Detection of GNSS interference through natural hazard monitoring systems and next steps towards the development of an interference early warning system

Nikolas Christoforou* [a,b], Dimitris C. Kakoullis [a], Chris Danezis [a,b]
[a] Cyprus University of Technology, Department of Civil Engineering and Geomatics, Cyprus
[b] Eratosthenes Centre of Excellence, Limassol Cyprus

ABSTRACT

The ability of GNSS to offer Positioning, Navigation and Timing (PNT) functions to existing and emerging applications and technologies is expected to drive significant advancement in multiple fields. Strategic Earth Observation infrastructure units, such as permanent GNSS station networks are increasingly integrated into civil protection strategies and operation plans, serving as decisive tools for monitoring the evolution of geohazards, and assessing their potential impact on the anthropogenic and physical environment. Nevertheless, GNSS performance is still vulnerable to unintentional or intentional interference, with the latter on the rise. Consequently, Interference Monitoring Networks have been developed worldwide to detect interference and pinpoint its sources by means of localization techniques, thereby enabling early warning and immediate resolution of interference problems.

The severe effects of interference on the GNSS signal integrity have prompted significant research endeavours towards the development of efficient methodologies for the timely detection of interference sources. Specifically, in Cyprus and the Eastern Mediterranean region, existing infrastructure for monitoring natural hazards is readily available and in use for a significant number of positioning or geophysical applications. In Cyprus, the largest GNSS strategic infrastructure unit, CyCLOPS, has been operational since 2021, featuring state-of-the-art Tier-1/2 GNSS permanent stations, and calibration-grade SAR corner reflectors installed throughout the country to monitor accurately active and ongoing geohazard incidents. Through this infrastructure, intentional interference events were recorded and analysed for the first time. This study reviews the ability of CyCLOPS to be utilized as an Interference Early Detection System by applying detection and analysis techniques. These techniques will be chosen appropriately taking into consideration existing equipment apparatus, topology and characteristics of the existing geohazard and similar monitoring stations. By incorporating additional equipment, the objective is to develop the first Cyprus GNSS Interference Early Warning System based on CyCLOPS, which will enable continuous monitoring of the GNSS signals for interference detection and localization.

Keywords: GNSS, Interference, Localisation, Geohazards, Monitoring Networks, RINEX

*nc.christoforou@edu.cut.ac.cy

Tenth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2024), edited by
A. Christofe, S. Michaelides, D. Hadjimitsis, C. Danezis, K. Themistocleous, N. Kyriakides, G. Schreier,
Proc. of SPIE Vol. 13212, 132120P · © 2024 SPIE · 0277-786X · doi: 10.1117/12.3037218

1. INTRODUCTION

The GNSS ability to offer positioning, navigation and timing functions to newly found applications and technologies is expected to drive evolution in the coming years in multiple fields. These include solutions for consumers, finance, transport, telecommunications, manned and unmanned aviation, maritime, emergency response, agriculture, geomatics and critical infrastructure [1], [2]. As a result, the number of installed receivers are expected to reach 9.5 billion by 2029, whilst the revenues from both devices and services are expected to reach €325 billion (European GNSS Supervisory Authority, 2019). The weak satellite navigation signals [1] are becoming more and more vulnerable to unintentional or intentional interference. Due to their low power levels, GNSS signals are susceptible to radio frequency interference from intentional or unintentional sources. A typical GPS signal is received 20 dB below the receiver noise floor range. A positive signal-to-noise ratio (SNR) is only achievable with signal processing in the range of frequencies. The GNSS receiver front end captures only a small proportion of this range [4]. GNSS signals can suffer from a wide range of interference factors, such as interference amongst satellites, interference amongst systems, space weather and atmospheric phenomena.

The expansion and criticality of the GNSS services have a substantial impact on the security and safety of personnel and a huge financial implication. Several cases of system failures and cases of unintentional and intentional interference have become the subject of extensive studies. A study from London Economics – an independent European economic consultancy, has estimated that a five-day loss of GNSS will cost more than £5.2 billion to the U.K. economy **[5]**. Another study conducted in the U.S. in 2011 has shown that more than 3.3 million U.S. jobs in agriculture and other industries relied heavily on GPS technology. Possible disruption of GPS would pose direct economic costs of up to $96 billion to U.S. commercial GPS users and manufacturers **[6]**.

Interference incidents can be split into those caused unintentionally and those caused intentionally. Unintentional interference is mainly caused by other technologies that make use of spectrum at nearby frequencies to the selected GNSS frequencies. Harmonic emissions from high-power transmitters, mobile satellite services, television, ultra-wideband radar and personal electronic devices interfere with the GNSS frequencies. According to **[7]**, even the harmonics by DVB-T, UHF IV and UHF V could coincide with the L1/E1 band causing disruption of the GNSS signals. This is confirmed through a campaign that ran in Norway that lasted almost two years. The results show that a total of 7.488 incidents have been reported where a large portion of them was due to faulty equipment **[8]**. International Frequency Coordination bodies and Local Regulatory Authorities need to protect the spectrum from existing and emerging technologies to avoid any controversies and interference imminent threads, such as in the case of LightSquared LTE deployment in the U.S. **[9]**. The latter need to have all necessary means in place to identify, locate and take all necessary actions to seize interfering sources. Interference incidents can be split into those caused unintentionally and those caused intentionally.

As GNSS becomes more widely used for revenue generation and human/assets protection, the rewards from criminal activity aimed at disrupting the system grow [10] leading to Intentional Interference. Intentional interference is distinguished in the three following categories:

- Jamming: This is the act of transmitting a high-power signal that can cause saturation or blockage of the GNSS signal leading to loss of tracking and acquisition capabilities. According to [11], jammers can be distinguished based on the type of signal transmitted:
    - Single Tone Amplitude Modulation (AM)
    - Single Tone Frequency Modulation (F.M.)
    - Continuous Wave (C.W.) Narrowband
    - Chirp Signals- Swept Continuous Wave (SCW)

- Spoofing: is a more sophisticated interference technique where falsified information is provided through GNSS look-alike signals manipulating the tracking receiver to provide false location or clock data. Spoofing GNSS signals creates a controllable misreporting of position, for example, to deceive tracking devices [12].

- Meaconing: is defined as the reception, delay and rebroadcast of an entire block of the radio-frequency spectrum containing an ensemble of GNSS signals. [13]. Meaconing can lead to falsified information to users concerning the location of interest.

Intentional Interference cases involve taxi services [14], truck drivers [15], maritime services [16] and civil aviation [17]. The growth of interference is such that, interference occurrence in 2017 has increased by 47 times compared to 2014 [18]. Other cases of interference involved impact on manned and unmanned aircraft [17] and fisheries.

2. USE OF GNSS CONTINUOUSLY OPERATING REFERENCE STATIONS FOR INTERFERENCE DETECTION

Many counties and International Collaborations have established throughout the years suitable infrastructure, on a National and Regional Level, for monitoring ground motion. Strategic infrastructure units are continuously incorporated in civil protection strategies and operation plans and constitute indispensable means for not only monitoring the hazards themselves but for serving as critical damage assessment tools.

At the same time, National Authorities and bodies in order to cope with the rise of interference incidents, have built networks of reference stations or further developed existing geodesic infrastructure with the aim of early detection and localisation of interference. Geodetic reference systems are the fundamental infrastructure that provides the basis for precision positioning and navigation using GNSS.

In Denmark GNSS experts from DTU in coordination with Aarhus local authorities and the Danish Agency for Data Supply and Efficiency SDFE have established the TAPAS monitoring system [20]. A system that comprises eleven GNSS reference stations that have been installed within the city of Aarhus and consists of high-quality Septentrio PolarX5S reference stations with Leica AR20 antennas. Through the implementation of a Sum-of-Squares (SoS) detector the Carrier-to-Noise (C/No) data archived through the receiver RINEX data is collected and processed.

Generalized Interference Detection and Localization System (GIDL) [21] is a system that was designed and implemented by Stanford university in collaboration with the Federal Aviation Administartion (FAA). The system consists of four antennas 100m apart slaved to a common clock to allow three-dimensional interference location. This system was originally designed to complement the aircraft precision approach and landing systems, namely the Local Area Augmentation System (LAAS) as well as the Wide Area Augmentation System (WAAS).

Interference Monitoring System (IMS) system [22] is a Pan-European system that was designed and implemented by Astrium GmbH and Iguassu Software Systems in order to provide Galileo GSS and EGNOS RIMS operators an early warning in case of interference presence at close proximity to the critical infrastructure of interest. A system of utmost importance given the significant role that the EGNOS RIMS and Galileo GSS stations play in the improvement of Galileo accuracy.

In a similar way, the Swedish Continuously Operating Reference Stations Network (CORS) named SWEPOS consisting of around 450 stations spanning across the Swedish territory was utilized for Interference Detection purposes. In accordance with [23], an experimental setup was set at three operative SWEPOS stations where data extracted from the RINEX files were compared against the results obtained from RF Oculus, a professional Interference Detection System that continuously monitors the RMS and average received power in order to calculate the Impulsiveness Ratio (IR). The IR results are further complemented with spectral plots in an effort to detect and characterize interference. Data extraction from a SWEPOS station is shown in Figure 1.

To reduce costs a variety of solutions have been examined. In [24] an enhancement of automotive receivers is suggested, in [25,25–33] low-cost commercial-off-the-shelf (COTS) receivers are utilized, whereas in [34–37], Software Defined Radios (SDR) that offer more flexibility in implementing detection algorithms are utilized. A few scientists have applied non-ground detection methods such as UAVs [38], observations through LEO satellites [39] and even helicopters [40].

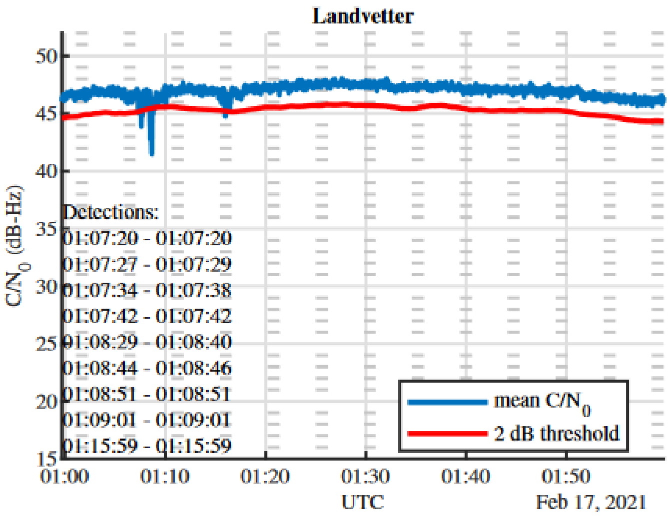

Figure 1: Fors et al- Mean carrier-to-noise-density ratio at Landvetter SWEPOS station

In Italy, Thales Alenia designed and implemented PV-SIS [41], a GNSS Signal-in-Space Verification platform under the project SENECA launched by the Italian authorities of Space and Air Navigation and has been tested in four Italian airports.

Further to the above, an international collaboration developed and tested an Advanced RFI Detection Analysis and Alerting System abbreviated as ARFIDAAS [42–44] with simultaneous deployment and recording of data in Norway, Finland and the Netherlands with a total of six stations. The system front ends continuously measure power levels, automatic Gain Control variations and monitor the RF spectrum. Via the use of specialized software, the measurements and other important parameters of the system are collected and processed. Finally, all data captured from the remote stations are transferred to a centralized unit. A capture of an interference incident by ARFIDAAS is shown in Figure 2.

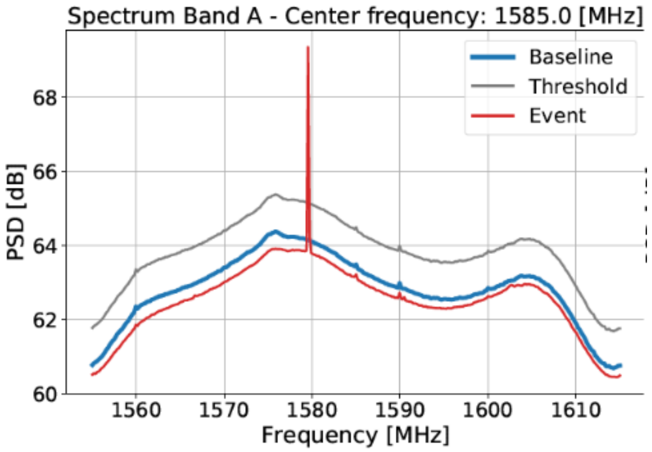

Figure 2: Morrison et al- Capture of Interference through ARFIDAAS stations

In the UK, a collaboration amongst governmental departments, the industry and academia has also performed a series of activities in an effort to early detect and localize interference incidents, especially in areas in the vicinity of critical infrastructure. Systems such as GAARDIAN and its predecessor SENTINEL [45] have been developed and operated successfully.

In [46] an Australian GNSS Environmental Monitoring System (GEMS) which consists of a number of sensor stations connected to a central processing unit, to achieve real-time interference is examined.

A system evolved through a regional CORS network is the NeVoCGPS system. The system consists of 30 GPS stations that constitute a geodetic surveillance system for volcanic activity in Naples [47].

The European Union was also alerted of the dramatic increase in interference incidents and funded several attempts on the related subject. Such a project cofounded by EUSPA, under the project name STRIKE3 [48] involved monitoring of interference in 23 countries. The results showed an extraordinary number of 450.000 cases where interference that affected L1 was detected.

3. THE PRESENCE OF INTERFERENCE IN THE EASTERN MEDITERRANEAN REGION

Cyprus is considered the southeasternmost border of the European Union at the crossroads of three continents and constitutes an important geopolitical location. This area has been greatly affected lately by political unrest and conflicts leading to a drastic increase in interference cases. This is confirmed through Cyprus Air Navigation Reports, Euro control and independent studies. Specifically, Euro control reported in March 2021[49] that the *"Cypriot airspace was one of the most regularly affected by RFI in the network, with 395 cases reported between March 2018 and September 2020 that caused significant GNSS outages over international waters where alternative navigation system coverage is limited."* Further to that, DLR and the Zurich University of Applied Sciences [50] organized in 2020 in collaboration with the Cyprus authorities a test flight within the Nicosia FIR in order to comprehend the impact of interference on the avionic hardware. An Airbus 320 equipped with a high-definition radio-frequency recording device and an experimental Multi-Mode Receiver performed a test flight. The trajectory of the test flight is shown in Figure 3. According to the study, the Multi-Mode receiver was not able to provide a position solution for 80% of the experimental time.

Figure 3 – Trajectory of experimental flight by DLR

4. CYPRUS GNSS NETWORKS AND INFRASTRUCTURE

Cyprus is located within an area where the African tectonic plate as it moves to the north collides with the Eurasian plate. This ranks Cyprus at the highest place with regard to seismic risks. It is worth mentioning that according to [51] a total of 285 earthquakes with a magnitude of four (4) on the Richter scale or above, have struck within 300 km of Cyprus in the past 10 years. Further to that, the island exhibits many active landslides and slope instabilities. These conditions constitute a permanent threat to the civilians, critical infrastructure as well as the rich cultural heritage of the island. At the same time, the region is ideal for scientific exploration and experimentation. In 2021, a collaboration between the Cyprus

University of Technology and the German Aerospace Agency (DLR) led to the development of the Cyprus Continuously Operating Natural Hazards Monitoring and Prevention Systems abbreviated as CyCLOPS [52]. CyCLOPS consists of a network of stations and an Operations Center. Each station is equipped with GNSS cutting-edge Tier 1/2 reference stations, weather stations and tilt meters. The geographical distribution of the reference stations is shown in Figure 4. According to [53], the CyCLOPS CORS are meeting a number of criteria defined by national bodies such as UNAVCO, IGS and EPN. The CORS are equipped with Trimble R9 receivers and Zephyr Geodetic 2 & 3 antennas. A picture of a CyCLOPS station is shown in Figure 5.

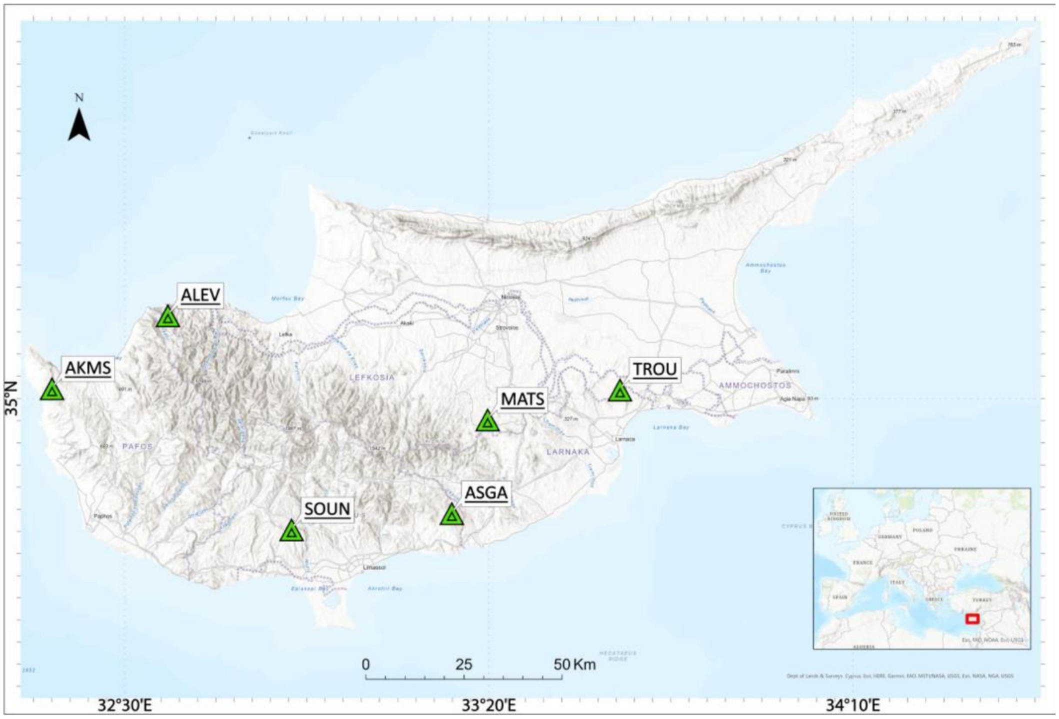

Figure 4 – CORS deployment over the Cyprus Territory

Figure 5 -CyCLOPS Reference Station

5. DETECTION OF INTERFERENCE THROUGH CYCLOPS

The way forward for capturing and analyzing interference through CyCLOPS CORS is via the processing of the RINEX data that are currently collected from all stations and stored on a daily basis for the last few years. The Receiver Independent Exchange (RINEX) is the International Standard developed for the distribution and storing of GNSS Data. The development of the format goes back to 1989 when scientists from the Astronomical Institute of the University of Bern developed a format to allow easy exchange of GPS data collected as part of the EUREF89 campaign [54]. Through the years the RINEX format has been further improved to allow processing of data from multiple GNSS receiver vendors. Currently, there are four different RINEX versions that have been developed through the years as necessary updates in order to account for the technological changes and improvements in the GNSS networks.

In environments with Radio Frequency Interference (RFI), GNSS receivers that rely on precise positioning and timing capabilities often suffer significant performance degradation. All GNSS receivers have a method for indicating the signal strength of the satellites they are tracking. This signal strength can be displayed in various formats, such as vertical bars, normalized signal strength, Carrier-over-Noise density (C/No), or Signal-to-Noise Ratio (SNR). Among these, C/No, which represents the ratio of the carrier power to the noise power, is commonly used for assessing the signal quality of tracked satellites and is easily obtainable from a GNSS receiver as it is included in the RINEX file [55].

Typically, GPS signals are received at about 20 dB below the noise floor, resulting in an SNR of -20 dB and leading to a nominal C/No of 43 dBHz for a GPS satellite. The typical C/No values in an L1 C/A code receiver, for example, range from 37 to 45 dBHz as the estimated C/No values can vary between receivers due to differences in the estimation algorithms used [55,56].

In our case, the availability of archived data that has been collected and stored in RINEX format from a CORS network consisting of State-of-the-Art receivers, provides an excellent basis for experimentation and development of an Interference Early Detection System, based on a model that will be developed, that takes into account the C/No observations. It is expected that if a number of extrinsic factors that affect the signal strength are taken into account, then any further reduction in C/No readings could be due to an active interfering signal. The most important factors impacting the stability of the C/No readings, and consequently, the SNR estimations are:

- Ionospheric Scintillation – the received satellite signals are impacted by electron density irregularities within the ionosphere [57]. The presence of strong Scintillation is expected to have a similar effect on all the receivers of the CORS Network in contradiction to the presence of Interference that normally should impact a limited number of receivers.

- Satellite Elevation Angle– Given that GNSS systems base their operation on Medium Earth Orbit satellites (MEO) it is foreseen that a number of parameters such as distance from receiver to satellite, varying elevation angle, and GNSS receiver antenna pattern contribute to the fluctuation of the SNR estimation [58]. Given that the satellite elevation factor is the dominant factor that affects the SNR, a simplistic method to avoid the impact of low elevation angles is to discard any C/No readings due to low elevation angles by carefully setting the exclusion limits.

- GNSS receiver setup unique characteristics - Especially in the case of low-cost GNSS receivers and antennas there is a variation in performance from station to station. In our case, the use of high-end GNSS receivers, antennas, and quality materials for installing the CyCLOPS stations, ensures uniform performance across the network.

A collection of C/No values per station will be processed in order to account for the presence of natural phenomena that have an impact on the signal strength. By creating a benchmark of the expected results any further reduction in C/No values by more than 5dBHz with a hysteresis of 10 seconds will trigger a process for further investigation and analysis of results including the presence of Spectral Plots (see Figure 6).

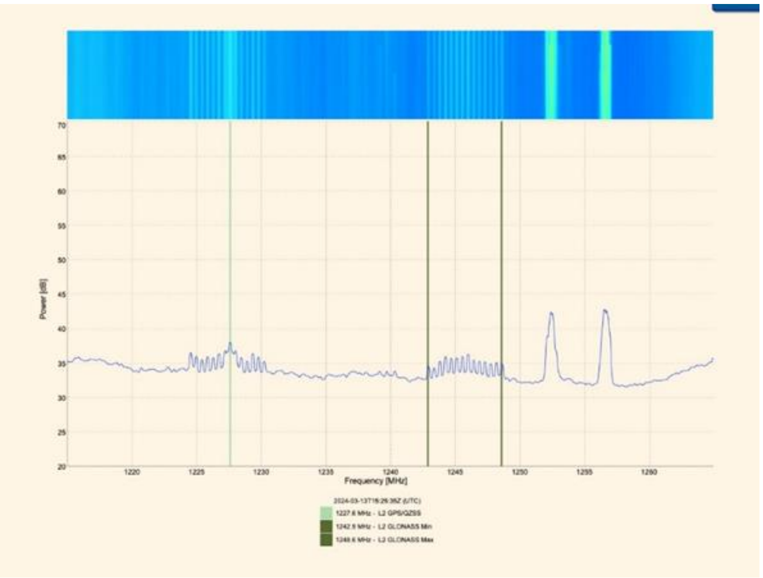

Figure 6 – Spectral plot from Troulloi station - Visible Interference on both L1 & L2

In addition, the mean daily signal strength for all available GNSS constellations across the GNSS bands is generated for each GNSS station during continuous daily tracking. A representative example from station TROU00CYP is illustrated in Figure 7, where the signal strength, estimated in terms of C/No, covers a two-year period from May 2022 to May 2024.

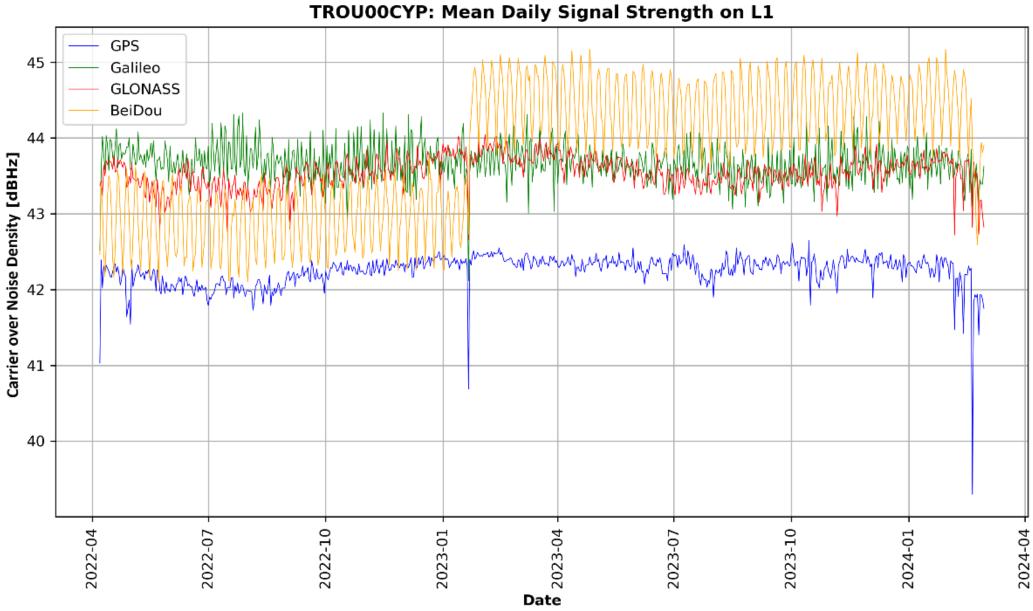

Figure 7. A representative example of the signal strength quality control in the TROU00CYP station**.**

The above plot demonstrates that GPS, Galileo and GLONASS display consistency in signal strength on the L1 band. However, sporadic spikes observed in GPS suggest that the decrease in the C/No could be related to occurrences triggered by various factors such as interference, ionospheric disturbances, or signal obstruction. The data spread demonstrates that the signal strengths vary within an acceptable range. The median value is 43.59 dBHz (including all bands and constellations), well above the threshold of 37 dBHz, implying that the signal strength is reliably strong.

6. FUTURE WORK-CONCLUSIONS

The advent of GNSS technologies is rapidly expanding across a large number of sectors with a critical impact on economic, social, health and safety pillars of human life. The convergence of telecommunications to wireless networks, the frequency reuse in order to serve the continuous demand for additional bandwidth and the malicious cause of Intentional Interference are causing serious degradations/ interruptions of GNSS signals.

The scientific community has been very active through the last decade in an effort to develop Interference detection, localisation and mitigation techniques. Various methods have been developed taking into account inherent GNSS receiver parameters such as AGC and C/No variation by developing a series of algorithms and statistical techniques in order to successfully confront the various interference types.

Through the years the GNSS technologies became an integral part of critical infrastructure. It became evident that it is crucial for the system operators and National authorities to be immediately alerted in cases where the quality and integrity of GNSS signals have been compromised. Under these developments, many Nations as well as Regional Collaborations already had in place CORS networks to further upgrade these in order to constitute early warning systems in case of interference presence.

Cyprus's unique geographical topology has become a point of interest for further study. The implementation of a National CORS Network with state-of-the-art equipment facilitates the requirements for accurate measurements that aid further scientific exploration and experimentation. At the same time, the island is located in a region that is heavily affected by geopolitical developments that lead to clashes and unrest. Due to this fact, it has been verified that the quality of the GNSS signals is frequently degraded due to man-made interference. To this end, it is of utmost importance to implement a National strategy for the development of an Interference Early Warning System. Our effort is focused on the full exploitation of the CyCLOPS infrastructure in order to enhance its capabilities for the detection of Interference through manipulation of the RINEX database.

Through processing the SNR readings captured from each station, a benchmark with SNR expected levels under interference-free conditions will be created for each station. Further to that, through International Collaborations results from preselected stations could be verified by running in parallel with existing Interference Detection systems.

Finally, the stations can be further enhanced with the installation of additional GNSS receivers such as Software Defined Radios that allow flexibility in the implementation of Statistical analysis and precorrelation techniques which could broaden the ability of the system to detect various types of interference.

ACKNOWLEDGMENTS

The authors would like to acknowledge the “CyCLOPS” (RIF/INFRASTRUCTURES/1216/0050) project, which is funded by the European Regional and Development Fund and the Republic of Cyprus through the Research and Innovation Foundation in the framework of the RESTART 2016-2020 programme.

The authors would like to acknowledge the “CyCLOPS+” (RIF/SMALL SCALE INFRASTRUCTURES/1222/0082) project, which is funded by the European Regional and Development Fund and the Republic of Cyprus through the Research and Innovation Foundation.

The authors would like to acknowledge the ‘EXCELSIOR’: ERATOSTHENES: EXcellence Research Centre for Earth Surveillance and Space-Based Monitoring of the Environment H2020 Widespread Teaming project (www.excelsior2020.eu). The ‘EXCELSIOR’ project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No 857510, from the Government of the Republic of Cyprus through the Directorate General for the European Programmes, Coordination and Development and the Cyprus University of Technology.

REFERENCES

[1] *Ioannides, R. T., Pany, T. and Gibbons, G., “Known Vulnerabilities of Global Navigation Satellite Systems, Status, and Potential Mitigation Techniques,” Proceedings of the IEEE* ***104****(6), 1174–1194 (2016).*

[2] *Sanou, D. A. and Landry, R. Jr., “Analysis of GNSS Interference Impact on Society and Evaluation of Spectrum Protection Strategies,” POS* ***04****(02), 169–182 (2013).*

[3] *European GNSS Supervisory Authority., [GNSS market report.Issue 6, 2019 .], Publications Office, LU (2019).*

[4] *Dempster, A. G. and Cetin, E., “Interference Localization for Satellite Navigation Systems,” Proceedings of the IEEE* ***104****(6), 1318–1326 (2016).*

[5] *“Economic_impact_to_UK_of_a_disruption_to_GNSS_-_Full_Report.pdf.”, .*

[6] *Pham, N. D., “The Economic Benefits of Commercial GPS Use in the U.S. and The Costs of Potential Disruption,” 19 (2011).*

[7] *Wildemeersch, M., Pons, E. C., Rabbachin, A. and Guasch, J. F., “Impact Study of Unintentional Interference on GNSS receivers” (2010).*

[8] *Rødningsby, A., Morrison, A., Sokolova, N., Gerrard, N. and Rost, C., “RFI Monitoring of GNSS Signals on Norwegian Highways,” presented at 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020), 28 October 2020, 3536–3549.*

[9] *O’Driscoll, C., Rao, M., Borio, D., Cano, E., Fortuny, J., Bastide, F. and Hayes, D., “Compatibility analysis between LightSquared signals and L1/E1 GNSS reception,” Proceedings of the 2012 IEEE/ION Position, Location and Navigation Symposium, 447–454 (2012).*

[10] *Attia, D. T. M., “An overview of intentional and unintentional interference on GNSS applications and mitigation techniques,” 9 (2012).*

[11] *Bartl, S., Berglez, P. and Hofmann-Wellenhof, B., “GNSS interference detection, classification and localization using Software-Defined Radio,” 2017 European Navigation Conference (ENC), 159–169 (2017).*

[12] *Li, J., Zhang, J., Chang, S. and Zhou, M., “Performance Evaluation of Multimodal Detection Method for GNSS Intermediate Spoofing,” IEEE Access* ***4****, 9459–9468 (2016).*

[13] *Dovis, F., [GNSS Interference Threats and Countermeasures], Artech House (2015).*

[14] *“No jam tomorrow.”, The Economist (2011).*

[15] *Gao, G. X., Sgammini, M., Lu, M. and Kubo, N., “Protecting GNSS Receivers From Jamming and Interference,” Proc. IEEE* ***104****(6), 1327–1338 (2016).*

[16] *Medina, D., Lass, C., Marcos, E. P., Ziebold, R., Closas, P. and García, J., “On GNSS Jamming Threat from the Maritime Navigation Perspective,” 2019 22th International Conference on Information Fusion (FUSION), 1–7 (2019).*

[17] *Morales-Ferre, R., Richter, P., Falletti, E., de la Fuente, A. and Lohan, E. S., “A Survey on Coping With Intentional Interference in Satellite Navigation for Manned and Unmanned Aircraft,” IEEE Communications Surveys Tutorials* ***22****(1), 249–291 (2020).*

[18] *“EUROCONTROL voluntary ATM incident reporting (EVAIR) safety bulletin 19.”, February 2020, <https://www.eurocontrol.int/publication/eurocontrol-voluntary-atm-incident-reporting-evair-safety-*

bulletin-19> (2 December 2021).

[19] *"Transparent transhipping: detecting illegal fishing with satellite data.", August 2018, <https://www.ship-technology.com/features/global-fishing-watch/> (20 November 2021).*

[20] *Larsen, S. S., Jensen, A. B. O. and Olesen, D. H., "Characterization of Carrier Phase-Based Positioning in Real-World Jamming Conditions," Remote Sensing* **13***(14), 2680 (2021).*

[21] *Gromov, K., Akos, D., Pullen, S., Enge, P. and Parkinson, B., "GIDL: Generalized Interference Detection and Localization System" (2002).*

[22] *Wendel, J., Kurzhals, C., Houdek, M. and Samson, J., "An interference monitoring system for GNSS reference stations," Proceedings of the 26th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2013), 3391–3398 (2013).*

[23] *Fors, K., Stenberg, N. and Nilsson, T., "Using the Swedish CORS Network SWEPOS for GNSS Interference Detection," presented at 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021), 13 October 2021, St. Louis, Missouri, 4323–4333.*

[24] *Bauernfeind, R., Krämer, I., Beckmann, H., Eissfeller, B. and Vierroth, V., "In-Car Jammer interference detection in automotive GNSS receivers and localization by means of vehicular communication," 2011 IEEE Forum on Integrated and Sustainable Transportation Systems, 376–381 (2011).*

[25] *van der Merwe, J. R., Franco, D. C., Jdidi, D., Feigl, T., Rügamer, A. and Felber, W., "Low-cost COTS GNSS interference detection and classification platform: Initial results," 2022 International Conference on Localization and GNSS (ICL-GNSS), 1–8 (2022).*

[26] *Gabrielsson, B., Fors, K., Eliardsson, P., Alexandersson, M. and Stenumgaard, P., "A portable system for autonomous detection and classification of electromagnetic interference in the GPS band," 2014 International Symposium on Electromagnetic Compatibility, 152–157, IEEE, Gothenburg (2014).*

[27] *van der Merwe, J. R., Contreras Franco, D., Hansen, J., Brieger, T., Feigl, T., Ott, F., Jdidi, D., Rügamer, A. and Felber, W., "Low-Cost COTS GNSS Interference Monitoring, Detection, and Classification System," Sensors (Basel)* **23***(7), 3452 (2023).*

[28] *Gattis, B., Akos, D., Kosmala, P.-A., Olivier, M., Chen, Y.-H., Lo, S. and Walter, T., "Test and Measurements from a Global Navigation Satellite System (GNSS) Monitoring System," presented at 35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022), 20 October 2022, Denver, Colorado, 3833–3847.*

[29] *Stader, J. and Gunawardena, S., "Leveraging Worldwide, Publicly-Available Data to Create an Automated Satnav Interference Detection System," presented at 2021 International Technical Meeting of The Institute of Navigation, 23 February 2021, Online, 69–83.*

[30] *Poncelet, J.-P. and Akos, D. M., "A low-cost monitoring station for detection & localization of interference in GPS L1 band," 2012 6th ESA Workshop on Satellite Navigation Technologies (Navitec 2012) & European Workshop on GNSS Signals and Signal Processing, 1–6, IEEE, Noordwijk, Netherlands (2012).*

[31] *Morrison, A., Sokolova, N. and Ahmed, N., "RFI Monitoring in Support of Safety-Critical Multi-Band GNSS-based Systems," 2019 European Navigation Conference (ENC), 1–6, IEEE, Warsaw, Poland (2019).*

[32] *Isoz, O. and Akos, D., "Development of a deployable low cost interference detection and localization system for the GNSS L1/E1 band," 2010 5th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC), 1–4 (2010).*

[33] *Lindström, J., Akos, D. M., Isoz, O. and Junered, M., "GNSS Interference Detection and Localization using a Network of Low Cost Front-End Modules," 8 (2007).*

[34] *Pirazzi, G., Cucchi, L., Marigi, D. and Dionisio, C., "A GNSS integrity monitoring station with Software Defined Radio and low cost receivers," 2012 IEEE First AESS European Conference on Satellite Telecommunications (ES^{TEL}), 1–6 (2012).*

[35] *Šture, F., Morong, T., Kovář, P. and Puričer, P., "High Performance SDR for Monitoring System for GNSS Jamming Localization," 2019 International Conference on Wireless Networks and Mobile*

Communications (WINCOM), 1–5 (2019).

[36] *Pellegrini, V., Principe, F., Tomei, A., Mori, M., Natali, M. and Cioni, R., "The GNSS operative monitoring equipment (GNOME): An SDR-based solution for integrity assurance," 2012 6th ESA Workshop on Satellite Navigation Technologies (Navitec 2012) & European Workshop on GNSS Signals and Signal Processing, 1–8, IEEE, Noordwijk, Netherlands (2012).*

[37] *Ying, Y., Whitworth, T. and Sheridan, K., "GNSS interference detection with software defined radio," 2012 IEEE First AESS European Conference on Satellite Telecommunications (ESTEL), 1–6, IEEE, Rome, Italy (2012).*

[38] *Ahmed, N., Winter, A. and Sokolova, N., "Low Cost Collaborative Jammer Localization Using a Network of UAVs," 2021 IEEE Aerospace Conference (50100), 1–8, IEEE, Big Sky, MT, USA (2021).*

[39] *Murrian, M. J., Narula, L., Iannucci, P. A., Budzien, S., O'Hanlon, B. W. and Humphreys, T. E., "GNSS Interference Monitoring from Low Earth Orbit," arXiv:2009.04093 [eess] (2020).*

[40] *Scaramuzza, M., Troller, M., Bertschi, M. and Leibundgut, H., "Investigation of Spatial and Temporal RFI Events Distribution within the Swiss Airspace," presented at 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019), 11 October 2019, Miami, Florida, 1392–1400.*

[41] *Gasbarra, M., Altieri, A., Morante, Q., Viviano, S., Bellapadrona, R., Pantini, G. and Di Salvo, A., "GNSS signal in space monitoring and interference control platform," 2016 IEEE Metrology for Aerospace (MetroAeroSpace), 325–329, IEEE, Florence, Italy (2016).*

[42] *Morrison, A. J., Sokolova, N., Gerrard, N., Rødningsby, A., Rost, C. and Ruotsalainen, L., "RFI Considerations for Utility of the Galileo E6 Signal," presented at 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021), 13 October 2021, St. Louis, Missouri, 2870–2878.*

[43] *Morrison, A., Sokolova, N., Hakegard, J. E., Bryne, T. H. and Ruotsalainen, L., "A Multi-Site Quad-Band Radio Frequency Interference Monitoring Alerting and Reporting System," 2020 European Navigation Conference (ENC), 1–10, IEEE, Dresden, Germany (2020).*

[44] *Gerrard, N., Rødningsby, A., Morrison, A., Sokolova, N. and Rost, C., "GNSS RFI Monitoring and Classification on Norwegian Highways – An Authority Perspective," presented at 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021), 13 October 2021, St. Louis, Missouri, 864–878.*

[45] *Proctor, A. G., Curry, C. W. T., Tong, J. and Watson, R., "Protecting the UK Infrastructure: A System to Detect GNSS Jamming and Interference."*

[46] *Cetin, E., Thompson, R. J. R. and Dempster, A. G., "Interference Localisation within the GNSS" (2011).*

[47] *D'Arco, M., Tammaro, U., Scarpato, G. and Vadursi, M., "An online quality control system for GPS stations used for geodetic surveillance," 2012 IEEE International Instrumentation and Measurement Technology Conference Proceedings, 507–511, IEEE, Graz, Austria (2012).*

[48] *Thombre, S., Bhuiyan, M. Z. H., Eliardsson, P., Gabrielsson, B., Pattinson, M., Dumville, M., Fryganiotis, D., Hill, S., Manikundalam, V., Pölöskey, M., Lee, S., Ruotsalainen, L., Söderholm, S. and Kuusniemi, H., "GNSS Threat Monitoring and Reporting: Past, Present, and a Proposed Future," J. Navigation **71**(3), 513–529 (2018).*

[49] *"eurocontrol-think-paper-9-radio-frequency-intereference-satellite-navigation.pdf.", .*

[50] *Osechas, O., Fohlmeister, F., Dautermann, T. and Felux, M., "Impact of GNSS-Band Radio Interference on Operational Avionics," navi **69**(2), navi.516 (2022).*

[51] *"The complete Cyprus earthquake report (up-to-date 2024).", <https://earthquakelist.org/cyprus/> (21 April 2024).*

[52] *Danezis, C., Hadjimitsis, D., Eineder, M., Brcic, R., Agapiou, A., Mendonidis, E., Christofe, A. and Tzouvaras, M., "CyCLOPS: A Novel Strategic Research Infrastructure Unit for Continuous In- tegrated Spaced-based Monitoring of Geohazards" (2019).*

[53] *Kakoullis, D., Fotiou, K., Melillos, G. and Danezis, C., "Considerations and Multi-Criteria Decision*

Analysis for the Installation of Collocated Permanent GNSS and SAR Infrastructures for Continuous Space-Based Monitoring of Natural Hazards," 4, Remote Sensing **14***(4), 1020 (2022).*

[54] Janssen, V., [Understanding the RINEX format] (2024).

[55] Thompson, R. J. R., Wu, J., Balaei, A. T. and Dempster, A. G., "Detection of RF interference to GPS using day-to-day C/No differences" (2010).

[56] Angelo, J., "Measuring GNSS Signal Strength," Inside GNSS (2010).

[57] Seo, J., Walter, T., Marks, E., Chiou, T.-Y. and Enge, P., "Ionospheric Scintillation Effects on GPS Receivers during Solar Minimum and Maximum" (2007).

[58] Roggenbuck, O., Reinking, J. and Lambertus, T., "Determination of Significant Wave Heights Using Damping Coefficients of Attenuated GNSS SNR Data from Static and Kinematic Observations," 4, Remote Sensing **11***(4), 409 (2019).*