most militarized commercial low-cost drones, widely used in conflict zones including civil wars, highly depend on GNSS signals for navigation, and reducing or denying GNSS signal power can degrade its performance or deter the attacks [*Wu,* 2024]. On the other hand, RFI events in the Eastern China and the Philippines Sea were initially very sporadic, occurring only for a few days until March

2021, but became more frequent afterword. The RFI occurrence in the Caribbean sector is a bit complicated – it is neither consistent nor random but occurs every month for several days, with some exceptions in a few months each year.

In addition to causing navigation blackout, the presence of strong RFI also affects scientific investigation by providing misleading information on the scintillation index values. Several groups [*e.g., Seechai et al.*, 2023; *Sousasantos et al.*, 2023; *Mrak et al.*, 2021; *Yizengaw and Groves*, 2018; *Paznukhov et al.*, 2012] have reported the global distributions of ionospheric density irregularities and the associated scintillation activities using GNSS observations both in space and on the ground and found strong and all year active irregularity in the African sector. However, many of these reports did not filter out RFI induced scintillation – "*fake scintillation*" – from the scintillation triggered by ionospheric irregularities when they characterize the global ionospheric dynamics. Given the frequency of RFI occurrences in the African sector, one can pose a potential question to the scientific community – "*do we understand the global climatology of ionospheric irregularity/scintillation distribution?*". Hence, the temporal and day-to-day variability of ionospheric irregularity and scintillation, reported in RFI active regions using GNSS measurements on the ground and onboard LEO satellite, requires careful reexamination by filtering out RFI associated scintillation events. One way to facilitate this reassessment could be using data from other instruments that are not affected by RFI events, such as in-situ ionospheric density irregularity measurements [*e.g., Yizengaw*, 2023].

In summary, the impact of RFI on GNSS signals requires a great deal of attention due to the increasing demand for GNSS applications, essential for scientific investigations, precision in PNT, and its integral role in modern economies and national defense operations. As demonstrated by both ground and spaced based GNSS observations, RFI significantly affects GNSS signals by sharply reducing signal power (SNR value), thereby compromising the accuracy of GNSS applications, and occasionally causing partial or complete signal disruption (e.g., loss of GPS signal tracking) [*e.g., Glomsvoll and Bonenberg*, 2017]. RFI transmitters emit artificial noise that increases total noise and leads to a substantial decrease in GNSS SNR value, depending on the power of the RFI transmitter. This indicates RFI impact is dependent on the characteristics of the transmitter. Therefore, it is critically important to characterize global RFI occurrence regions, understand the nature of signals transmitted from unintended RFI sources, and develop real-time detection capabilities to mitigate their effects on operational GNSS applications.

RFI also affects the environmental monitoring capabilities of GNSS, presenting a critical problem for the scientific community by inflating the scintillation index that is not attributed to ionospheric irregularities. This creates misleading information, particularly for those who rely on GNSS observations to characterize the day-to-day and global variabilities of scintillation associated to ionospheric irregularities. Consequently, the existing climatological distribution of GNSS scintillations may require careful reevaluation, as it may not adequately filter out RFI induced scintillations. Given that GNSS signals face significant issues due to the man-made problem of RFI, the scientific community needs to carefully consider this issue and carefully isolate the GNSS tracks that experienced RFI before using the GNSS data to characterize ionospheric impacts on communication and navigation systems.

4. Acknowledgments

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5. Data Availability Statement

The space based GNSS data from COSMIC missions are available at *https://data.cosmic.ucar.edu/gnss-ro/cosmic2/postProc/level2/*. The high-rate ground-based GNSS data from UNAVCO database can be accessed at *https://data.unavco.org/archive/gnss/highrate/*.

Table 1: List of GNSS receivers used to produce RFI event maps shown in *Figure 3g.*

GNSS code	Geographic Coordinates		Geomagnetic Coordinates	
	Longitudes	Latitudes	Longitudes	Latitudes
AGPR	67.11°W	18.47°N	8.64°E	29.35°N
AOPR	66.75°W	18.35°N	9.09°E	29.15°N
BARA	71.10°W	18.21°N	3.39°E	29.75°N
CN06	70.66°W	18.79°N	4.05°E	30.25°N
CN12	76.75°W	18.00°N	3.99°W	29.87°N
CN19	70.05°W	12.16°N	3.87°E	23.87°N
CN20	82.26°W	9.35°N	11.32°W	21.03°N
CRLR	68.94°W	18.42°N	6.24°E	29.65°N
LVEG	70.53°W	19.22°N	4.28°E	30.64°N
RDSD	69.91°W	18.46°N	4.98°E	29.83°N
SROD	71.34°W	19.47°N	3.25°E	30.98°N
STVI	64.97°W	18.34°N	11.40°E	28.70°N
TGDR	71.09°W	18.21°N	3.40°E	29.75°N
UXAL	96.92°W	19.52°N	28.55°W	29.22°N
OLO5	35.89°E	2.63°S	107.54°E	12.24°S
OLO6	35.91°E	2.71°S	107.56°E	12.33°S
OLO9	35.87°E	2.75°S	107.52°E	12.37°S

Figure Captions

Figure 1: Presents the space based GNSS SNR fluctuations due to RFI and ionospheric density irregularities as well as the corresponding amplitude and phase scintillation indices. The durations of ionospheric and RFI disturbances are portrayed between solid and dashed vertical lines in each panel.

Figure 2: Shows the different characteristics of two different RFI events (jamming and spoofing) triggered SNR fluctuation and the corresponding RFI indices along two randomly picked satellite passes. The bottom panel depicts the geographic locations of GNSS jamming and spoofing zones along the given satellite passes.

Figure 3: The top six panels and a 2D map present typical examples that illustrate RFI impacts on ground based GNSS observations, significantly inflating scintillation index values. The bottom two panels display the RFI impact on the GNSS receiver onboard LEO during the same time the ground GNSS receiver experienced RFI. The ground-based SNR data is in dB and has smaller amplitude compared to that of space-based SNR which is in volt/volt.

Figure 4: The top two panels present four months (August – November) statistical dayside (a) and nightside (b) global RFI occurrence within the lower latitude band bounded by the COSMIC-2 orbits (24° inclination). The bottom four panels show the dayside (c & d) and nightside (e & f) RFI occurrence as function of local time versus day of the year, identified from two ground GNSS receivers located in the Caribbean (c & e) and African (d & f) sectors. The GNSS station code and geographic location are depicted at the top of each panel.

Figure 5: The figure shows the global RFI occurrence throughout the observation periods (2019 - 2024), exhibiting RFI is not a randomly occurring event rather it is a consistently occurring event in the African sector.

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