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Morrison, Aiden

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RFI considerations for utility of the Galileo E6 signal

Aiden J. Morrison, Nadezda Sokolova, *SINTEF*
Nicolai Gerrard, *Norwegian Communications Authority*
Anders Rødningsby, *Norwegian Defence Research Establishment*
Christian Rost, Norwegian Space Agency
Laura Ruotsalainen, The University of Helsinki

Biography

Aiden Morrison received his PhD degree in 2010 from the University of Calgary, where he worked on ionospheric phase scintillation characterization using multi frequency civil GNSS signals. Currently, he works as a senior research scientist at SINTEF. His main research interests are in the areas of GNSS and multi-user collaborative navigation systems and GNSS RFI monitoring and analysis.

Nadezda Sokolova received her PhD degree in 2011 from Norwegian University of Science and Technology (NTNU), where she worked on weak GNSS signal tracking and use of GNSS for precise velocity and acceleration determination. She is now working as a senior research scientist at SINTEF, and adjunct associate professor at the Engineering Cybernetics Department, NTNU, focusing on GNSS integrity and multi-sensor navigation for autonomous system operations.

Nicolai Gerrard is a Senior Engineer in the section for Supervision and Guidance at the Norwegian Communications Authority (Nkom). He received a M.S. in Theoretical Physics from NTNU in 2018. At Nkom, he is working with GNSS radio frequency interference, spectrum monitoring and governmental coordination on GNSS challenges.

Anders Rødningsby received his PhD in 2010 from Norwegian University of Science and Technology (NTNU), where he worked on multi-target multi-sensor tracking. He is currently a senior scientist at the Norwegian Defence Research Establishment (FFI), and associate professor at University of Oslo (UiO). His research interests are in the area of target tracking and navigation.

Christian Rost is a senior advisor in the satellite navigation division at the Norwegian Space Agency. He received the Dr.-Ing. degree in geodesy from Technische Universität Dresden (TUD, Germany) in 2011. Currently he is working with GNSS radio frequency interference and performance analysis of GNSS, especially Galileo, in Norway.

Laura Ruotsalainen is an associate professor at the Univeristy of Helsinki, department of Computer Science. She leads a research group in Spatiotemporal Data Analysis for Sustainability Science (SDA), which consists of nine scientists. SDA performs research on estimation and ML methods using navigation data, namely GNSS, 5G, image and other sensor data.

Abstract

While it is generally known that multi-frequency GNSS implies the coexistence of the satellite navigation signals with other users of the spectrum, the extent to which some of the signals may be impacted by shared spectrum allocations might be underappreciated. This paper presents top level observations from a multi-year international radio frequency interference (RFI) monitoring project covering all L-band signals with specific focus on the challenges facing the E6 band. The context of discussion of the RFI challenges to E6 and their potential mitigations is based on the assumption that most users will be non-authorized and have access to only the open data bearing signal component. In virtually all locations where the Advanced RFI Detection, Analysis and Alerting System

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(ARFIDAAS) monitoring stations were deployed, frequent disruption of the E6 band from systems such as RADARS or other authorized users of the spectrum was observed. In the presented paper, an effort is made to put the observations in the context of the expected use cases of the E6 signal, as well as the motivations of the other users of the spectrum and the options for coexistence from the point of view of the GNSS receiver.

Background of ARFIDAAS

ARFIDAAS was a European Space Agency NAVISP element 3 project running from 2018 through 2019 focused on the capture and collection of RFI events impacting GNSS L-band signals. One of the key features of the ARFIDAAS project was that it utilized custom monitoring hardware front-ends to simultaneously observe 240 MHz of aggregate spectrum divided into four tuneable sub-bands. The typical configuration is of one covering the L1 band including BeiDou B1 through GLONASS G1 signals, and the other three partially overlapping bands spread between the Galileo E5a+E5b, GPS L2 and Galileo E6 signals.

The detection strategy of ARFIDAAS is based on detecting increases in the received L-band signal power level using a microelectromechanical system (MEMS) RF power meter after each of the two upper and lower band surface acoustic wave (SAW) filters, followed by optional monitoring of the feedback state of the Automatic Gain Controls (AGC) of each of the four bands. To support a wide variety of installation environments, this dual stage detection approach can be tuned to be either extremely sensitive to in-band power level changes via the RF power meters, or extremely insensitive to adjacent band sources via the AGC feedback monitoring.

Between 2019 and the present, twelve ARFIDAAS quad-band RFI monitoring stations have been deployed between Norway, Finland, the Czech Republic, and the Netherlands, and have together observed nearly five thousand RFI events impacting one or more GNSS signal bands.

Known hazards to E6 use

It is well understood that the E6 band is neither dedicated to GNSS alone nor to Aeronautical Radio Navigation Service (ARNS) systems exclusively, and that the rights of pre-existing users in various jurisdictions can allow the presence of high pulsed or continuous power signals in bands overlapping the main lobe of the E6 signal. In [1] and [2] the authors present a partial listing of signal types known to be potential sources of interference to the E6 band, including but not limited to RADAR, while [3] expands the list with specific examples of other harmful sources including security cameras from China and amateur TV in Germany. While the camera example given is believed to be illegal in most jurisdictions, the German amateur TV signal is legal yet fits the criteria of a jammer of E6 due to the signal having substantial bandwidth (multiple MHz) overlapping the main lobe of the E6 signal, and continuous transmission at a relatively high-power level.

A separate report dealing with the potential availability impacts to E6 on German roadways in [4] concludes that in the worst case, amateur radio interference could prevent use of signal on the majority of the national highway network in Germany.

ARFIDAAS observations in the field and E6 use implications

An unfortunate consistent observation between deployment sites has been the prevalence of nuisance signals within the L2 and E6 bands, which have ranged from occasional observations at some sites, to persistent disruptions at others. Due to the detection method of the ARFIDAAS system being sensitive to variation in local power levels, a strong continuous transmission source will be ignored while an unstable or intermitted one will appear as a potential event of interest. Below follow several examples of such nuisance signals observed in field.

Two stations deployed in the Netherlands both experienced strong narrowband interference at 1 284 MHz, despite this being in the system SAW filter transition region and one of these sites having an antenna which had a nominal cut off frequency of 1 260 MHz. In order to prevent triggering based on this nuisance signal it was necessary to tune the anti-aliasing filter and shift the centre frequency of the band to intentionally cut off the upper lobes of the E6 signal.

In Helsinki, a RADAR installation would trigger the system so frequently with spurious signals near GLONASS L2 and BeiDou B6 that low band detection had to be turned off entirely to prevent tens of daily detections based on these nearby transmission sources.

In Trondheim, one site with an antenna pointed laterally to cover a busy freeway also covered a residential neighbourhood with the main lobe of the monitoring antenna. Somewhere within residential area a strong signal near GLONASS L2 would trigger multiple daily detections, necessitating the deactivation of low band sensitivity.

Multiple other sites within Norway are subjected to both continuous in-band power due to proximity to primary RADAR sites (Figure 1), but more troublingly their associated emissions which appear to be jamming tests. As an example, the primary RADAR site near Trondheim uses a centre frequency of 1 272 MHz, placing it almost directly on the main lobe of E6. The RFI emissions that are thought to be used for testing the RADAR have been observed covering from the top end of ARFIDAAS reception at 1 300 MHz down through 1 200 MHz and the associated E5b signal.

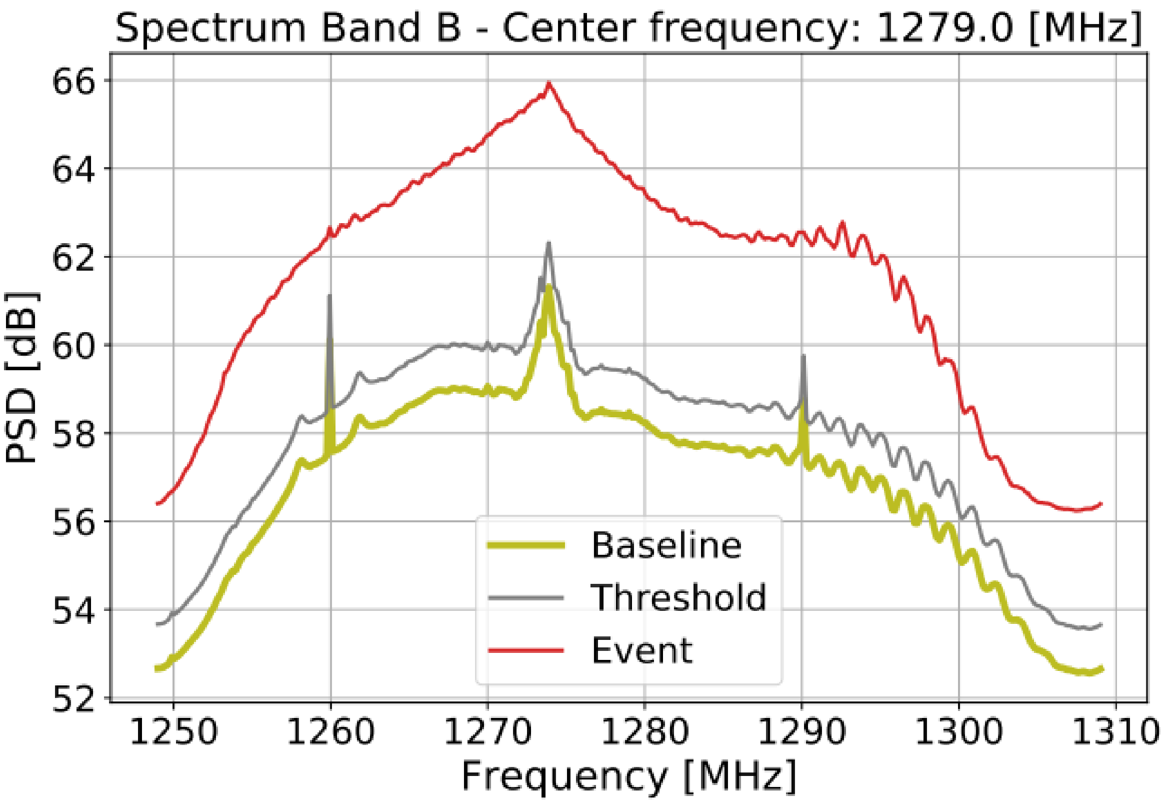

Figure 1: Example of interference assumed to be RADAR related jamming events from Norway on the 19th of January 2021 (not showing leakage into the L2 band).

Other sites, such as one recently installed in the Czech Republic, show a RADAR installation (Figure 2) operating near 1 290 MHz. This installation appears to have better spectral separation from the E6 main lobe, though may still be a challenge to receivers operating in close proximity, and may be causing intermodulation effects to appear within the L2 and E5 bands as well. It should be noted that this impact is observed when using an antenna which has a nominal pass-band extending only to 1 254 MHz.

Some of the events observed are assumed to be related to parts of pre-announced “electronic warfare tests” [5], and manifest as regular two-hour periods of activity spanning Monday through Friday interspersed with quiet periods. Other tests are both unannounced and follow no apparent schedule. In light of the frequent and widespread impacts to signals in the E6 and upper L2 bands, it is appropriate to reconsider some of the recent publications discussing the signal tracking challenges faced by E6 civil receivers through the lens of potential Electro-magnetic Interference (EMI) presence.

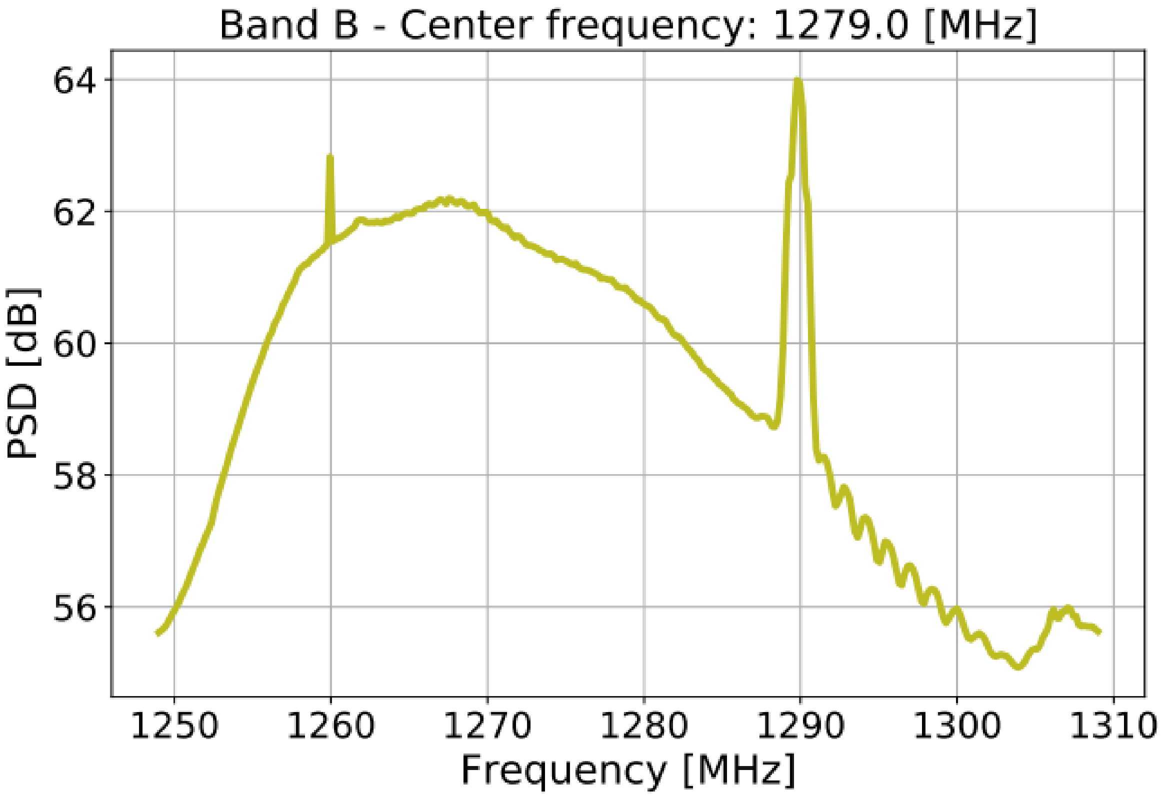

Figure 2: Czech Republic installation environment baseline of E6 band.

Over the past 15 years of development, the exact contents and purpose of the various Galileo signals has changed, but the frequency diversity benefits discussed by [6] remain, as do the known and discussed drawbacks of the use of non-ARNS spectrum and adjacency or overlap with military RADAR.

While [6] focused on the benefits of the possibility of an additional carrier phase measurement, [7] looked into the potential use of the E6 signal implementing the proposed encrypted pilot plus high symbol rate data channel, and elaborated the signal tracking challenges faced by non-authorized users of E6.

Others including [8] and [9] provide viable solutions to the signal tracking issues presented for users wishing to track the high symbol rate portion of the E6 signal without the benefit of pilot tracking through leveraging aide from the tracking of more robust signals broadcast from the satellite such as E1 or E5. This process is reminiscent of past tracking approaches adopted for semi-codeless L2 use, and implies that similar secondary issues including ionospheric decorrelation and a lack of true frequency diversity in the event of jamming in the aiding bands would impact this approach to some degree.

Spectrum enforcement and defence research perspectives

In both electronic warfare (EW) and navigation warfare (NAVWAR) the main purpose is to control the electromagnetic (EM) spectrum to be able to deny an adversary the advantage of the EM spectrum, and at the same time ensure friendly unimpeded access to it. That means that military forces have to be prepared to operate in an unfriendly environment where intentional interference is present. To ensure that the military forces can operate in such an unfriendly environment, exercises with jamming of the appropriate frequency band(s) are necessary and in the national interest seen from a strategic security perspective. Unfortunately, such exercises will also have the side effect of denying civilian users in affected areas access to the jammed parts of the EM spectrum per [5]. Since the E6 frequency band is allocated to the encrypted Galileo Public Regulated Service (PRS), appropriate for authorised users (e.g., police and military), and also used by L-band radars, interference and denial of this part of the electromagnetic spectrum should be expected during military exercises. Unfortunately, the implication of this expectation for prospective users of an E6 borne High Accuracy Service (HAS) would be denial of access to the correction stream during such activities.

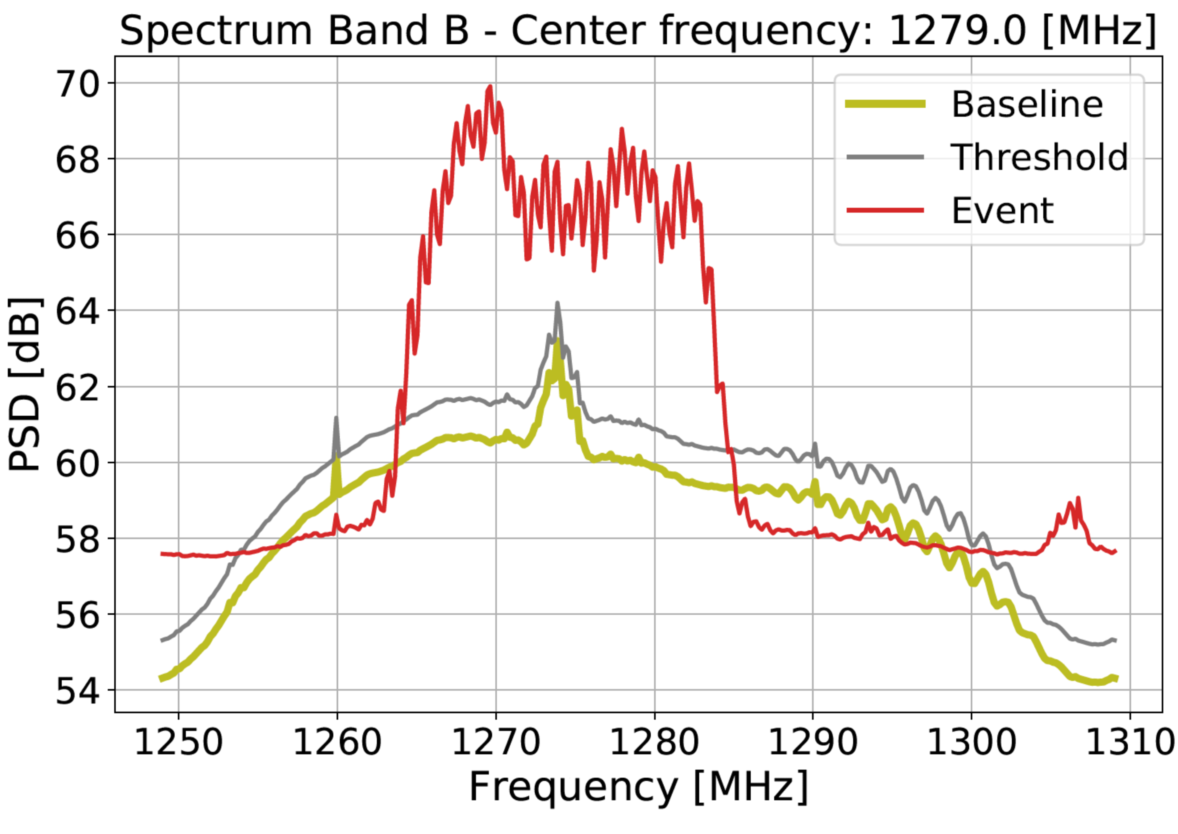

Figure 3: Interference in the E6 band assumed to be jamming during announced electronic warfare exercises.

The Norwegian Armed Forces are given the right to use the band 1 250–1 350 MHz for (military) radiolocation. They are within their rights to employ frequencies in their designated band, as long as it does not reduce the quality of, disturb or cancel out another radio service protected by the Norwegian Electronic Communications Act. However, radionavigation is not given any special protection in the bands covered by the Armed Forces' authorised use. There are many recorded examples of this type of frequency use, for example during the week 24.–28.02.2020 including the instance shown in Figure 3.

In general use of spectrum outside the designated band is not allowed. A typical example of this is "leakage" of jamming signals from electronic warfare exercises. This "leak" sometimes reaches the L2-band, which is acted on upon discovery by the spectrum/communications authority. Examples of this exists, for example in September and November 2020. The "leakage" is typically accidental, caused by misconfigured filters, or similar, in the jamming equipment. The Armed Forces are quick to take corrective action when they are made aware of these types of events and are not always aware that the "leak" is happening, however this demonstrates one of the challenges facing E6 arising from other sanctioned frequency use in the shared band.

While we have so far focused on the signal tracking concerns posed for non-authorized users of the E6 signal High Accuracy and Commercial Authentication Services (HAS, CAS), since the relative vulnerability of this user segment is higher, it should be pointed out that some of the threats discussed will seriously disrupt the E6-A signal (PRS) as well. In cases where the signature of the interfering signal is pulsed (e.g. RADAR), pulse blanking or time-frequency strategies used for mitigation of Distance Measuring Equipment (DME) type interference on the L5/E5 bands could be employed. Mitigation techniques such as adaptive notching may mitigate static narrowband sources such as amateur radio, the remaining category of high power, persistent and wide-bandwidth RFI sources cannot be so directly addressed. Sources such as amateur TV transmissions covering several megahertz of spectrum, or electronic warfare exercises saturating the entirety of the band, will leave receiver designers with less options for mitigation, and even with access to the encrypted pilot and dynamics aiding the signal will still be lost.

Classifying GNSS as the primary user of the frequency band (1 215–1 300 MHz) is not sufficient as it does not prevent interference [10]. Either the frequency band is allocated exclusively to GNSS without exceptions, or stricter guidelines must be adopted to allow interference-free coexistence of multiple users. In both cases, action by the International Telecommunication Union (ITU) is imperative.

Conclusions

Due to potential future encryption of some signal components of E6 [11], recovering the data from the remaining unencrypted signal component may pose a challenge in the presence of any perturbing interference sources. Time-frequency adaptive filtering to address narrowband amateur radio, and short pulse-length RADAR signals may be necessary to ensure robust operation of E6 in many regions of Europe. In other regions where wideband continuous emissions are permitted in an overlapping band, no amount of filtering may be sufficient to allow reasonable use of the E6 signal, regardless of whether they are authorized to track the encrypted pilot and PRS, or not.

If dynamics aiding approaches are adopted by receiver manufacturers to permit the reliable exploitation of the data component of the E6 signal for non-authorized users, it can be expected to mitigate the issues caused by the small tracking margin. However, this will come with the cost of reintroducing drawbacks previously experienced before the availability of civil signals on carriers other than L1. While there will still be value to users which wish to exploit the contents of the high-rate data message carried by E6, the message contents should be sufficiently redundant in the context of frequent loss of data to be practically useful.

Future work: increased event detail and monthly reporting for site specific statistics

Presently ARFIDAAS send event specific rapid analysis information with the notification emails to site stakeholders, and centrally store collected raw IQ signal samples along with these reports to the cloud service. Within 2021 it is planned to implement additional edge unit analysis as well as centralized processing within the cloud that will produce daily and monthly site reports to allow the collection of per site statistical summaries of the likelihood of encountering RFI within each band. Sites that presently have L2, L5, or E6 band detection disabled will need to be re-evaluated to determine the true rate of occurrence, or the parameters available may be reduced to calculating the likelihood of multi-band RFI impacting a system when L1 band RFI is present. This latter information will still be useful when considering the availability level of the discussed "aided" tracking strategies which might employ an L1 carrier to aid in tracking of the E6 signal.

One of the planned additions to the edge unit produced reporting emails sent after each detected event is the time-frequency waterfall visualization of the captured RFI signal as is shown in Figure 4 for a RADAR operating slightly below the E6 centre frequency.

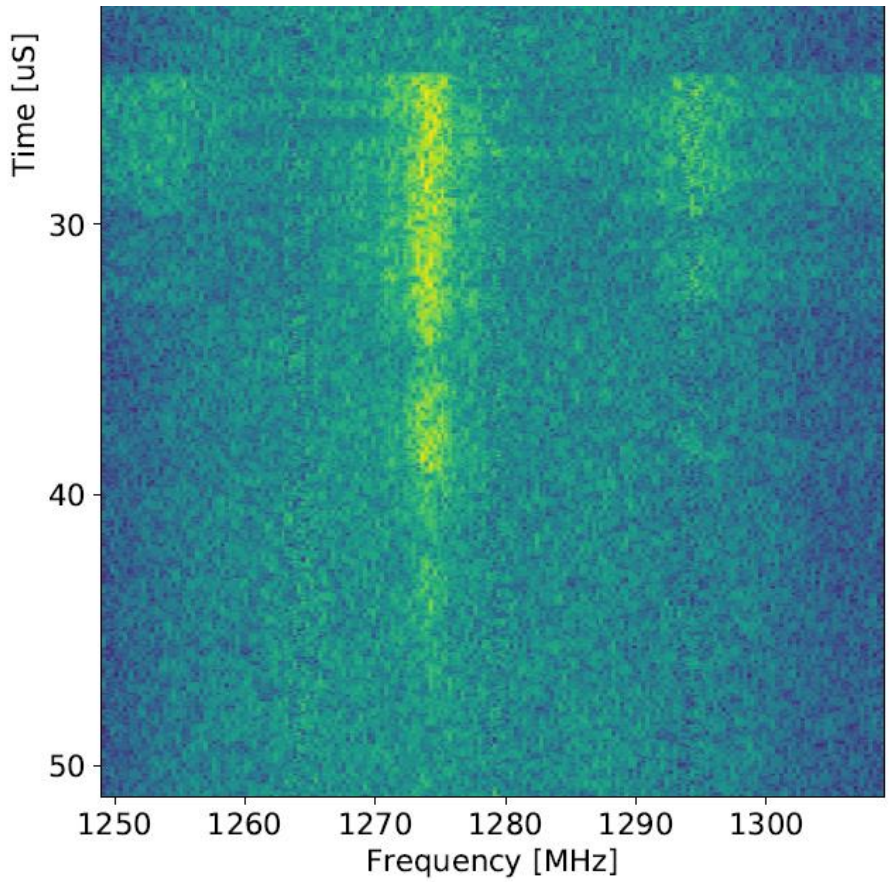

Figure 4: RADAR pulse overlapping the E6 main lobe captured in Norway during an unrelated L1 triggered detection.

An example of one of the pieces of information expected to be provided within the monthly reporting includes the information contained in Figure 5 which visually indicates to the user which signals were impacted throughout the month. In this particular case band B suffered 14 wide-band RFI events which fully or partially overlapped the main-lobe of the E6 signal. Additional information is provided in Figure 6 where the data is disaggregated by band occupancy and modulation type where the relatively large number of narrowband events impacting L1 relative to the other bands is apparent. In Figure 6, the distinction between wideband and time modulated signals is that those whose modulation type and characteristics can be identified (e.g. chrip and multi-level chirp) are classified as time-modulated while those whose characteristics cannot be measured with confidence or are unknown to the classifier but meet the bandwidth criteria to be considered wideband are placed in the wideband category. Additional information on the design of the quad-band ARFIDAAS front-end and software systems can be found in [12], while information on the ongoing ARFIDAAS follow-on project underway between SINTEF and the University of Helsinki which will leverage machine learning techniques to attempt to uniquely identify jamming devices in support of enforcement will be published in the near future.

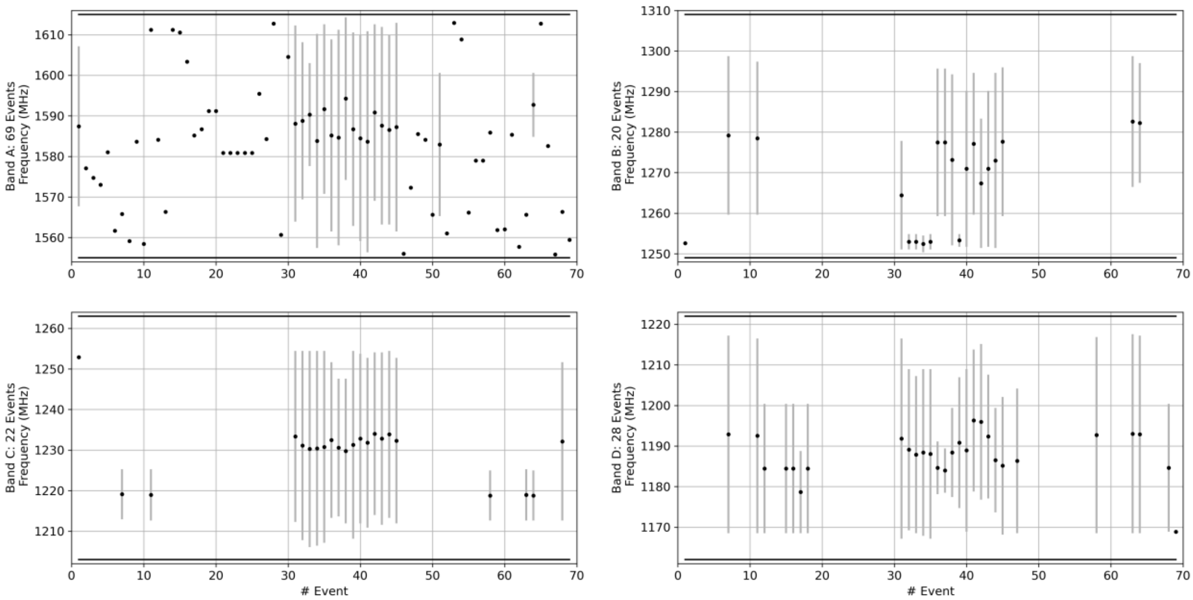

Figure 5: Extract from monthly reporting information showing band occupancy and bandwidth versus ordinal event number.

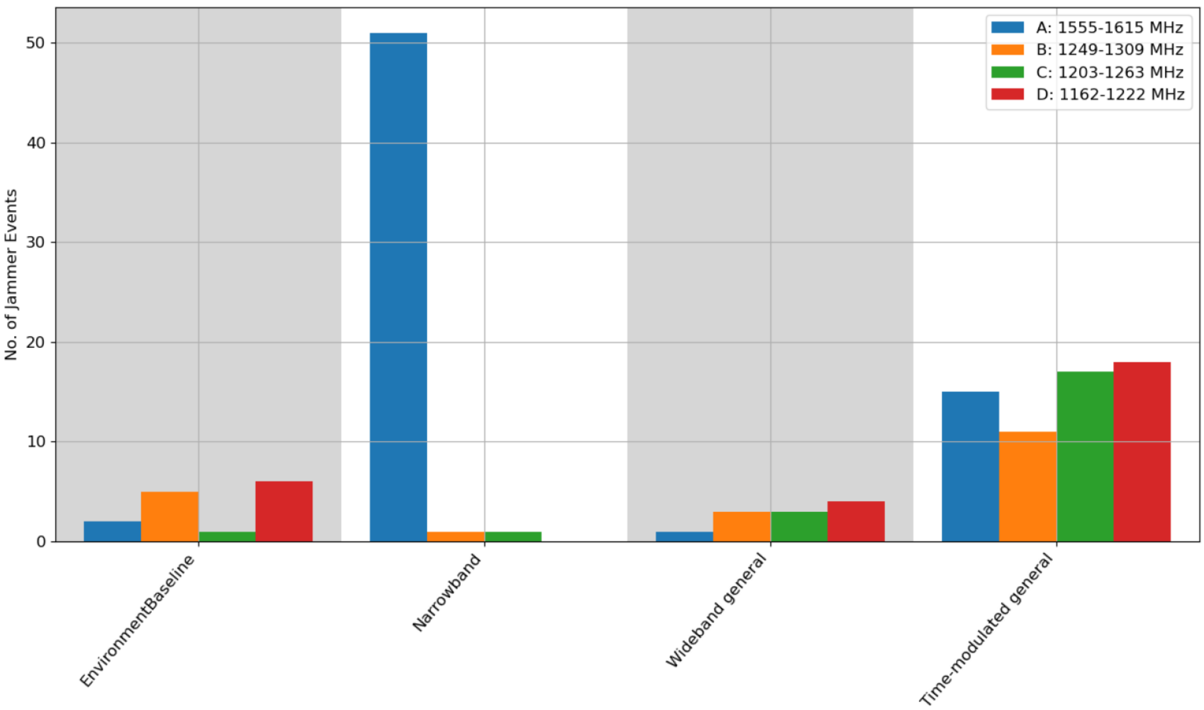

Figure 6: Extract from monthly reporting information showing RFI classification and population count versus band.

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