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# GNSS security and resilience in Eastern Finland

## Report for South-Eastern Finland University of Applied Sciences/Logistics and Seafaring RDI unit

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Abstract:

This report was prepared by the Finnish Geospatial Research Institute (FGI) following a competitive tendering process initiated by South-Eastern Finland University of Applied Sciences Ltd (Xamk). It forms part of the project *Growth from Modern Air Traffic to Eastern Finland* funded by European Union and public and private entities.

The aim of this report is to identify and recommend methods to improve the safety and resilience of satellite navigation (Global Navigation Satellite Systems – GNSS) and to examine alternative positioning methods. The report is based on a review and experiences from scientific research and expert level analysis and provides a detailed discussion of current measures and future research and development to support the safety and robustness of civil aviation under GNSS interference.

The study examines GNSS resilience from the perspectives of both crewed commercial aviation and uncrewed aerial operations (i.e., drones). It provides a research-based list of recommended actions to ensure the safety of GNSS navigation in Eastern Finland.

The key findings of the report and the research it reviews concern not only GNSS interference mitigation, but also the current and future best practises on GNSS-independent positioning. It also considers the limitations coming from the regulation and standardization involved in civil aviation for safety, efficiency, and interoperability. The most important findings are related to situational awareness, rigorous testing of GNSS receivers and interference mitigation methods, maintaining the capability and coverage of distance measurement equipment (DME) to provide an accurate enough backup during GNSS outages, and constant development of GNSS-independent methods, which will be of particular use in the rapid emergence of drone technology.

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## Executive Summary

This expert report has been prepared by the Finnish Geospatial Research Institute (FGI) as part of the project *Growth from Modern Air Traffic to Eastern Finland*, commissioned by South-Eastern Finland University of Applied Sciences Ltd (Xamk) and funded by European Union and public and private entities. FGI was selected to carry out the study through a competitive tendering process. The report aims to support the development of safe and resilient air navigation and geospatial data production in Eastern Finland, with a particular focus on the challenges posed by GNSS interference.

Modern aviation, both crewed and uncrewed, relies heavily on Global Navigation Satellite System (GNSS)-based navigation and positioning. As traditional ground-based navigation aids are phased out, the vulnerability of air operations to GNSS disruptions increases. In addition to navigation, GNSS positioning is critical for aerial mapping activities such as Light Detection and Ranging (LiDAR) scanning and aerial image-based applications. GNSS interference (jamming and spoofing) can compromise flight safety and render collected geospatial datasets unusable, affecting the reliability of derived information products.

Based on an extensive literature review, the study identified current practices, technologies, and approaches to address four key questions regarding GNSS resilience:

- How can intentional GNSS signal interference be rapidly detected, and how can its effects be technically mitigated?
- How can the resilience of GNSS receivers and Real-Time Kinematic (RTK) base stations to intentional interference be improved?
- What kinds of backup systems should be maintained or introduced to complement GNSS navigation?
- What alternative navigation methods should be considered for future implementation?

Key findings are as follows:

- GNSS interference can be detected through continuous monitoring of signal quality and RF spectrum characteristics, with authentication services such as Galileo Open Service Navigation Message Authentication (OSNMA) supporting spoofing detection.
- Receiver resilience improves with multi-constellation, multi-frequency designs and advanced antennas. RTK alone cannot maintain positioning during full GNSS outages.
- Existing aviation navigation aids, including Distance Measurement Equipment (DME), radar, and multilateration, remain critical for operational continuity.
- Hybrid navigation approaches combining Inertial Measurement Units (IMU), cameras, LiDAR, and terrain- or map-based methods are alterative positioning techniques in GNSS-denied environments.
- AI-driven sensor fusion shows strong potential for integrating these methods and enhancing navigation reliability across platforms.

Based on the findings, the report recommends the following actions:

- Signal tracking and integrity monitoring (to detect jamming and spoofing) must be an inherent feature in all GNSS-dependent activities. These capabilities require constant testing and development. This situational picture of the current GNSS signal quality should be either

produced by the user themselves or it can be provided as a service. Interference mitigation is mostly based on receiver technologies or alternative and back-up positioning (see the answers to the next questions).

- The jamming resilience of a GNSS receiver is mostly based on multi-frequency operation or antenna solutions that enable blocking the interference detection, but in the presence of large-scale, multi-frequency jamming, this is not always possible. RTK-GNSS is a network-based correction service to improve the accuracy of the positioning, not to improve its resilience. RTK cannot serve as a backup system, because if the user's own receiver is not getting a GNSS-fix, the RTK corrections are not capable of securing the positioning, navigation and timing (PNT.)
- Multiple backup systems for GNSS-navigation, e.g., distance measuring equipment, radars and multilateration are already in use in aviation, but none of them alone can replace GNSS entirely. These systems should be maintained as a backup, since introducing new technologies in the aviation goes through time-consuming testing and approval process.
- In GNSS-denied environments, reliable navigation requires alternatives that operate independently of external radio signals. Resilient positioning combines relative, absolute, and cooperative methods fusing data from onboard sensors, such as IMUs, cameras, and LiDAR, with terrain, map, point cloud, and satellite datasets for absolute positioning. For lightweight Unoccupied Aerial Vehicles (UAV), visual-based techniques are most practical; however, LiDAR-based methods are necessary in dark conditions, increasing system weight. Larger platforms, such as crewed aircraft and heavy UAVs, can employ Synthetic Aperture Radar (SAR), terrain, and map-based techniques that are robust in most environmental conditions.

Future research and development should focus on hybrid and adaptive navigation systems that combine GNSS and non-GNSS techniques through intelligent/Artificial Intelligence (AI) -driven sensor fusion. Such systems must be capable of real-time interference detection and mitigation to ensure continuous, secure, and autonomous navigation across diverse operational conditions for both uncrewed and crewed aviation platforms. Positioning is often overlooked in current research programs and policies in Finland. A strategic research initiative in Finland should therefore be established to advance operational concepts and architectures for resilient navigation in GNSS-denied environments. Increasing synergy with the navigation research and development community, including a large number of companies and startups, will help in this.

## Tiivistelmä

Tämän asiantuntijaraportin on laatinut Maanmittauslaitoksen Paikkatietokeskus FGI osana hanketta *Kasvua modernista ilmaliikenteestä itäiseen Suomeen.* Selvityksen toimeksiantaja on Kaakkois-Suomen ammattikorkeakoulu Oy (Xamk) ja hanke on EU:n sekä julkisten että yksityisten toimijoiden rahoittama. FGI valittiin tutkimuksen toteuttajaksi kilpailutuksen kautta. Selvityksen tavoitteena on esittää keinoja ja suosituksia turvallisen ja kestävän ilmaliikenteen navigoinnin sekä paikkatiedon tuotannon edistämiseksi itäisessä Suomessa, erityisesti Global Navigation Satellite System (GNSS)-häiriöiden aiheuttamien haasteiden osalta.

Laajan kirjallisuuskatsauksen perusteella raportissa tunnistettiin nykyiset käytännöt, teknologiat ja lähestymistavat neljän keskeisen kysymyksen ratkaisemiseksi:

- Miten tahallinen GNSS-signaalin häirintä voidaan havaita nopeasti ja miten sen vaikutuksia voidaan lieventää?
- Miten GNSS-vastaanottimien ja Real Time Kinematic (RTK)-tukiasemien häiriönsietokykyä voidaan parantaa?
- Minkälaisia varajärjestelmiä tulisi ylläpitää tai ottaa käyttöön GNSS-paikannuksen täydentämiseksi?
- Mitä vaihtoehtoisia navigointimenetelmiä tulisi tulevaisuudessa harkita toteutettaviksi?

Selvityksen keskeiset havainnot ovat:

- GNSS-häiriöt voidaan havaita jatkuvalla signaalin laadun ja taajuusspektrin seurannalla, ja tunnistuspalvelut, kuten Galileo OSNMA, tukevat huijaussignaalien (spoofing) havaitsemista.
- Vastaanottimen kestävyyttä parantavat monikonstellaatioiset, monitaajuuksiset ratkaisut sekä kehittyneet antenniteknologiat. RTK yksinään ei pysty ylläpitämään paikannusta täydellisissä GNSS-häiriötilanteissa.
- Nykyiset ilmailun navigointijärjestelmät, kuten DME, tutkat ja multilateraatiomenetelmät, ovat edelleen keskeisiä toiminnan jatkuvuuden kannalta.
- Hybridinavigointimenetelmät, jotka yhdistävät inertiaalimittauksen, kamerat, LiDARin sekä maasto- tai karttapohjaiset menetelmät, ovat mahdollisia ratkaisuja luotettavalle paikannukselle GNSS:n puuttuessa.
- AI-pohjainen sensorifuusio tarjoaa potentiaalia näiden menetelmien yhdistämisessä ja navigoinnin luotettavuuden parantamisessa eri alustoilla.

Tulosten perusteella suositellaan seuraavia toimenpiteitä:

- GNSS-signaalin laadun monitoroinnin (erityisesti häirinnän ja harhautuksen tunnistuksen) tulee olla olennainen osa kaikkia GNSS-riippuvaisia toimintoja. Ajantasainen tilannekuva GNSS-signaalin laadusta tulisi olla saatavana joko käyttäjän itsensä tuottamana, itse tai sitä voidaan tarjota palveluna. Häiriöiden torjuminen perustuu pääosin vastaanotintekniikoihin tai GNSS-vapaaseen tai sitä täydentävään paikannukseen.
- GNSS-vastaanottimen häirinnänsietokyky perustuu pääasiassa monitaajuustoimintoon tai antenniratkaisuihin, joilla neutraloidaan häirintäsignaalia. Laaja-alaisen, monitaajuisen häirinnän aikana tämä ei kuitenkaan aina ole mahdollista. RTK-GNSS on verkkoon perustuva korjauspalvelu paikkatiedon tarkkuuden parantamiseksi, mutta se ei sinällään paranna

GNSS:n häiriösietoisuutta. RTK ei voi toimia varajärjestelmänä, koska jos paikannusratkaisua ei saada, RTK-korjaukset eivät pysty korvaamaan GNSS:aa.

- Ilmailussa on jo käytössä useita GNSS:aa tukevia varajärjestelmiä, kuten etäisyydenmittausjärjestelmät (DME), tutkat ja multilateraatiomenetelmät, mutta mikään niistä ei yksin pysty kokonaan korvaamaan GNSS:aa. Näitä järjestelmiä tarvitaan kuitenkin varajärjestelminä.
- Kun GNSS ei ole saatavilla esim. häirinnän vuoksi, luotettava navigointi edellyttää vaihtoehtoja, jotka toimivat riippumatta ulkoisista radiosignaaleista. Resilientti paikannus yhdistää suhteellisia, absoluuttisia ja verkottuneita menetelmiä, joissa hyödynnetään aluksen omien sensorien – kuten IMU, kamera ja LiDAR – tuottamaa dataa sekä maasto-, kartta-, pistepilvi- ja satelliittiaineistoja absoluuttiseen paikannukseen. Kevyille UAV-alustoille visuaaliset menetelmät ovat käytännöllisimpiä, mutta pimeissä olosuhteissa tarvitaan LiDAR-pohjaisia ratkaisuja. Suuremmat alustat, kuten miehitetyt lentokoneet ja raskaammat UAV-järjestelmät, voivat hyödyntää tutka- (synthetic aperture radar, SAR), maasto- ja karttapohjaisia menetelmiä, jotka ovat toimintavarmoja useimmissa valaistus ja sääolosuhteissa.

Tulevan tutkimuksen ja kehityksen tulisi kohdistua hybridi- ja adaptiivisiin navigointijärjestelmiin, jotka yhdistävät GNSS-riippuvia ja -riippumattomia menetelmiä älykkään sensorifuusion avulla. Tällaisilta järjestelmiltä vaaditaan reaaliaikaista häiriöiden havaitsemista ja korjausta, jotta jatkuva, turvallinen ja autonominen navigointi voidaan varmistaa erilaisissa käyttöolosuhteissa niin miehittämättömissä kuin miehitetyissä lentolaitteissa. Paikannus on jäänyt nykyisissä tutkimusohjelmissa ja politiikkatoimissa Suomessa varsin vähälle huomiolle. Suomessa olisi suositeltavaa käynnistää strateginen tutkimusohjelma, joka edistäisi kestävän navigoinnin mahdollistavien toimintakonseptien ja arkkitehtuurien kehittämisen GNSS-häirittyihin ja -estettyihin ympäristöihin. Yhteistyön lisääminen navigointialan tutkimus- ja kehitystoimijoiden kanssa on keskeistä kestävien ratkaisujen aikaansaamiseksi.

## List of abbreviations

ADS Automatic Dependent Surveillance, ADS-B Automatic Dependent Surveillance-Broadcast
AGC Automatic Gain Control
AHRS Attitude and Heading Reference System
AI Artificial Intelligence
BVLOS Beyond Visual Line of Sight
Chimera Chips Message Robust Authentication
CISP Common Service Providers
C/N0 Carrier-to-noise density ratio
CRPA Controlled Reception Pattern Antenna
DEM Digital Elevation Model
DME Distance Measuring Equipment
DoA Direction-of-Arrival
EKF Extended Kalman filter
FLARM Flight Alarm
FMCW Frequency-Modulated Continuous Wave
FMS Flight Management System
GBAS Ground Based Augmentation system
GNSS Global Navigation Satellite System
HAS High Accuracy Service
HDOP Horizontal Dilution of Precision
HUD Head Up Display
ILS Instrument Landing System
IMS Inertial Measurement System, IMU Inertial Measurement Unit
LEO Low Earth Orbit
LiDAR Light Detection and Ranging
LiDAR Odometry LO, Lidar Inertial Odometry LIO
LORAN Long Range Navigation
MCMF Multi Constellation, Multi Frequency
MEO Medium Earth Orbit
ML Machine Learning
MLAT Multilateration
Mode S ES Mode-S Extended Squitter
NACp Navigation Accuracy Category–Position
NIC Navigation Integrity Category
OSNMA Open Signal Navigation Message Authentication
PNT Positioning, Navigation, and Timing
PSR Primary Surveillance Radar
RAM Route Adherence Monitoring
RF Radio Frequency
RFI Radio Frequency Interference
RMSE Root-Mean-Square Error

RTCA Radio Technical Commission on Aeronautics
RTK Real-time Kinematic
SDR Software Defined Radio
SID Standard Departure Route
SLAM Simultaneous Localization and Mapping
SOP Signal of Opportunity
SSR Secondary Surveillance Rada
STAR Standard Arrival Route
SUA Special Use Airspace
SAR Synthetic Aperture Radar DOA Time Difference Of Arrival
TAN Terrain-aided navigation
TERCOM Terrain Contour Matching
TESLA Timed Efficient Stream Loss-tolerant Authentication
TOA Time Of Arrival
TRN Terrain-referenced Navigation
UAV Unoccupied Aerial Vehicle
UWB Ultra-Wide Band
USSP U-space Service Provides
VIO Visual–inertial odometry, VO Visual odometry
VOR VHF Omnidirectional Radio Range
WAM Wide Area Multilateration

# 1. Introduction

Global Navigation Satellite Systems (GNSS) have been widely used in aviation for a long time, assisting in both landing and take-off operations as well as during the flights. Interference against GNSS systems has been an issue for some time, and for example in South Korea, Doppler based radio ranging system was developed to assist local airports during landing and take-off operations [1]. Recent changes in geopolitics have also caused a significant increase in GNSS jamming [2, 3] events in the European airspace and the vulnerability of GNSS has become increasingly more apparent. Furthermore, recent reports are also showing increase in GNSS spoofing attacks [4], which further underlines a dire need for solutions that can effectively detect the presence of GNSS interference and warn the end user of the potential threat. The European Union is also actively funding research to improve navigation safety around the Baltic Sea [5].

Due to the low signal power at ground level, typically below the natural noise floor [6], GNSS signals are extremely susceptible to interference, both naturally occurring and man-made. Natural causes of interference are typically caused by ionospheric events, and as the solar cycle nears its maximum, the number of these events has also increased. Modern receivers can effectively mitigate ionospheric problems by using either corrections parameters broadcast along the GNSS navigation messages or by computing a so-called ionosphere-free correction by utilising measurements from two different wavelengths. Thus, the effect of natural interference is typically low, as the errors can be corrected, but position deviations are still possible during for example solar storms. Man-made interference is commonly divided to two categories, unintentional and intentional. Unintentional interference can be caused by for example a faulty, or low quality, electronic device that is leaking signal to GNSS bands and causing disruptions [7]. These kinds of events are typically small scale and are easily corrected, but they can still cause severe problems and finding the cause can be challenging. GNSS inference is visualized in Figure 1.

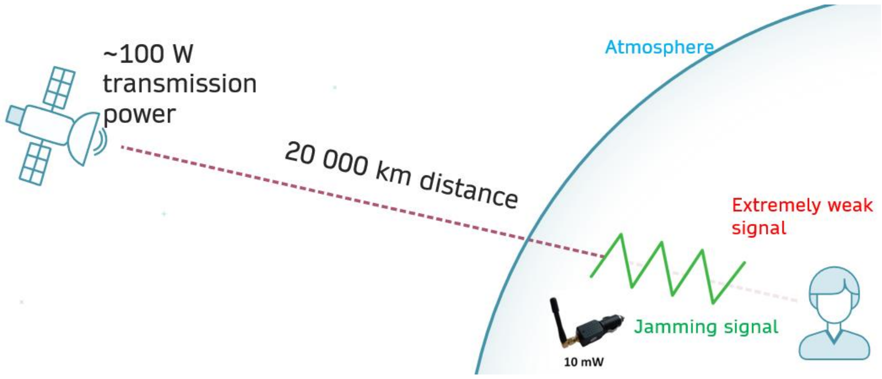

*Figure 1. GNSS jamming: As the signal coming from space is extremely weak, even a low-power jamming signal blocks the receiver from getting the signal and hence the position fix.*

Intentional interference can be further classified to two categories: jamming where the attacker tries to obfuscate the GNSS signals under noise and deny the use of GNSS and spoofing, where the attacker is broadcasting counterfeit GNSS signal and tries to force the target receiver to show incorrect time and/or location information. Compared to spoofing, a jamming attack is considerably simpler and requires less equipment and understanding of GNSS system. Because of the low signal power at ground level, jamming GNSS signals can be done even with cheap equipment [8].

Detecting and identifying GNSS spoofing can be a difficult task as the spoofing signals will appear as real GNSS signals. To successfully spoof a modern receiver will require specific equipment, understanding how receivers operate, and a source of precise time synchronisation [9, 10]. If the spoofing signals are not perfectly aligned in time with the real signals, the spoofing will act more like jamming as the real signal and jamming signal will intervene with each other. For older receivers, the situation is more complicated, as these receivers typically lack internal safety measures and they can be spoofed more easily, for example because they are programmed to lock to the strongest available GNSS signals. Thus, broadcasting spoofed GNSS signals with slightly higher power compared to the real signals can be enough to hijack such a receiver.

With the increasing number of GNSS interference reports, the need for robust detection and mitigation techniques has become apparent. Methods ranging from software solutions [11, 12, 13] to antenna arrays [14] have been suggested, but all of these will increase the cost and complexity of the end system. Furthermore, considering the needs of civil aviation, any new technology or hardware solution must pass a rigid testing and certification process, which can take years. Any new solution will also be discussed and evaluated internationally; thus, any hostile actor will have ample time to develop and test new methods to bypass these safety measures. On the other hand, for drone applications, weight, size, and energy consumption are important metrics, and applying interference mitigation techniques can impact one or all of them. One example of rigorous testing: is the Norwegian Jammertest, an international GNSS testing event organized annually in Andøya, Norway [9], where different types of jamming and spoofing are produced in a controlled environment to allow the participants test their methods and equipment in the presence of varying types of interference.

The deteriorating usability of GNSS and the potential harm the situation can hold, has lead the United States Federal Aviation Administration of the Department of Transportation to issue a Safety Alert for Operators (SAFO) bulletin [21] describing the potential effects that can occur during a flight, as well as guidelines on how to defend against loss of GNSS.

The list of potential harmful effects included

- GNSS based navigation solutions are not available
- In navigation approaches where the inertial measurement unit (IMU) is mainly guided by GNSS-IMU integration, a ‘strong enough’ interference can cause the unavailability of Inertial Navigation System (INS).
- Time-dependent systems, for example clocks, fuel computation system, or Flight Management System (FMS) may show degraded performance
- The jamming can degrade the accuracy of the position fix, which can lead to false EGPWS (Enhanced Ground Proximity Warning System) warnings.
- Inability to use GNSS for arrival and approach procedures.
- During landing operations, the Head Up Display (HUD) may show the aircraft to be misaligned in comparison to runway
- Route deviations or un-commanded turns that can lead to an Airspace infringement or entering a Special Use Airspace (SUA) because of erroneous GNSS fix
- Loss of separation with other aircraft

- The ADS system (Automatic Dependent Surveillance) can show incorrect location for the aircraft, which may trigger other systems to display warnings, or prevent the warnings from being displayed.

Depending on the operational level, there are some countermeasures than can be taken, without the need to invest in new technological solutions. For airport operators and flight crews, a simple method can be to fallback to conventional radio navigation methods like VOR, (VHF Omnidirectional Radio Range), Distance Measuring Equipment (DME), or Instrument Landing System (ILS). The benefit of these systems is that they are independent of GNSS and can provide distance or bearing to a fixed beacon, but they do not reach same accuracy as GNSS based systems. On the other hand, any radio system has the same inherent weakness of potential jamming. For airport operators, radar vectoring can be used to updated erroneous approach vectors etc. Individual pilots and air traffic controllers should also report any issues related to unavailability of GNSS or suspected interference. It is also advised to provide training for pilots and operators on how to identify potentially erratic aircraft behaviour and to maintain vigilance that it may be caused by GNSS interference.

Airlines and national agencies can also increase the collection and analysis of reports on interference hotspots, what is the regionality and duration of GNSS interference and can these be avoided by strategic rerouting. Airport operators and flight crews should also be actively informed of potential problems or dangerous zones. The risks associated to the loss of GNSS will also affect different airlines and aircraft differently, so the risks need to be carefully analysed. How will the loss of GNSS affect other systems onboard, what input they require from GNSS, and can it be provided by other means, and can the aircraft be operated safely without GNSS based navigation systems.

National agencies and international organisations can also provide guidelines and instructions to flight crews on how to react to GNSS outages, so that flight crews would operate as similarly as possible to avoid confusion. On a national level, the maintenance of ground-based navigation systems and other backup systems should be given high priority. Furthermore, for airports that have removed older ‘obsolete’ navigation aids, re-introducing these, especially to airports close to problematic zones is also advisable.

On international level, the promotion of modernisation of GNSS based navigation equipment should be placed as a high priority objective. Many of the older certified and approved receiver are single or dual constellation and single frequency receivers. The inherent problem with these types of receivers is that they are much more susceptible to jamming, as the attacker only needs to target a narrow frequency space. Modern receivers are fully capable of Multi Constellation, Multi Frequency (MCMF) operation, meaning that they can utilise all available GNSS constellation and all available signals. As such, the lack of a single frequency band does not prevent the receiver of deriving a valid GNSS fix. However, some consideration should be placed on how the receiver manufacturers have implemented the utilisation of the more modern signals, as some receivers are driven by GPS L1-band, meaning that if this band is not available the receiver cannot track other signals.

This modernisation effort is hindered by the understandably tight regulation requirements that are in place in the aviation industry. Thus, any new receiver with improved operational capabilities will be in use after several years. The same is true to any new electronics and software solutions. The lengthy process related to regularisation and the requirement that the specifications of these solutions are freely available also makes it easy to develop new attack vectors that will be in place well before the technology is well adopted by the aviation industry. In any case, adopting any new solutions or technology is still advisable, as it increases the cost of any harmful activity.

## 2. GNSS Interference

### 2.1. Methods to detect GNSS jamming

### 2.1.1. Antenna techniques

To estimate the Direction-of-Arrival (DoA), two or more antennas are required. Another option is to use an antenna that consists of several antenna elements. However, in a typical setup, the receiver is only supported by a single antenna, thus estimating the DoA of any interference signal will require a more dedicated system architecture. On the other hand, antennas that have several antenna elements can also be used to mitigate interference by not utilising signal from certain elements in the array, as the desired satellite signals and interference signals typically arrive from different directions. Such antennas are commonly called Controlled Reception Pattern Antennas (CRPA) and they utilise spatial [15], or temporal [16], diversity. A synthetic antenna array can also be formed from one moving antenna [19]. The CRPA antennas have also been tested in the Jammertest event in Andøya, Norway [17,23].

Another option that requires several antennas and receivers is to utilise the time difference of arrival (TDOA) techniques [18] that operate on the temporal diversity between the GNSS signals and the jamming signals. However, these techniques require the receiver to be time synchronised so that the time of arrival (TOA) of the signals between the different locations can be measured. The TDOA methods also require a more detailed software solutions and thus are computational expensive, but the advantage is that the distance of the jammer can also be estimated.

While multiantenna solutions provide clear a clear advantage compared to the typical single antenna setups, there are also drawbacks, and they are strictly not needed if spoofing detection is the main motivation. One of the major issues is the increased complexity of the system, if it is required to assess the DoA of any interfering signals. The complexity is related to both geometrical issues, as the distance and angle between the antennas needs to be know, as well as the need to achieve high level synchronisation between the antennas.

### 2.1.2. Spectrum Monitoring

A common and often deployed method to detect GNSS interference is to monitor the spectrum of the GNSS frequencies using a spectrum analyser or a dedicated software-defined radio (SDR). Any irregularities in the measured spectrum can then be detected by comparing the measurement with the expected spectrum. Jammers typically transmit signals only on specific frequencies so they will appear as spikes in the spectrum, because the true GNSS signals are buried in the noise. In a similar way, any anomaly can be detected from the spectrum samples, including faulty electronics. Spectrum monitoring can also be used to estimate the jammer's power and distance, although an accurate estimate will typically require modelling the signal propagation and the chosen model will also affect the result (i.e. using free path loss model or a more sophisticated model). One can also attach the spectrum analyser or SDR to an antenna with narrow beamwidth to try to estimate the general direction towards the interference source, but the interpreting the resulting measurements can be difficult [7].

### 2.1.3. Signal Quality Monitoring

Another commonly used way to detect GNSS jamming is to monitor the quality of the GNSS signals with either a GNSS receiver or an SDR [41, 42]. There are several parameters that can be used to detect GNSS interference, of which carrier-to-noise density ratio (C/N0) and the Automatic Gain Control (AGC) are the most used to detect interference. The C/N0 describes the strength of the GNSS signal over the background noise and is typically given independently for each satellite in view. As any interfering signal is seen as an additional noise component, the C/N0 will decrease in the presence of jamming. C/N0 is also susceptible to natural variation as any obstructions, even light obstructions like tree leaves, will decrease the C/N0 value. Furthermore, the value can suddenly drop to 0 if the receiver moves to indoors or goes for example through a tunnel and the visibility to GNSS satellites is completely blocked. One way to mitigate this is to use average C/N0 over a single GNSS channel instead of individual C/N0 values for each satellite, as the jammer will affect all satellite signals equally.

The AGC describes how much the receiver is amplifying the received signal to be able to process it. Because the GNSS signals are below the noise floor, it is expected that the AGC should remain near constant even over long periods of time. A jammer will introduce an additional signal in the GNSS band and thus the AGC value will be decreased as there will be more power in the band. The AGC is also not expected to change due to environmental changes, thus any change in the AGC value is a more direct measure of jamming detection.

### 2.1.4. Receiver position monitoring

In the case of a static receiver, for example a monitoring station, the location of the receiver is well known and there should not be large deviations under nominal operating conditions. Thus, a sudden increase in positioning errors, or if the derived location starts to 'wander', can be indicative of interference. Although a more detailed analysis is required to determine if it is caused by jamming or spoofing. For mobile platforms, there is the additional difficulty of discerning if the increased uncertainty in the derived position fix is real and caused by actual movement of the platform or caused by jamming.

### 2.1.5. Machine Learning

The increased popularity of machine learning (ML) methods has also been adapted to the field of GNSS. In principle, the amount of data produced by GNSS receivers and variety of GNSS frequency bands and signal types can be seen as an advantage for ML, as model training typically requires a significant amount of data. The typically used jamming signals have simple shapes, for example 'chirp' signal, that is clearly defined in frequency space. Training a classifying model that identifies different types of jamming signals can be a simple task, but it will require a significant amount of spectrum samples. There is also the added difficulty that laboratory made samples can be too 'clean' compared to signals seen under open sky conditions. Another problem is the multitude of possible jamming signal types, that will make training a universally accurate model a difficult task. While training the model can be computationally extremely costly, utilising the final model for classifying measurement samples will take considerably less resources and can be used as a part of field equipment.

## 2.2. Spoofing detection methods

The harm caused by GNSS jamming is evident and easier to detect than GNSS spoofing, for which the situation becomes much trickier as detecting a well-executed spoofing attack can be challenging. The transmitted signals appear as genuine GNSS signals, and the power levels used should not be much higher than the actual satellite signals. This is assuming that the spoofed signals are time synchronised with the actual GNSS signals [22]. If the synchronisation is not well maintained, the spoofing signals will interfere with the real GNSS signals, and the spoofing will appear as jamming like interference [9].

If the spoofing attack is successful, the potential threat can become life threatening, as the attacker can, for example, try to slowly pull the plane towards a restricted or hostile airspace [20]. Thus, detecting GNSS spoofing is more critical for safety of aviation.

### 2.2.1. Antenna techniques

In a system where there are two or more antennas, the phase measurements for the same satellite between the antennas can be used to extract estimates for the DoA for that satellite relative to the antenna baselines. Computing a so-called double difference between satellites is used to compare the DoA between different satellites. For real satellites, the signals should be uniformly spread on the sky, but for the spoofed signals, they are typically broadcast from a single point, thus they share geometrical terms that will cancel out in the double difference computation. Thus, the receiver-to-receiver phase measurements will be characterised by noise only, whereas the real signals will retain effects from the geometrical terms.

### 2.2.2. Received Signal Strength (RSS) and monitoring of GNSS observables

A relatively common way of spoofing a GNSS receiver is to broadcast the spoofing signal at a higher power level than the genuine GNSS signals. This requires understanding of the real power level at the location that is under spoofing and modern receivers are starting to have counter measures against ‘too high’ signal power levels [24]. However, there are still plenty of legacy receivers that are susceptible to this kind of spoofing attacks, and techniques that assume high power level for the spoofing signals are typically very effective on detecting this kind of spoofing.

The signal strength of individual satellites, the CN0, can for example, be used to detect spoofing, but it should be remembered that the CN0 values can show variation also due to natural occurrences. Power distortion monitoring, structural power analysis of the GNSS frequency bands as well as received power variations versus the movement reported by the GNSS receiver can also be used to monitor the presence of spoofing signals [25]. A simple method to detect single band spoofing is to monitor the relative power between the different GNSS bands. A potential power spike in one band can be an indication of a spoofing attempt (or a jamming signal) [22]. Furthermore, machine learning methods, for example support vector machines [26] can be applied to the monitored parameters like the power spectrum, C/N0, the correlator output to test against unexpected variations. Running these at real time can be difficult, as the observables need to be first extracted from the data and then passed to the ML model.

### 2.2.3. Correlation peak monitoring

At the receiver level, the GNSS correlation peak can be monitored using techniques, that are typically used to tackle multipath, because spoofing affects the correlator output similarly as multipath. The techniques can detect changes in the correlation peak and thus alert the end user of possible spoofing. The technique is extremely effective at detecting spoofing, but in scenarios where there can be a significant multipath component, the method cannot distinguish between the two [36]. At the tracking level, multiple tracking loops and a feedback structure of adaptive filter techniques can also be applied to simultaneously detect the correlation peaks of both the real satellite signals and the spoofed signals [37]. The estimates from the tracking loops can then be used to remove the spoofed signals so that only genuine signals will remain.

### 2.2.4. Consistency checks between GNSS observables

There are several parameters and observables that a GNSS receiver either computes or produces simultaneously as it computes a position solution. Even if a spoofing attack is successful, correctly mimicking all the different parameters and variables is extremely difficult, and as such consistency checks can be used to detect the presence of spoofed signals. For example, for a single spoofer the doppler shift of the satellites in view will be inconsistent with the real signals as the doppler affects the carrier frequency [27]. Inconsistencies between the doppler frequency and code delay rate or the rate of change of phase range measurements can also reveal spoofed signals [22, 28].
Similarly, the received ephemeris of the satellites in view might contain errors when compared against the information in the navigation messages [22]. The time information of the navigation messages between individual satellites should also be consistent, so any variation in the time information can be caused by time spoofing [29]. The derived pseudoranges of the satellites in respect to the receiver location can also show unusual jumps if the signals are being spoofed [30].

For more complex systems that have access for additional sensor, for example inertial measurement units (IMU), consistency check with other navigation and positioning technologies are possible. The information from these sensors can be used to either discriminate against spoofing signals or to verify the position and navigation solution [22].

### 2.2.5. Navigation message authentication

Instead of trying to detect possible spoofing signals, authentication can be used to ensure that the navigation messages received by the receiver are originating from a legitimate source. For civilian users, Galileo constellation provides a navigation message authentication service, called OSNMA (Open Signal Navigation Message Authentication), meant to be operated at the receiver level [31, 32]. The main use of the service is for the end user to be able to verify that the signals they are receiving are originating from a Galileo satellite and are unmodified. The service has been implemented in research receivers and the first experiences are promising in the sense that the OSNMA can verify that the signal actually comes from Galileo [32].

The verification is achieved via a sequence of authentication keys following the Timed Efficient Stream Loss-tolerant Authentication (TESLA) protocol [33]. The end user needs to download a

Galileo public key, which is available at the European GNSS Service Centre (GSC) website and needs to have a Merkel tree root pre-installed on the receiver. Once the first received key has been authenticated, the following keys can be verified by a simple hashing operation. Because of the cryptographic hash functions, it is extremely difficult to compute or forge the next key in the chain, making it extremely resistant.

The OSNMA is designed for civilian end users but can also be used by governmental authorities. For use cases that require even higher security, a fully encrypted navigation message service is currently under development for the Galileo constellation, the Public Regulated Service (PRS) [34]. This service is meant to be offered only to specific governmental operators, military, and healthcare services. The service is meant to be operational by the end of 2027 and the signals are live.

In addition to the Galileo constellation, there are currently plans to add authentication services for the GPS constellation. The proposed Chips Message Robust Authentication (Chimera) method is planned to be able to simultaneously authenticate both the navigation data and the spreading code of a GPS civilian signal [35]. The initial schedule for chimera was to be operational by 2022, with the launch of GPS type III satellites, but due to delays, the current estimated operational readiness is by the end of 2027 at the earliest [20].

## 2.3. Utilising tools available in aviation to mitigate GNSS interference

### 2.3.1. Route Adherence Monitoring (RAM)

For airport operators Route Adherence Monitoring (RAM) can be used to detect deviations between the planes current and expected trajectory. This can be an important early warning to prevent lateral deviations that could lead to loss of separation or the plane straying to an SUA or other controlled airspace. Thus, any deviations that are detected should be investigated and corrected to maintain the safety of operations. Because GNSS jamming, and spoofing, can cause the pilots to lose situational awareness causing the plane to start drifting from the intended course, the RAM could be used to detect GNSS interference via monitoring the aircraft position. The RAM is readily available to all correlated, or tracked aircraft, but the effectiveness of its use heavily depends on the accuracy of the planned trajectory and how often it is updated. However, because the RAM is also used for flight planning and as a general safety feature, its use for this kind of interference monitoring should be carefully assessed. Furthermore, any monitoring system depending on the RAM should likely be as independent as possible, to assure that the air traffic controllers can concentrate on more immediate issues.

### 2.3.2. ADS-B messages

The Automatic Dependent Surveillance-Broadcast (ADS-B) messages can be sent by different protocols, but the Mode-S Extended Squitter (Mode S ES) radio broadcast is commonly in use. The messages are not encrypted and can be received by any receiver, weather it is installed on another airplane or to a ground monitoring station. These receivers are also widely adapted to airplanes, since in the US they are mandatory in most controlled airspaces and in the Europe required to have in aircrafts with certified take-off mass exceeding 5700kg or maximum true airspeed capability exceeding 250 knots. This also means that many general aviation aircraft are not required to have the ADS-B capability.

The RTCA DO standards [43] specify that, if no new GNSS position data is received within 2 seconds of the previous data update, the ADS-B transmitting subsystem will clear all position information on the aircraft, except for the altitude and status subfields of the airborne position message, and if GNSS is unavailable but barometric altitude is, ADS-B should continue transmission and send a Type 0 position report, meaning that the position information is unknown. Although the position information can be derived from other onboard system, for example an IMU, GNSS is the only accepted system that can provide accuracy and integrity readings, as other navigation systems can only provide a relative position. Thus, the ADS-B has been used as a probe of the GNSS 'weather', and there are publicly available resources where these monitoring results are displayed [38].

The ADS-B messages contain parameters that describe the accuracy and integrity level of GNSS observables, but unfortunately, do not contain any direct receiver observables, for example CN0 or AGC values. The broadcast intervals of these parameters also vary based on the type of parameter. Position and velocity parameters have a typical broadcast interval of ~0.5 seconds. The operational status message category (Navigation Accuracy Category–Position (NACp)) of the ADS-B broadcast contains the estimated horizontal and vertical position uncertainties. The probability that the airplane is located within a circle defined by these parameters is 95% under nominal GNSS conditions. Thus, the larger the values, the more uncertain the location estimate is. Similarly, the Navigation Integrity Category (NIC) parameters specify an integrity containment radius, stating that the current position is guaranteed to be within the horizonal protection level of a specified containment radius with 99.999% probability.

There has been significant research interest towards using the ADS-B messages to directly detect GNSS interference. For example, the quality indicators of NACp and NIC parameters reaching 0, in combination with the HDOP (Horizontal Dilution of Precision) value which describes the geometrical distribution of satellites on the sky and how this affects the horizontal accuracy, has been proposed as a tool to detect interference [46]. A more qualitative study on the effect of jamming on different types of aircraft (with different receiver architectures) has been carried out to increase the understanding on how interference affects aircraft and to support development of mitigation techniques [47]. Pattern recognition and cluster analysis methods have also been successfully deployed to detect jamming from the ADS-B messages [45].

Machine learning methods for detecting interference from the ADS-B messages has also been studied [44], and the results seem promising. The proposed CNN model utilises latitude, longitude, altitude, time, and NIC as input parameters and the model output is a bounding box for the estimated jammer location given in degrees. Thus, the ADS-B messages could be used to directly identify possible jammers and airplanes could be instructed to avoid the zone or issue warnings of potential GNSS outages in the region.

### 2.3.3. Other services to increase aviation safety

Automatic Dependent Surveillance - Light (ADS-L) is a newer protocol to enable low-cost, low-power devices to transmit position and other data to increase situational awareness in aircraft where ADS-B is not required. It transmits identical parameters to those in ADS-B, with less compulsory parameters, making the device more affordable. Currently ADS-L operates over the SDR860 frequency band, but the future specifications will enable the transmission also over mobile networks.

FLARM (Flight Alarm) is a traffic awareness and collision avoidance system, initially designed for the needs of light aviation, such as gliders, helicopters, light aircraft and drones. It obtains the position and altitude reading from internal GNSS and barometric sensor and then broadcasts them together with a predicted 3D flight track. Depending on the area, FLARM uses the frequency in the SRD860 band or an ISM band. In Europe, the frequency used is 868.2-868.4 MHz on the SRD860. Simultaneously, it listens for broadcasts from other FLARM devices within its range and alerts the user when risk of collision is predicted.

Another protocol intended for light aviation, especially gliders, is the Open Glider Network Tracking Protocol (OGNTP). It is an open-source protocol to enable transmission of aircraft positional data through ground stations to online servers. It is a low-cost alternative to commercial tracking systems such as FLARM to increase the situational awareness in light aviation.

While ADS-B, ADS-L, FLARM and OGNTP use different frequencies and message formats, all periodically broadcast the position of the aircraft together with the identifying address. However the typical range of technologies intended for light aviation is rather short compares to the range of ADS-B, which limits their use in other than collision avoidance applications.

Remote ID is a drone’s ability to provide identification and location information that is receivable by authorities and public to identify and track drones in flight. The information, such as unique ID, position, altitude and timestamp are broadcast using Wi-Fi or Bluetooth. The Remote ID requirements are mostly similar between the US and the EU rules. The main difference is that in EU the remote ID broadcasts information about the user, such as the operator registration number and the geographical position of the remote pilot. Another difference is so called Network Remote ID, which is mandatory in the upcoming EU U-spaces. It is a Remote ID system, where the information is sent to a trusted service supplier using an internet connection. This is a key technology for managed airspaces for drones, allowing BVLOS flights, and combined manned and unmanned traffic in the airspace. Since Remote ID uses the position data acquired with the GNSS, it is not an independent alternative for GNSS based positioning. However, broadcast Remote ID can be used in multilateration, further discussed in Section 4.2. Remote ID is not required in class C0 drones, which limits the detection of many small consumer-class drones.

Even though the U-space framework exists, the commercial U-spaces are just starting to emerge. The latest Eurocontrol survey about U-space services implementation from 2022 expected that by 2025 about 41% of Single European Sky member states would have Network Remote ID capabilities ready for implementation. In Finland, multiple pilot projects have been undertaken, but currently no need for U-spaces have been seen. Thus, there are no decisions on U-space governance, including the roles and selection of Common Service Providers (CISP) and U-space Service Provides (USSP). necessary for the deployment of U-space.

## 2.4. Effect of interference on GBAS stations

The use GNSS in precision landing approach can be facilitated by Ground Based Augmentation system (GBAS), which provides differential corrections to the received GNSS signals. In addition to the correction data, the system can also be used to monitor the integrity of the GNSS signals. The main intended use of the GBAS system is to assist, or enable, in safety critical operation, for example zero-visibility landings. As such, the integrity, continuity, and availability requirements are extremely strict and even low interference can cause the system to discard satellite signals.

GBAS stations are typically deployed in proximity of the airport that they are supporting, and the airports are in turn typically surrounded by high traffic roads. Thus, the probability of experiencing GNSS interference from so called Personal Protection Devices (PPD), small jammers used by for example truck drivers to circumvent restrictions in allowed monthly drive hours or road tolls, is significantly increased. Small jammers deployed by hostile agents or state level electronic warfare can also easily hamper a GBAS station.

The interference events and their threat profile have been characterised recently [39] and considering a dual L1/E1 - L5/E5a band GBAS stations. The study considered 14 stations scattered across northern and western Europe and the aggregate observations totalled over 8 years and contained over 18 000 interference events. It was noticed that most of the detected events were targeting the L1/E1 frequency band, and typically in the cases where the L5/E5a band was targeted, also the L1/E1 band was affected. These results again highlight the importance of MCMF receivers, as they offer a fallback frequency ranges in situations where the jamming is only targeting the basic L1/E1 band. Unfortunately, due to the high-performance requirements, the service can be easily disrupted by even light interference events [40], additional protections, for example blocking the signal from nearby major roads, and more distant antenna locations might be necessary.

## 2.5. Applicability for civil aviation and drone uses

Considering the variety of methods for identifying and detecting GNSS jamming, by far the easiest method is monitoring, both signal quality and spectrum. However, applying these methods at airplane level can be difficult due to precise rules and regulations, but depending on the receiver type, these methods might not need any additional hardware as most of the parameters are readily available from GNSS receivers. For drone use cases, the applicability will likely heavily depend on the use case for which the drone is used.

Monitoring the signal quality, GNSS observables, or the GNSS spectrum in general will increase the computational requirements as well as the energy consumption of the system. The regulatory space and the need of approval for new software solutions might still hinder the wider adaptation of in-flight monitoring solutions. On the other hand, monitoring or advanced signal processing can be applied at ground level, but the jamming level might not match the situation in airspace. Compared to on-board systems, ground-based systems have advantages, such as reduced constraints on size, power consumption and computational complexity, capability of network-based detection, and improved environmental control. Real-time processing and synchronization across multiple stations can be used to increase detection sensitivity, while data fusion can be used to increase detection accuracy and reliability. Furthermore, compared to on-board mitigation measures, ground stations can better utilize the computational freedom to run several parallel mitigation methods to find the best solution. Another advantage is the control over the antenna pose, to focus on the legitimate signals while minimizing the interference from known or detected jammers.

Dedicated RFI (Radio Frequency Interference) monitoring networks, consisting of specialized GNSS monitoring stations, both fixed and mobile, that are designed explicitly for detecting interference. could also be installed to the vicinity of airports or other locations that are considered critical for air safety. These networks should then be equipped with surveillance data processing systems capable of processing also the ADS-B messages downlinked by aircraft to identify potential GNSS disruptions. Thus, by cross-comparing of ADS-B data with other surveillance systems (Secondary Surveillance Radar, SSR or Wide Area Multilateration, WAM) as well as GNSS observables, could provide enhanced situational awareness for airport operations.

Processing the data at on ground level would help keeping the system easier to implement and broadcasting quality and trust indicators back to the planes could be done in real time. Before this system is available for airplanes, drones could be used to probe the airspace, but they would not be able to reach altitudes where airplanes typically operate. However, they could be used to sample the signal quality ‘behind’ the radio horizon of any ground level monitoring stations.

## 3. RTK-GNSS and its resilience

Real-time kinematic positioning (RTK) is based on real-time correction measurements from a reference station or interpolated virtual station to achieve centimetre-level accuracy [48]. The correction is based on error monitoring in a reference station (or a network of stations) of known position. RTK is being widely used in, e.g., surveying, construction, and transport applications.

### 3.1. User perspective

Essentially, an RTK-GNSS receiver is a GNSS receiver capable of receiving these correction signals to improve the standard GNSS position fix. This means that the absence of GNSS - because of interference or failure – will disable RTK positioning as well. Thus, from the user’s perspective, the resilience of RTK-GNSS is equal to the resilience of the standard GNSS receiver, which has been discussed in Section 2. This is the case even if the correction data were transferred by other frequencies than those being affected by interference. In fact, the professional grade receivers intended for RTK-GNSS are even more sensitive to disruptions than the consumer grade ones, because they have been designed to deliver precise rather than robust positioning. Mass-market GNSS receivers tend to prioritize the availability of the solution over its accuracy [49]. This will also mean that while the mitigation methods for RTK receivers are similar to those discussed in Sect. 2 for receivers in general, the effect of mitigation efforts (such as the use of directional antenna arrays) on the accuracy of the GNSS solution is likely to result in a more pronounced effect on the quality of the RTK solution.

The above also concerns other precise positioning methods, including Galileo’s new High Accuracy Service (HAS), in which the corrections are obtained either directly from space or via internet distribution [50]. As a multi-frequency service (mainly Galileo E1/E5b/E5a/E6 and GPS L1/L5/L2), HAS may provide a high-accuracy alternative in a situation, where jamming occurs in one frequency only (typically E1/L1) or when there is no internet or other radio connection for RTK. FGI has tested HAS monitoring for NLS’s reference stations to provide situational awareness for surveying operations and the possible future integration of the feature in surveying receivers. The FGI has published an open-source correction library to support the implementation of Galileo HAS in GNSS receivers [51].

## 3.2. Network perspective

From the RTK-network point of view, the density of the network can in some cases have a role in RTK resilience. As RTK-GNSS services are mostly based on reference networks, such as National Land Survey's FINPOS [52], the resilience of these base stations also contributes to the availability of the RTK solution: if there is an outage in one station of the network, RTK corrections may be possible using other base stations, given that the standard GNSS solution is available in the user's receiver as noted above. In this case, however, the accuracy of the RTK solution may be compromised from that provided using multiple stations. This means that increasing the number of reference stations can increase the resilience of RTK-GNSS. When it comes to the performance of network-based RTK, it has been shown that while the density of the network, i.e., the distance to the nearest reference station, plays a role, the choice of the solution will also affect the accuracy [53].

The FGI has studied the impact of jamming and spoofing on GNSS base stations with a temporary FINPOS station in the Jammer test campaign in Andøya, Norway [54], in 2024 (see also Figure 2). Jamming detection features, such as FGI's GNSS-Finland [55] were found to be important, even though large-scale jamming could not be mitigated. While the receivers typically used at FINPOS and other reference stations were disrupted by intense jamming, spoofing resilience could be improved using the Galileo Open Service Navigation Message Authentication (OSNMA). OSNMA-based RTK for road transport applications has also been found to improve the resilience of RTK-GNSS [56], but no standard solutions are yet available commercially. Receiver manufacturers (such as Septentrio and U-Blox) are getting ready to provide OSNMA receiver solutions at the same time as Galileo OSNMA reached its initial operational capability in July 2025 [57].

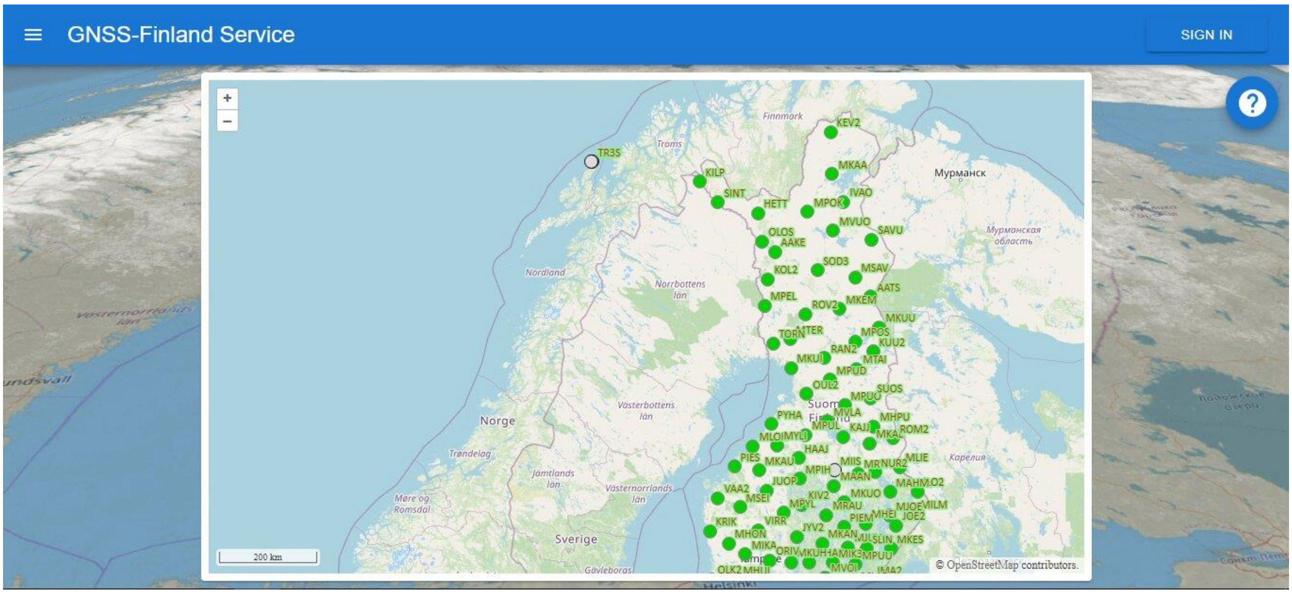

*Figure 2. Additional reference station set up in Andøya to test the resilience of NLS's GNSS reference station network in 2024. See also [42].*

Another critical vulnerability of the RTK approach lies in the broadcast of the correction streams. They too can be spoofed, especially if they are openly broadcast via UHF and VHF. This also applies to GBAS discussed in Section 2.4, which is similarly based on ground station networks and typically utilizes VHF frequencies. The same goes for Automatic Identification Systems (AIS) used in maritime traffic [58].

The resilience of RTK methods to other types of challenging conditions (e.g., signal multipath or occlusions, or ionospheric disturbance) is a widely studied topic (e.g., [59]). Ionospheric and atmospheric delays are the most common error sources when it comes to GNSS (and as discussed in Sect. 2), especially during ionospheric activity. In addition to RTK-GNSS being inherently reliant on the atmospheric products, any interruptions in their transmission will potentially cause a disruption, these potential risks are being mitigated with extensive research for correction and extrapolation methods [60]. Multipath too is a widely known phenomenon, and correction methods have been developed and are constantly being applied in commercial receivers [61].

## 4. Backup systems for GNSS

In case of inflight GNSS failure, other navigational backup systems can be used. In addition to onboard systems, such as attitude and heading reference system (AHRS), ground based navigational aids can be used. The traditional navigational aids used in aviation include Distance Measuring Equipment (DME), Very high-frequency Omni-directional Ranging (VOR). In addition to these systems that are in active use, there are also other possible systems that are in different stages of development and testing.

### 4.1. DME and VOR

Distance Measuring Equipment (DME) is a radio navigation technique, that measures the slant range between the aircraft and the ground DME transponder. The aircraft's DME interrogator radio sends pulse pairs and receives a timed reply from the ground station, yielding the range. The frequency band of DME is between 960 and 1215 megahertz, further specified by the channel used.

Very High-Frequency Omnidirectional ranging (VOR) is a radio navigational system used in aviation to determine the angle between the aircraft and the ground station. The ground station radiates both constant reference signal and a rotating variable signal. By comparing the phase of a fixed reference signal to the phase of a rotating variable signal, it is possible to determine the bearing of the aircraft from the ground station. Individually, a single VOR gives a line-of-bearing and a single DME gives a radius distance. Thus, together co-located VOR + DME can fix the aircraft's position in 2D. This technique is called VOR/DME navigation. More commonly, multiple DMEs or VORs are used to triangulate the position in area navigation. In practice, DMEs are more accurate than VORs.

As VOR and DME are already in use, no new infrastructure is needed to leverage this technique. However, due to GNSS, many countries have reduced VOR/DME counts to minimum operational network to ensure safe landing without GNSS. Virtually all aircraft have VOR/DME receivers and can navigate using these aids. Many modern aircrafts are also capable of using DME/DME navigation together with inertial navigation, which provides a seamless backup for GNSS navigation. DME/DME is also the only current navigation infrastructure in addition to GNSS supporting RNAV 1 and 2 operations, such as following Standard Instrument Departure Routes (SID) and Standard Arrival Routes (STAR). On the regulatory side, maintaining these ground navigational aids as a backup is official policy: EASA and IATA's 2025 plan explicitly calls for a "minimum operational network of traditional navigation aids" to be kept as GNSS backup [64]. Currently, in Finland, six combined VOR/DME beacons are in active use, while DME beacons are more common. Still, the coverage of DME/DME is sufficient only in the southern part of Finland.

Disadvantage of these systems is the inferior accuracy compared to the GNSS and the inability to provide guidance only for vertical plane. With DME/DME positioning, the accuracy is in the order of few hundred meters. For vertical guidance, aircraft rely on barometric altitude or the Instrument Landing System (ILS), which is only used for approach. In unmanned aerial vehicles VOR and DME are not typically used. These systems were designed for manned aircraft and thus the size, weight and power requirements are too demanding for small drones. It is, however, conceivable to equip larger drones with the equipment needed to use the technique.

### 4.2. Triangulation and multilateration systems

As ADS-B, discussed in Section 2.3.2, has become increasingly common, its use for localisations has also been studied. The interest has especially increased, because triangulation or multilateration (MLAT) based on the ADS-B messages could be used if GNSS fails. Because of the support for datalink communication between aircraft and control stations, the messages can be received in at several locations at the same time, creating an effective sensor network of beacons that can be utilized for triangulation [62]. Multilateration is a backup method for surveillance, independent from other systems. For MLAT, the time difference of arrival (TDOA) of used signals, i.e., transponder reply or ADS-B squitter from the aircraft to several ground-based receivers is utilised to determine the position of an aircraft.

MLAT is often integrated with ADS-B ground stations, making it relatively easy and affordable to maintain. Depending on the area the system covers, a multilateration system is either referred as MLAT or wide area multilateration (WAM). MLAT provides surveillance around airport surface and close-range airspace, while WAM covers wider area, such as regional or national airspace to enable terminal maneuvering area and en-route surveillance. Currently, Finland has a nationwide WAM network covering 75% of the Helsinki flight information region.

This technology is already widely developed, and systems are increasingly being deployed worldwide. As only radio signal is used, the technique is resilient to aircraft-centric jamming. However, if the ground stations utilize GNSS to maintain timing, they can be jammed, which affects the positioning estimate. ADS-B ground networks are widely deployed in controlled airspaces, but to use MLAT, synchronization between the ground stations is needed as well as the processing system to estimate the aircraft’s location. One way to solve the time synchronization issue is to use a “common” aircraft broadcasting ADS-B messages. If the position of the airplane is known, the ADS-B the relative time it takes light to travel to each receiver can be solved to calibrate the time synchronisation. The signal flight times can then be converted to spatial distances between the airplanes and the ground stations [63]. These techniques can also be utilised to track any aircraft that is not broadcasting GNSS information, either intentionally or because of lack of proper equipment. Recent proof-of-concept [65], extended WAM by using satellite-based wide area multilateration. The advantage of space-based WAM is that unlike terrestrial WAM ground stations, the satellites don’t use GNSS for timing, meaning they cannot be jammed in the same means to influence the system.

Performance-wise, MLAT and WAM are comparable to secondary surveillance radar (SSR), further discussed in Section 4.4. However, where SSR requires line-of-sight propagation paths, MLAT and WAM can operate without it. Since drones don’t typically have ADS-B or other communications commonly used in aviation, localization of them with multilateration is not possible by the same mean. While it is in theory possible to use the same technique with drones, but with different signals, the research is still ongoing and no reliable system for that purpose exist yet.

In addition to ADS-B messages, multilateration can be performed using other signals as well. In [66], a combination of ADS-B and FLARM sensors were used for detecting GNSS spoofing using multilateration. In the research the reported positions from the ADS-B/FLARM messages were compared to the position calculated with multilateration to detect manipulations. The second test was to compare reported positions of multiple aircraft. If multiple aircraft receive signal from same spoofer, they appear to be in same position, which indicates either serious incident or a GNSS spoofing attack.

Even though FLARM can be used for multilateration, it has some major differences compared to ADS-B. Where the range of ADS-B is a minimum of 100 km, with the ATC receivers having the range closer to 300km, FLARM has the typical maximum range around 10km. FLARM is not certified for use in commercial aviation, which limit its use to general aviation only. At the same time, it is independent from ATC. However, in situations where large number of small aircrafts share a limited airspace, the independency can be seen as benefit.

Multilateration using Remote ID is also possible, although the research on the topic is still limited. If the same Remote ID message is received by multiple receivers, the location of the broadcaster can be calculated. However, the location of the receivers needs to be reliably known to accurately determine the broadcast location. In consumer grade receivers, such as mobile phones, the GNSS is not accurate enough for precise localization of the drone. If the receivers are fixed assets, higher trust can be placed on the multilateration calculation.

As a last resort, multilateration can be performed using AM-modulated radio signals in the VHF band, which are used for voice communication between pilots and air traffic operators. While the existing radio infrastructure could be used for this, a sub-microsecond time synchronization would be needed. Most modern ATC receivers use the digital audio interface compliant with the ED-137 standard. In this protocol, the time stamping resolution is 125µs, which is not enough for estimating time differences in multilateration. Thus, additional hardware would be required to achieve the level of accuracy necessary for reliable aircraft localization.

### 4.3. Loran and eLoran

Long Range Navigation (Loran) was a terrestrial radio navigation system, which used low-frequency pulses from fixed transmitters. Receivers measured the time-difference-of-arrival of signals from a chain of stations to obtain hyperbolic position lines. The legacy version, Loran-C, provided a very large coverage with typical accuracy of tens to few hundred meters. Nowadays, Loran stations are largely shut down: US and Canada terminated the transmissions in 2010 and Norway and France in 2015, making the European coverage insufficient for positioning.

Enhanced Loran (eLoran) is a modernized version with improved transmitters, timing and data channels, capable of achieving accuracy of ±8 meters. The accuracy, availability, integrity and continuity meet the requirements for aviation non-precision instrument approaches, making it a viable backup system for GNSS. ELoran signals are transmitted with very high power at very low frequency, which makes jamming the signal difficult.

In practice, eLoran is not yet widely adopted in commercial aviation, but interest in eLoran systems is grooving, thanks to its robustness against the limitations of the satellite-based systems. ELoran systems are continuously being planned and deployed in multiple areas. UK has planned to build a nationally owned eLoran system with initial operating capability by 2028 and full system operational by 2030. South Korea has been running an operation eLoran pilot service since 2021, supporting maritime navigation and China has been actively expanding the use of eLoran, mostly in the coastal areas for navigation but also in the inland to support time synchronization services [67].

Overall, eLoran can serve as a standalone substitute for GNSS over large areas, with modest accuracy but high coverage and interference tolerance at the cost of maintaining a dedicated ground network. The system is, however, more suitable for maritime applications than aviation, due to its lack of vertical positioning.

### 4.4. Radar-Based Positioning

Radar-based positioning can indirectly support navigation, when GNSS is unavailable. Two types of radars are relevant: Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR). PSR bounces radio waves off the aircraft to get the range and bearing of the aircraft as return. SSR interrogates the aircrafts transponder to get a reply, with the data depending on the interrogation mode, the commonly used ones being Mode A, Mode C and Mode S. Mode A reply includes a configured transponder code used for identifying the aircraft. This can be augmented with pressure altitude response, which is referred as Mode C. Mode S allows interrogations with a specific aircraft using a unique address. This results a single reply, from which accurate range and bearing can be determined. Depending on the interrogation form, the reply can include data from the aircraft on-board data sources, such as information about the aircraft speed, heading or angle.

These systems are not navigational aids that the aircraft can use onboard, instead they are used from the ground, where, for example, air traffic control can follow the position of the aircraft. In a scenario where an aircraft loses its own navigation capability, air traffic controllers can provide heading and altitude instructions to safely guide the aircraft. In UAV applications, radar systems are typically used for detecting and tracking of unknown UAVs [68, 69]. However, the same technique can be in theory used to feed the position information to drone positioning system.

From an infrastructure standpoint, radars are already deployed. SSR radars cover high-altitude airways, and approach control radars cover terminal areas around airports. Radar-based positioning is a completely independent backup method for GNSS; if aircrafts transponder or reflective cross-section works, it is detectable by ground-based radar. Limitations include the possible lack of radar coverage in remote low-level airspace. Also, UAV operating in a low altitude might not be picked up by standard air traffic control radars, and for detecting them specialized small-target primary radars are needed.

One emerging concept is so called Mode N, which substitutes DME with a system based on Mode S signal protocol used in SSR [70]. In Mode N, ground stations broadcast a downlink signal with a timestamp and the location of the ground station. With signals from multiple stations, the aircraft can passively derive its position. Since this is independent from GNSS, Mode N can also be used for backup position source for position data for ADS-B. Mode N would need installing of new ground stations; however, they could be installed in the existing DME sites to offer adequate coverage. Since synchronized in time, the Mode N can be also used to multiliterate the aircraft position in the same way as conventional MLAT systems. The technology is also possible to fit into drones by utilizing recent software defined radio -based Mode N devices, which are light enough to be carried onboard.

### 4.5. Signals of opportunity

Signals of opportunity (SOP) refer to signals not intended for positioning, but that can be used for it. These signals can be cellular networks, AM/FM radio or Wi-Fi signals to name a few. Navigation using these signals is called opportunistic navigation. The advantage of opportunistic navigation is that no new infrastructure is needed. However, as the signals are not specially designed for navigation, the transmitters' locations and timing might be unknown, making the navigation challenging. To address this, algorithms, like simultaneous localization and mapping (SLAM) are used. Particularly cellular signals have appeared to be promising alternative PNT source. The advantages include great availability, geometric and spectral diversity, high carrier-to-noise ratio and readily implemented infrastructure with great coverage [71].

Multiple recent studies have been conducted regarding the navigation using signals of opportunity. In [72], UAV navigation was demonstrated using cellular signals at different frequencies. In the experiments, which were done in an open, semiurban environment under multipath-free line-of-sight conditions, a submeter horizontal positioning accuracy was achieved. Another recent research [73] demonstrated the signals of opportunity navigation in GNSS denied environment, which proves the viability of the technology.

In aircraft navigation, SOP navigation has also proven to be promising. In [71], the usage of cellular signals was evaluated for high-altitude aircraft navigation. In the experiments, an aircraft was flown at different altitudes in different regions in Southern California, USA. Three radio frequency channels were used, one of which was a 3G channel and two were 4G LTE channels. It was found out that cellular signals can be reliably acquired and tracked even in high speeds and altitudes up to 7000 meters above ground level. Similar results were gathered in [74], where different flight manoeuvres were performed while positioning the aircraft with two different radio SLAM frameworks. In the experiment, both known SOP emitter locations and unknown locations were used. To further increase the accuracy of SOP navigation, SOPs should be collaboratively used with the inertial navigation system. In this collaborative estimation, a “GNSS-like” performance is demonstrated to be possible [75].

### 4.6. LEO-PNT

Traditional satellite positioning systems have the satellite constellations on Medium Earth Orbit (MEO) or Geostational Earth Orbit. However, in many space applications, the focus has increasingly shifted towards Low Earth Orbit (LEO). LEO constellations are used for example broadband connectivity (e.g., Starlink, OneWeb), Earth Observation and Synthetic Aperture Radar (e.g. Iceye) and Internet-of-Things. All these applications benefit from the shorter distance between Earth and the orbit, which results in higher signal power. This will require more signal power from the potential attacker as well, which will contribute to jamming resilience. Furthermore, lower orbits are easier and cheaper to access, the latency between Earth and the satellite is smaller and it allows capturing high resolution satellite images of Earth. Still, commercial solutions for LEO Positioning, Navigation and Timing are not yet available.

During the recent years, increasing interest for LEO-PNT solutions has emerged. Generally, the proposed solutions can be grouped into three different approaches [76]:

1. Signals of opportunity approach. No specific positioning signals are used. Instead, SOP navigation is performed as described previously, with a difference that signals used are transmitted from LEO satellites. During the few recent years, well above 5000 LEO communication satellites have entered use with the number increasing all the time. As a result, the satellite signal coverage is global, making the opportunistic LEO-PNT highly potential global alternative PNT system.
2. Modifying the existing LEO communication satellites to provide PNT. In this approach, additional payload is added to the existing satellites to transmit signal for PNT purposes. In another, closely related approach, the same hardware is use for transmitting both communications and PNT signals. In this fused LEO-PNT approach, the constellation design as well as antennas and frequency bands are still mostly driven by the communication system requirements. Recent research [77] proposes the fused PNT approach to be used to enable PNT with the future IRIS2 constellation, highlighting the opportunity of integrating it in the constellation from the start. The idea behind enhanced communication satellites is to provide a functionality similar to dedicated PNT systems with minimizing costs caused by additional satellites.
3. Completely new LEO-PNT system. This approach includes a dedicated system built and optimized for PNT purposes. The dedicated PNT system allows optimization of the constellation design, antennas and clocks of the satellites as well as designing the transmitted signal to enable very accurate positioning. The dedicated system would offer the best performance with the cost of launching and operating a new satellite system. This approach is used by the ESA's LEO-PNT mission, named Celeste, which is currently entering the demonstration phase featuring a constellation of 10 satellites. The first satellites are planned to be launched in December 2025.

*Table 1: Comparison of GNSS Backup solutions for UAV and aircraft*

| | **Lightweight UAV** | **Medium UAV** | **Large UAV** | **Crewed aircrafts** |
|---|---|---|---|---|
| **Operating altitude** | < 150m | 150m – 1km | up to 10km | up to 10km+ |
| **DME & VOR** | ✗ (Too low for good coverage, too heavy equipment) | ✗ (Too low for good coverage) | ✓ | ✓ (standard system) |
| **MLAT** | ✓ (technically possible, but rare) | ✓ (possible, not widespread) | ✓ | ✓ (standard system) |
| **eLoran** | ✓ | ✓ | ✓ | ✓ |
| **Radar-based** | ✗ (small low altitude target challenging for most radars) | ✓ | ✓ | ✓ (PSR and SSR standard systems in aviation) |
| **Signals of opportunity** | ✓ (demonstrated accuracy) | ✓ | ✓ | ✓ (promising, but more research needed. |
| **LEO-PNT** | ✓ | ✓ | ✓ | ✓ |

### 4.7. Summary of backup systems.

Table 1 summarizes the technologies and their suitability to act as a GNSS backup on different aerial platforms. Some systems such as conventional radio navigation aids and radar-based systems are not applicable for the smallest drones flying in low altitude. Apart from that, most of the systems can be used on drones of any sizes and on crewed aircraft (such as helicopters used by rescue operations, e.g., that in FinnHEMS helicopter emergency medical services). The maturity of these alternative PNT technologies varies significantly. Established systems, such as DME/VOR are fully operational and in active use in aviation procedures. In contrast, emerging technologies, such as opportunistic navigation or eLoran have demonstrated technical feasibility but remain in transitional phases with limited coverage and certification. At the experimental end, LEO-PNT and UAV-specific radar navigation are still undergoing prototyping and flight trials with operational suitability yet to be validated.

## 5. Alternative (non-GNSS) positioning

In GNSS-contested environments, aerial platforms must rely on alternative positioning methods that do not depend on external radio signals, which can be interfered. These techniques should be resilient to jamming, spoofing, and signal degradation, enabling safe and autonomous navigation even under adverse conditions [78]. This section presents an overview of available approaches, organized into three main categories: (1) relative positioning, (2) absolute positioning, and (3) collaborative positioning systems (Figure 3). Throughout this section, we primarily use the term *positioning*, reflecting the assumption that the aerial vehicle operates along predefined waypoints within a known environment. Accordingly, the term *localization* is used interchangeably in contexts where it aligns with established techniques or literature.

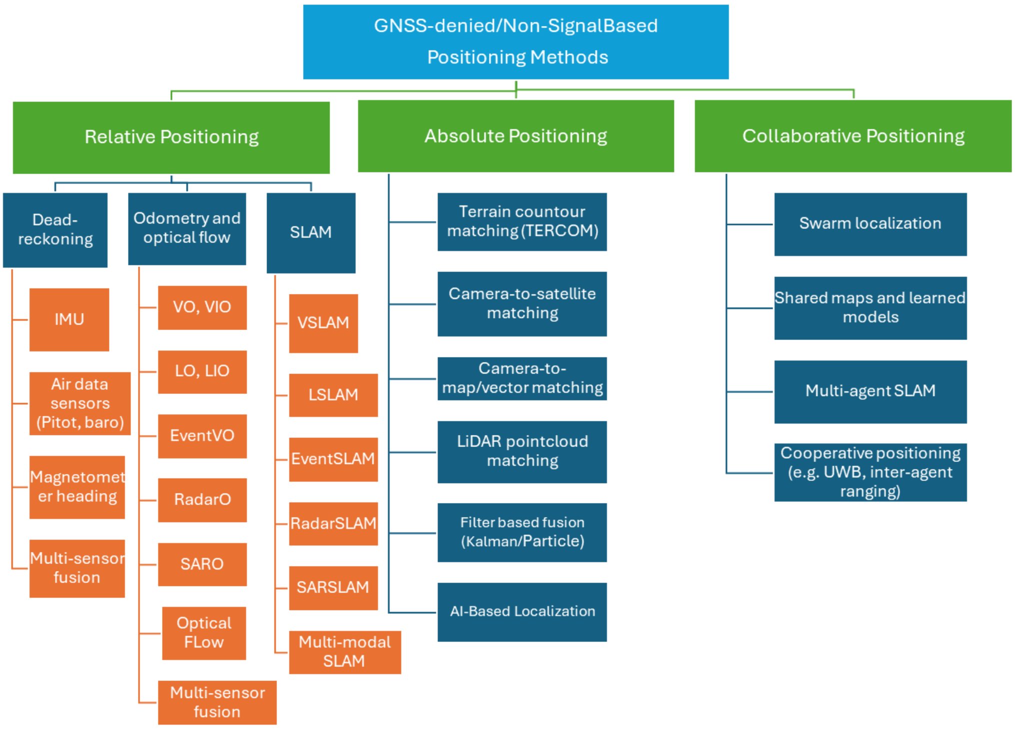

*Figure 3. Categorization of non-GNSS based positioning techniques.*

### 5.1. Relative Positioning

Relative positioning refers to the estimation of motion using only onboard sensors, without relying on external maps or absolute references [79].

Dead reckoning is a foundational method of relative navigation that estimates a platform's current position based on its previously known location, combined with measurements of heading, speed, and elapsed time [80]. In aerial systems, dead reckoning typically integrates data from onboard sensors, such as, inertial measurement units (IMUs) for acceleration and angular velocity; air data sensors (e.g. Pitot tubes, barometers) for estimating airspeed and altitude, and magnetometers for heading estimation. While dead reckoning offers short-term autonomy and simplicity, its accuracy degrades over time due to cumulative sensor drift and integration errors. For this reason, it is often used as a baseline method, feeding into more advanced systems such as SLAM, Kalman filters, or map-based localization, which correct and refine the position estimate.

IMUs rely on integrating measurements from accelerometers and gyroscopes to estimate position and orientation [81]. IMU enables full independence of external signals, updates at high frequency, and works at any altitude and terrain. Hence, inertial navigation systems are not prone to jamming, or spoofing. However, it is inherently prone to cumulative drift due to sensor noise and bias, depending on the quality of the system (Table 2). While strategic grade systems provide a standalone navigation performance, they are not useful in regular applications due to their high cost and size. While aircrafts could incorporate navigation grade systems, for UAVs, commercial to tactical grade systems are the most feasible. Consequently, IMU data are commonly fused with complementary sensing modalities, such as cameras, LiDAR, or GNSS, to constrain error growth and ensure long-term accuracy and reliability. Recently, advanced neural network based approaches have offered further improvements to inertial navigation [82].

*Table 2. A summary of IMUs classification as per performance, adopted from (El-Sheimy & Youssef, 2020)*

| **Grade** | **Strategic grade** | **Navigation grade** | **Tactical grade** | **Commercial/Automotive grade** |
|---|---|---|---|---|
| **Positional error** | 30–100 m/h | 0.5 m/s; 1.9 km/h | 5 m/s; 19 km/h | Large variation |
| **Gyroscope drift** | 0.0001–0.001°/h | < 0.01°/h | 1–10°/h | 0.1°/s |
| **Gyroscope random walk** | – | <0.002°/√h | 0.05– < 0.02°/√h | Several °/√h |
| **Accelerometer bias** | 0.1–1 µg | < 100 µg | 1–5 mg | 100–1000 µg |
| **Applications** | Submarines, intercontinental ballistic missiles | General navigation, high precision georeferencing, mapping | Integrated with GNSS for mapping, weapons (short time) | Research, low-cost navigation, pedometers, anti-locking breaking, active suspension, airbags |
| **Cost** | ~ $1 million | ~ $100,000 | ~ $2000–$50,000 | $1 for accelerometers<br>$10 for gyroscopes |

Visual odometry (VO) provides incremental position and orientation estimation by tracking visual features across successive camera frames. It is lightweight and well-suited for feature-rich environments. VO can depend on a single monocular camera, stereo cameras, or even multiple cameras [83]. However, its performance declines under challenging conditions, such as low light, fog, motion blur, or textureless surfaces like water or snow. In such cases, the scarcity of reliable visual features can lead to rapid and erratic variations in odometry estimates. Furthermore, VO inherently suffers from odometry drift, since small estimation inaccuracies accumulate over time, leading to substantial deviations from the true trajectory. Visual–inertial odometry (VIO) extends the capabilities of VO by integrating camera observations with inertial measurements from an inertial measurement unit (IMU) [83, 84, 85]. This fusion enhances robustness, particularly during rapid manoeuvres or periods of visual degradation, and mitigates the odometry error accumulation. Advanced methods can further reduce the estimation error, e.g., probabilistic modelling, extended Kalman filter (EKF), and SLAM. VIO systems strike a balance between accuracy and computational efficiency. Thus, they are widely used in lightweight drone navigation. It's suitable for low- and medium altitude (0-150m) if terrain provides enough features. The paper by [86] introduced an enhanced monocular VIO method for UAV navigation in GNSS-denied environments, combining adaptive gamma correction, efficient line feature extraction, and a two-step backend optimization with dynamic weighting. Compared to existing systems, the proposed approach significantly improved positioning accuracy and robustness, especially under challenging visual conditions.

Event camera–based odometry (EventVO) [87] leverages the asynchronous output of event-based vision sensors, which record per-pixel brightness changes at microsecond resolution rather than capturing conventional image frames. This sensing paradigm offers exceptionally high temporal resolution, low latency, resistance to motion blur, and a wide dynamic range, making it well-suited for fast-motion scenarios and challenging illumination conditions where standard cameras often fail. However, the sparse and unconventional data format introduces challenges for feature extraction and state estimation. To address this, event-based odometry methods are often integrated with traditional frame-based vision, inertial sensors, or LiDAR to improve robustness and enable deployment in real-world SLAM systems [88].

LiDAR odometry (LO) estimates motion by performing scan matching across direct three-dimensional structural point cloud data. Owing to its ability to provide high-precision range measurements, LiDAR reduces sensitivity to illumination changes and visual degradation, enabling more reliable long-term trajectory estimation. In contrast to vision-based approaches, LiDAR demonstrates reliable performance under low-illumination and texture-deficient conditions, including dense vegetation, urban canyons, homogeneous wall structures, and nocturnal flight scenarios. LiDAR–inertial odometry (LIO) [89, 90], provides enhanced motion estimation accuracy and robustness. However, flat and uniform targets are challenge for LiDARs. Nevertheless, the increased weight and power consumption associated with LiDAR sensors impose practical constraints, often restricting their integration to medium- or large-scale UAVs and aircrafts. Nowadays, with the increasing availability of lightweight LiDAR sensors tailored for aerial platforms, LIO has emerged as a promising alternative for accurate state estimation and an increasingly attractive solution for autonomous drone navigation.

Radar odometry (RadarO) refers to techniques for estimating a platform's motion by analyzing radar signals over time [91, 92]. Traditional approaches often rely on frequency-modulated continuous wave (FMCW) radar or Doppler radar to extract range and velocity information, enabling scan matching or feature tracking between successive radar frames. More advanced methods incorporate Synthetic Aperture Radar (SAR), which produces high-resolution terrain imagery and supports motion estimation through image registration and analysis of temporal backscatter variations. SAR odometry (SARO), is particularly effective for high-altitude platforms and challenging operational environments, such as nocturnal operations, adverse weather, or feature-sparse regions like open water, although its use on small UAVs is limited due to payload and processing requirements. To enhance robustness and accuracy, radar odometry systems are often fused with complementary modalities such as inertial measurement units (IMUs), visual sensors, or LiDAR, enabling resilient navigation in GNSS-denied and complex environments [92, 93, 94].

SLAM systems estimate a platform's position while concurrently constructing a map of the surrounding environment. SLAM builds upon odometry techniques, however, they introduce a critical enhancement: the ability to close loops and correct accumulated drift by recognizing previously visited locations [95]. This closed-loop capability enables SLAM to maintain long-term positional accuracy, in GNSS challenged situations. SLAM systems can operate with inputs from a wide range of sensors, including cameras (monocular, stereo, RGB-D), LiDARs, SAR, and IMUs [96, 97]. These sensors provide complementary data for both motion estimation and environmental reconstruction. Unlike pure odometry, which estimates motion incrementally and is prone to drift over time, SLAM integrates sensor data into a global map, allowing for re-localization and drift correction through loop closure and map optimization. SLAM is particularly valuable in unknown, unstructured, or dynamic environments where prior maps are unavailable or incomplete. It supports autonomous navigation by enabling platforms to understand their surroundings, avoid obstacles, and adapt to changes in terrain or structure. In GNSS-denied scenarios, SLAM serves as a cornerstone of robust positioning.

### 5.2. Absolute positioning

Absolute positioning determines a platform's global location by comparing onboard sensor data with georeferenced datasets. These methods complement relative navigation and are particularly valuable for long-range missions and GNSS-denied operations.

Terrain-aided navigation (TAN) enhances aircraft positioning by matching measured altitude, typically from a barometric or radar altimeter, with known terrain elevation models [79]. TAN is most effective at low to medium altitudes where terrain variation provides distinct reference cues, but at high altitudes, flatter terrain, reduced barometric precision, and increased ambiguity degrade reliability. Traditional terrain-referenced navigation (TRN) systems such as Terrain Contour Matching (TERCOM) [98], SITAN [99], and Digital Scene Matching Area Correlator (DSMAC) [100] rely on distinctive terrain features and pre-stored digital elevation maps, achieving meter-level accuracy when terrain variability is high. However, they are limited in flat or homogeneous landscapes or when terrain databases are outdated. In mountainous or coastal regions, integration with radar altimeters or SAR can substantially improve performance. SAR enables terrain imaging regardless of weather or lighting and supports terrain matching when fused with digital elevation models. Accuracy and robustness can be further enhanced through multi-sensor fusion, such as integrating IMUs, or by employing cooperative localization approaches, where multiple aircraft share positioning data. Factor-graph-based optimization techniques have been shown to improve overall localization solutions and reduce drift [79, 101, 102]. Reported accuracies range from a few meters in terrain-rich regions to tens of meters in high-altitude or feature-sparse areas.

Satellite-image-based positioning methods estimate UAV position by aligning onboard aerial imagery with high-resolution satellite data. These techniques address challenges related to cross-view differences in resolution, perspective, and illumination. For instance, Kinnari et al. [103] proposed a seasonal-invariant visual localization framework using a Siamese convolutional neural network (CNN) architecture, achieving sub-10 m accuracy under varying seasonal and lighting conditions. Liao et al. [104] introduced an Adaptive Threshold-Guided Ring Partitioning Framework (ATRPF) for UAV–satellite cross-view image matching, reducing matching errors by up to 35% compared to conventional descriptors. Similarly, [105] developed Spatial Hybrid Attention Architectures (SHAA) that improve robustness to viewpoint changes, providing mean absolute localization errors between 1 and 5 m on benchmark datasets. For model training, satellite imagery from publicly available datasets [106] supplemented with historical images from Google Earth to ensure coverage of seasonal variability have been used. These methods can recover absolute position and correct drift even in GNSS-denied environments, particularly in urban or semi-structured landscapes, however, their performance depends on adequate scene visibility.

Map- and vector-based localization methods determine position by matching onboard imagery or LiDAR point clouds with georeferenced maps, aerial photographs, or 3D road databases. Li and Shan [107] presented a 3D road network pose estimation method using image triplets, achieving sub-2 m accuracy in urban environments. Wang et al. [108] developed a vector map-based UAV localization framework that employs altitude-adaptable feature extraction, a robust weighted vector map representation, and parameter-free pose estimation, maintaining 1–3 m RMS (Root-Mean-Square) error under diverse flight conditions. In the simplest configurations, absolute localization can be achieved through georeferenced control points known in the target area. Trigkakis et al. [109] demonstrated 0.5 m accuracy when integrating a SLAM solution with a single control point, while Tonini et al. [110] achieved similar precision using a visual–inertial fusion method in urban mapping scenarios. Fusion algorithms such as the EKF, Unscented Kalman Filter (UKF), and Particle Filters (PF) are commonly employed to integrate map-matching results with relative odometry, providing real-time state estimation and uncertainty propagation.

LiDAR- and point cloud based localization aligns real-time point clouds with archived LiDAR datasets, digital elevation models, or hybrid maps. Xu et al. [111] proposed a visual point cloud map (VPCM) approach that achieves centimetre-level alignment accuracy in structured environments by fusing multi-source sensor data with regional road networks. Similarly, Yao et al. [112] developed a UAV visual localization system effective both day and night, integrating satellite image management, 2D–3D geo-registration, visual odometry, and terrain-weighted optimization to achieve drift-free localization over extended trajectories, with a mean absolute error below 7 m. Hao et al. [113] compared several localization strategies, showing that the fusion of range–visual–inertial odometry with image-registration-based geo-localization significantly improves performance by combining local pose estimation with global alignment.

Semantic Mapping and Place Recognition (PR) are interconnected and enhancing global localization capabilities in autonomous systems [79]. Semantic Mapping focuses on creating a detailed and structured representation of the environment by processing the data from sensors such as cameras and LiDARs. In contrast, PR is the overarching framework that identifies and correlates places based on sensory data. PR methodologies are divided into distinct branches: (1) appearance-based PR relying on visual features; (2) geometric-based PR using spatial relationships; (3) semantic-based PR leveraging semantic labels and spatial relationships; (4) and semantic-structural PR, a hybrid approach combining semantic and geometric data. AI plays a critical role in map matching and semantic localization. Deep learning models, including convolutional neural networks and transformer-based architectures, enhance feature recognition and semantic understanding of terrain. AI also supports cross-domain alignment between onboard sensors and heterogeneous map sources, optimizes map matching across modalities, and enables real-time decision-making in complex environments.

Recent developments increasingly leverage artificial intelligence for localization. Deep learning architectures, including convolutional neural networks and transformer-based models, enhance feature recognition, cross-domain alignment, and semantic understanding of terrain. AI also supports semantic mapping and place recognition by enabling appearance-, geometric-, and semantic-based matching, as well as hybrid semantic–structural approaches [79]. These methods improve map matching across heterogeneous modalities, optimize localization accuracy, and support real-time decision-making in complex, dynamic environments.

### 5.3. Collaborative and Experience-Based Navigation

Collaborative navigation and trajectory reuse are emerging strategies that enhance robustness in GNSS-denied environments by leveraging historical data and multi-agent cooperation to improve localization and decision-making [114]. UAV swarms achieve collaborative localization by sharing relative positions and sensor data among multiple vehicles. By treating neighboring UAVs as mobile anchors, swarms maintain formation and reduce drift, providing redundancy and resilience when individual sensors degrade. This approach is particularly effective in GNSS-denied environments, though performance depends on communication reliability, latency, and cumulative error.

Several methods have been proposed to support cooperative localization. Cheng et al. [115] combined IMU data with inter-vehicle ranging using an EKF for two-UAV systems, achieving approximately 0.55 m positioning accuracy. Wang and Deng [116] developed CI-SAM (Collaborative Incremental Smoothing and Mapping) for UAV swarms, integrating ultra-wide-band (UWB) ranging and VIO for distributed, anchor-free localization. Han et al. [117] addressed inter-aircraft direction-of-arrival estimation using a tetrahedral array and a genetic algorithm to resolve phase ambiguities, demonstrating promising simulation results. Yengin et al. [118] proposed a particle filter-based cooperative terrain navigation method, improving state estimation in flat or featureless terrain by sharing relative positions across an aircraft fleet. Li et al. [119] presented a UAV formation positioning system combining inertial navigation and data-link-based relative measurements, constructing a relative pose optimization graph for real-time state estimation.

Collaborative frameworks also enable heterogeneous UAV operations, where high-end drones equipped with LiDAR or SAR guide low-cost UAVs by sharing SLAM maps and updates. AI supports real-time coordination, semantic understanding, adaptive mission planning, dynamic task allocation, predictive path planning, and collision avoidance through multi-agent reinforcement learning. Novel algorithms integrate range-based measurements with common onboard sensors (e.g., low-cost IMUs, optical flow) to enhance relative navigation accuracy.

These approaches improve resilience to disturbances and cyberattacks. Shahkar et al. [120] demonstrated that multi-agent consensus and relative range measurements can achieve near-perfect localization in sufficiently large and well-connected networks. Cooperative formations can also act as a “cyberattack shield,” where small drones absorb intrusions to protect fleets. However, consensus-based methods remain sensitive to sensor errors, which may destabilize localization.

Trajectory reuse complements collaborative methods by leveraging historical flight data to build local maps and initialize SLAM systems. Integrating prior trajectories via EKF or particle filter frameworks enables proactive error correction and more efficient navigation. Originally developed for UAV swarms, collaborative navigation and trajectory reuse frameworks are now being explored for manned aircraft, supporting coordinated operations, dynamic rerouting, and shared autonomy in congested or contested airspace.

### 5.4. Challenges and Future Research Directions

#### 5.4.1. Comparison of suitability of different algorithms

The previous sections listed various positioning methods available for aerial vehicle navigation. Table 3. summarizes the advantages and challenges of different absolute and relative positioning methods. (Adopted from [79])

*Table 3. Comparison of advantages and challenges of absolute and relative positioning methods. (Adopted from [79])*

| **Positioning type** | **Technique** | **Pros** | **Cons** |
|---|---|---|---|
| **Absolute** | Template and feature matching | Achieves high precision in environments with distinct terrains, utilizing detailed feature comparison. | Loses effectiveness in uniform landscapes with a lack of distinct features. |
| | Semantic mapping and recognition | Offers in-depth insights into the environment, utilizing semantic information to enhance accuracy and awareness. | Demands extensive computational resources, posing challenges for real-time application. |
| **Relative** | Dead reckoning, filtration, & error optimization | Provides reliable continuous tracking crucial for GNSS-independent navigation through IMU data integration and error correction. | Tends to accumulate errors over time, requiring periodic recalibration or adjustments. |
| | SLAM | Enables mapping and positioning in unknown environments, offering a comprehensive solution for exploration in GNSS-denied areas. | Requires sophisticated algorithms and extensive computational resources, making implementation challenging on constrained UAVs. |
| | Visual odometry & optical flow | Performs effectively in dynamic environments by providing accurate motion estimation through visual data analysis. | Suffers from degraded performance and drifts under poor lighting, rapid movements, or in featureless environments. |
| | Visual-inertial odometry | Enhances robustness of localization by combining visual data with inertial measurements, improving accuracy and stability. | Necessitates complex integration and precise calibration, presenting significant technical challenges. |

Aerial platforms can be categorized by altitude and flight profile, which strongly influence suitable sensors and navigation strategies. In the envisioned Finnish operational scenarios, platform categories range from lightweight, low-altitude UAVs (flight altitude below 150 m), to medium-altitude UAVs (150 m–1 km), mid-altitude UAVs or crewed aircraft (1–5 km), and ultimately to high-altitude fixed-wing crewed platforms operating at approximately up to 10 km. Sensor selection and navigation strategies for each platform type depend on factors such as payload capacity, environmental conditions, and mission-specific requirements. The operational envelope, such as flight altitude and speed, and the vehicle type (fixed-wing vs. rotorcraft) are key design considerations when selecting suitable sensor payloads and navigation algorithms [79]. Table 4 summarizes typical platform classes, sensor combinations, and operational considerations. Low-altitude, lightweight UAVs favour SLAM, VO, and VIO for local feature-rich mapping, while RF and

UWB can complement positioning in obstructed environments. Medium- and high-altitude UAVs integrate LiDAR or SAR for all-weather and long-range monitoring. High-altitude fixed-wing aircraft exploit SAR and LiDAR archives for large-scale and night-time operations. Crewed rotorcraft require also all-weather and 24/7 capability thus SAR and IMU based approaches are often needed.

*Table 4. Recommended technologies for different UAV categories*

| **Platform** | **Altitude** | **Key Sensors & Methods** | **Notes / Limitations** |
|---|---|---|---|
| **Lightweight UAV** | <150 m | Camera and Compact LiDAR odometry or SLAM, RF, UWB, Map/Image/Lidar archives | Local operations, High precision in structured terrain/daylight; sensitive to fog, low light, motion blur, featureless surfaces; RF/UWB affected by multipath/NLOS in dense forests |
| **Medium UAV** | 150 m–1 km | Camera, compact SAR & LiDAR Odometry & SLAM, Map/Image/Lidar archives | All-terrain, all-weather, day-night operation; moderate payload constraints |
| **Mid-altitude UAV** | 1–5 km | IMU, SAR, LiDAR, Camera Odometry & SLAM Map/Image/Lidar archives | Medium-range monitoring and mapping; cloud/visibility resilient; SLAM/odometry integration recommended |
| **High-altitude fixed-wing** | up to 10 km | IMU, SAR, LiDAR, hybrid fusion, DEM | Long-range monitoring and mapping, night/all-weather; relies on terrain matching; 24/7 operationality |
| **Rotorcraft (low-altitude UAV)** | <150 m | Visual/LiDAR/Radar/SAR SLAM, IMU | 24/7 operationality |
| **Crewed aircraft** | 1–10 km+ | Digital Elevation Models (DEMs), radar altimetry, SAR | High-altitude and long-range; GNSS-denied support via terrain/radar-based navigation. 24/7 operationality |

Absolute localization performance varies across UAV platforms and altitudes. Lightweight UAVs typically rely on VIO or compact LiDAR, achieving 0.5–2 m accuracy but with sensitivity to low-light or featureless conditions. Medium UAVs that integrate cameras, LiDAR, and compact SAR achieve sub-meter accuracy under moderate weather conditions. Mid- and high-altitude UAVs and crewed aircraft can reach few-meter accuracy through IMU–SAR fusion, even under cloud cover. By integrating terrain-aided, satellite-based, and map/vector-based approaches, aerial platforms can achieve resilient and precise absolute positioning across diverse environments and operational scenarios.

The UAV-developed strategies are increasingly relevant for manned aviation in GNSS-denied or low-visibility scenarios. Vision-based methods provide high precision in favorable conditions but degrade under low-light or adverse weather. In contrast, inertial and radar-based sensors maintain reliable performance across diverse flight conditions, making them essential for resilient navigation across different types of aerial platforms, from small UAVs to high-altitude or crewed aircraft. Integrating these sensors into hybrid and fusion frameworks further enhances robustness, ensuring accurate positioning and operational continuity in challenging environments.

Despite notable progress in recent years, deploying non-GNSS navigation systems in aviation still faces significant technological and environmental challenges. Technologically, the main limitations concern sensor capability, platform constraints, and real-time computation. Selecting sensors that provide reliable positioning data is difficult, especially for lightweight UAVs with strict payload and power limits. The miniaturization of cameras, LiDAR, and SAR systems is therefore essential for wider adoption on small aerial platforms. Real-time processing further limits performance, as many

AI-based SLAM and sensor fusion algorithms require computational resources that exceed onboard capacities. Additionally, sensor degradation and environmental dynamics introduce uncertainty, demanding robust fusion and continuous error correction. Integrating visual, LiDAR, SAR, and inertial data into a unified real-time framework remains complex, requiring advances in software architecture and optimization.

From an environmental perspective, operational context strongly influences navigation reliability. Factors such as lighting, weather, and terrain diversity affect feature extraction and sensor performance. Poor visibility, reflective surfaces, and uniform textures, common in fog, snow, or marine conditions, can severely degrade positioning accuracy. The marine environment is particularly challenging, as shown by Peti et al. [121], who employed a UAV with LoRa and RGB sensors for vessel tracking; yet surface reflections and sparse features still limit precision.

Overall, achieving reliable non-GNSS navigation requires progress in sensor miniaturization, adaptive multimodal fusion, computational efficiency, and environmental modeling. Addressing these issues will be critical for developing resilient, high-precision, and autonomous UAV systems capable of operating effectively in GNSS-denied conditions.

### 5.4.2. Opportunities

Artificial intelligence (AI) has the potential to enhance performance across all core modules of an autonomous UAV navigation stack, namely perception, positioning, planning, and control. In perception and positioning, AI improves odometry and SLAM by enabling robust feature extraction in low-texture or dynamic environments, adaptive sensor fusion based on context and sensor reliability, anomaly detection, drift compensation, and faster real-time processing. In the planning and control modules, AI supports predictive path planning and model predictive control by identifying regions of high uncertainty, incorporating physical constraints, and dynamically adjusting navigation strategies. Furthermore, transformer-based models offer the potential to unify these modules into a single end-to-end framework that maps raw sensor data directly to control commands. This integration can reduce error propagation between modules and improve overall system efficiency, although challenges related to domain adaptation and robustness remain.

A recent survey by [122] provides a comprehensive overview of AI-based approaches for autonomous UAV navigation, encompassing both optimization-based and learning-based methods. It reviews the use of algorithms such as particle swarm optimization, ant colony optimization, genetic algorithms, reinforcement learning, and deep reinforcement learning for path planning, control, and decision-making, highlighting their role in improving UAV autonomy and operational efficiency. Despite substantial progress, unresolved challenges persist in computational efficiency, energy management, and fault tolerance. The authors emphasize that while AI significantly enhances UAV reliability and adaptability in complex environments, continued innovation is required to address these limitations.

Many future research topics evolve [122]. Federated learning for decentralized, privacy-preserving, and communication-efficient UAV coordination; investigate ontology-based reasoning to enable knowledge sharing and collaborative decision-making in UAV swarms; and prioritize energy-efficient strategies, including AI-assisted autonomous charging and in-flight energy harvesting. Additionally, the development of lightweight AI models suited to UAVs' limited onboard resources, along with AI-based physical threat detection and fault-tolerant systems for handling hardware and communication failures, remains critical. Advancing these areas will contribute to the realization of resilient, energy-efficient, and fully autonomous UAV systems capable of operating reliably even in complex or GNSS-denied environments.

There is also a lot of promise in using quantum sensor technology, particularly quantum inertial sensors and quantum clocks as a part of sensor fusion for PNT. Quantum sensors are particularly promising as they enable GNSS-independent positioning and timing with high precision and reliability. There is significant progress in the development of quantum inertial sensors and quantum clocks, and this technology is expected to be used more commonly in some 10-20 years [123]. The accuracy of the position fix decreases rapidly over time and distance travelled, when using conventional sensors. Quantum gravimeters, being extremely sensitive to Earth's gravity, can retain the positioning accuracy over long distances, and are gradually emerging in, e.g., ship navigation [124]. Quantum sensor technology is a viable future option for robust and reliable PNT alternative.

In practical operation, hybrid and adaptive navigation systems are the future goal aimed to maintain continuity when GNSS signals are degraded, jammed, or spoofed. These systems combine GNSS with non-GNSS methods to ensure reliable positioning. Hybrid navigation systems typically use GNSS as the primary source and automatically switch to VO, VIO, SLAM, SAR, or LiDAR etc. when GNSS becomes unreliable. Sensor fusion frameworks rely on EKF, UKF, particle filters, and factor graph optimization to integrate multiple inputs. Adaptive sensor weighting dynamically prioritizes the most reliable sources, and even degraded GNSS signals can serve as auxiliary inputs to improve overall accuracy. GNSS signal monitoring involves real-time detection of spoofing, jamming, and multipath errors (see Section 2). Signal quality metrics and AI-based anomaly detection algorithms are used to assess integrity and trigger fallback mechanisms. For manned aircraft, resilient navigation under GNSS interference is critical during approach and landing, where integration of radar altimeters, barometric data, and LEO-PNT signals can maintain continuity.

## 6. Conclusions and recommendations

The aim of this report was to identify methods to improve GNSS resilience. Based on the survey, answers to the key questions and corresponding recommendations are provided in this Section.

***How can intentional GNSS signal interference be detected quickly, and how can its effects be mitigated?***

The nature of GNSS interference can be detected by analysing both the signal quality and the RF-spectrum of the signal. While many commercially available receivers already include these features, development is still needed for improving their performance as different types of interference patterns and methods keep emerging. It is also important to distinguish jamming from spoofing and to this end, authentication services are being offered by, e.g., the European Galileo (i.e., the OSNMA). This activity must be continuous, i.e., signal tracking and integrity monitoring must be an inherent feature in all GNSS-reliant activities, as they will allow the user to employ the backup technologies, which is the best means of interference mitigation.

There are two factors that should be emphasized in ensuring the resilience of GNSS:

- Situational awareness. To increase GNSS security and resilience, the first step is to know the situation. For this, capability of signal tracking and analysing will provide the information necessary for assessing the quality and integrity of the GNSS signal. Situational awareness will help GNSS users to choose and employ the mitigation methods (as discussed in this report) needed for safe positioning. Situational awareness will not only help avoid the risks but also the choice of equipment. It can either be provided by the users themselves (in their receiver) or as a real-time external service. These are not yet available, but heatmaps are publicly available from previous days [38].

- Rigorous (live) testing. While many of these features are being implemented in the newest receivers, there is still a clear need for further testing and development, especially when it comes to GNSS-independent methods and their seamless implementation. Rigorous (live) testing for jamming resistance for the existing receivers and auxiliary equipment describe in the previous sections are essential, as well as related testing platforms. The experience from the Norwegian Jammertest has shown both the need and the added value of testing in live situations, and the inclusion of many different scenarios [54].

***How can the resilience of GNSS receivers and RTK base stations to intentional interference be improved?***

Traditionally the best way to tackle GNSS interference in a receiver is the use of Multi Constellation, Multi Frequency (MCMF) receivers, which can utilise all available GNSS constellation and all available signals. As such, the lack of a single frequency band does not prevent the receiver of deriving a valid GNSS fix. However, some receivers are driven by GPS L1-band, meaning that if this band is not available the receiver cannot track other signals. This means that the user cannot rely on MCMF only. Furthermore, on many occasions the jamming covers all frequencies. Another commonly used mitigation method is to utilize antenna technologies, such as CRPA, to block the reception from the interference direction. It must be noted that when large-scale, multi-frequency jamming occurs, GNSS is practically unavailable, and backups must be put in place.

As an RTK-GNSS receiver is a GNSS receiver improved with RTK correction signals from reference stations to improve the standard GNSS position fix, the absence of GNSS because of interference will disable RTK positioning as well. In network-RTK, a dense network can sometimes provide a solution in a case where one station was jammed, but if the user’s own receiver is not getting a GNSS-fix, the RTK station network is not capable of securing the PNT.

***What kinds of backup systems should be maintained or introduced to replace GNSS navigation?***

Several technologies are used and developed to replace and complement GNSS, increase the positioning accuracy, and mitigate the effects of interference. Some of them (e.g., DME, radars, multilateration, etc.) are already in use in aviation, but none of them alone can replace GNSS entirely. These should, however, be maintained to be used as backup in GNSS outages. Many of them also require an external infrastructure, which limits their applicability without a large investment (this is the case with, e.g., eLoran). They might also require some additional training for pilots to be able to use them. Furthermore, in addition to navigating a single aircraft, the situational picture for flight control requires accurate positioning, which has posed new challenges to the GNSS-operated airports and decreases their capacity during GNSS outages [78].

In aviation, every system must meet strict standards to ensure airworthiness and operational safety. Getting the certification for new or even updated technologies can take years due to extensive testing and multi-layered approval process. Thus, primary short-term solution should be based on the techniques already approved for aviation use. From the technologies currently in use, DME/DME navigation, also referred as DME/IRU when coupled with the inertial reference unit, is the only one in addition to GNSS that fulfills the accuracy requirements for RNAV 1 specification.

Expanding DME coverage has proven beneficial in both Finland and Estonia. In Finland, DME/DME approach was reactivated in Joensuu and Savonlinna airports in 2024. In Estonia, the number of the DME stations was increased to enhance coverage and extend services to lower airspace. This upgrade enabled aircraft to land at the Tartu Airport using DME procedures. Earlier that year, Finnair had suspended scheduled flights to Tarto due to persistent GNSS interference in the region.

***What alternative methods to GNSS navigation should be adopted?***
In GNSS-contested environments, aerial platforms must have alternative positioning methods that do not depend on external radio signals. The methods can be categorized into relative, absolute, collaborative, and experience-based approaches.

Among independent onboard sensors, IMUs play a key role in navigation without GNSS. However, IMUs accumulate a drift over time, which limits the duration of accurate positioning. While high-grade IMUs can significantly extend the drift-free period, they are often too large and costly for lightweight UAVs with limited payload capacity. Therefore, it is recommended to combine lightweight IMUs with complementary navigation methods, such as visual odometry, LiDAR-based localization, or barometric and magnetic sensing, to achieve optimal accuracy with lightweight systems.

Resilient navigation should employ a hierarchical combination of relative, absolute, and cooperative methods. Lightweight UAVs should prioritize onboard sensing and visual localization, potentially supported by map or satellite image based absolute localization. Larger UAVs and crewed aircraft can incorporate synthetic aperture radar (SAR), terrain-based navigation, and map- or satellite-based methods, combined with cooperative positioning, to ensure robust performance under all conditions. Artificial intelligence (AI) offers promising opportunities to enhance navigation performance.

Although many of these approaches have been already demonstrated at good performance levels, and are incorporated into commercial systems also, robust solutions are still missing. Therefore, these technologies should be actively researched and developed, with attention to both navigation capabilities and cybersecurity aspects. Looking ahead, hybrid and adaptive navigation systems are expected to become the standard. These systems will smartly combine GNSS and non-GNSS sensors, automatically adapt to signal degradation, and exploit AI-based integrity checks to maintain seamless navigation continuity. Such architectures represent the next step toward resilient, secure, and autonomous positioning under all operational conditions.

Methods for resilient PNT currently available that can either improve the accuracy of GNSS or replace it in a disruption have been discussed in this report. These include the use of Signals of Opportunity (SoO) and other RF-positioning, including those discussed for aviation purposes. While, e.g., optical and inertial sensors are increasingly used, more work is needed for their integration in the existing and standardized systems. Integrity monitoring is vital and becomes even more important for autonomous systems.

In future, when the LEO-PNT layer has been added to complement the MEO GNSS (GPS, Galileo, BeiDou, Glonass), it will also increase the resistance to disruptions by posing further challenges to the attacker, even though LEO-PNT itself is vulnerable to jamming. The most powerful jamming resistance is expected to be available from quantum sensors, which are gradually increasing in, e.g., maritime applications. The best resilience will be achieved by the integration and seamless use of all the available navigation signals and methods and constantly updating situational awareness. This is already taking place in different applications, but the implementations are application specific, and more research is needed to enable a more ubiquitous and general application of the methods.

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